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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

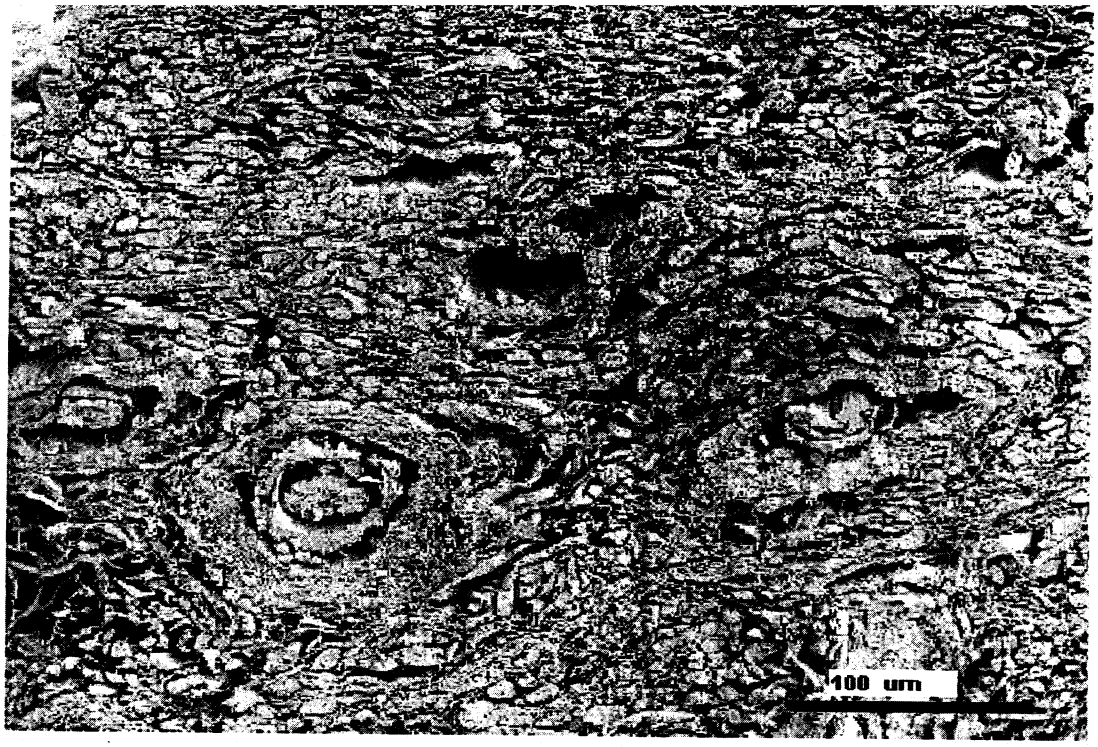

FIGURE 1. — Micrograph showing grain layer with sheet structure.

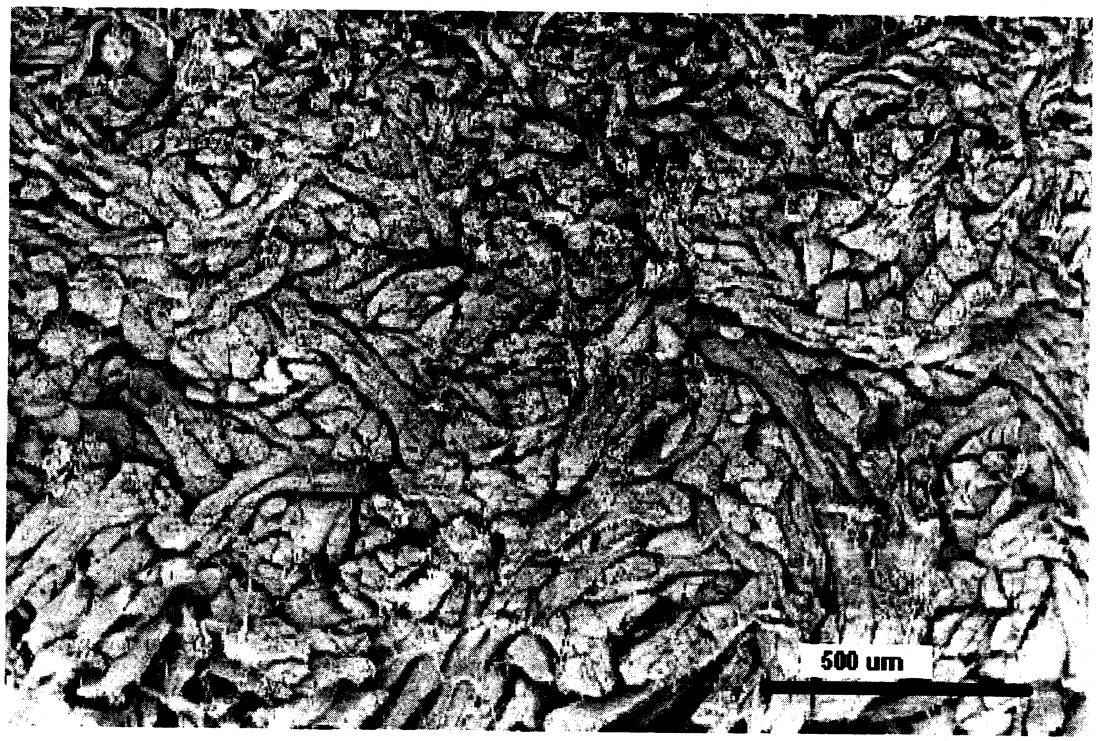

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

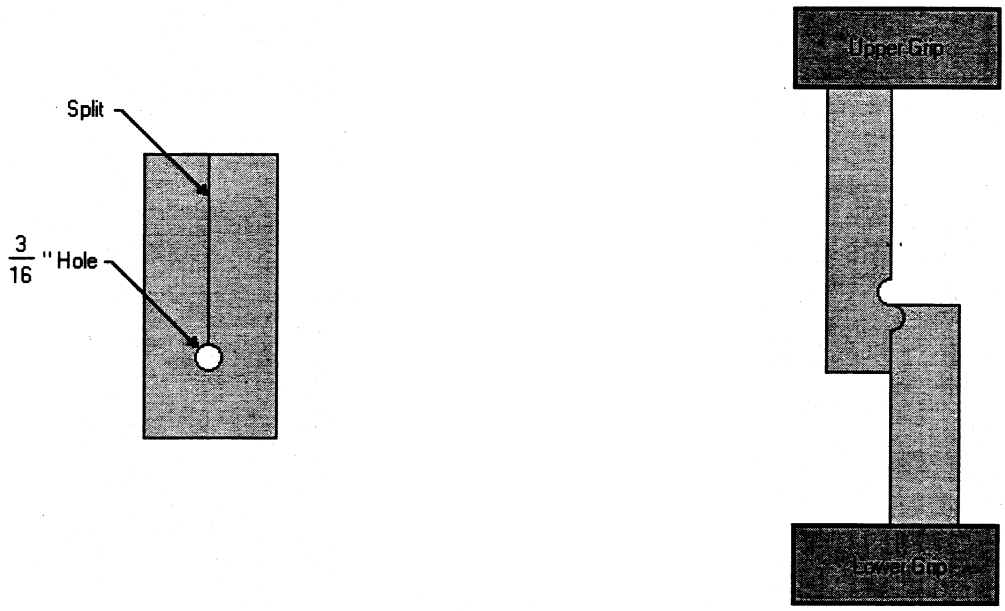

FIGURE 3. — Tear test scheme.

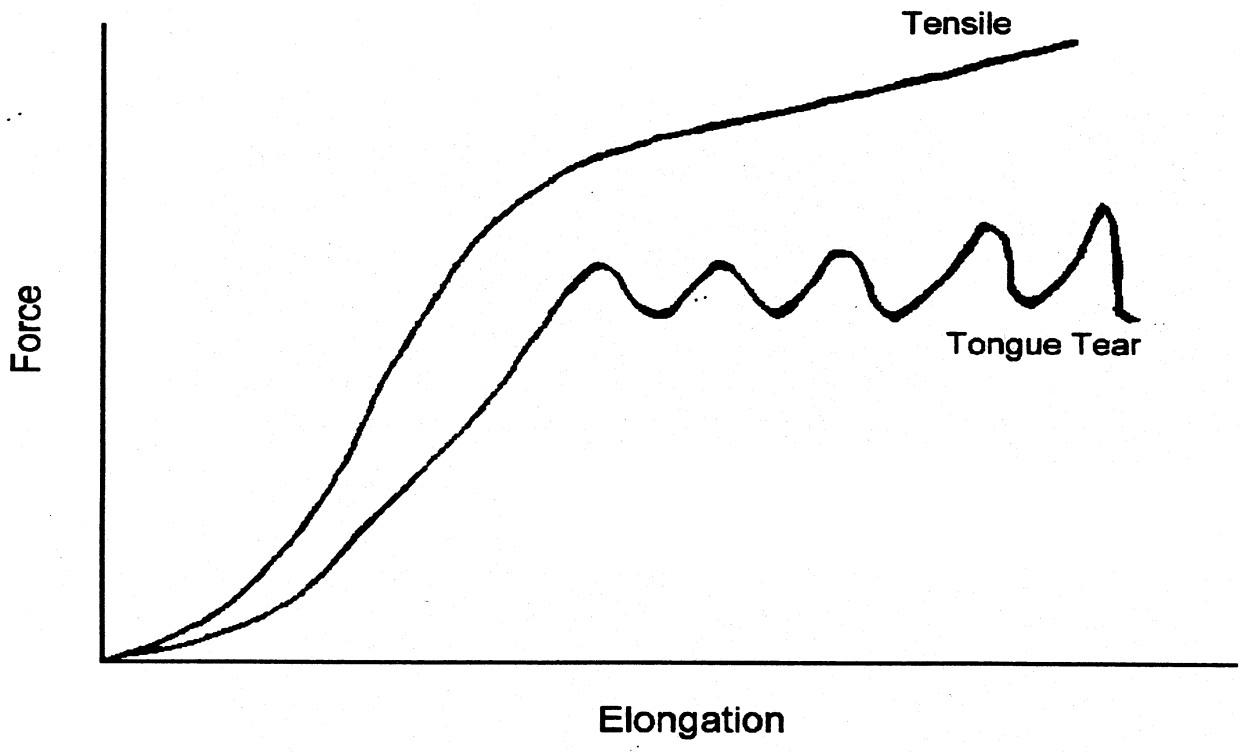

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

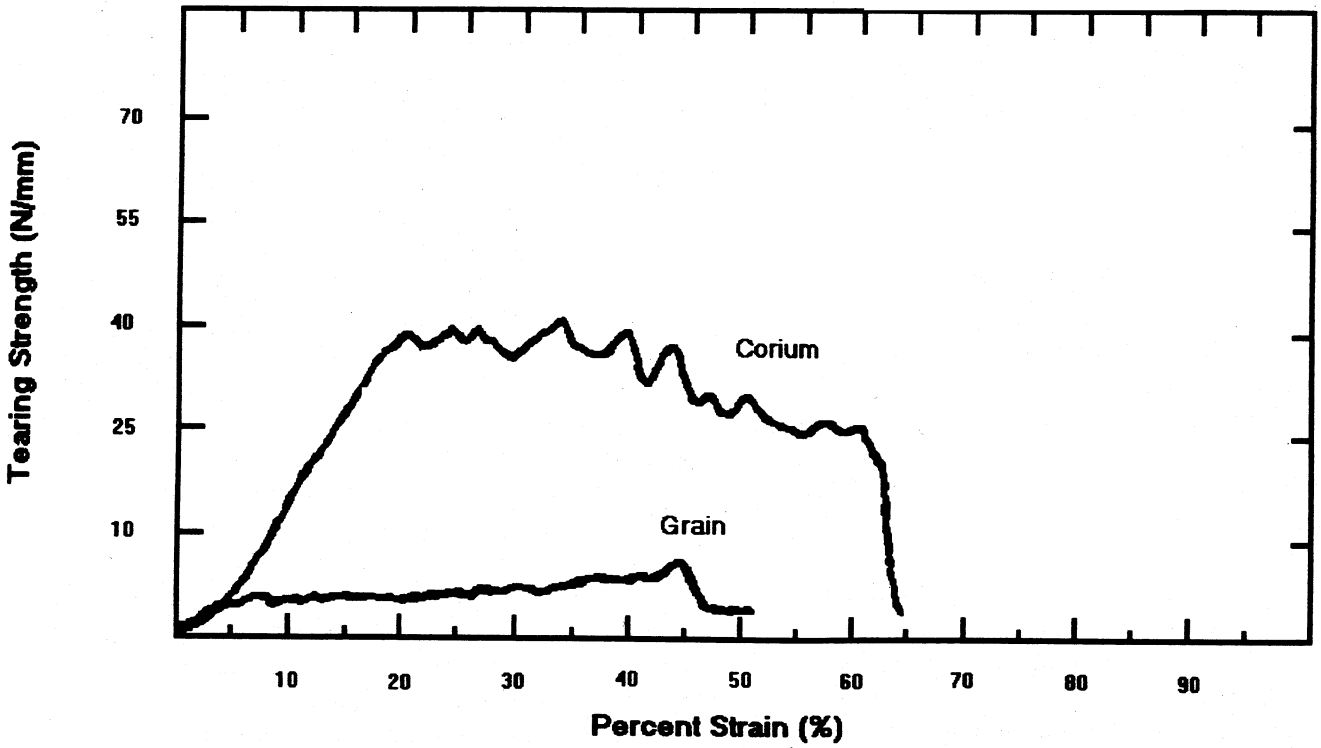

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

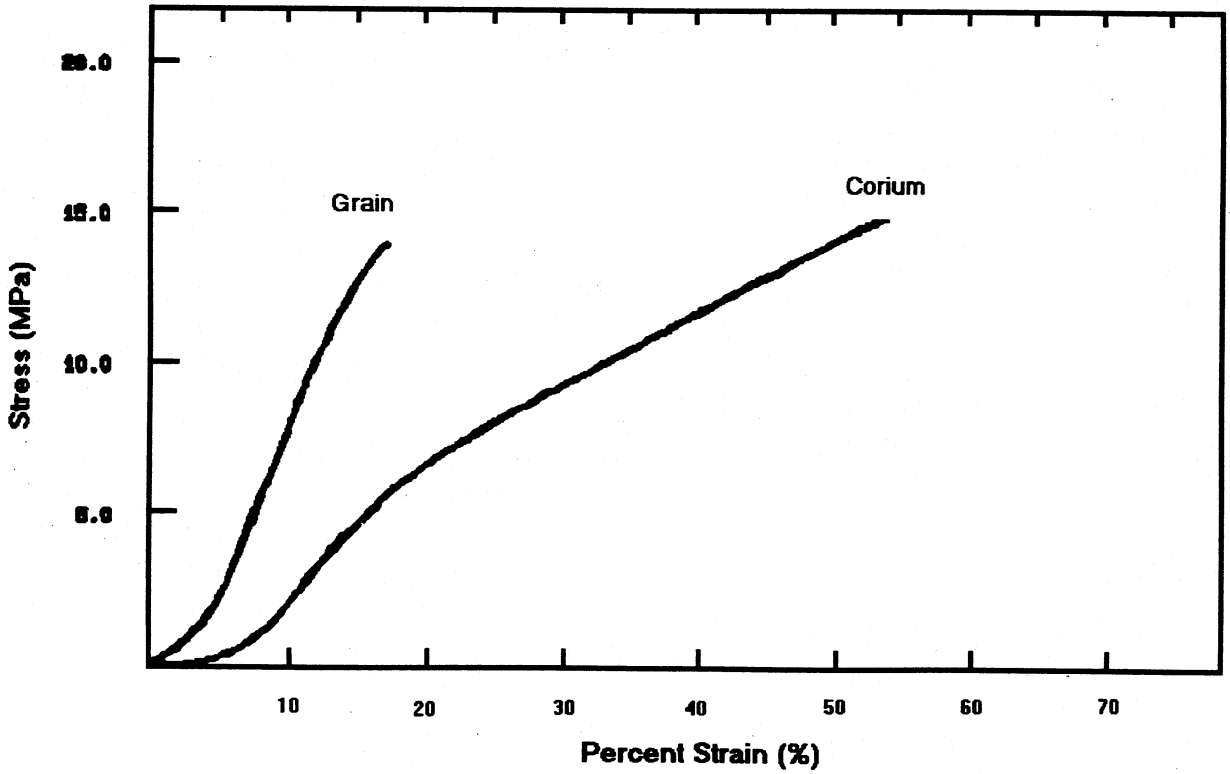

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

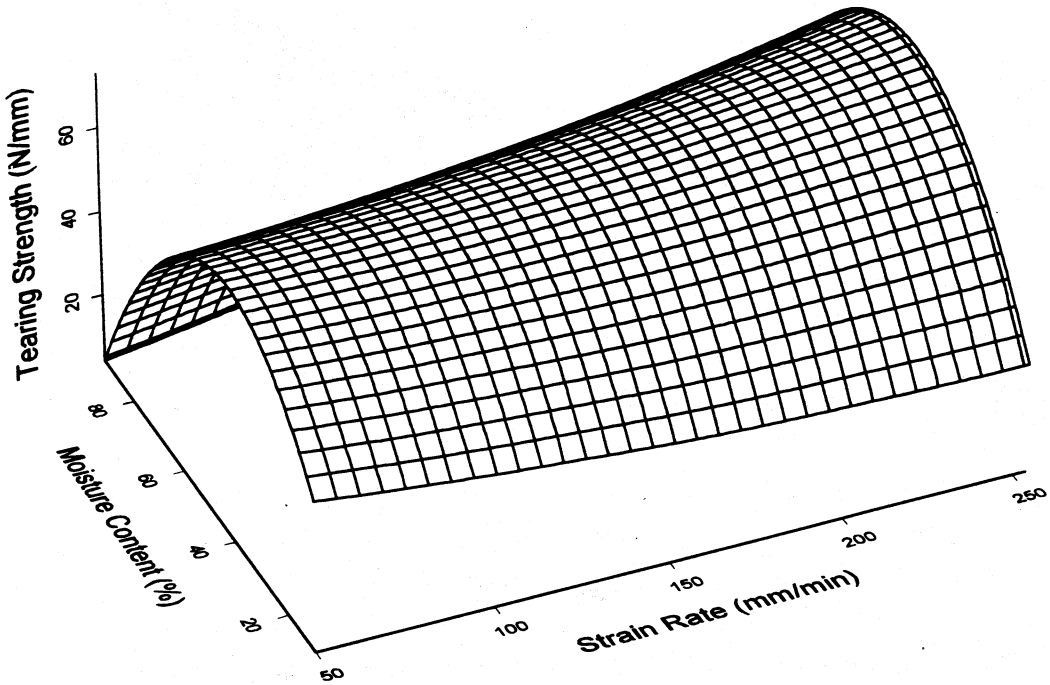

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

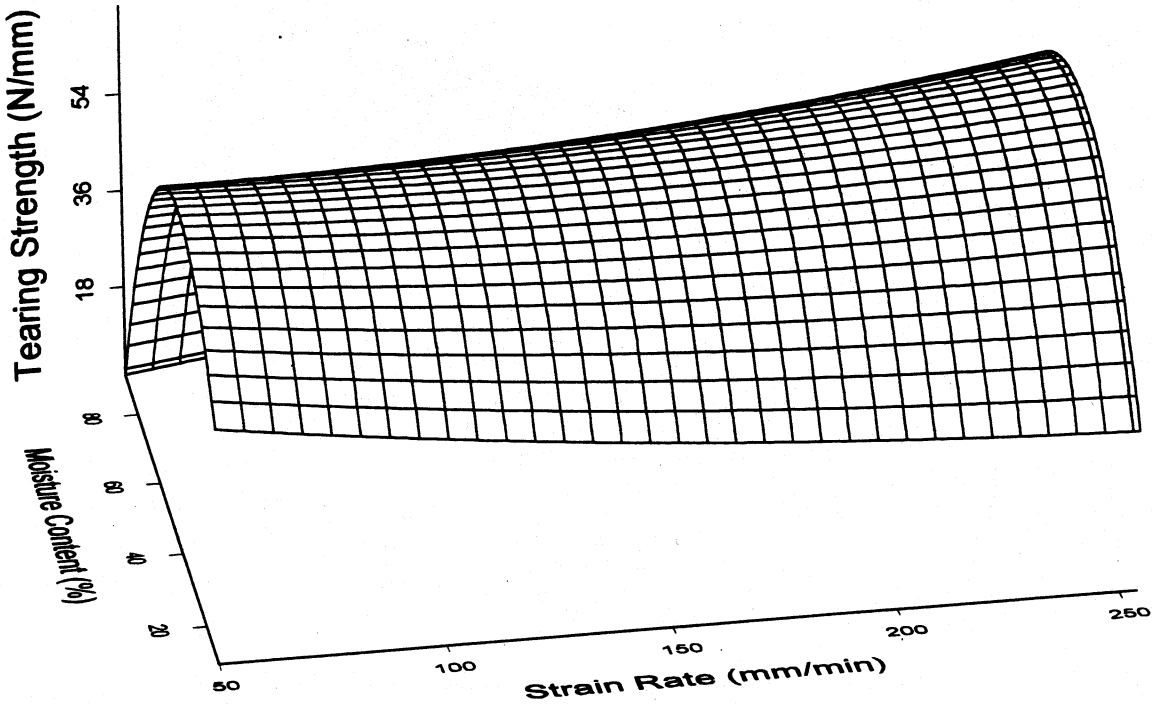

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

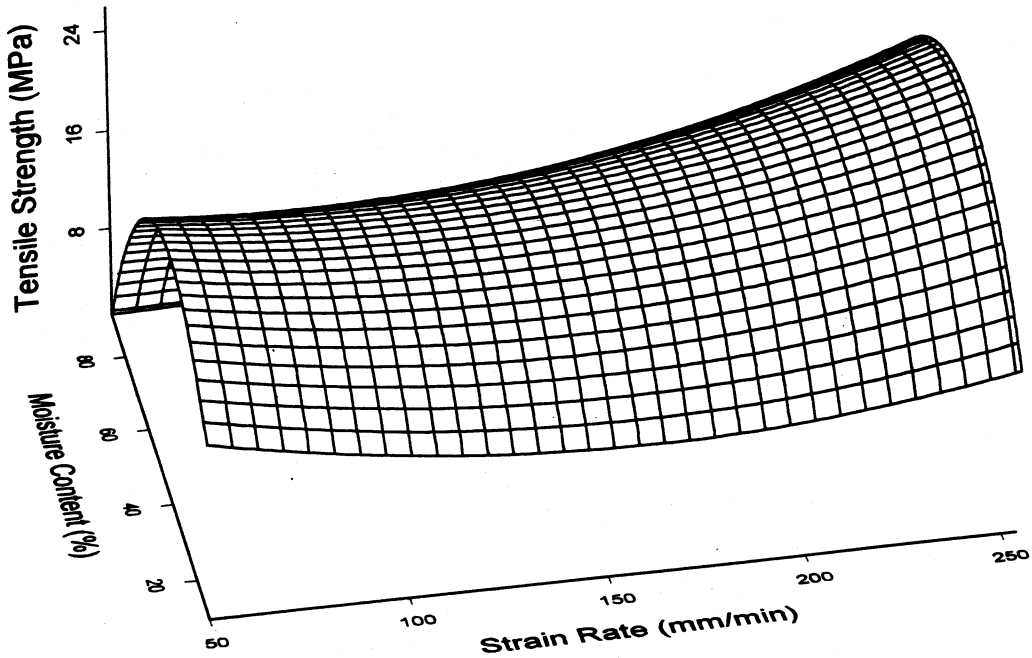

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

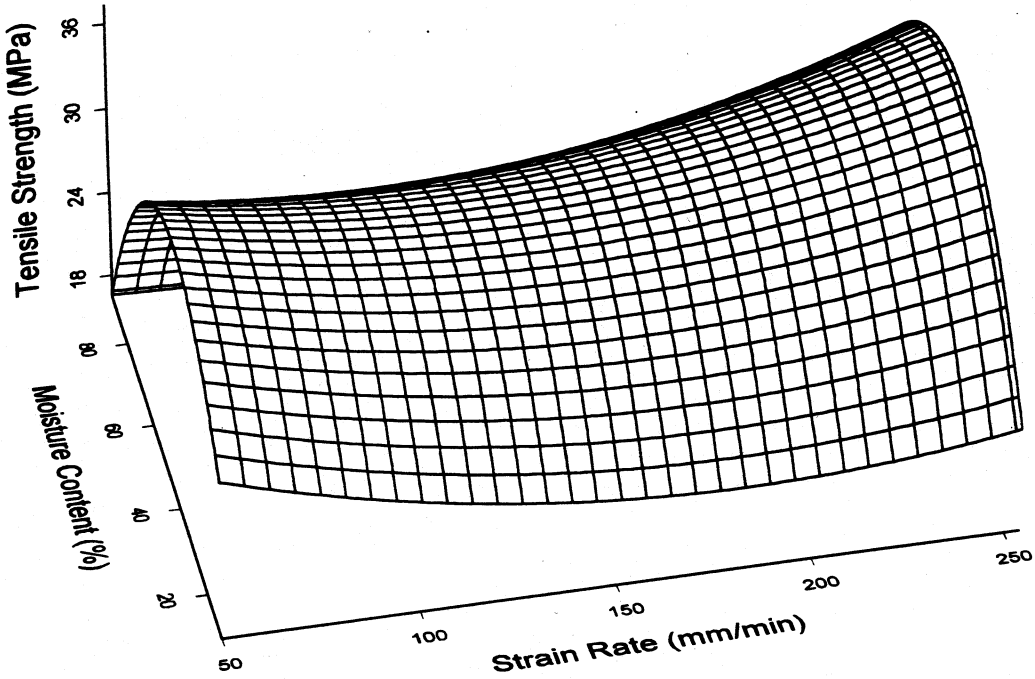

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

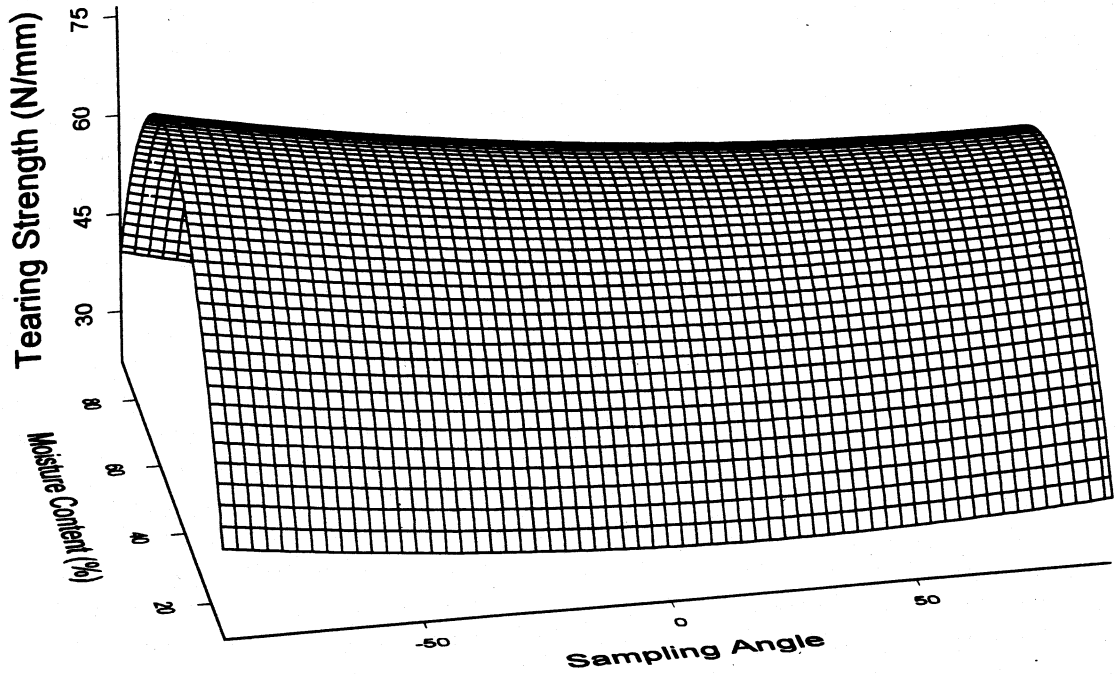

FIGURE 11. — Effect of sampling angle on tearing strength.

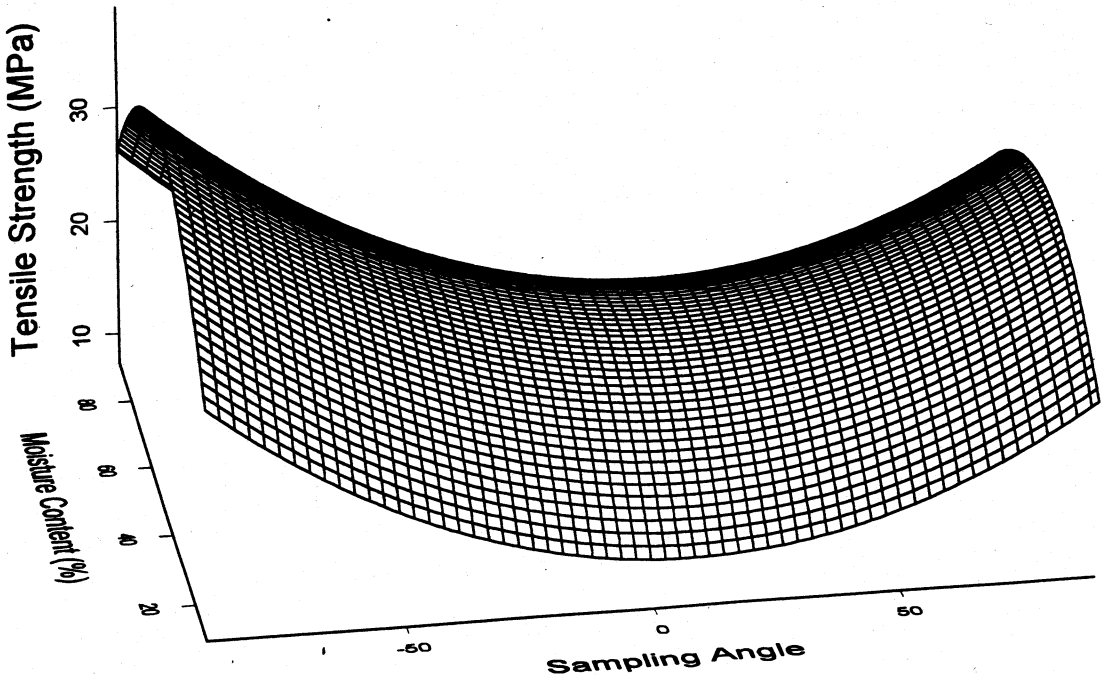

FIGURE 12. — Effect of sampling angle on tensile strength.

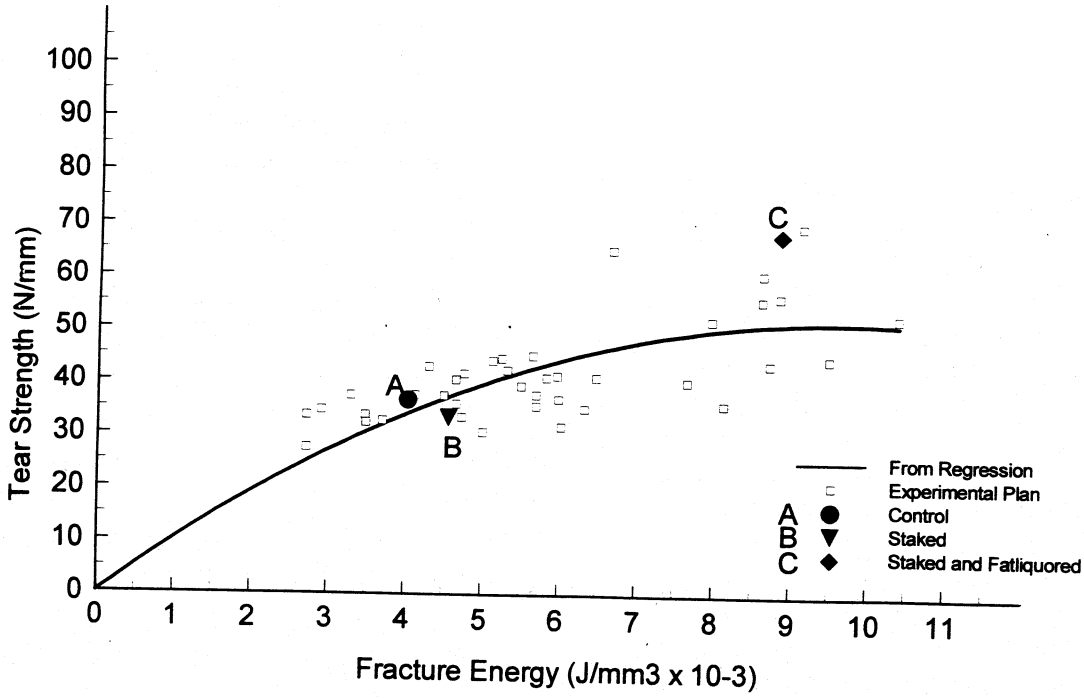

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

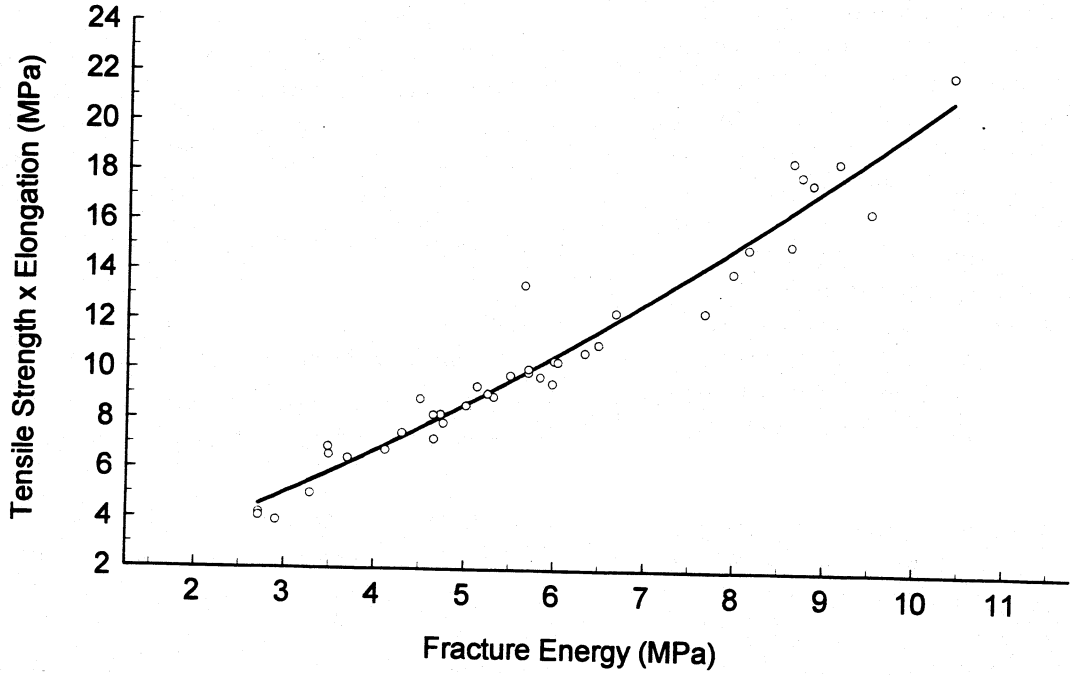

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

We wish to thank Dr. John G. Phillips for advice on SAS statistical program. We also thank Dr. Peter H. Cooke and Mr. Lenier W. Tucker, Sr., for the SEM micrographs. Particular appreciation is extended to Mr. Satyendra De of Howes Leather Corporation and Drs. David Coffin and James Shieh for their invaluable suggestions.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

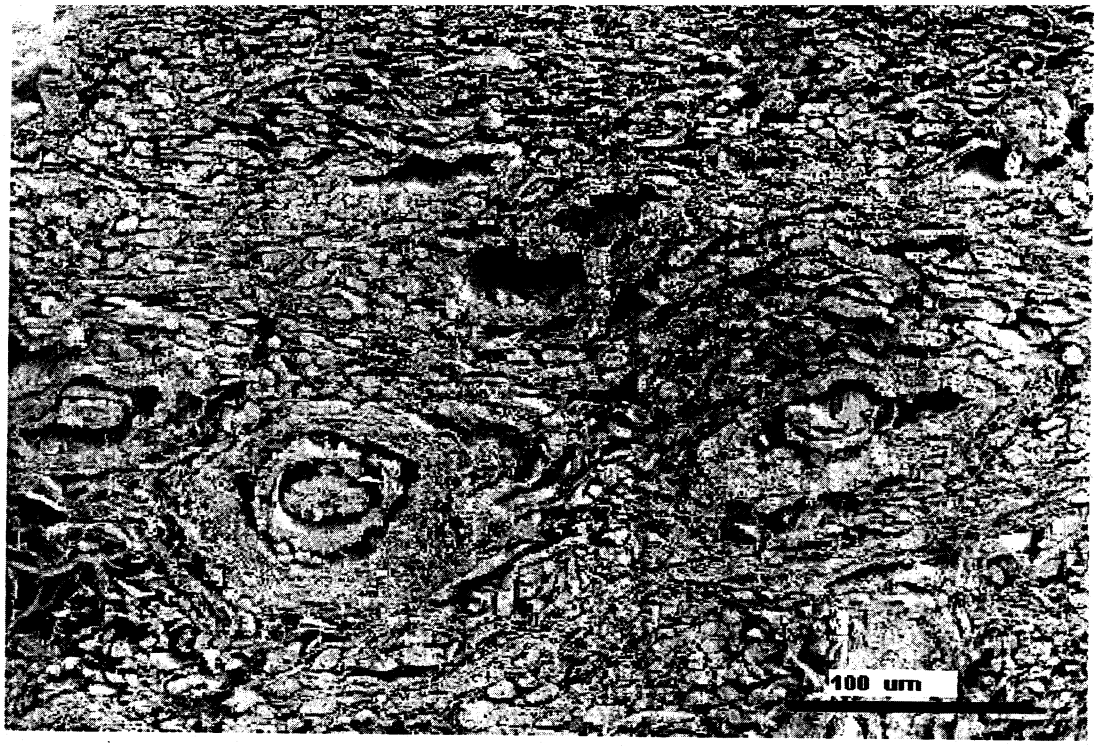

FIGURE 1. — Micrograph showing grain layer with sheet structure.

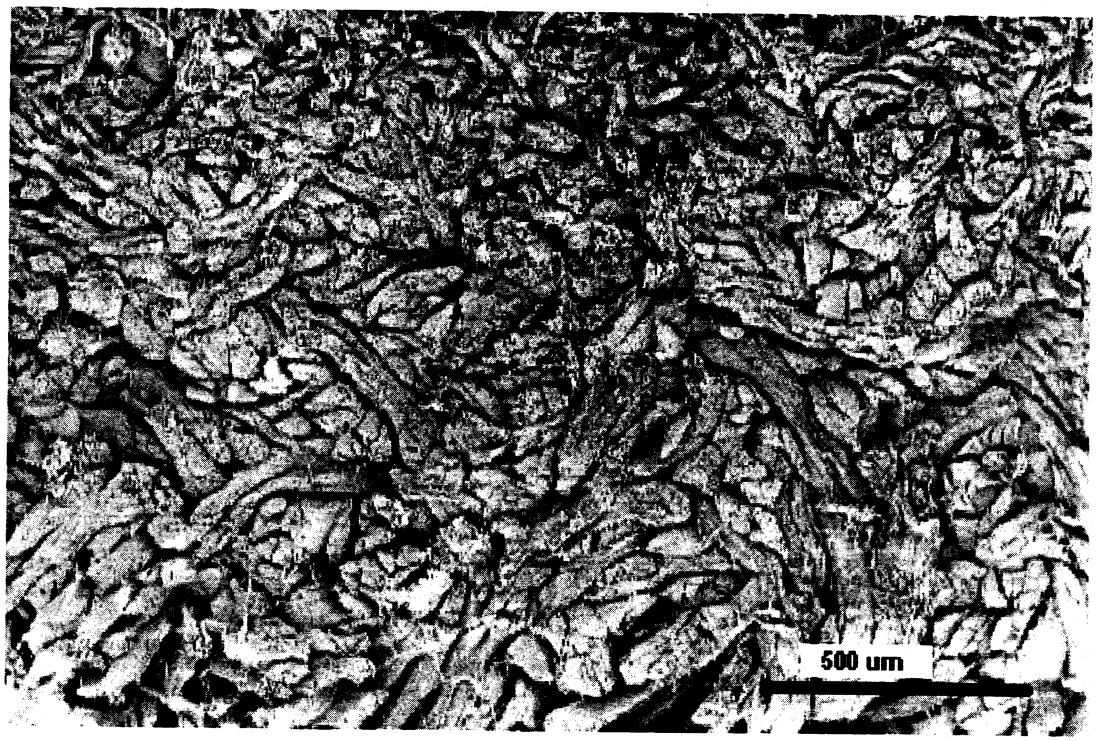

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

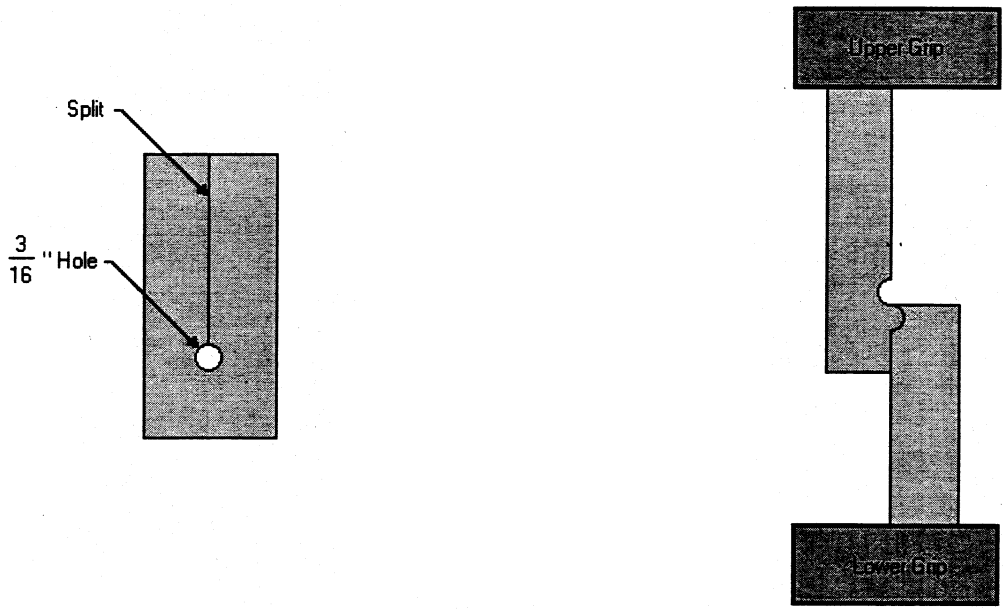

FIGURE 3. — Tear test scheme.

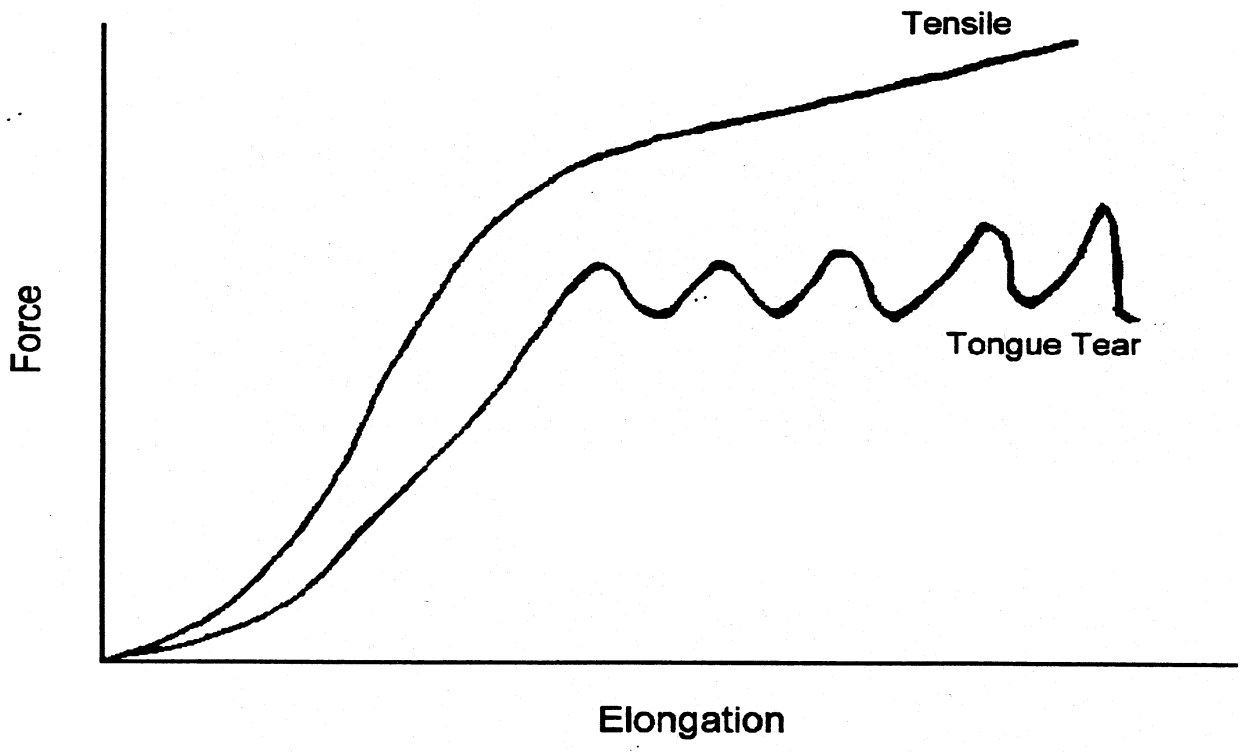

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

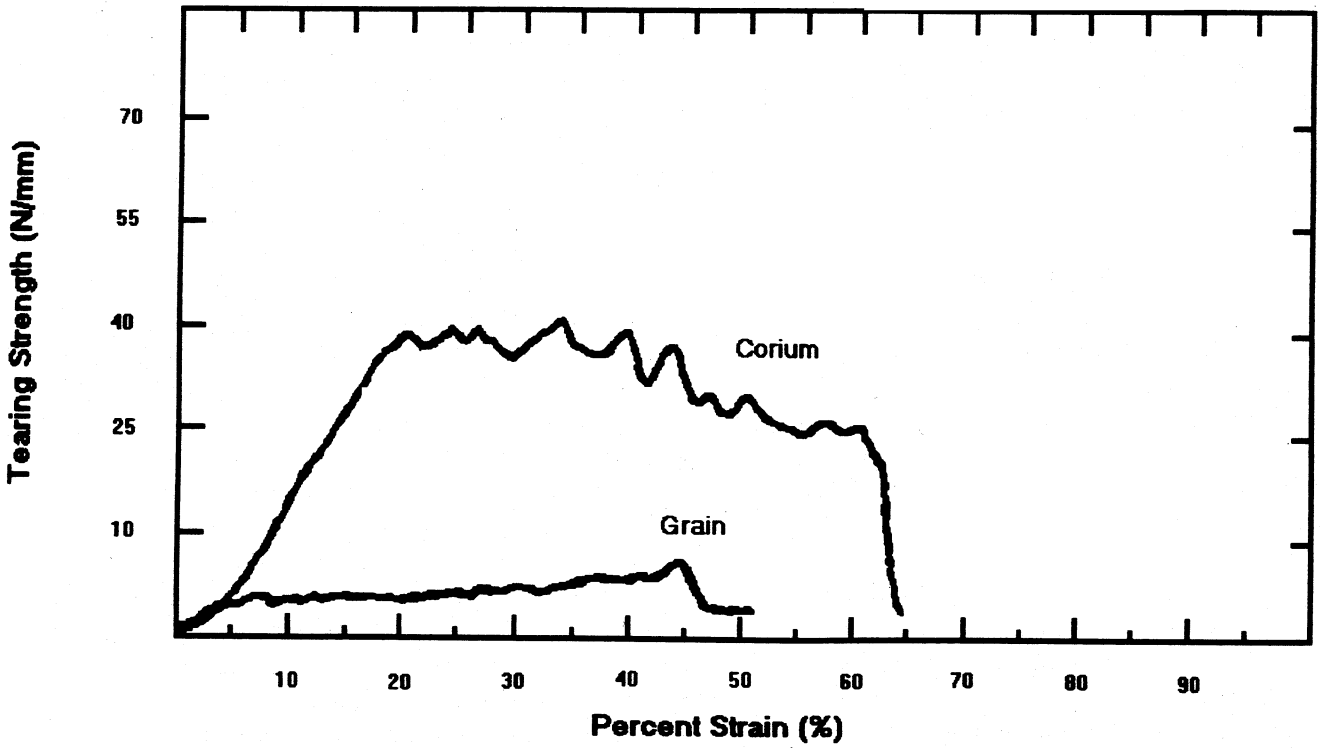

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

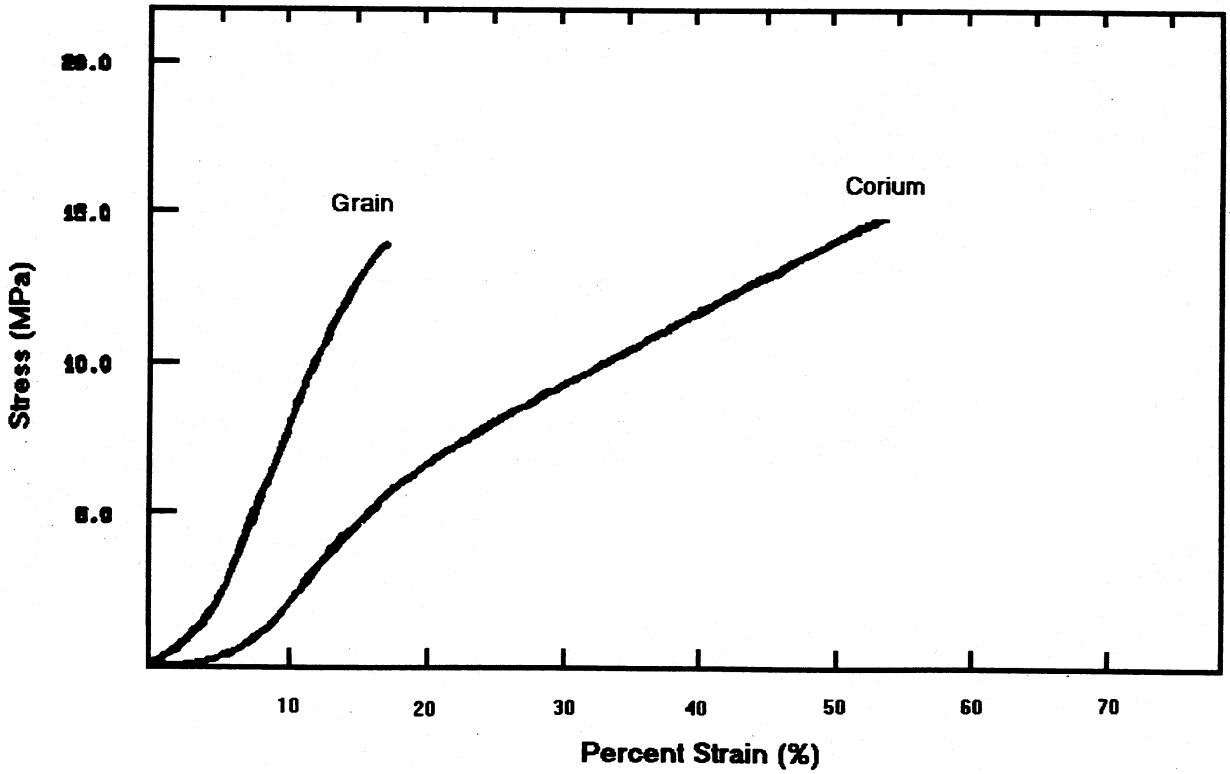

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

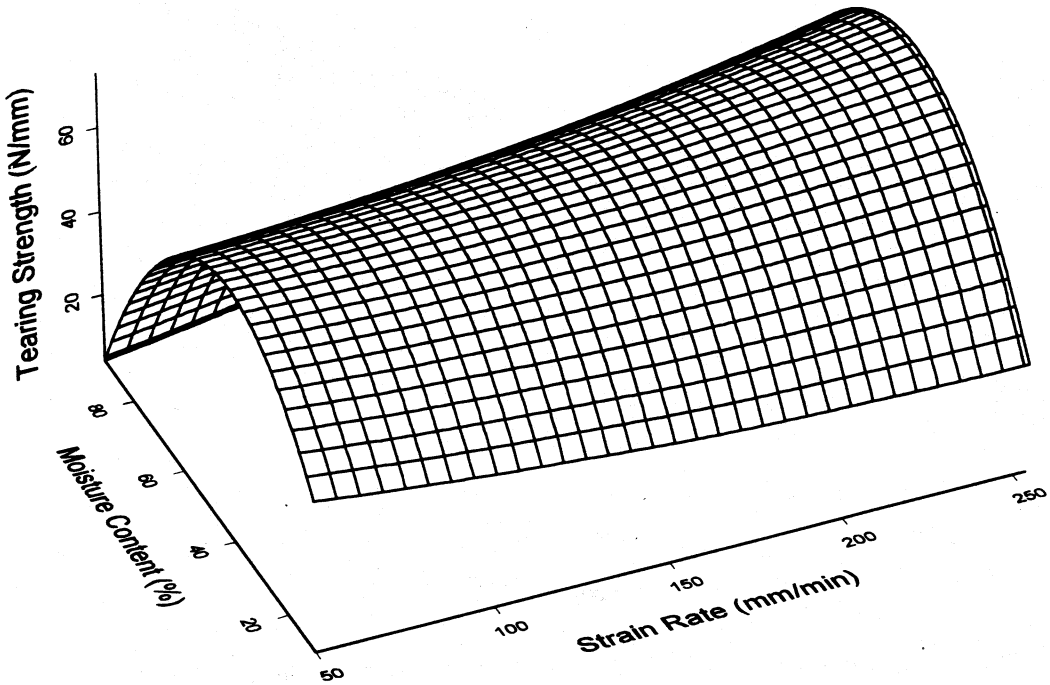

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

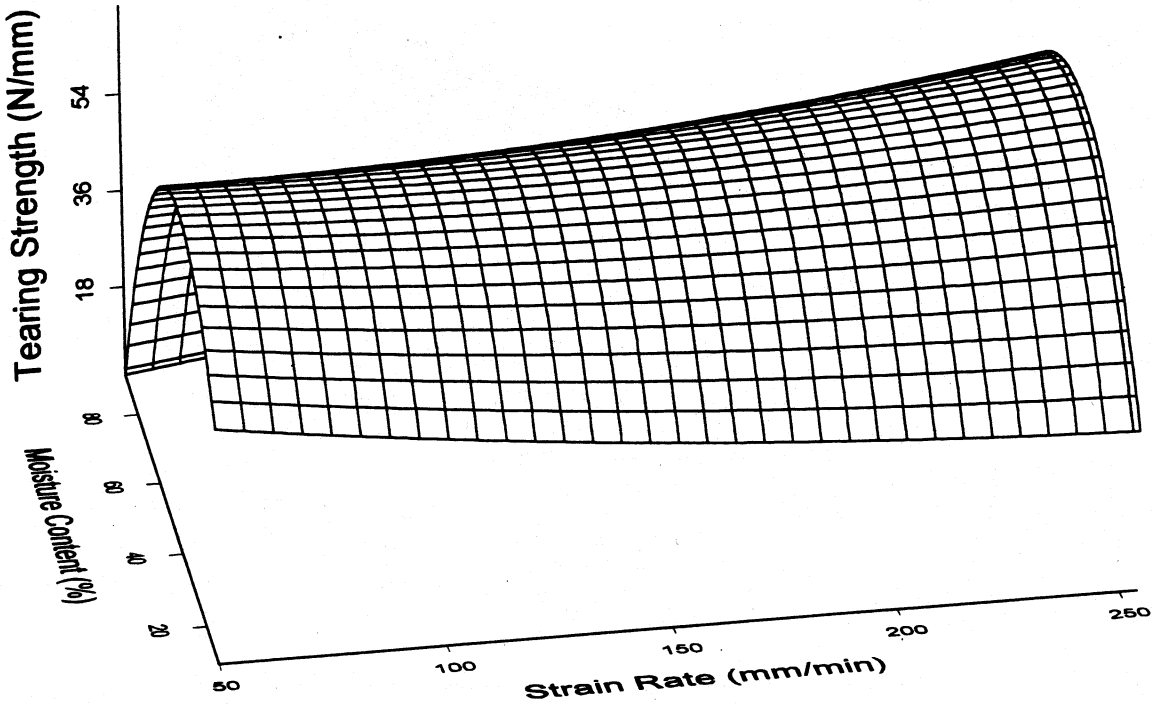

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

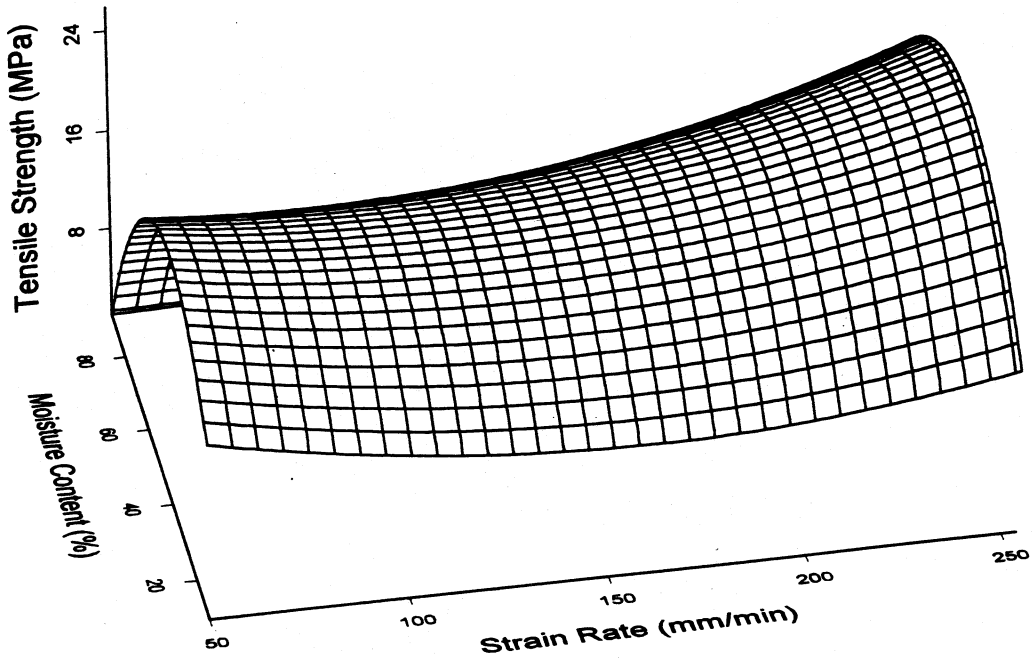

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

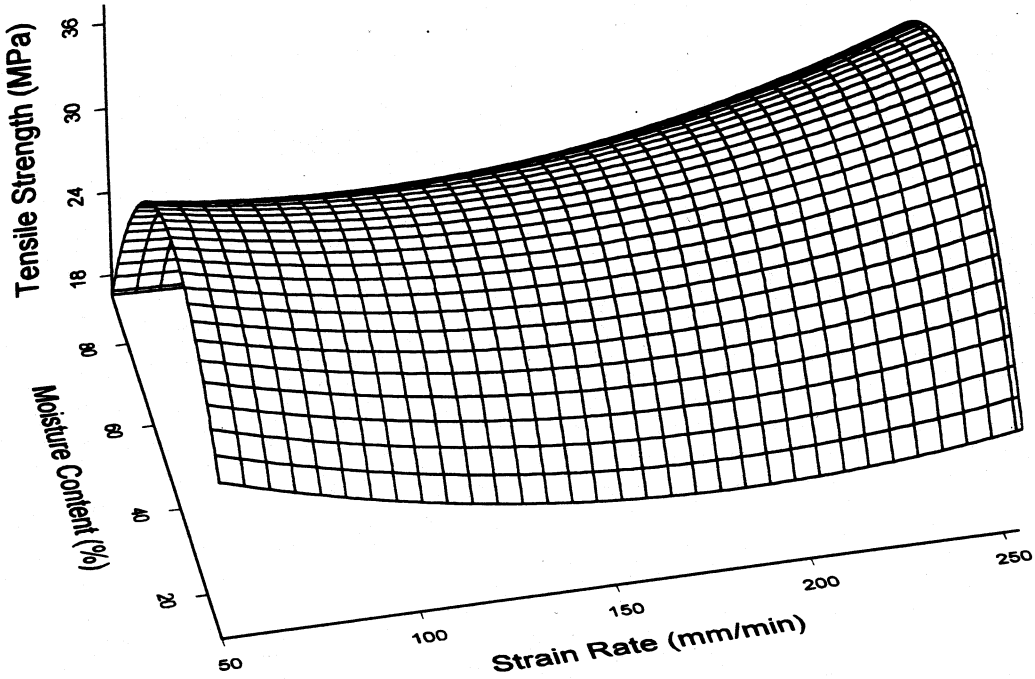

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

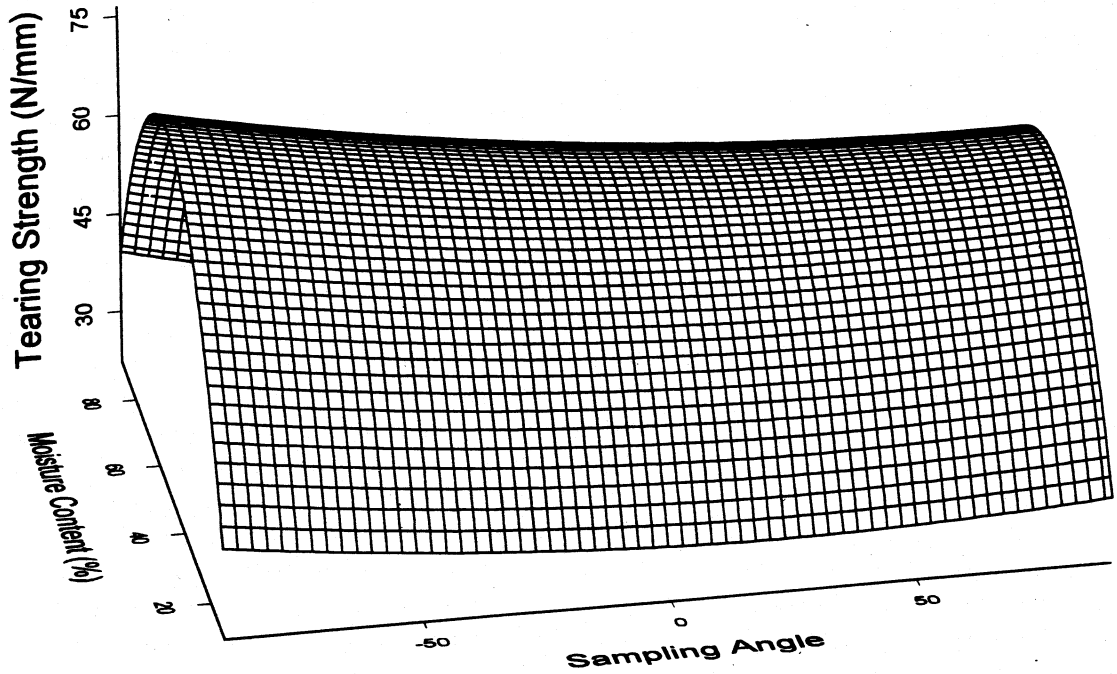

FIGURE 11. — Effect of sampling angle on tearing strength.

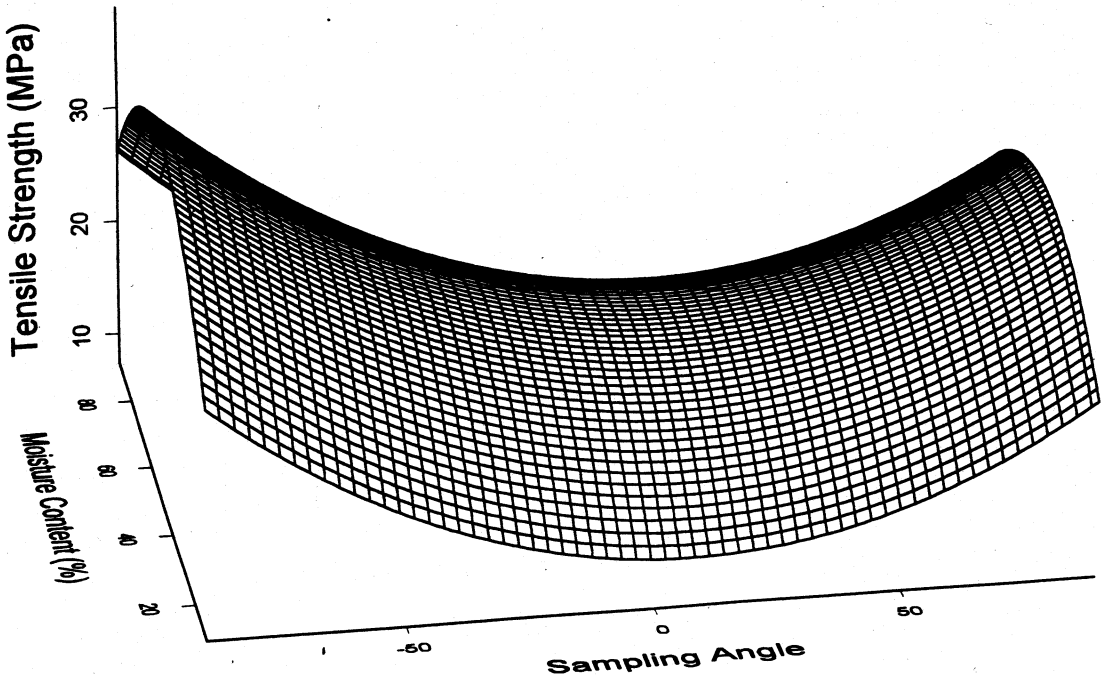

FIGURE 12. — Effect of sampling angle on tensile strength.

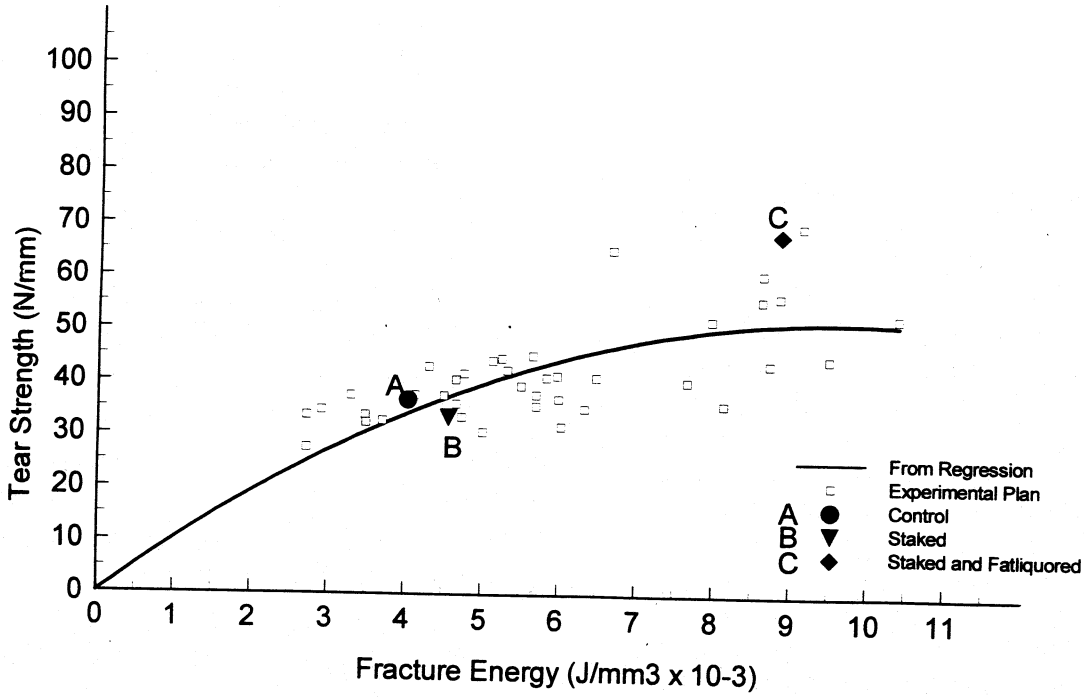

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

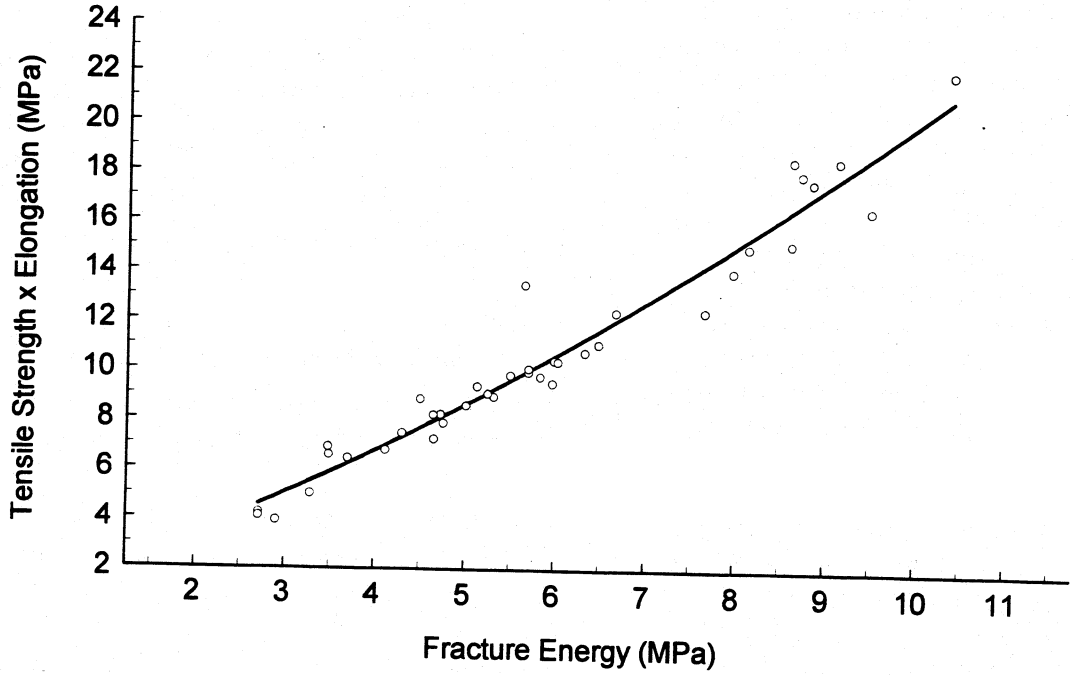

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

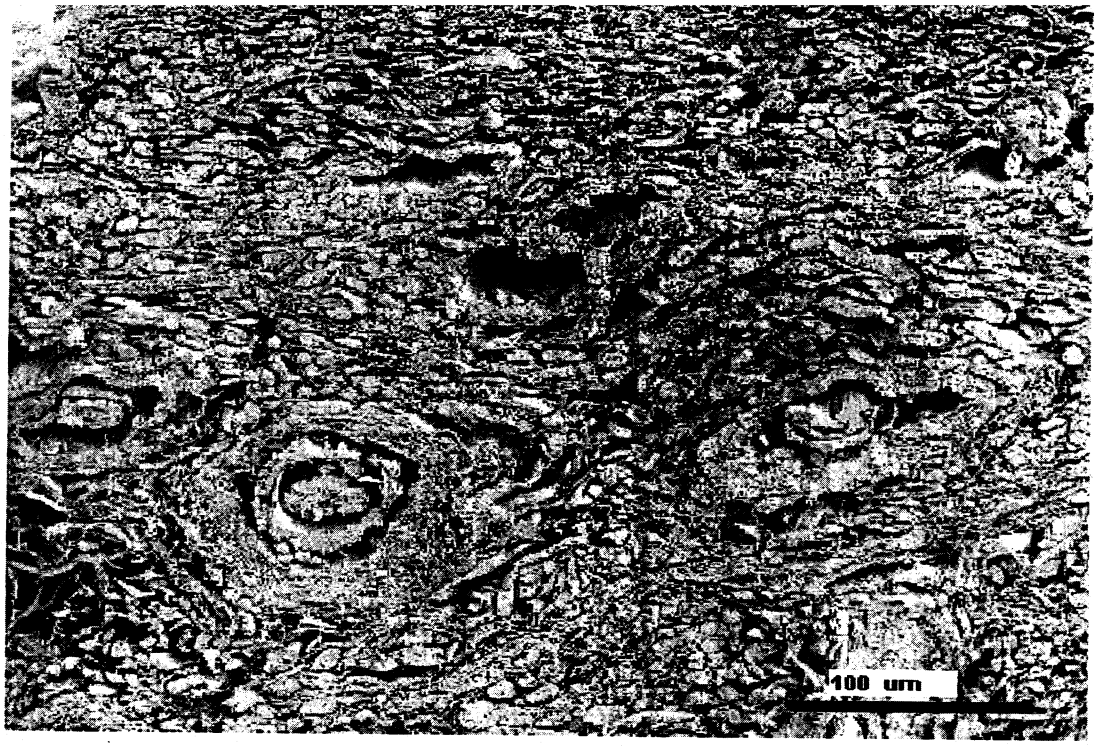

FIGURE 1. — Micrograph showing grain layer with sheet structure.

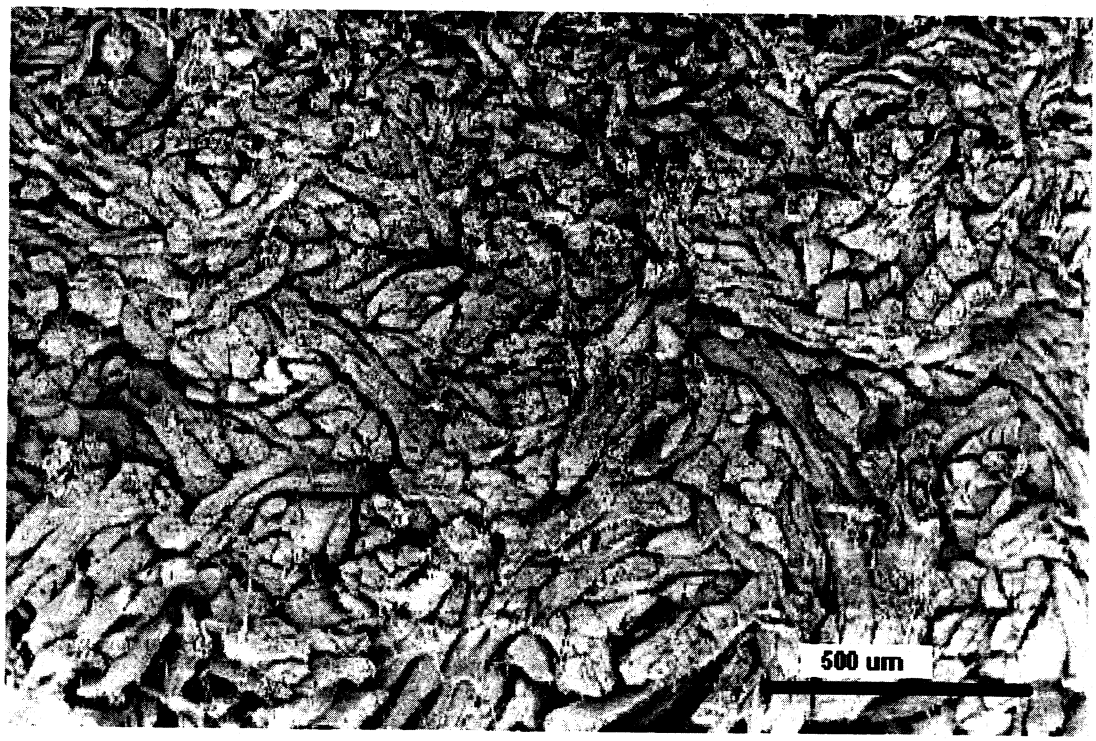

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

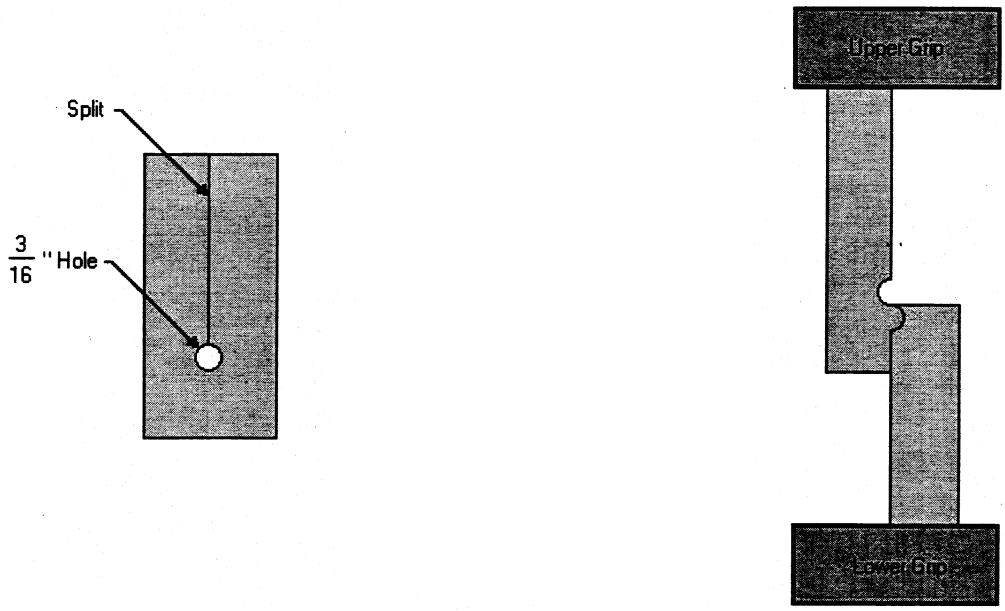

FIGURE 3. — Tear test scheme.

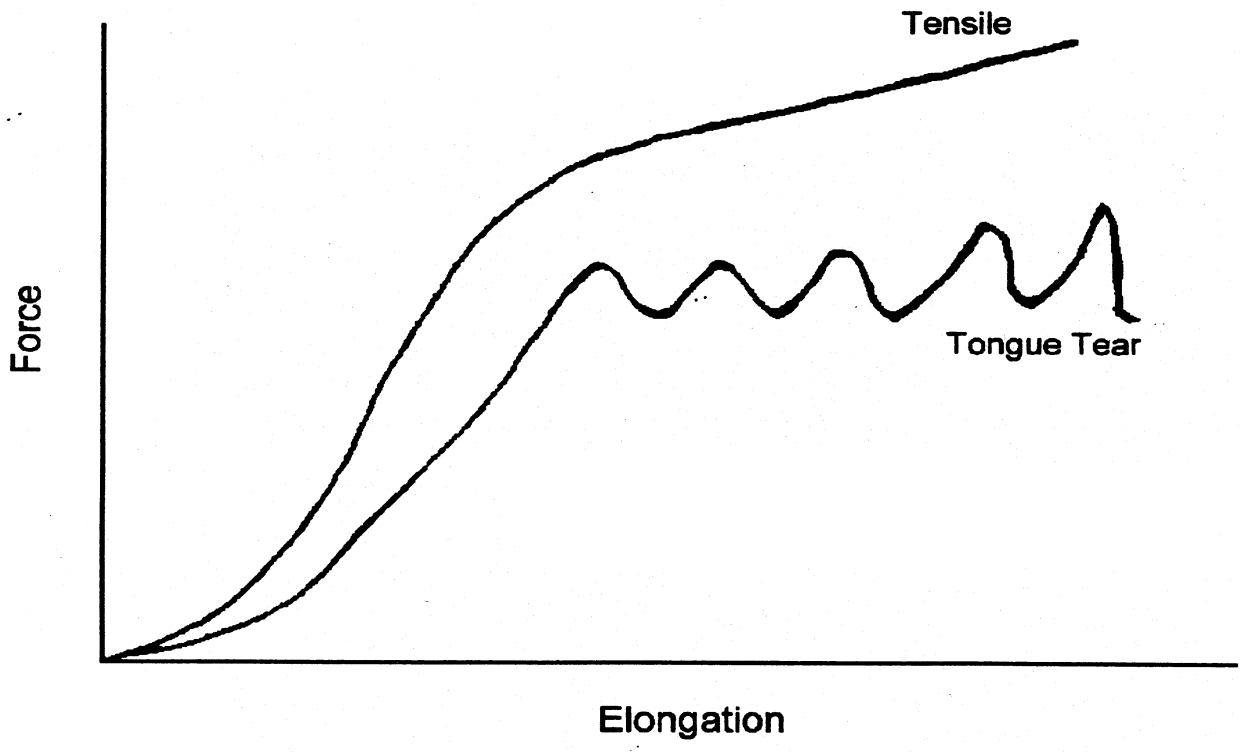

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

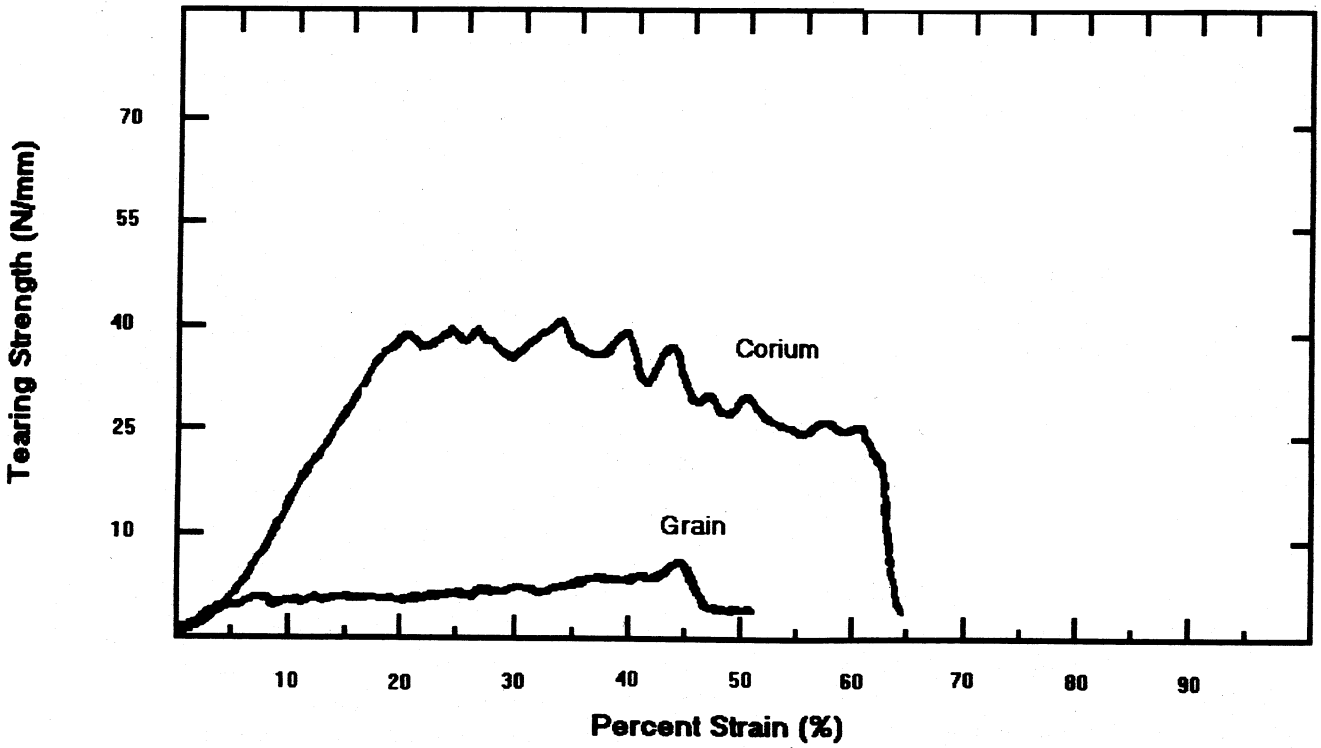

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

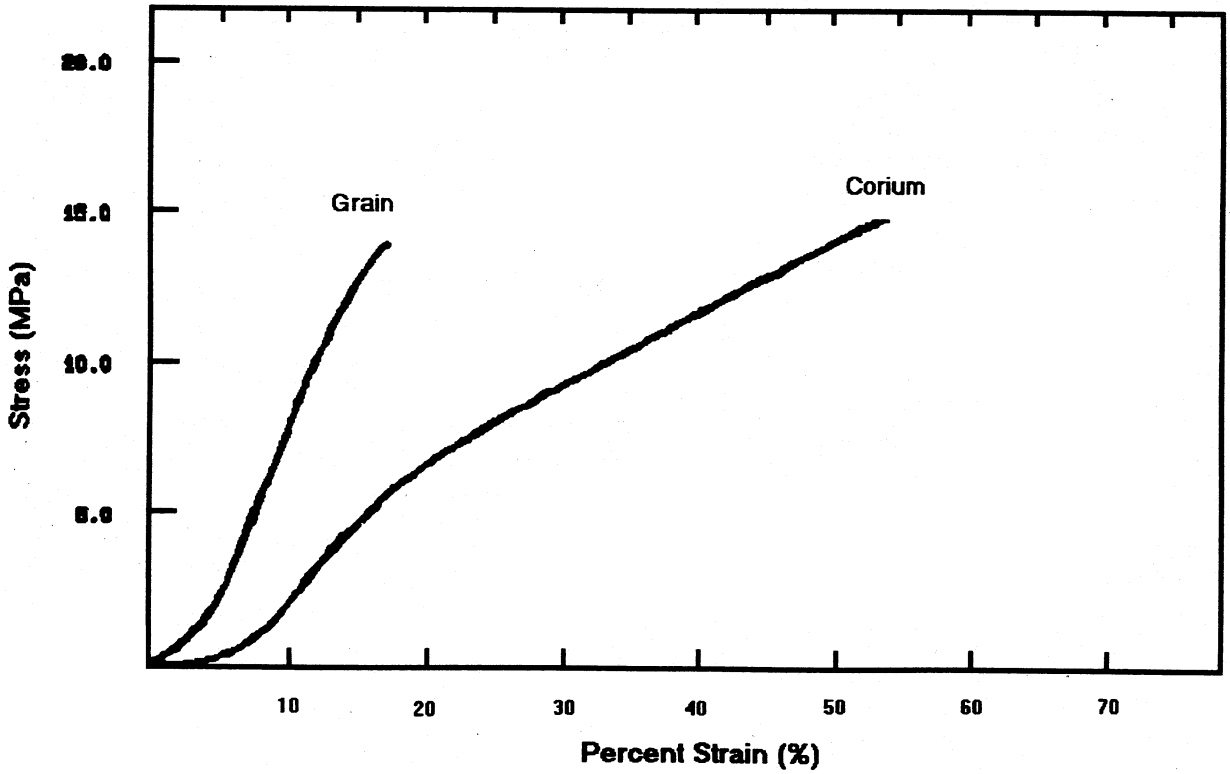

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

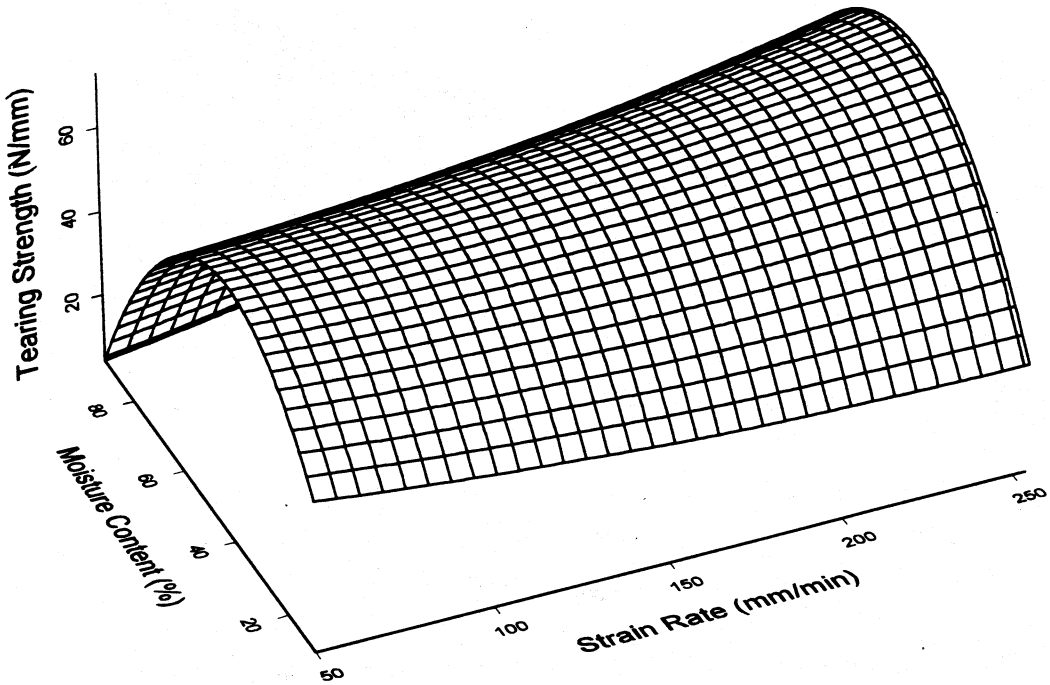

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

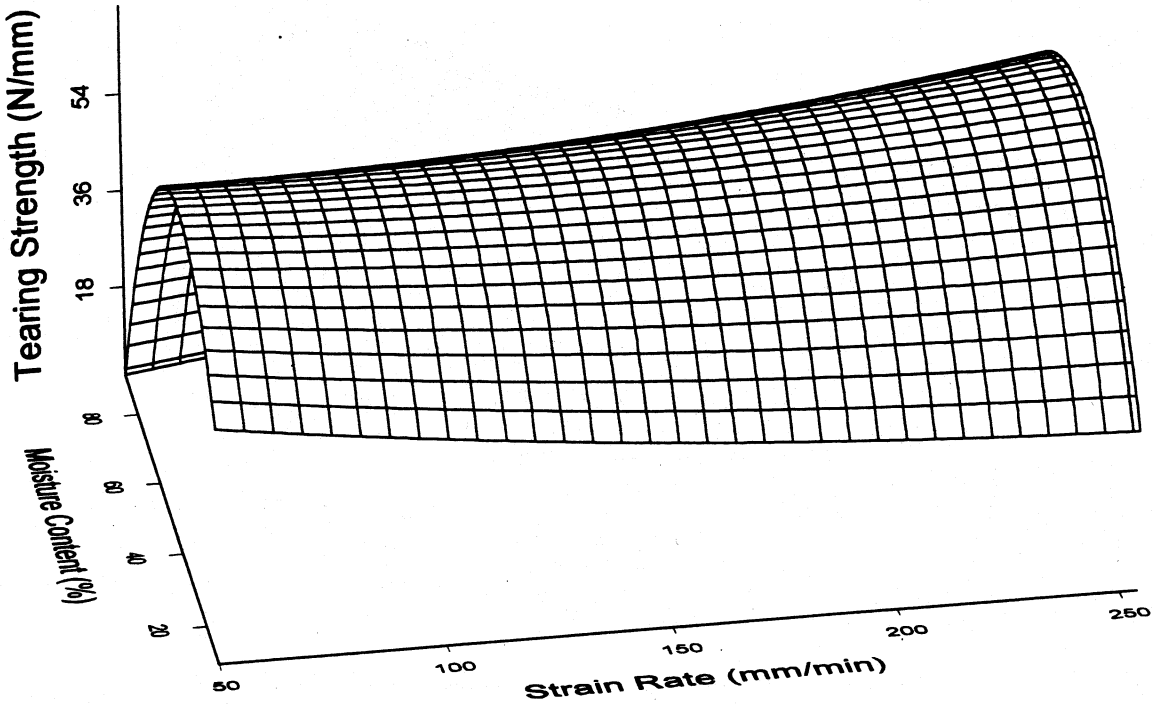

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

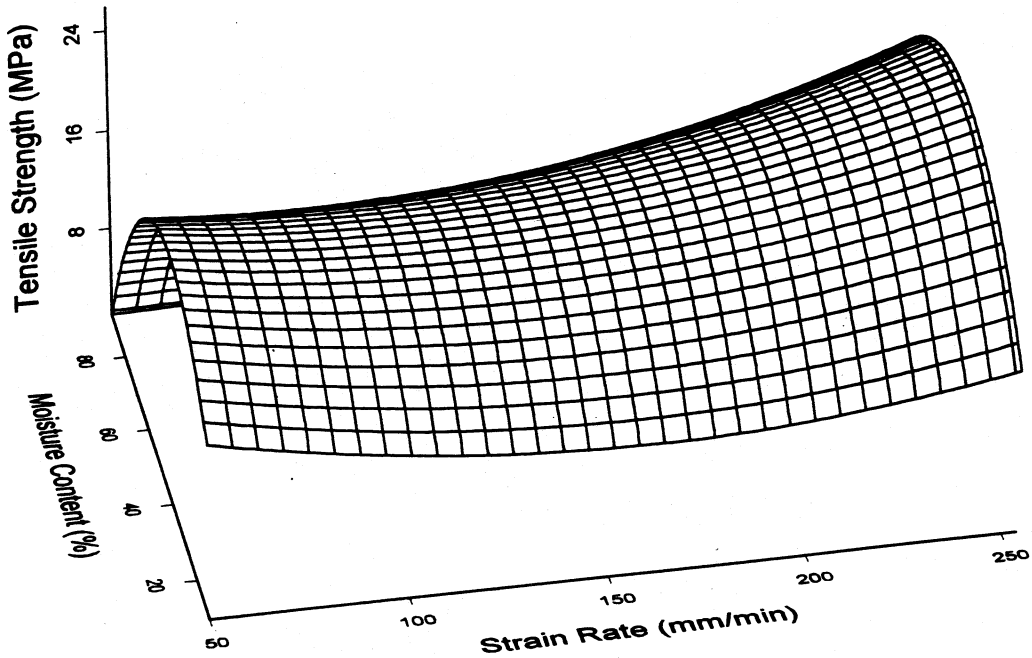

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

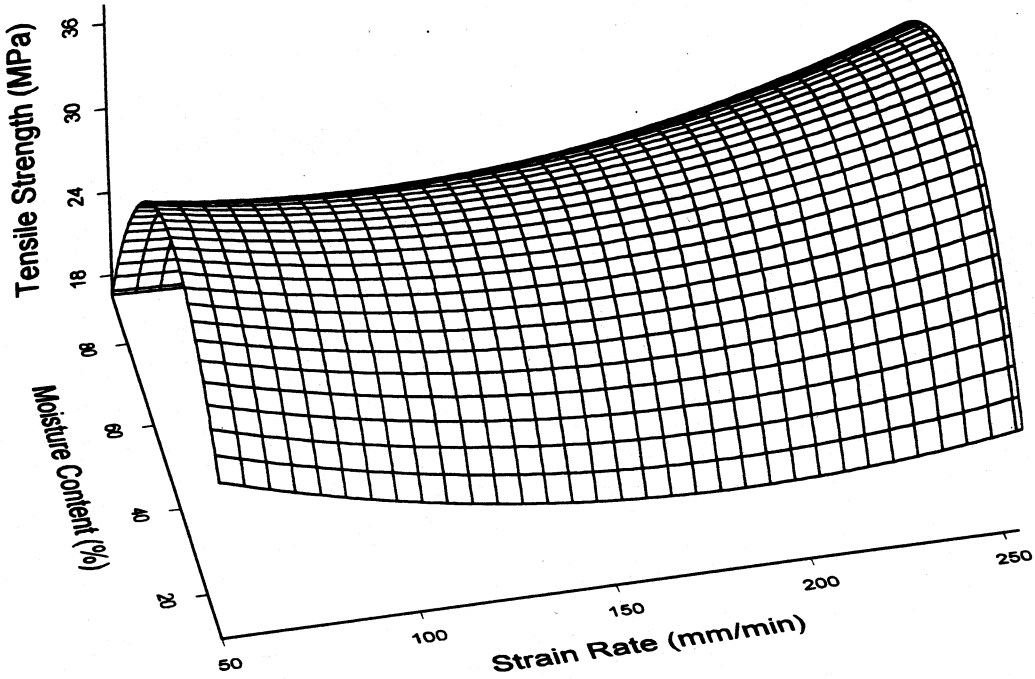

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

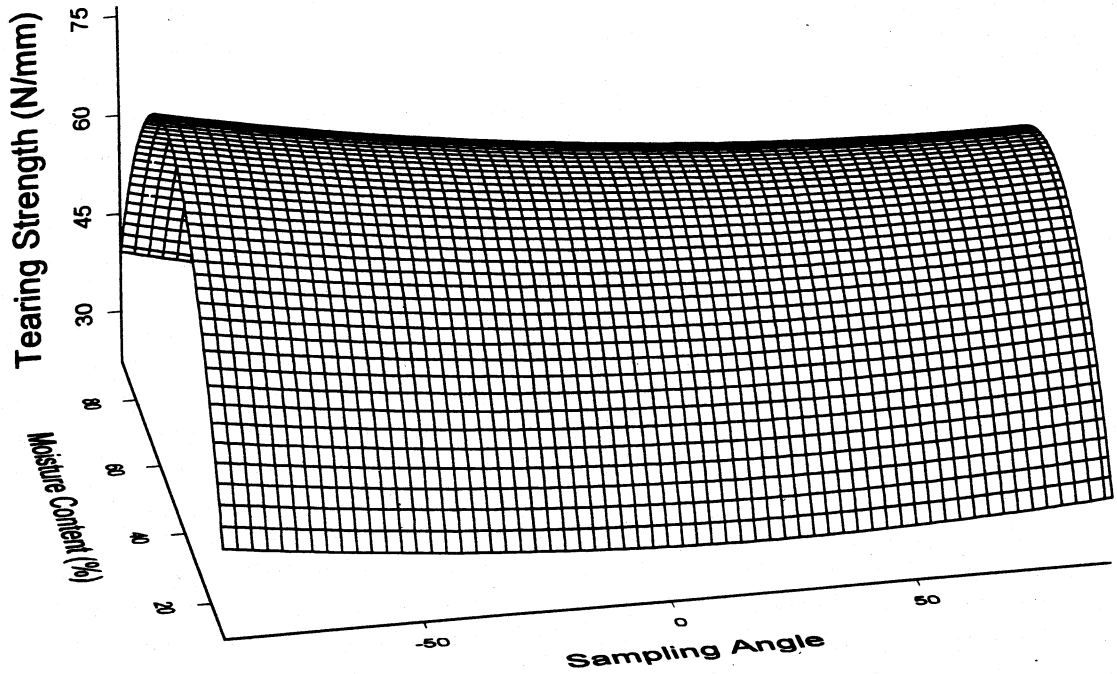

FIGURE 11. — Effect of sampling angle on tearing strength.

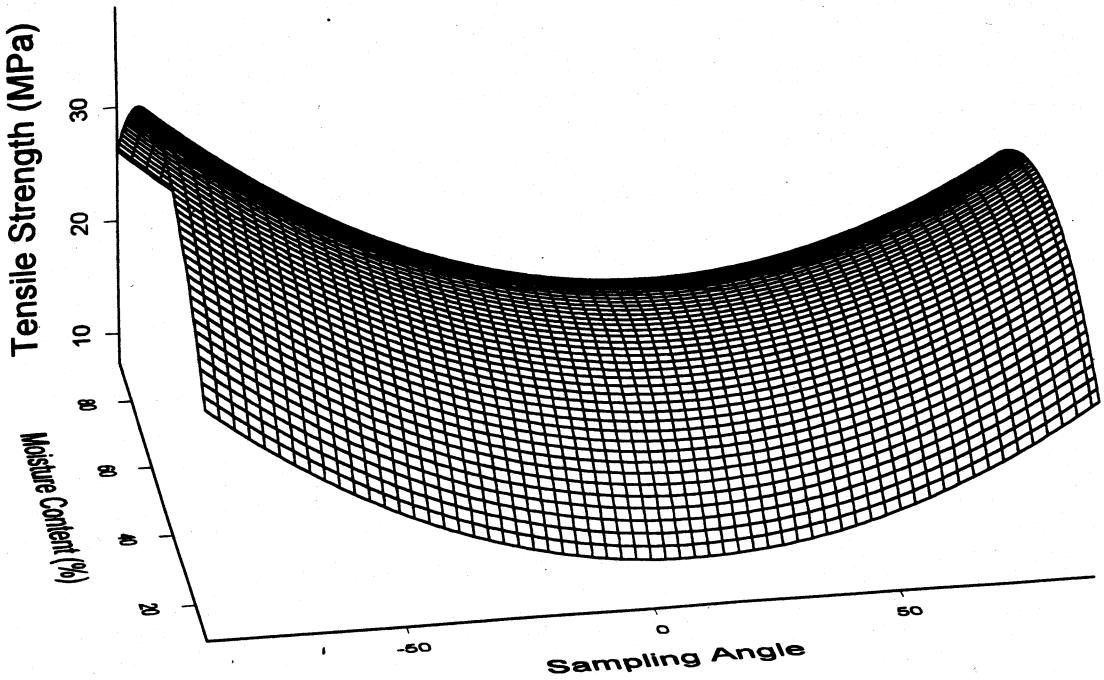

FIGURE 12. — Effect of sampling angle on tensile strength.

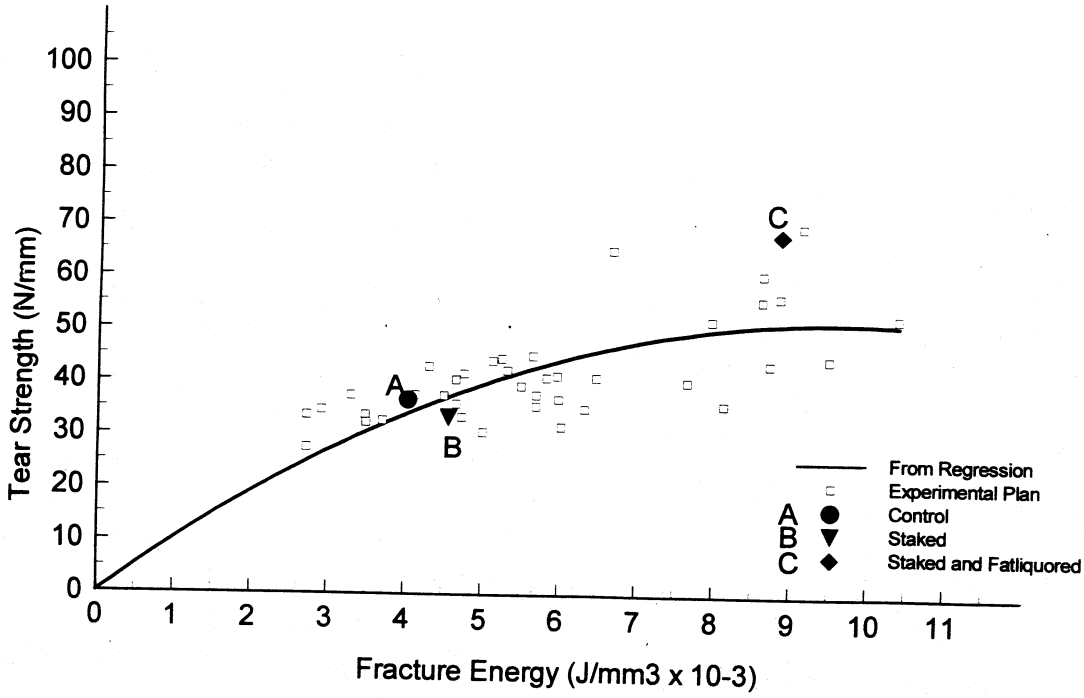

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

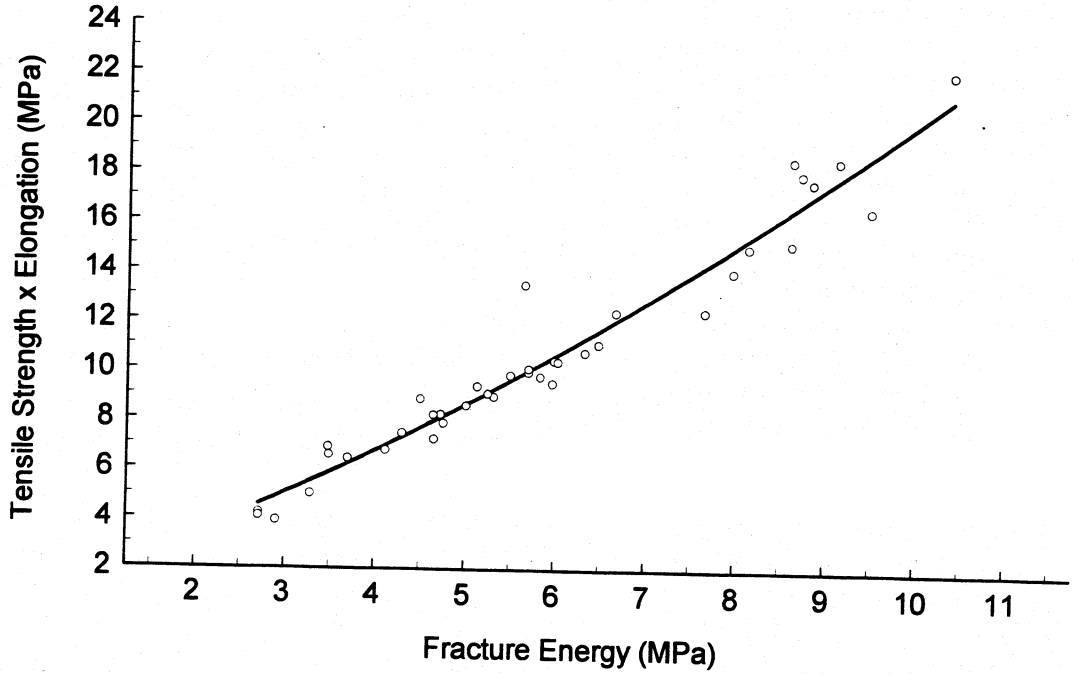

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

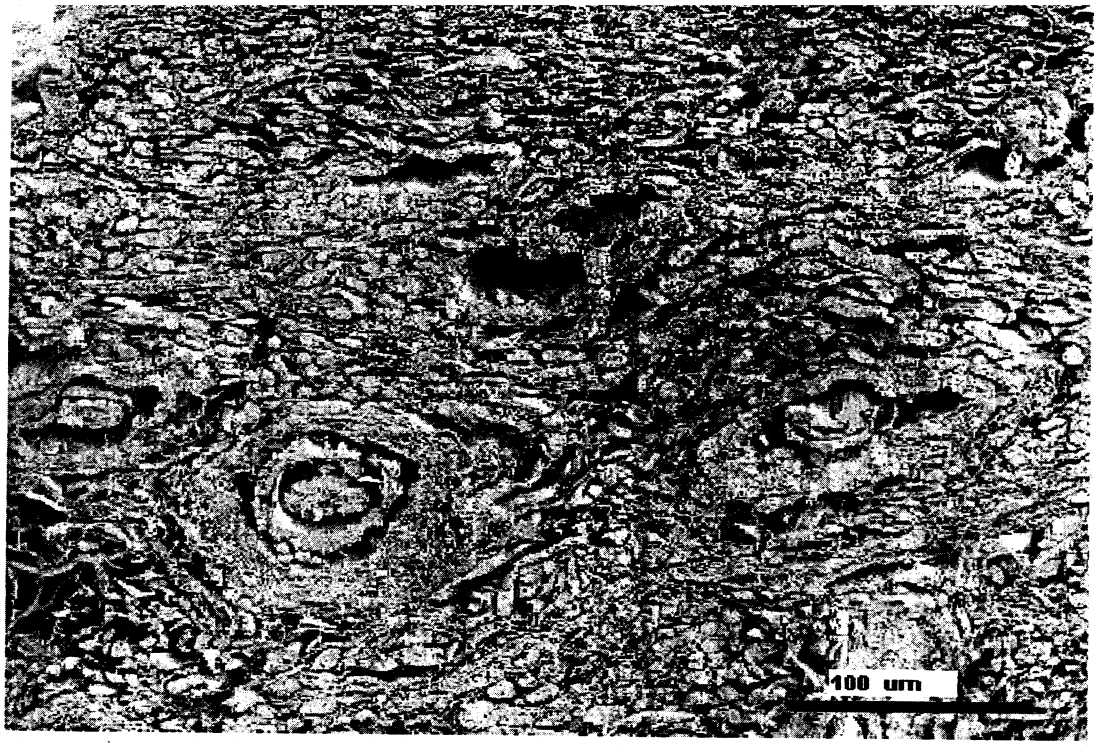

FIGURE 1. — Micrograph showing grain layer with sheet structure.

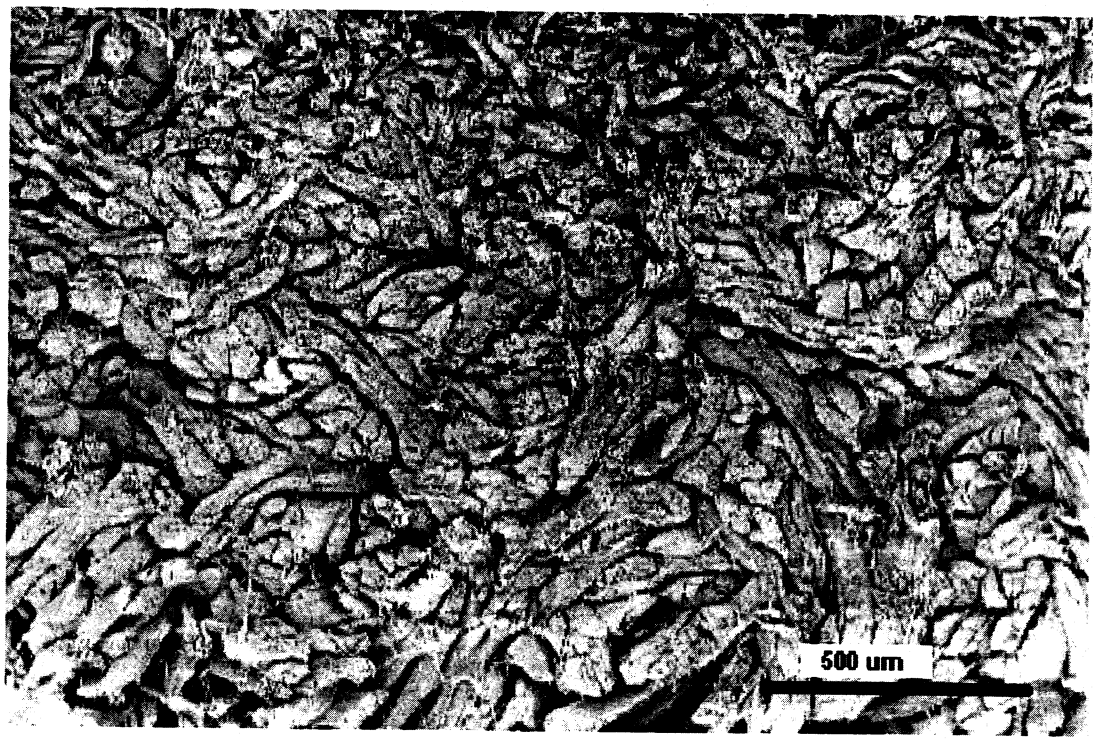

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

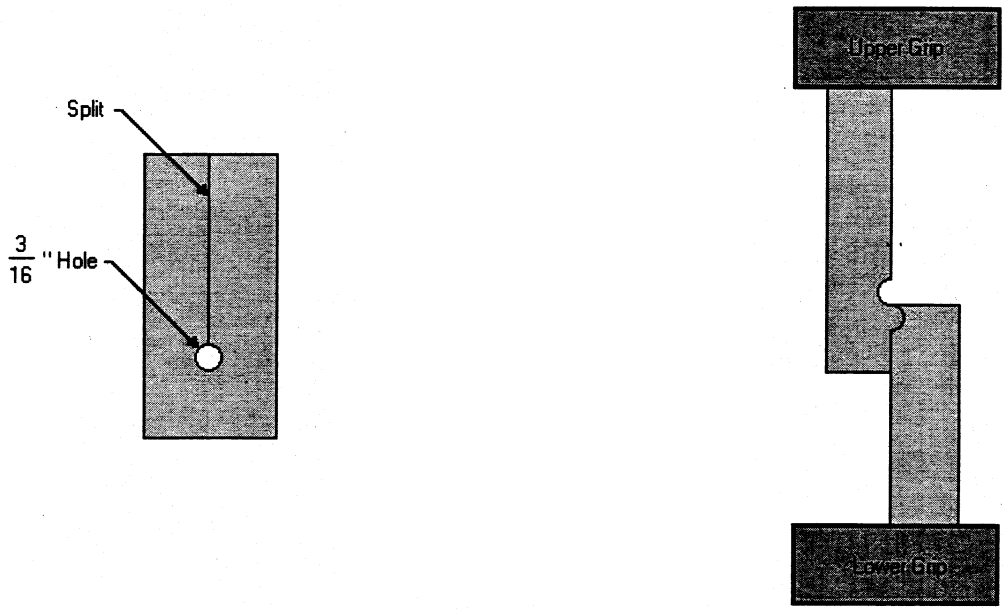

FIGURE 3. — Tear test scheme.

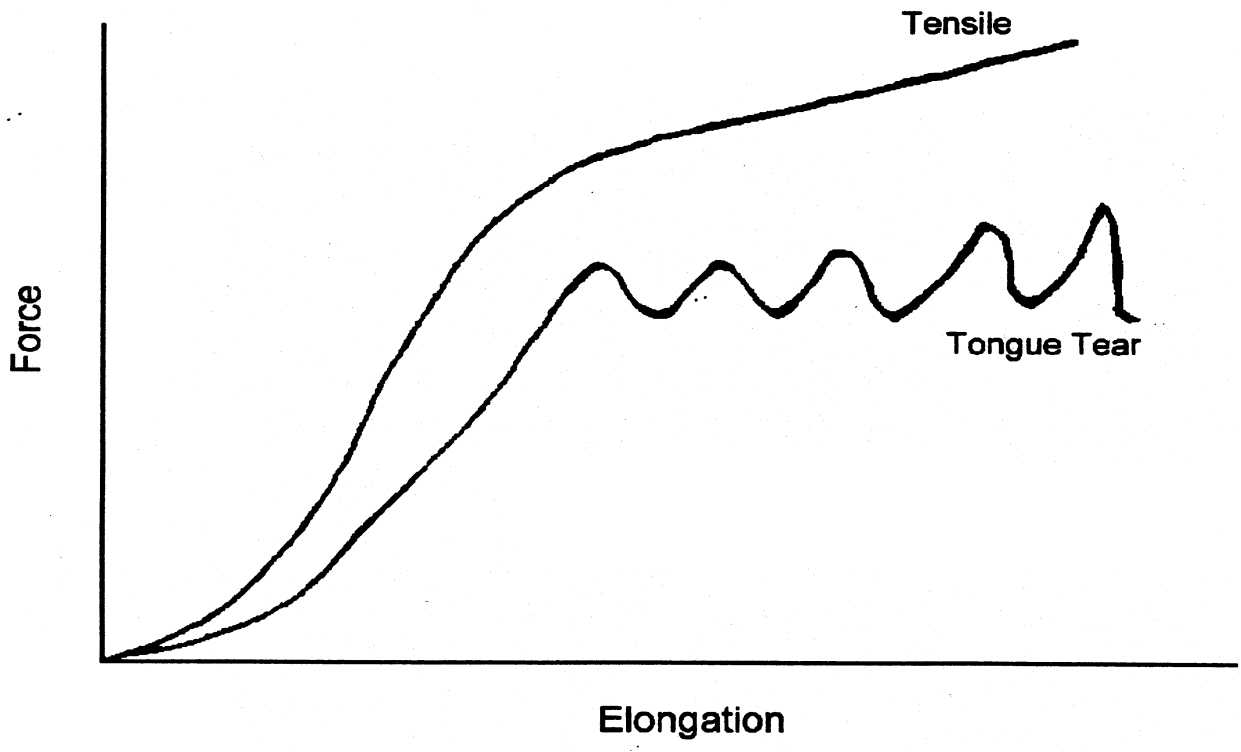

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

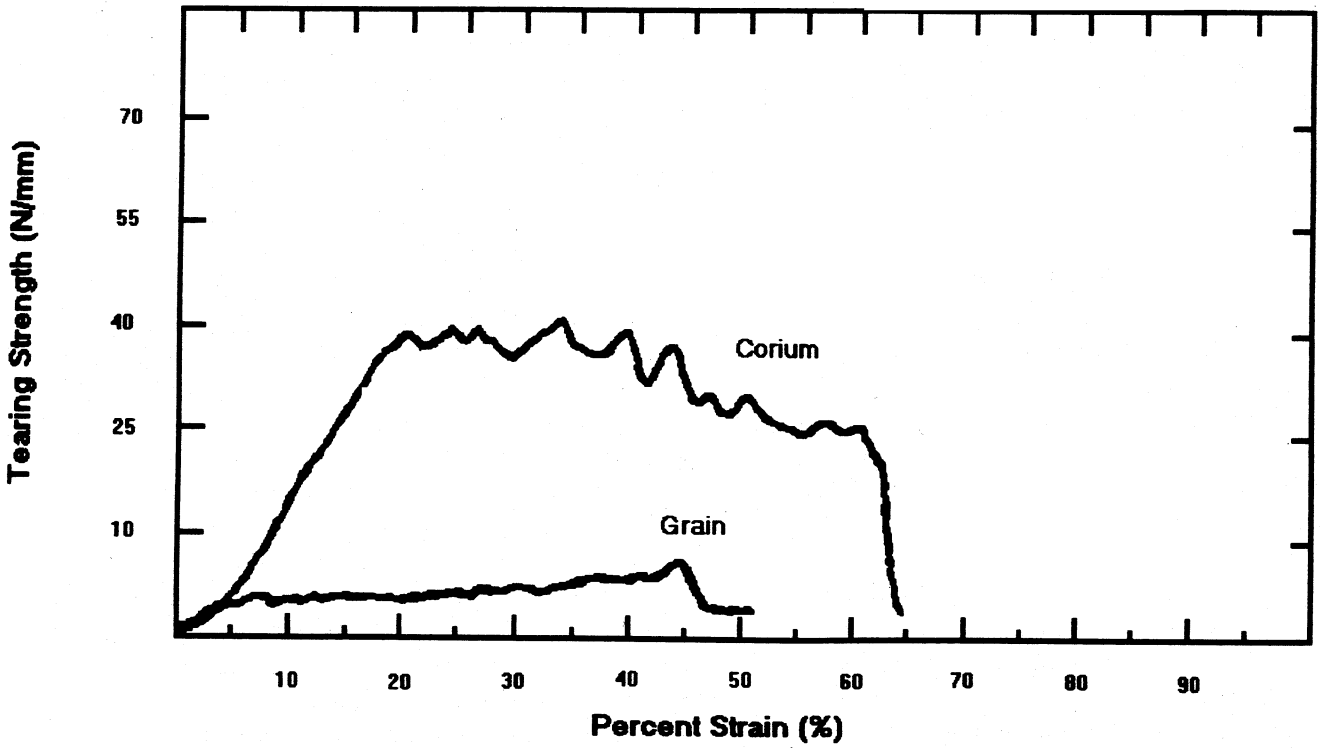

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

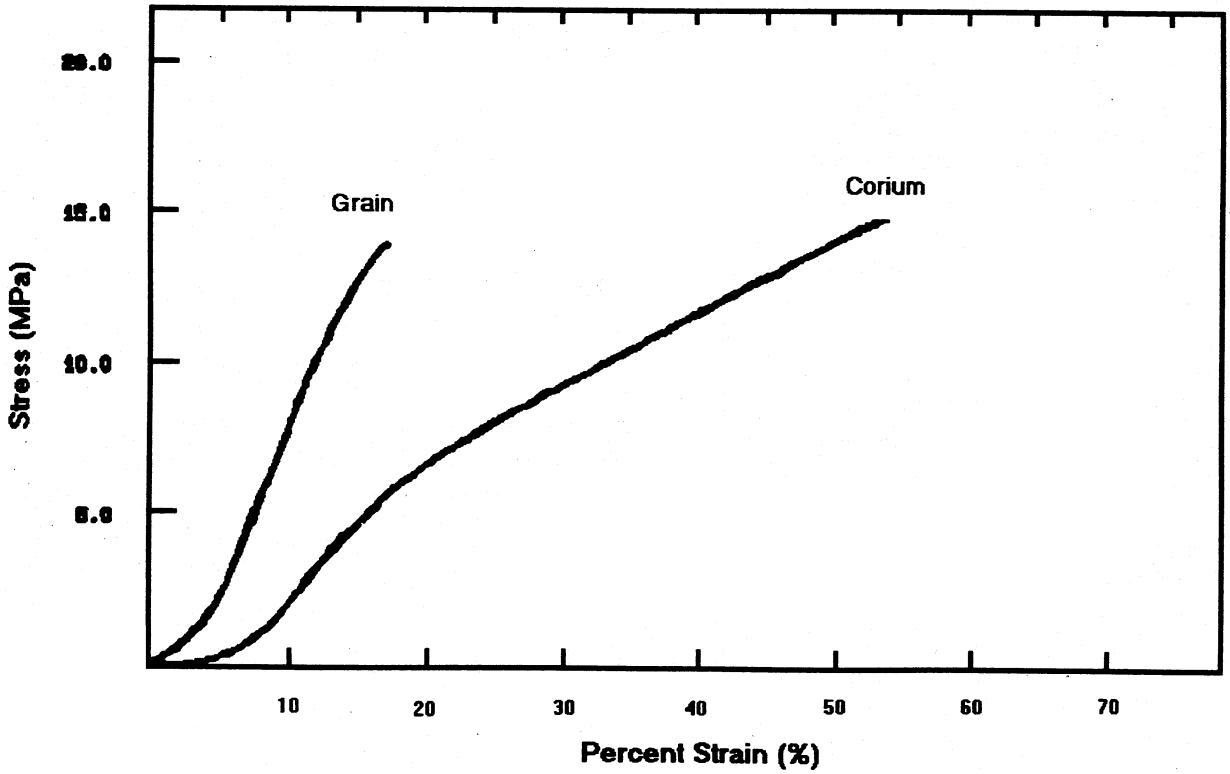

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

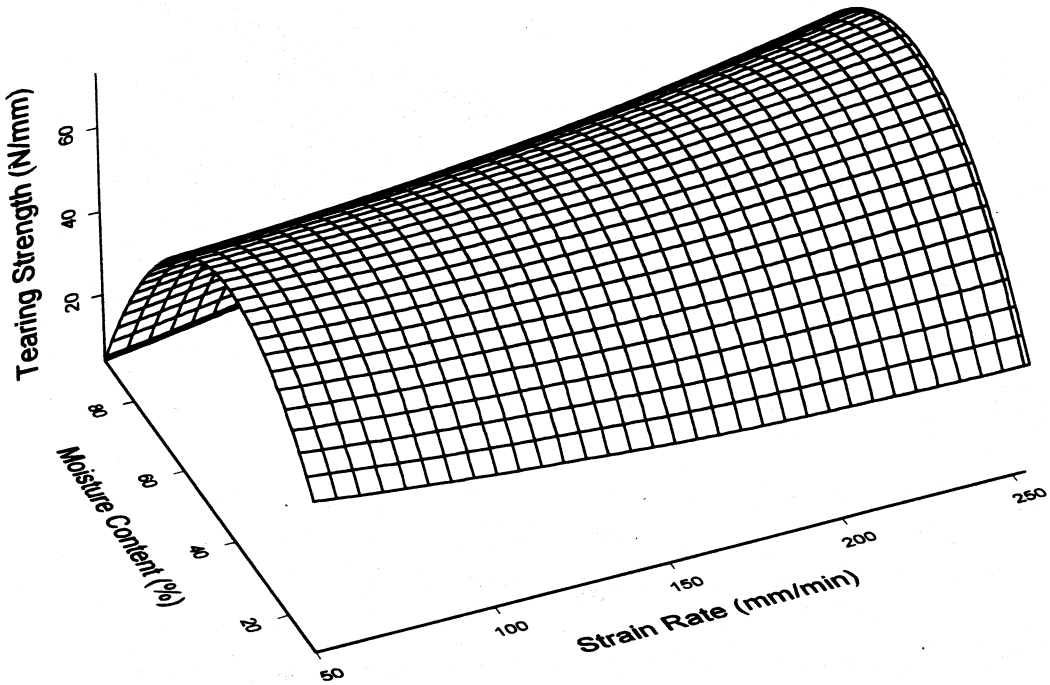

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

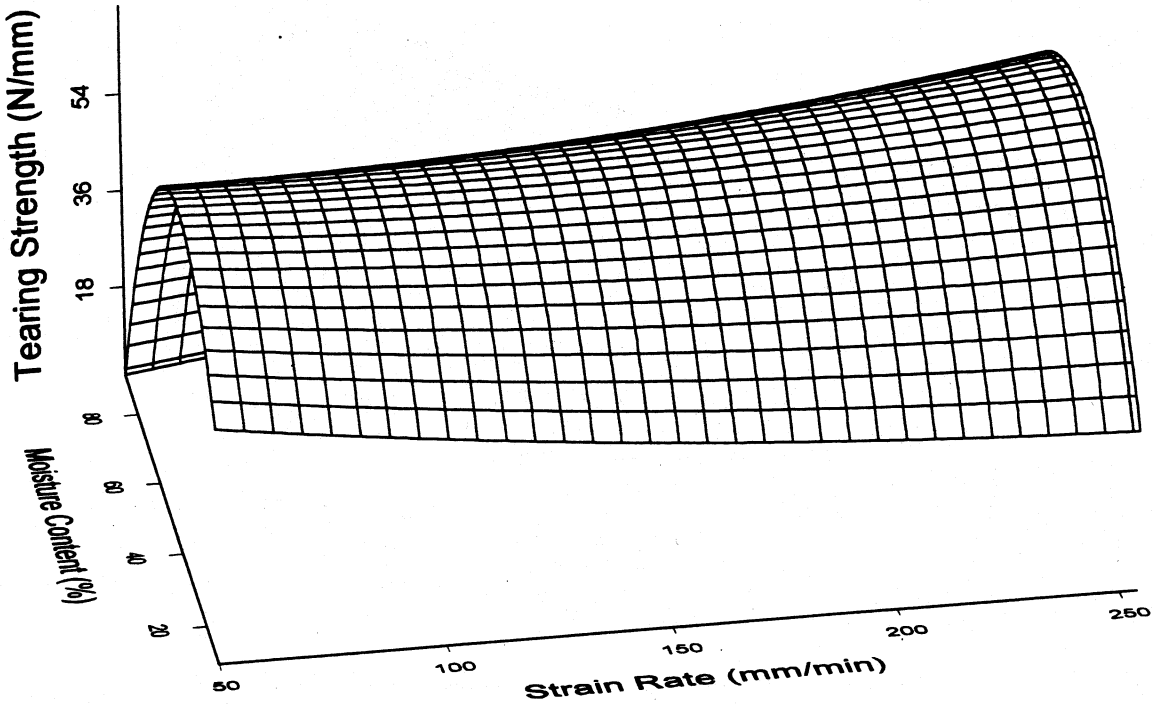

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

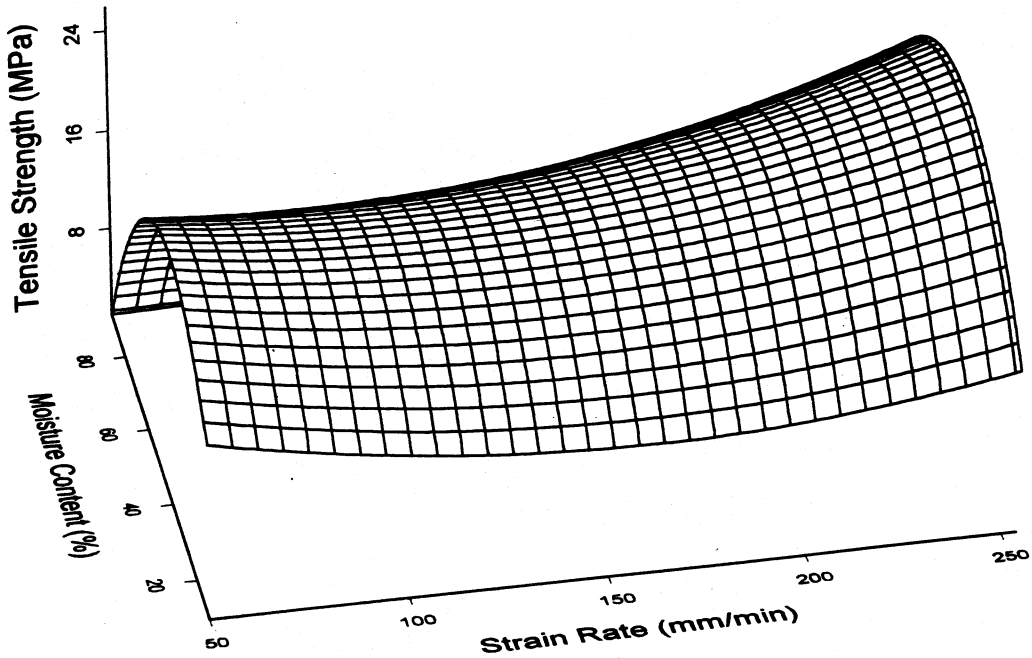

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

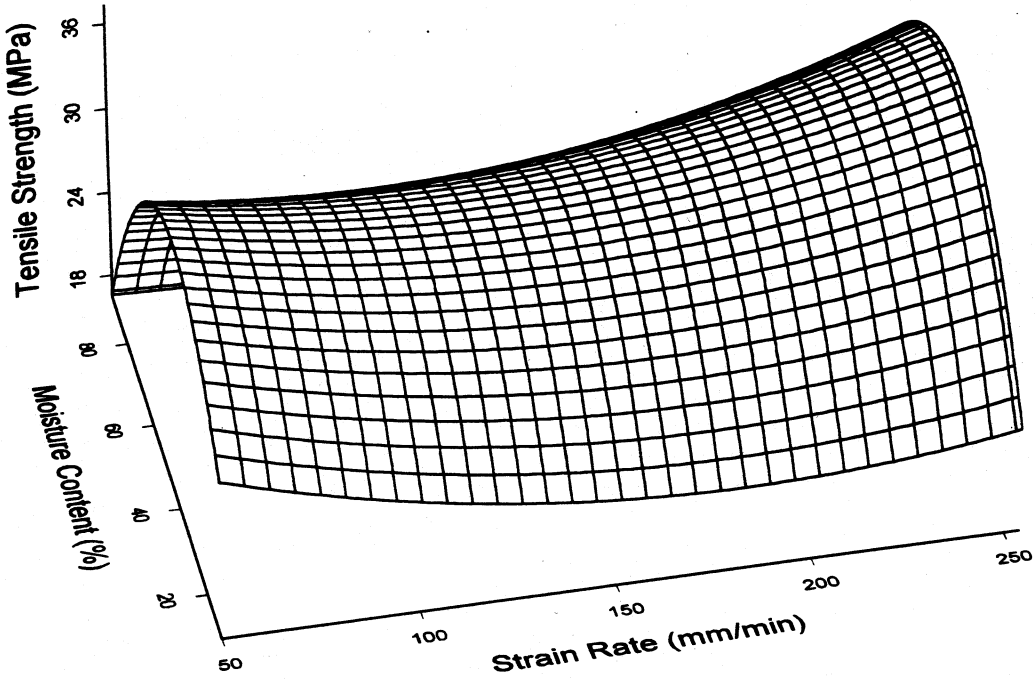

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

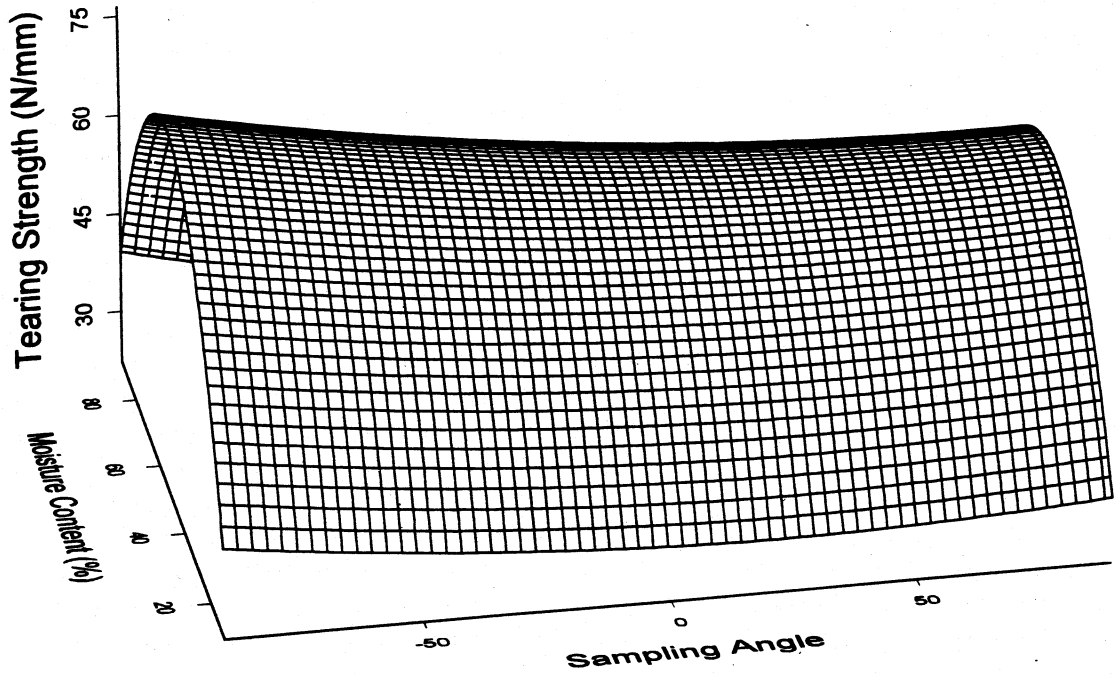

FIGURE 11. — Effect of sampling angle on tearing strength.

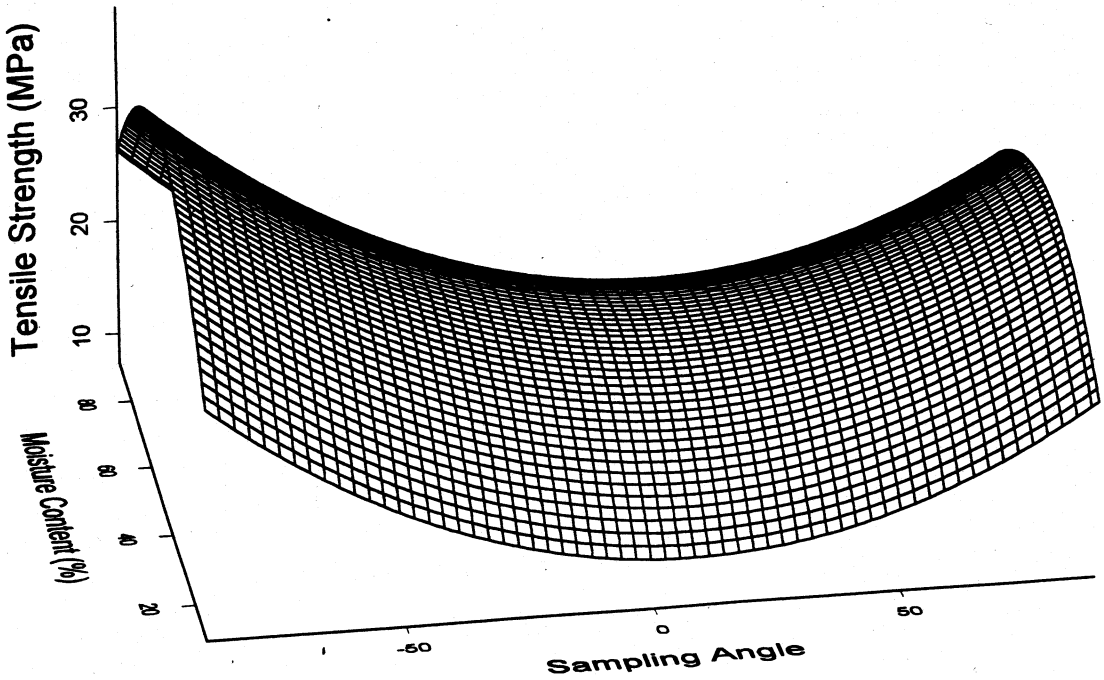

FIGURE 12. — Effect of sampling angle on tensile strength.

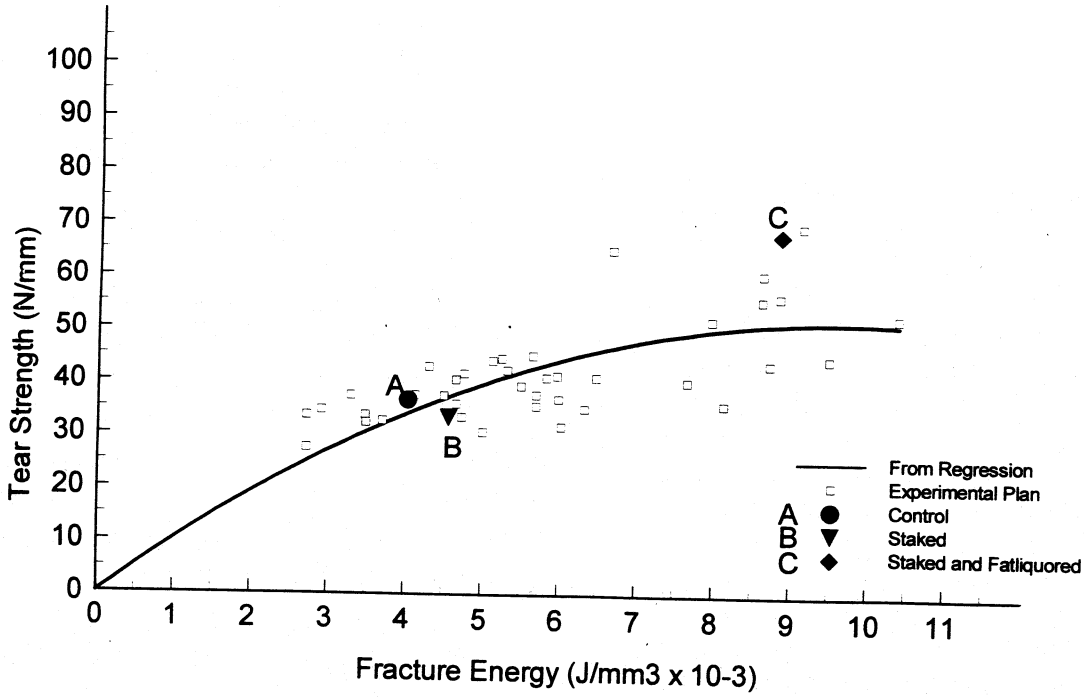

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

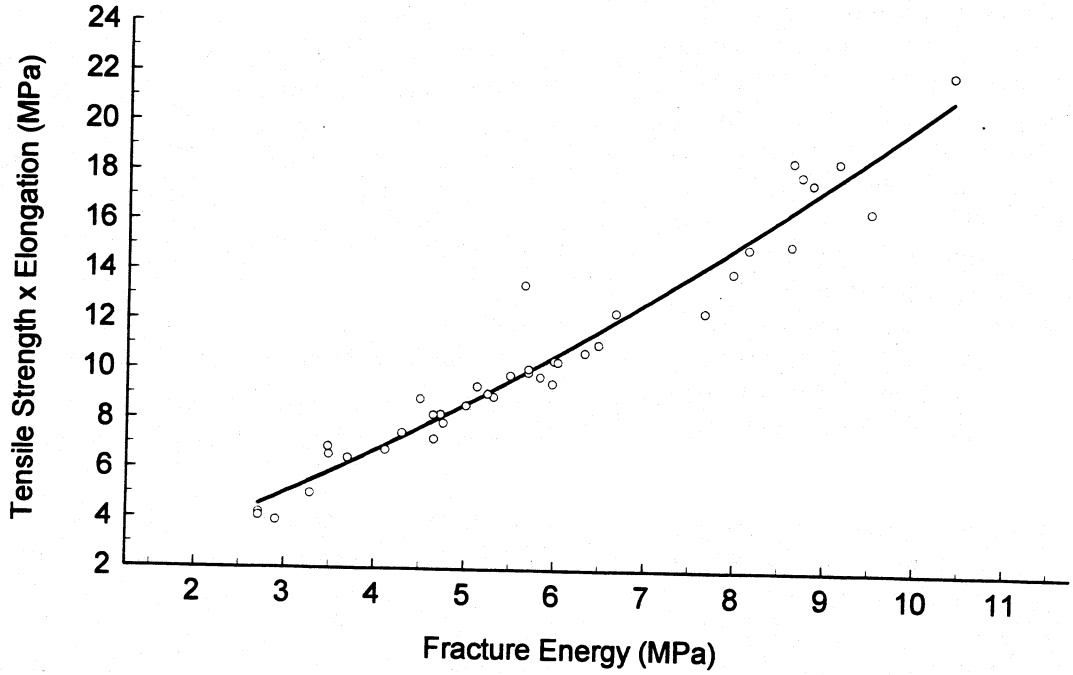

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

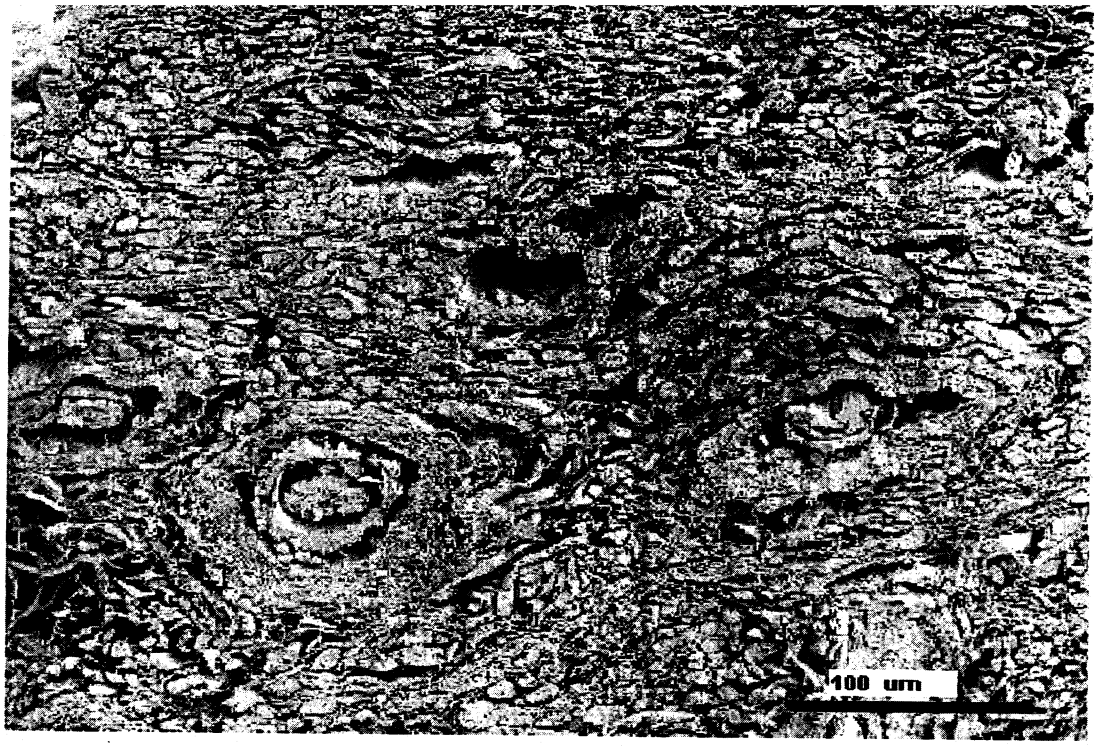

FIGURE 1. — Micrograph showing grain layer with sheet structure.

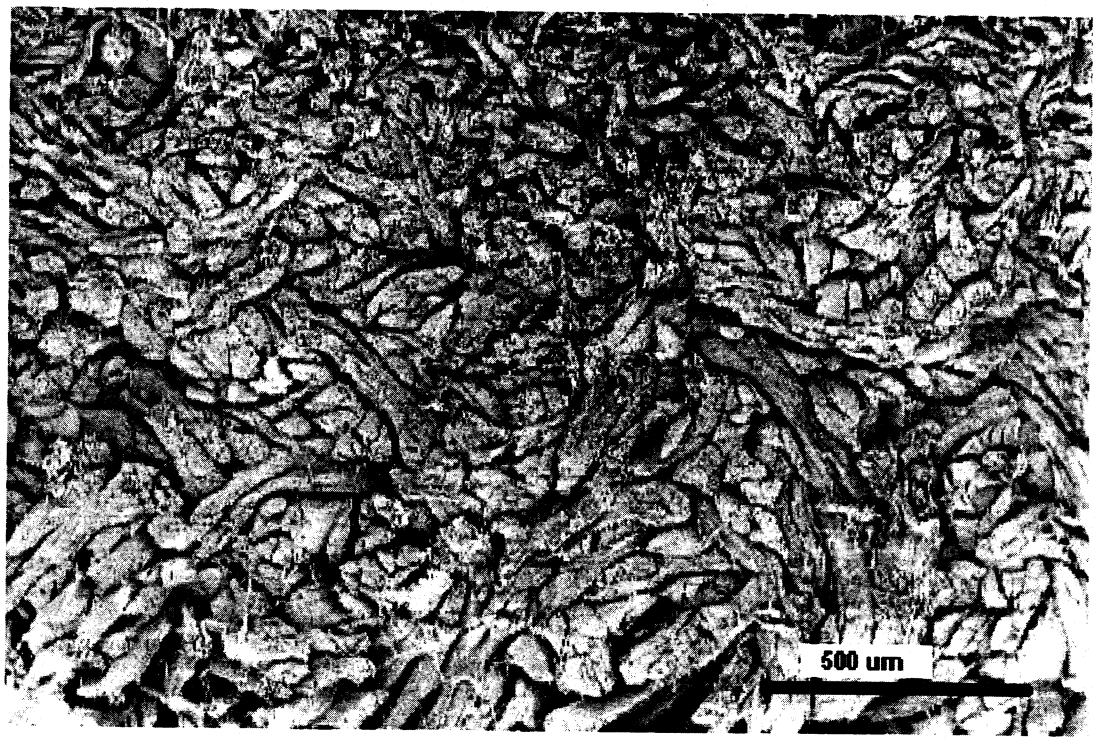

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

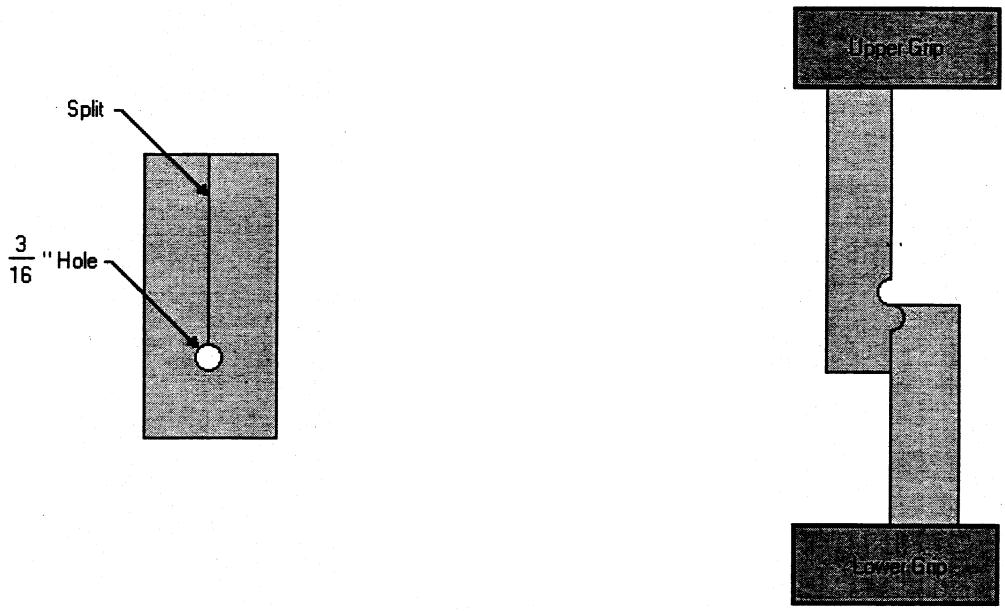

FIGURE 3. — Tear test scheme.

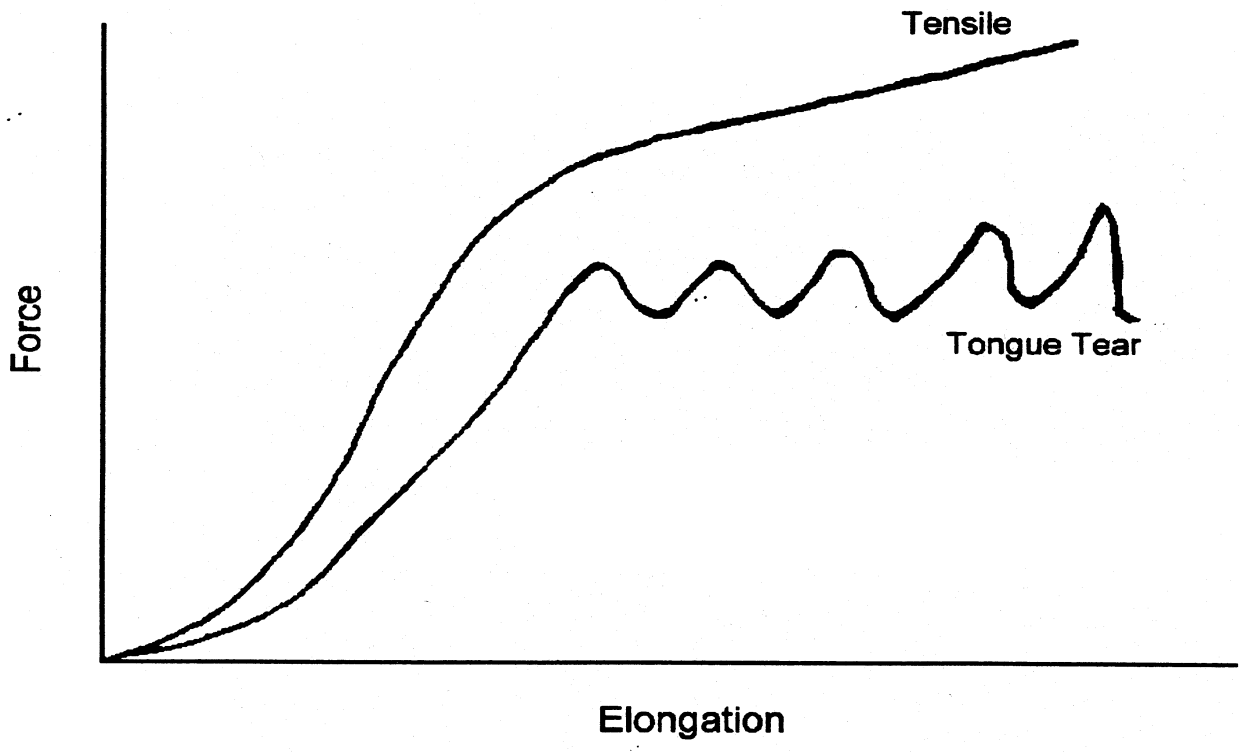

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

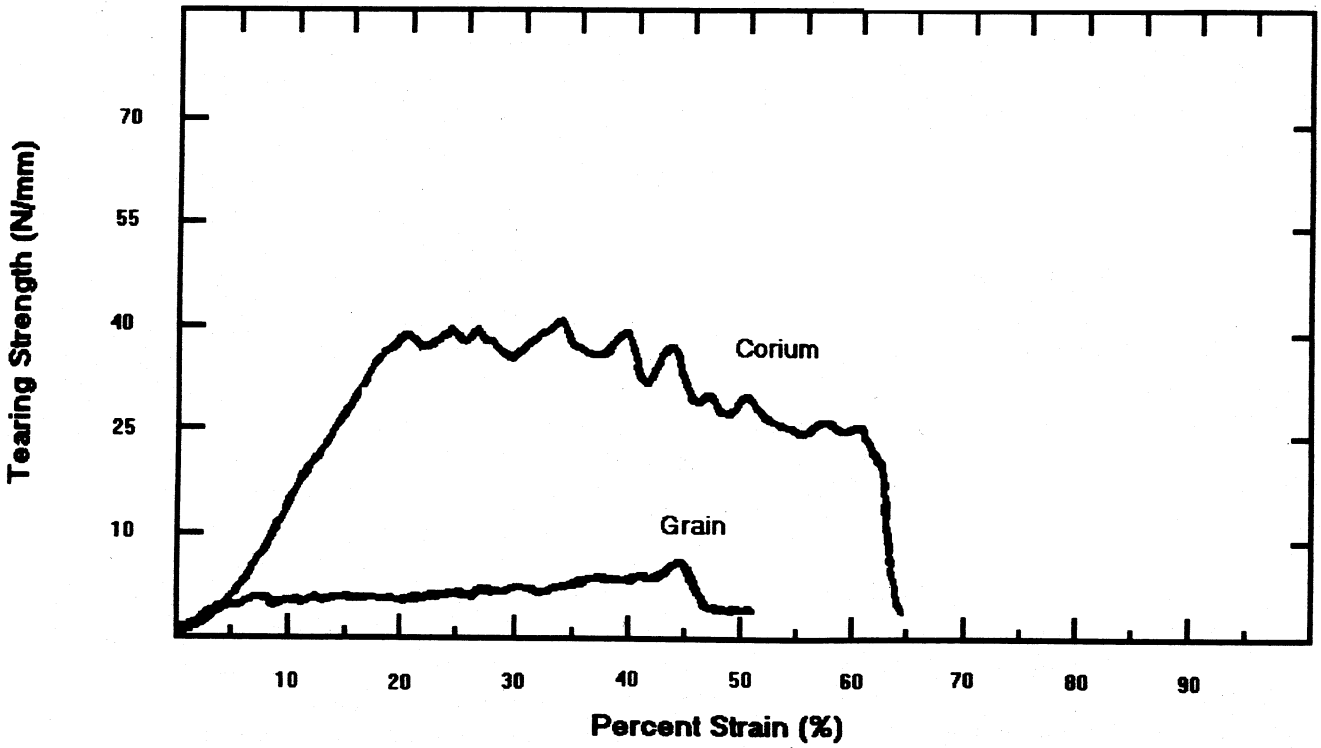

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

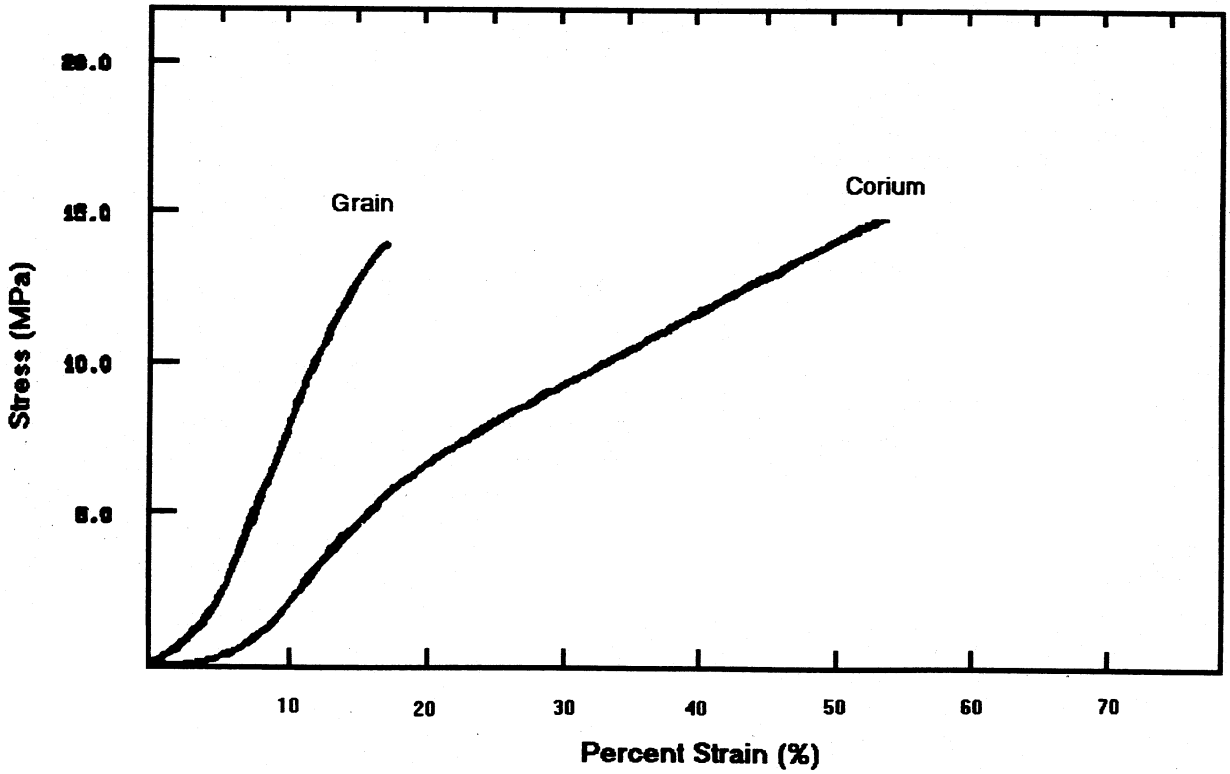

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

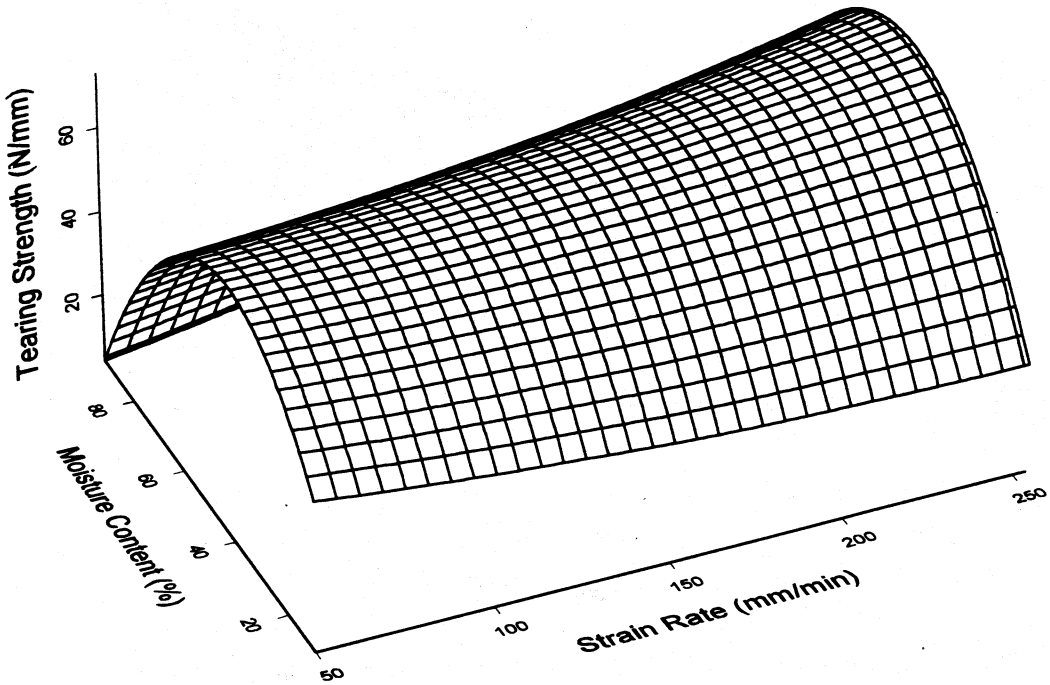

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

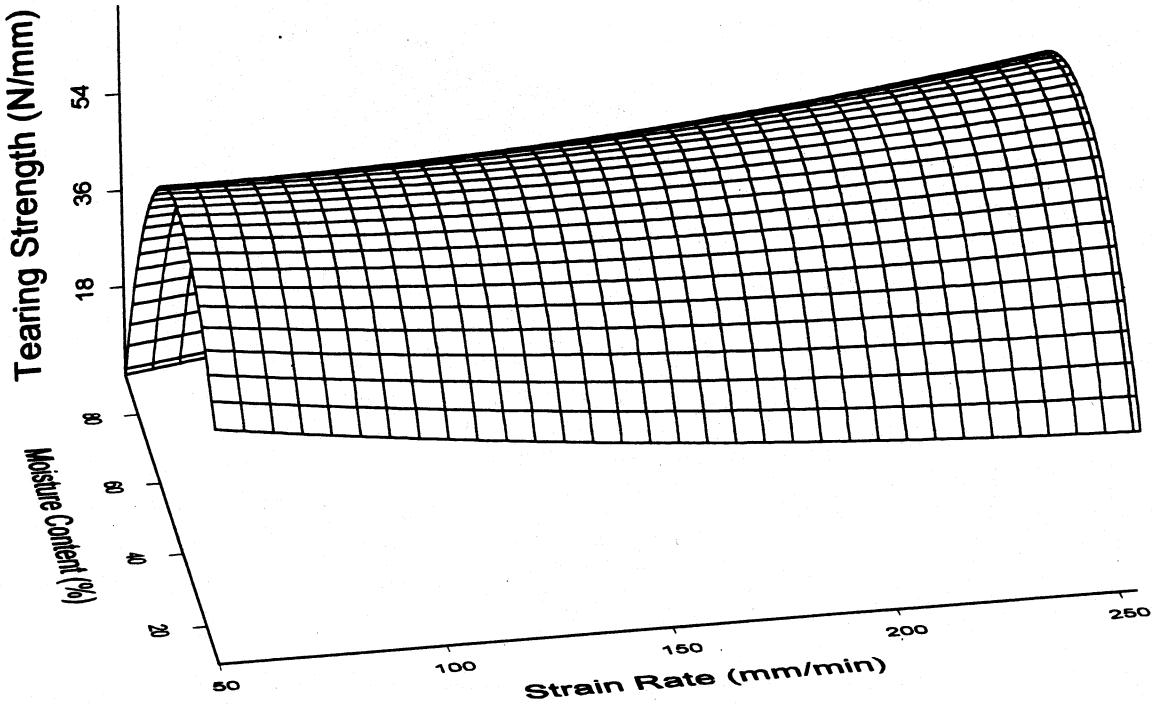

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

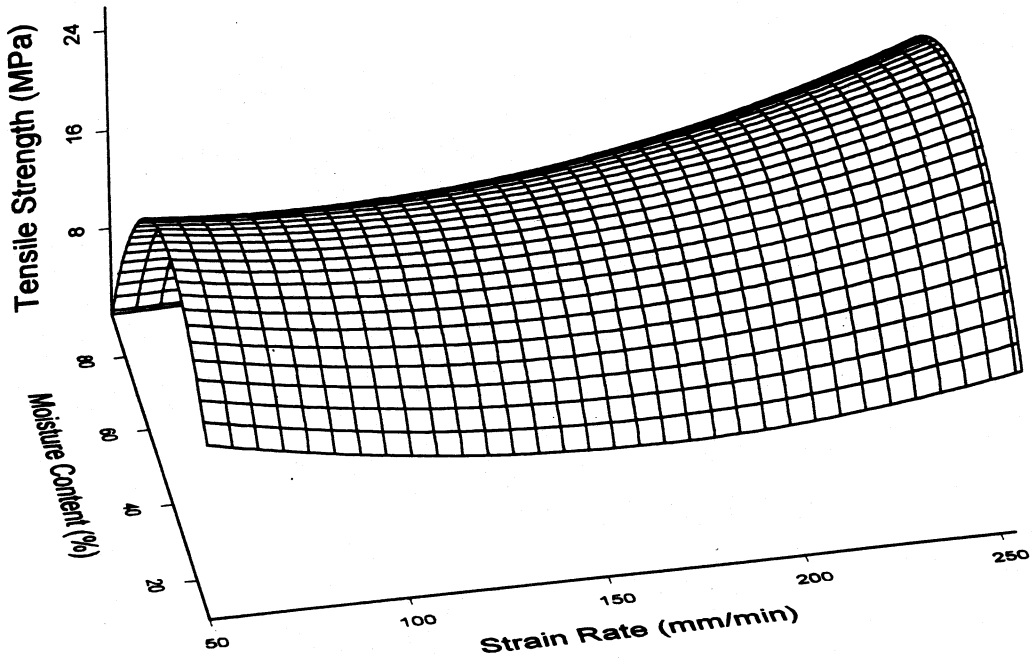

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

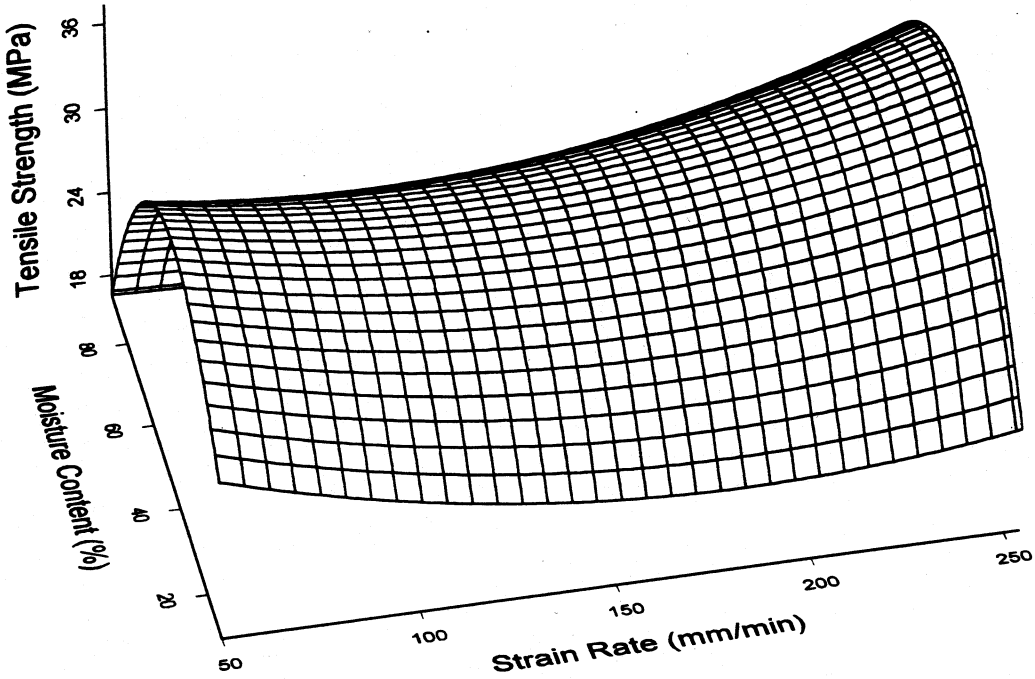

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

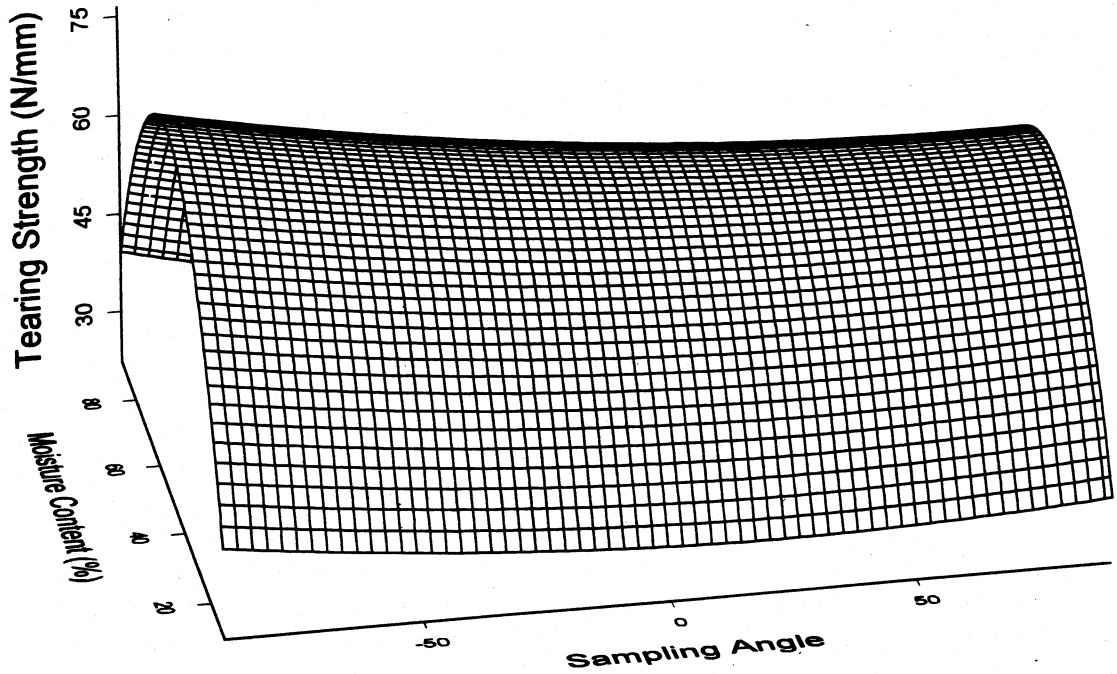

FIGURE 11. — Effect of sampling angle on tearing strength.

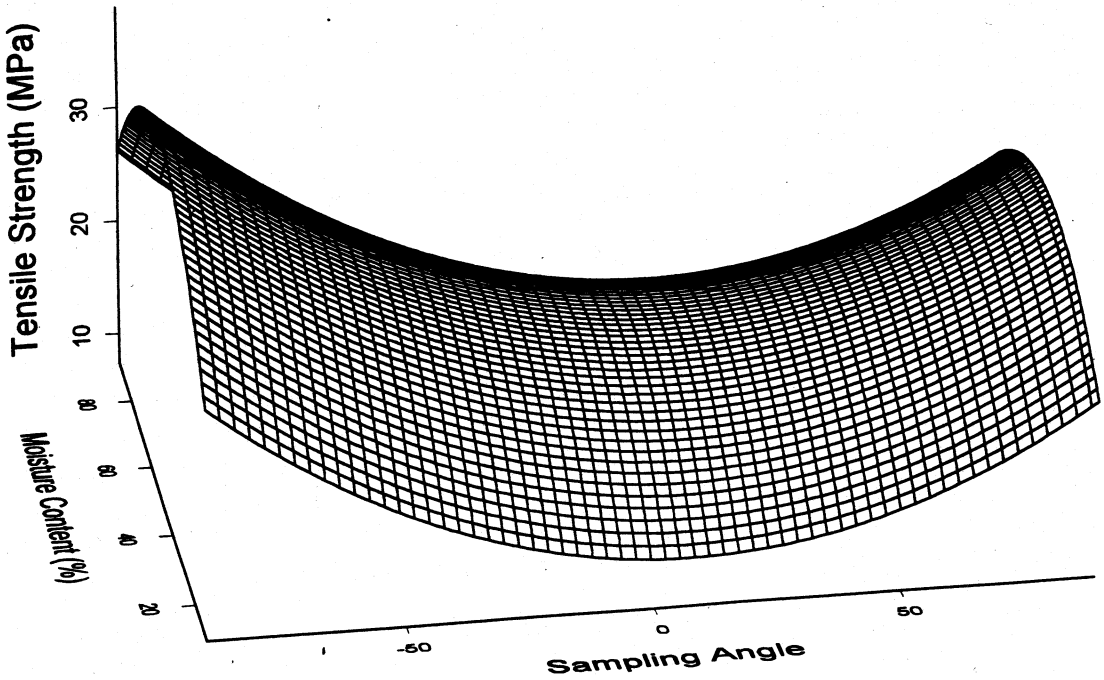

FIGURE 12. — Effect of sampling angle on tensile strength.

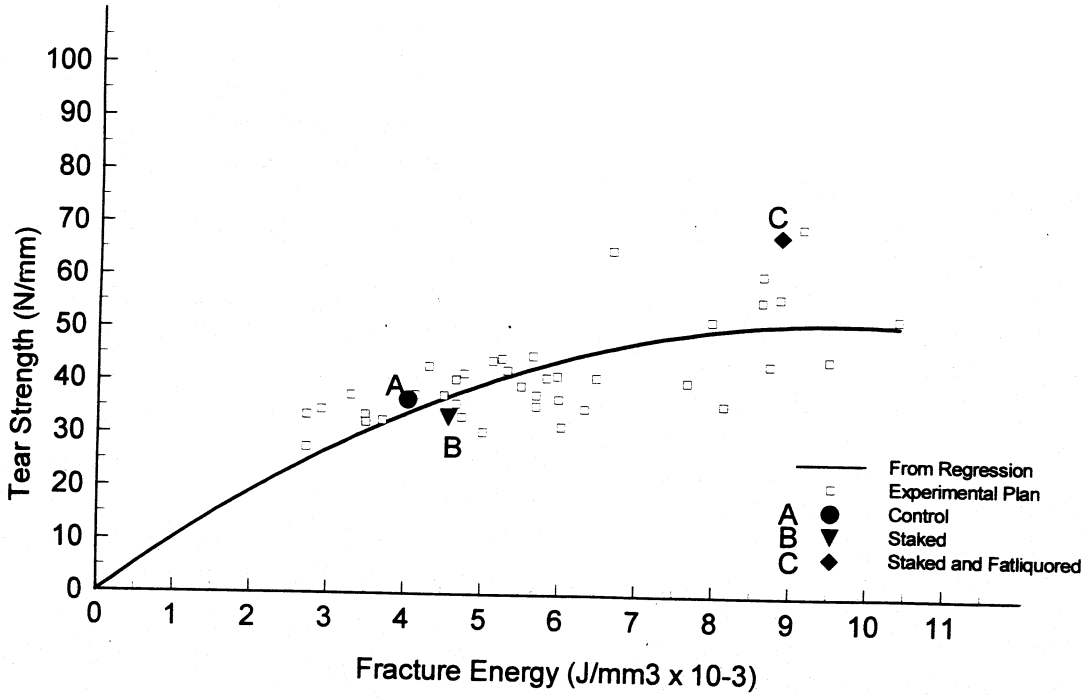

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

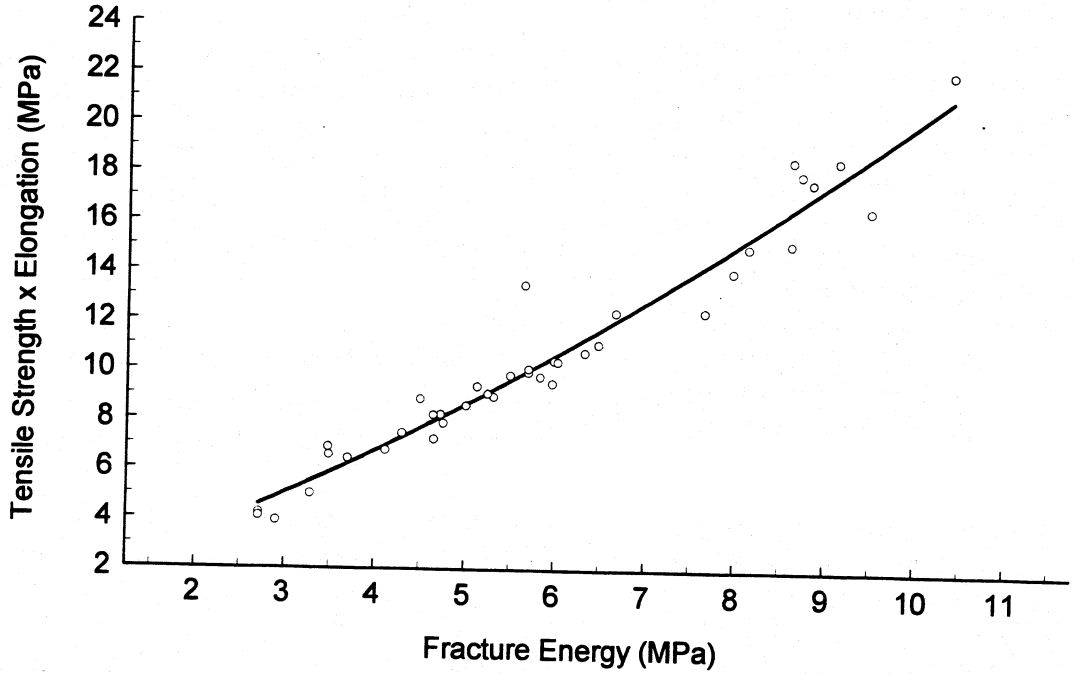

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

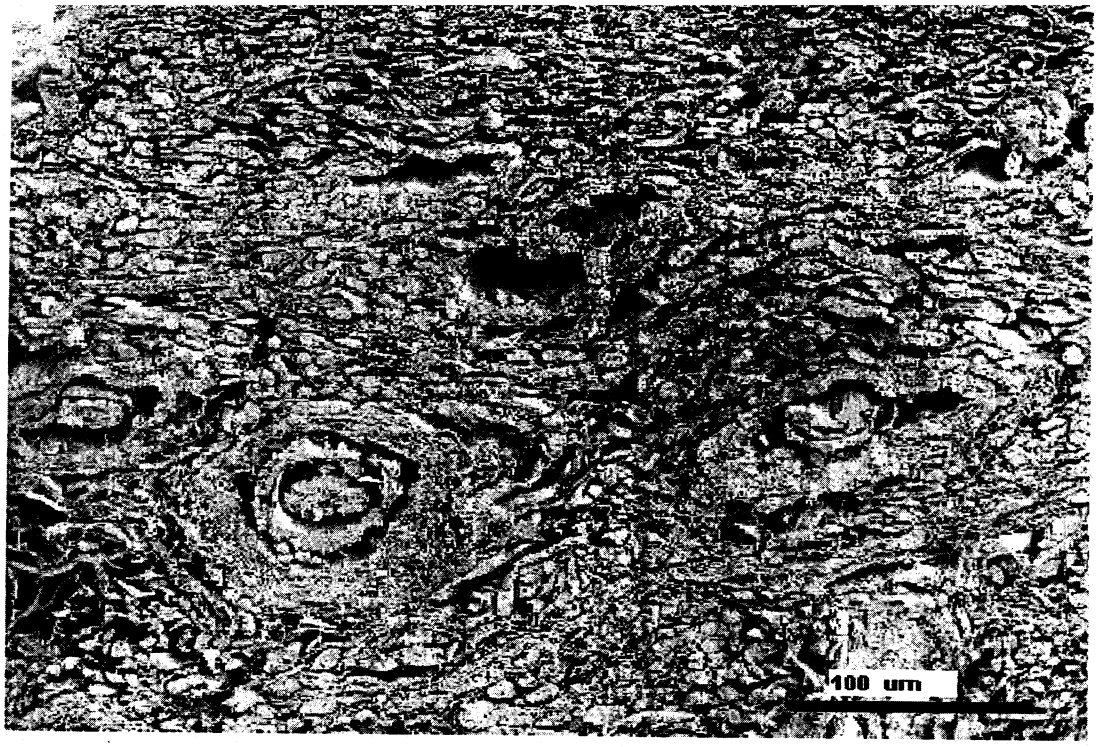

FIGURE 1. — Micrograph showing grain layer with sheet structure.

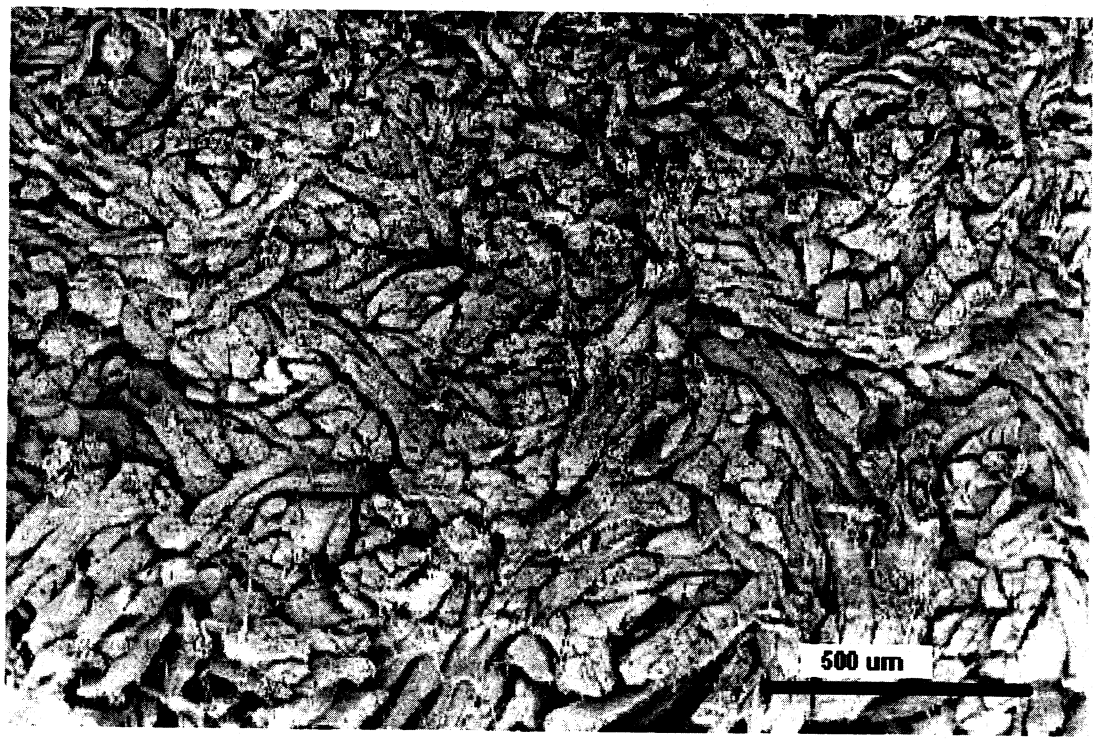

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

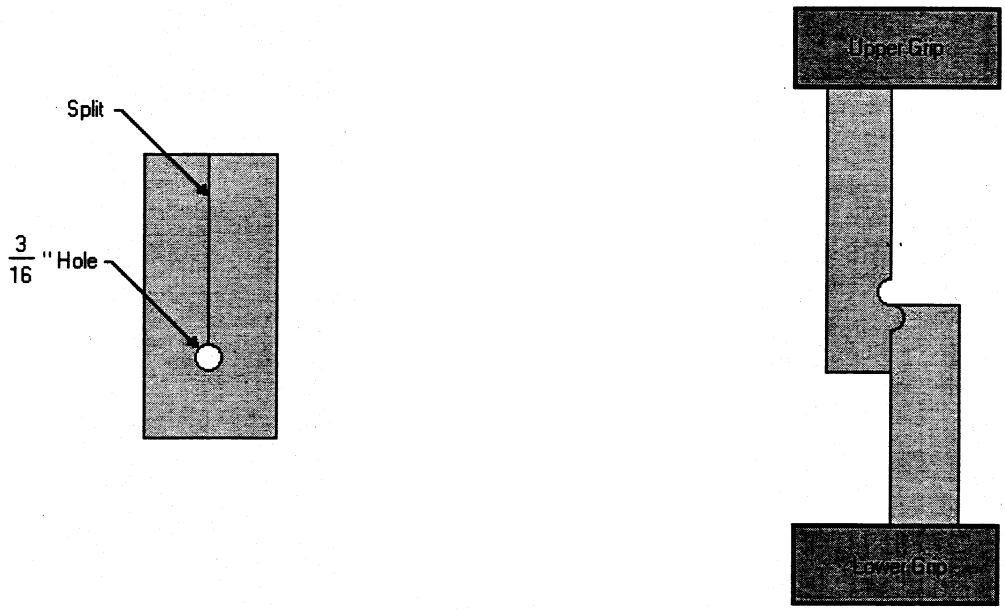

FIGURE 3. — Tear test scheme.

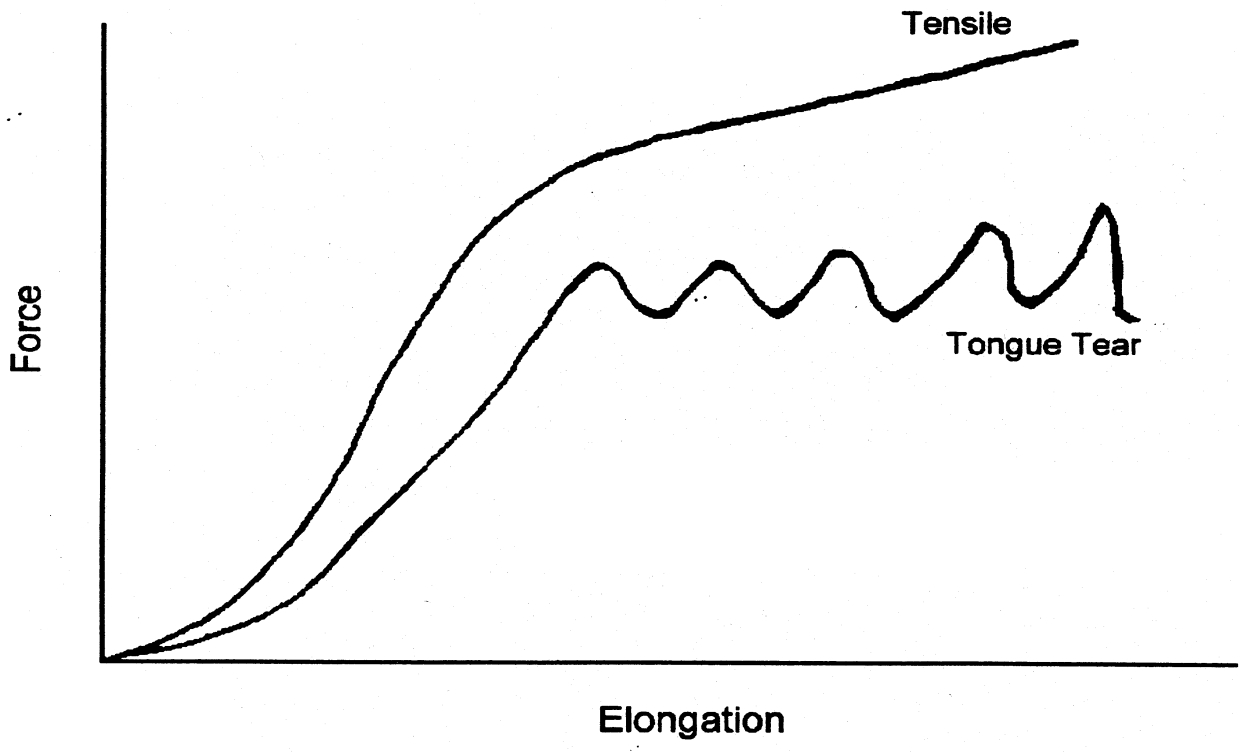

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

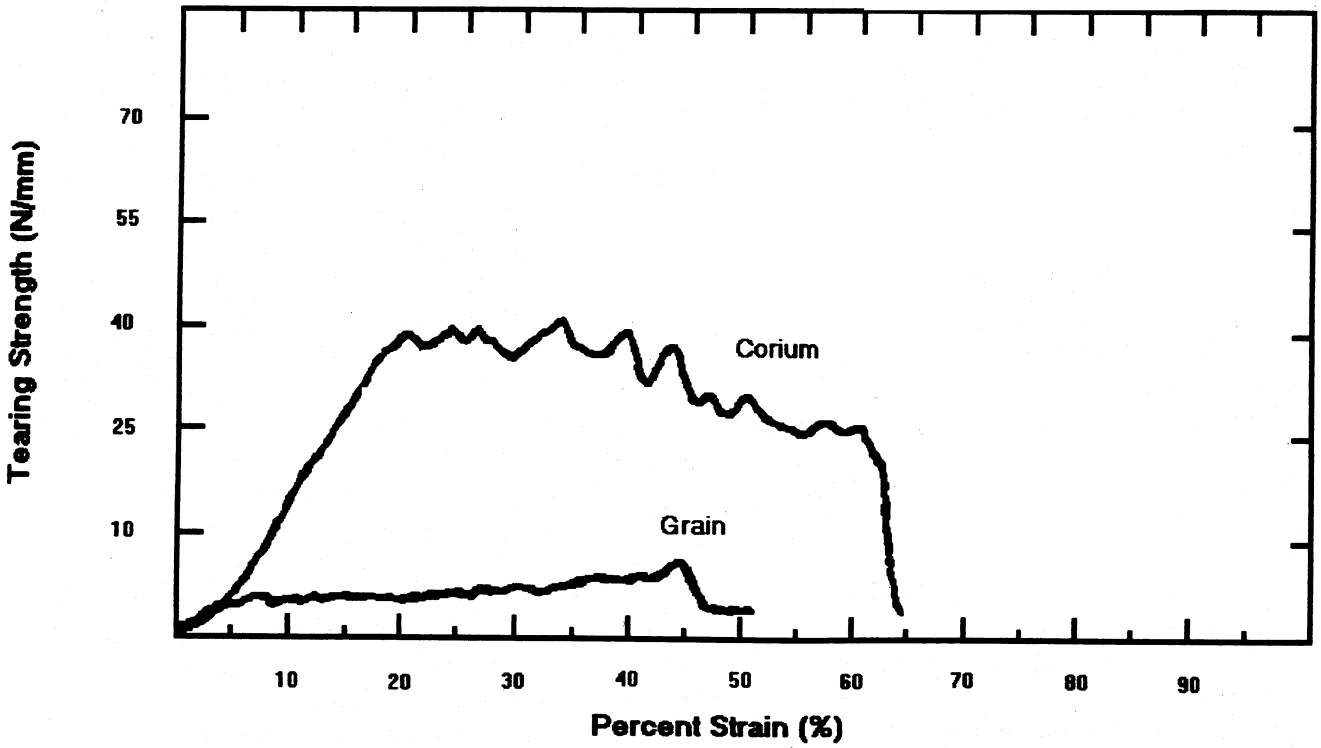

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

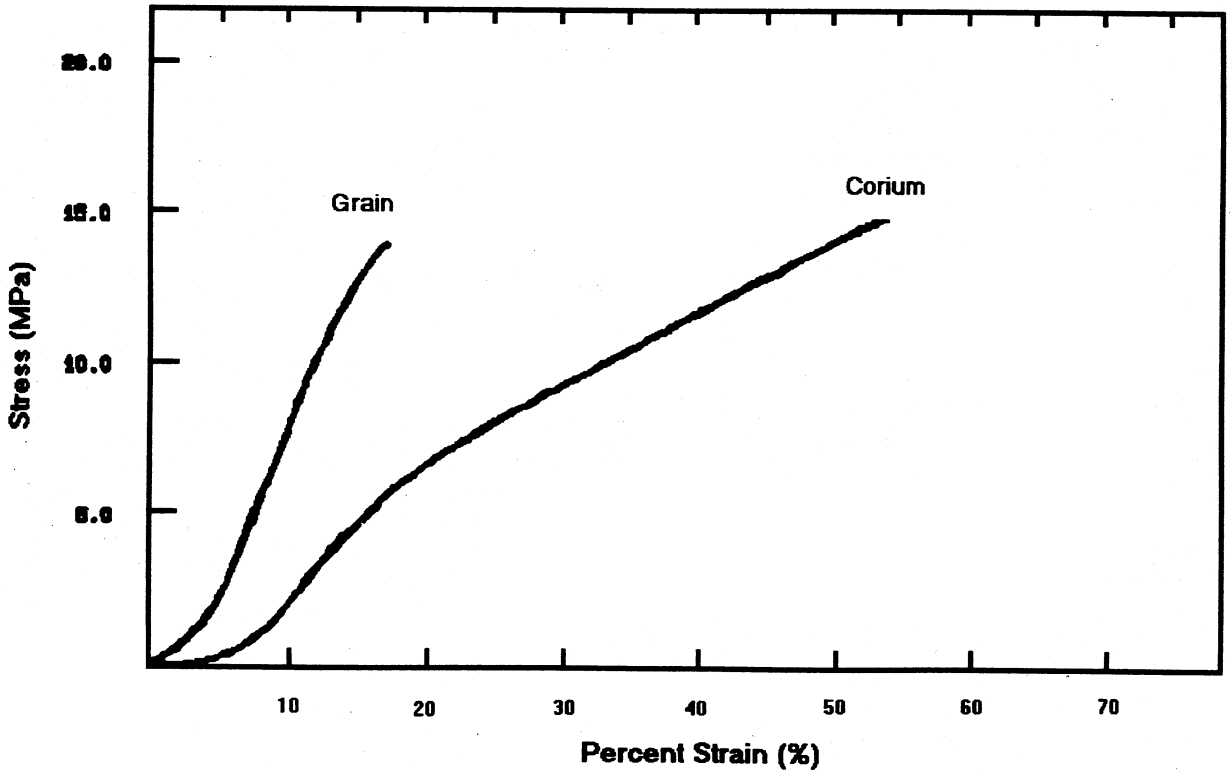

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

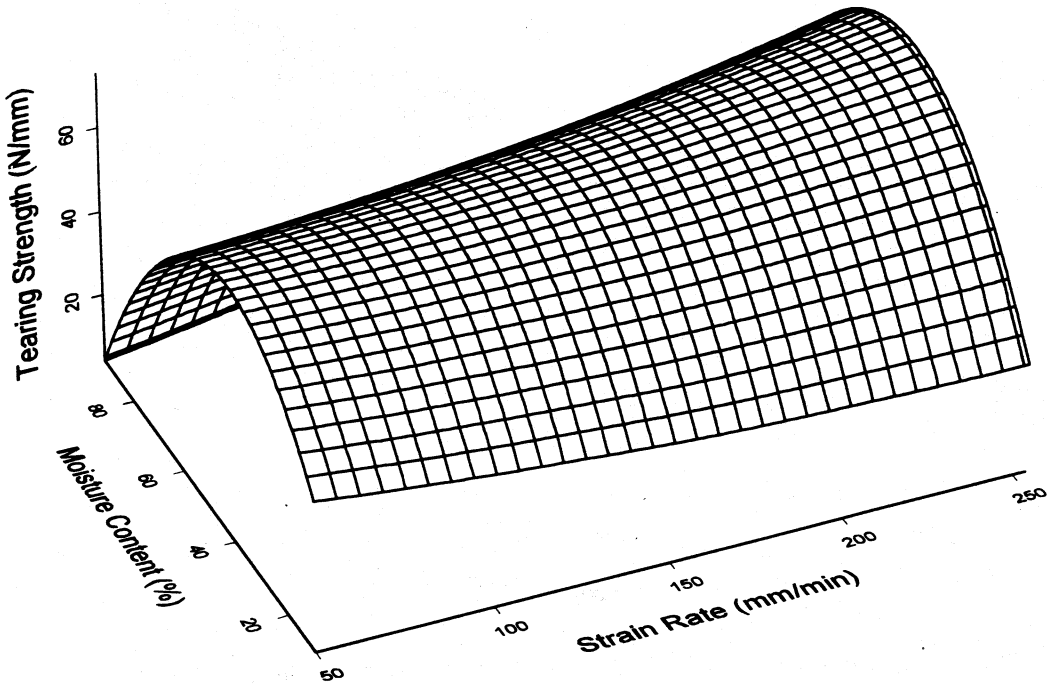

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

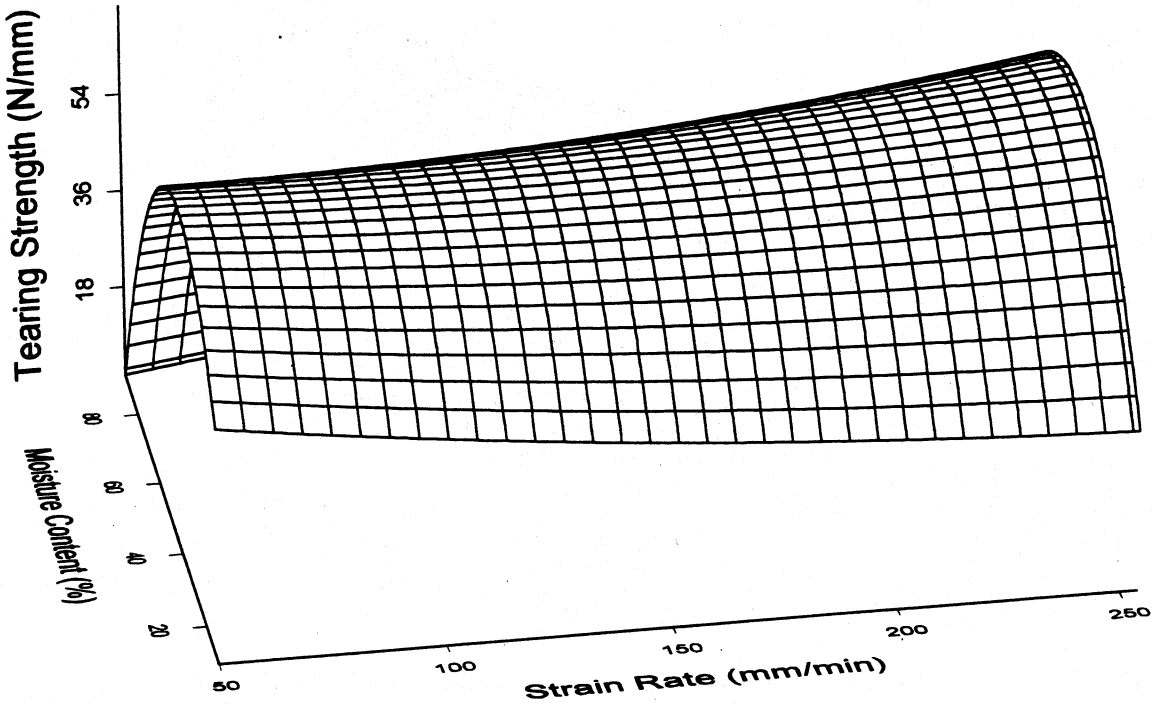

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

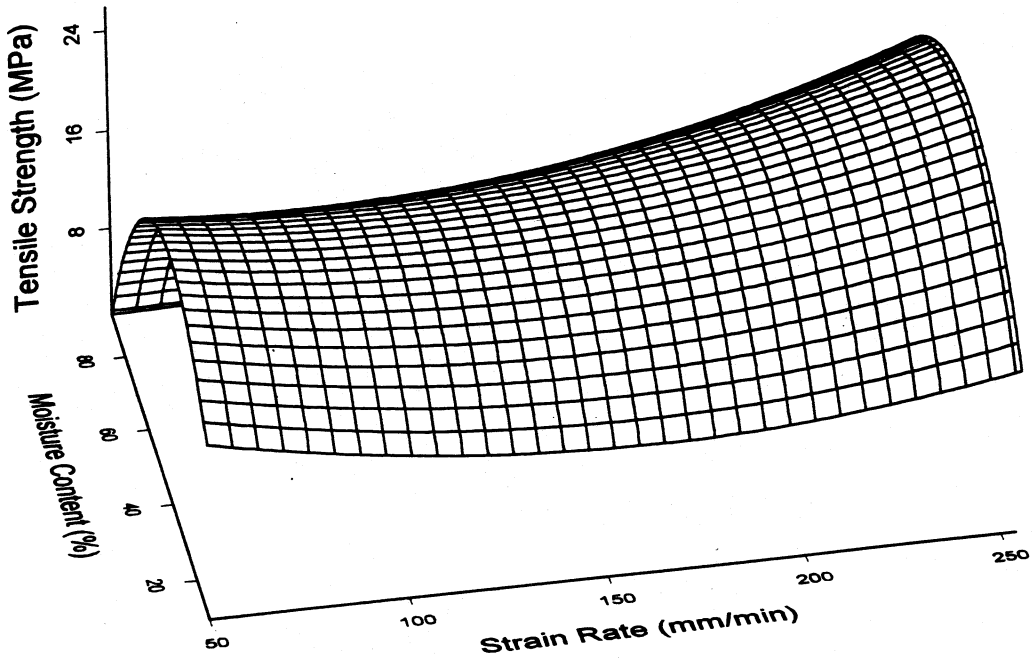

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

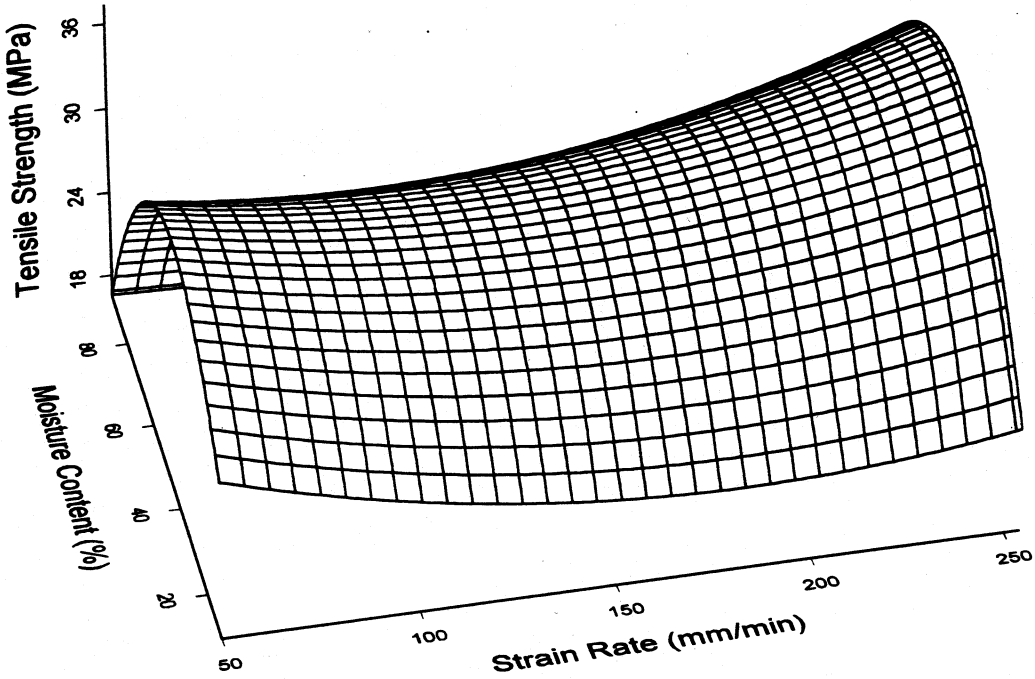

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

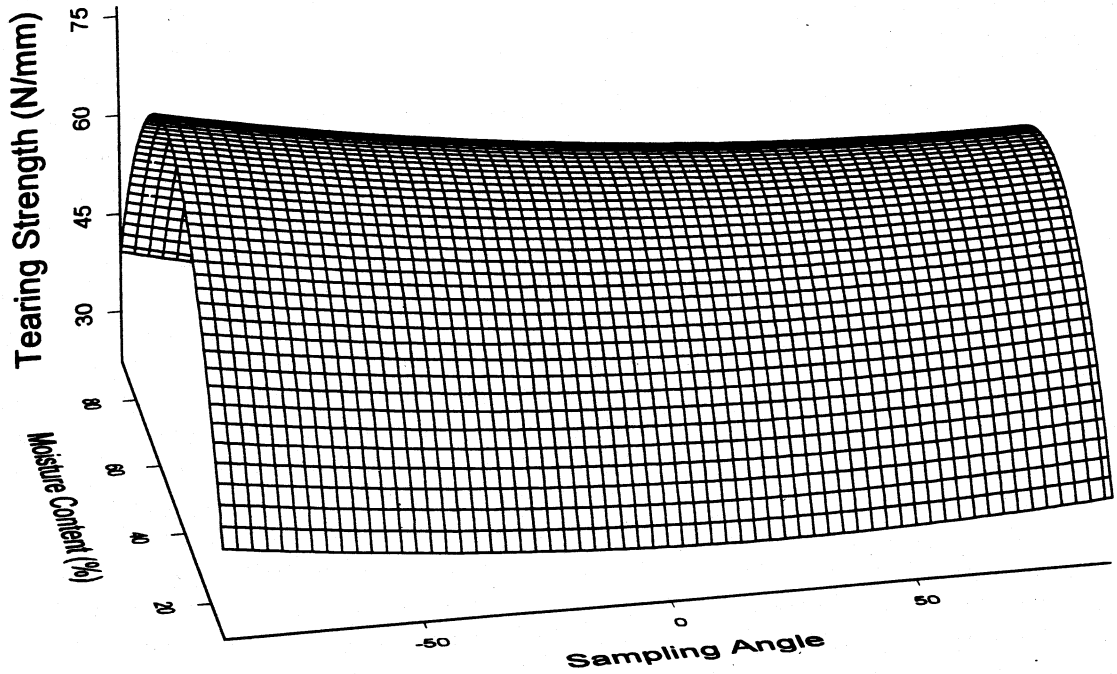

FIGURE 11. — Effect of sampling angle on tearing strength.

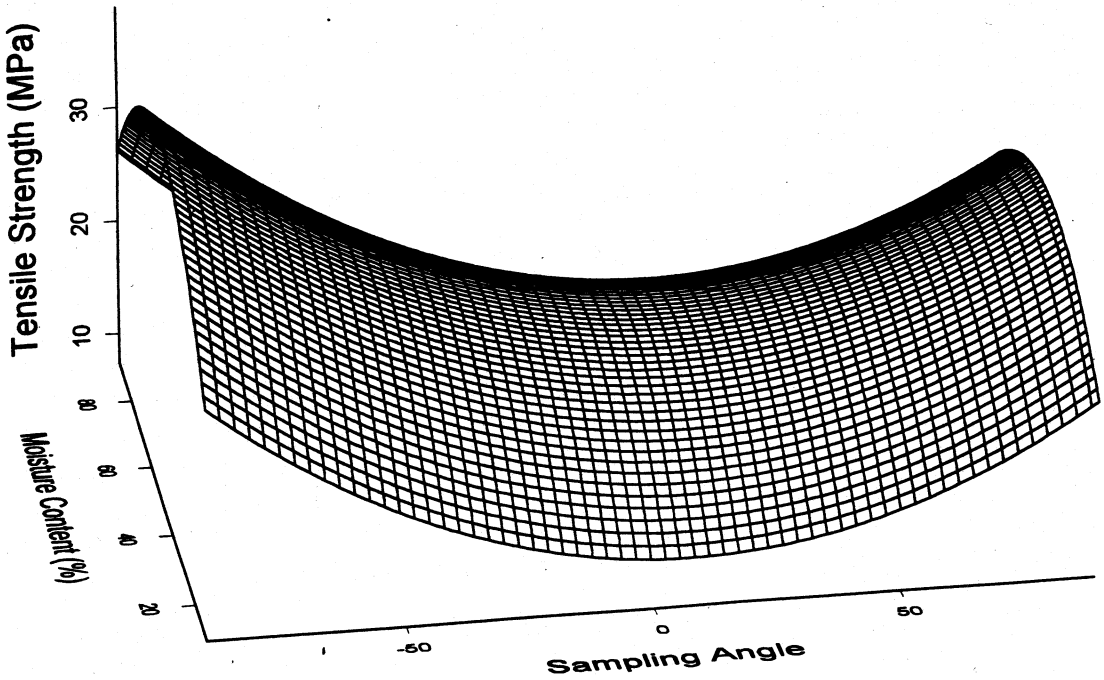

FIGURE 12. — Effect of sampling angle on tensile strength.

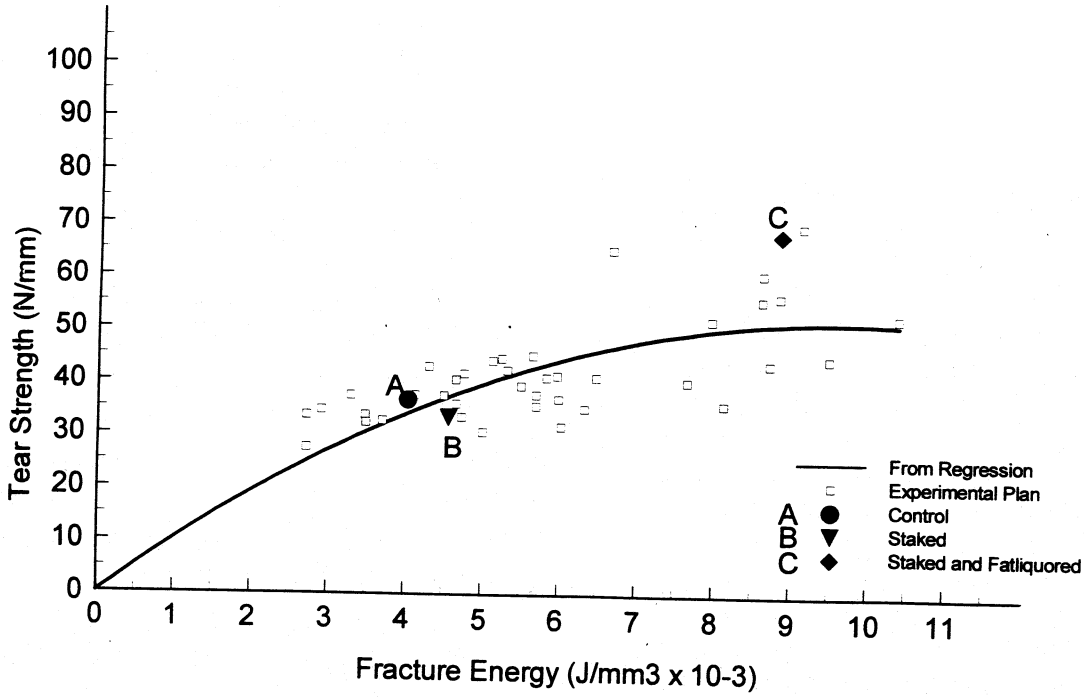

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

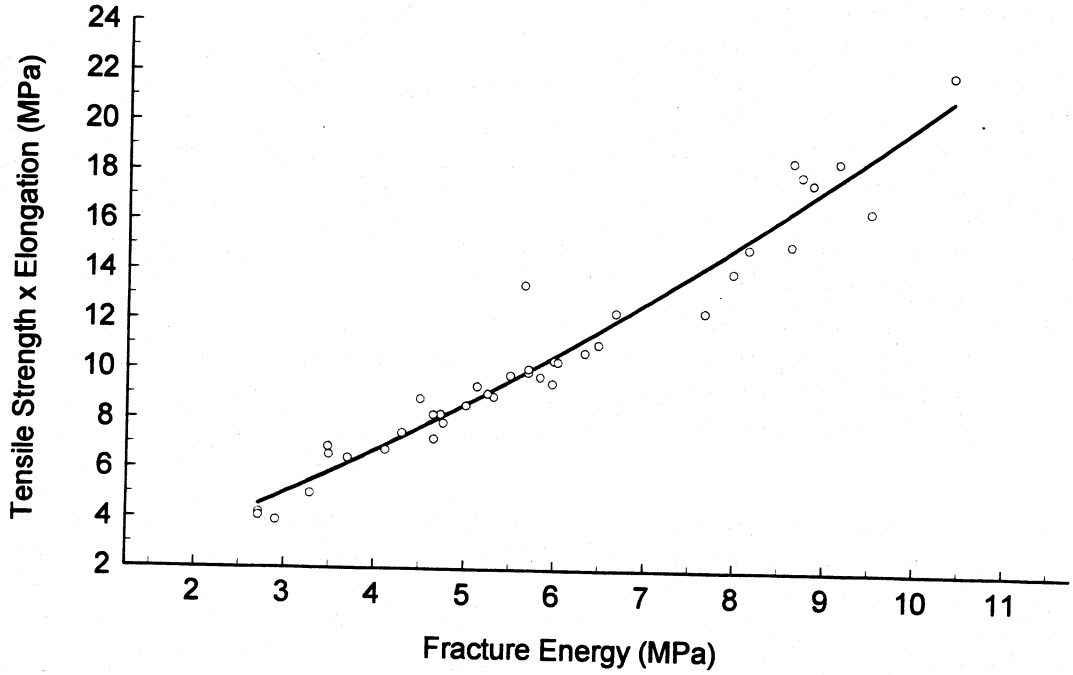

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

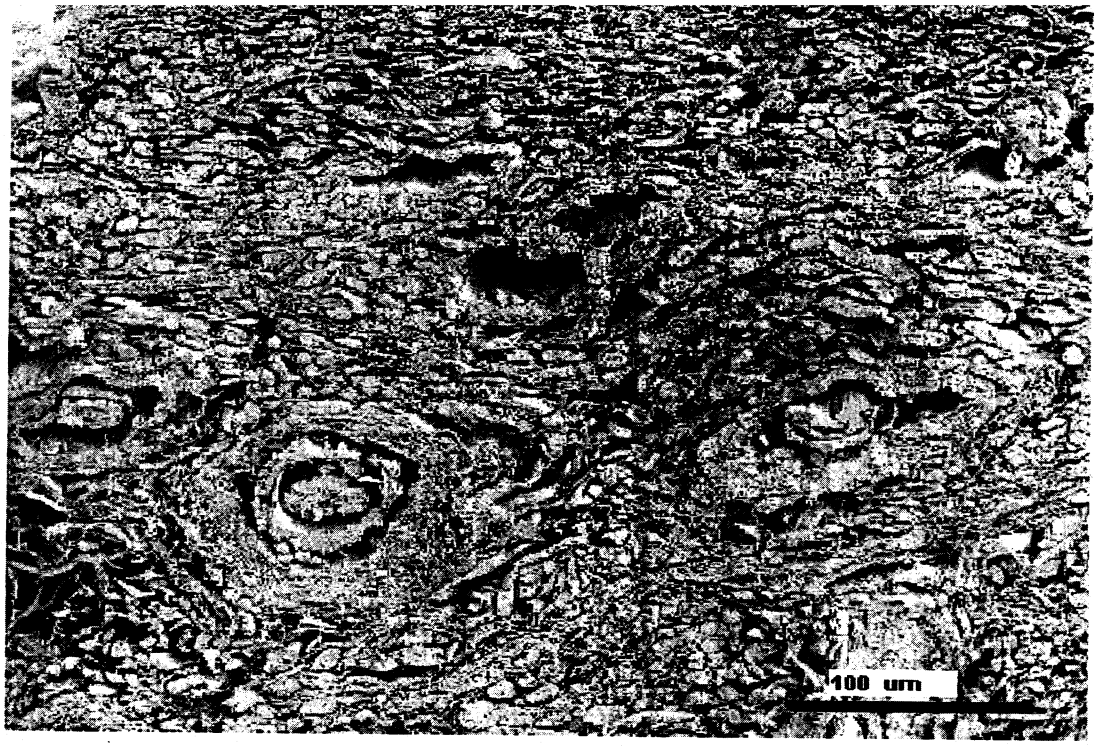

FIGURE 1. — Micrograph showing grain layer with sheet structure.

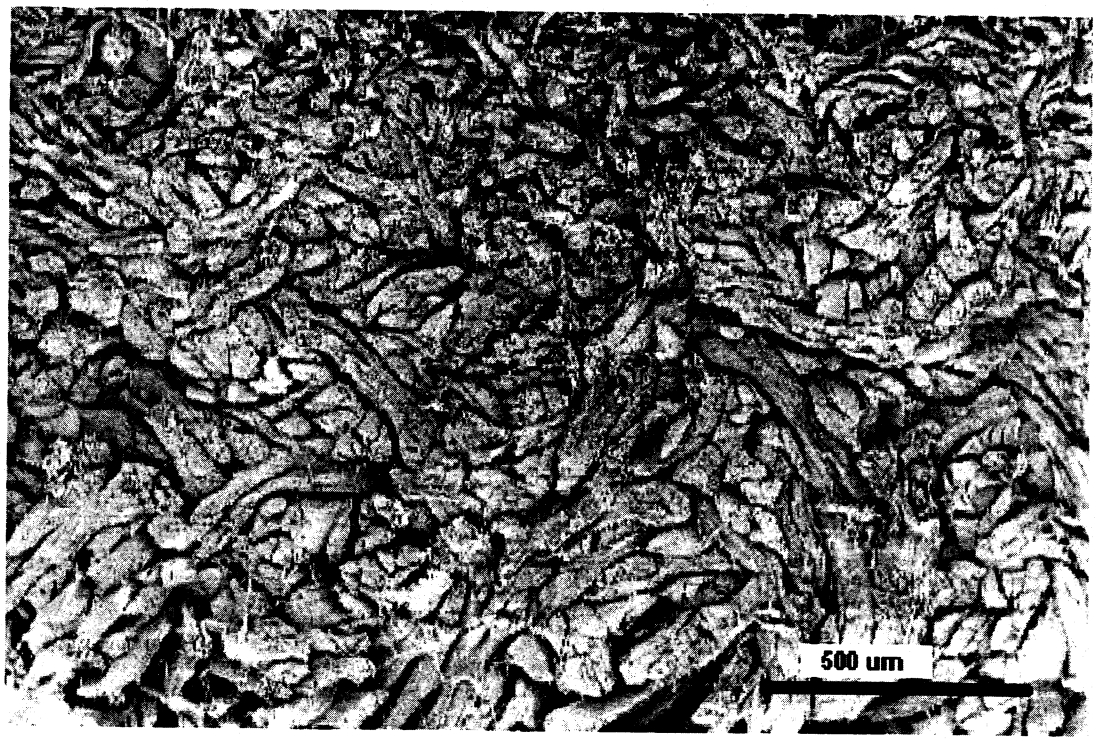

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

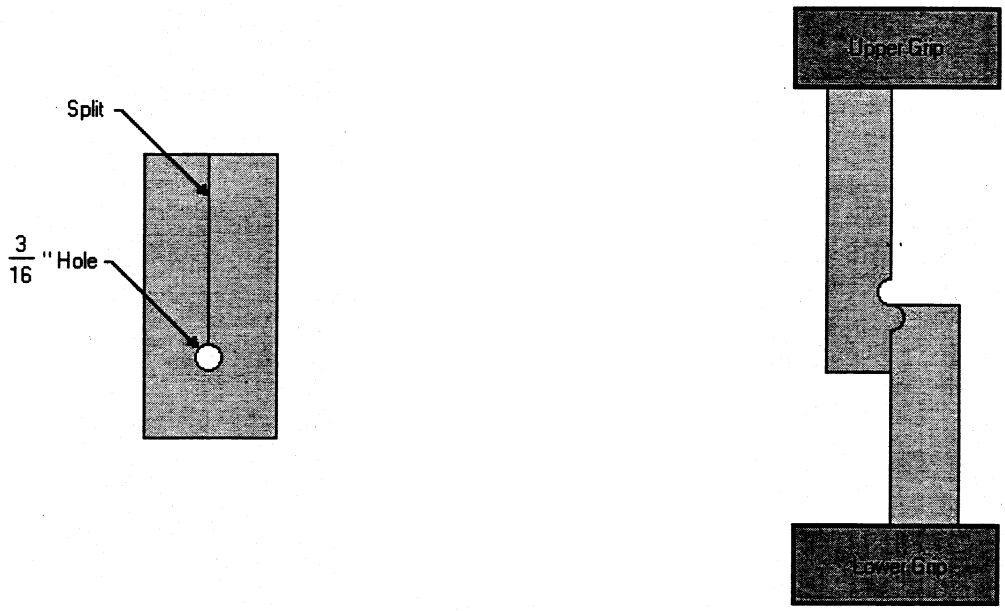

FIGURE 3. — Tear test scheme.

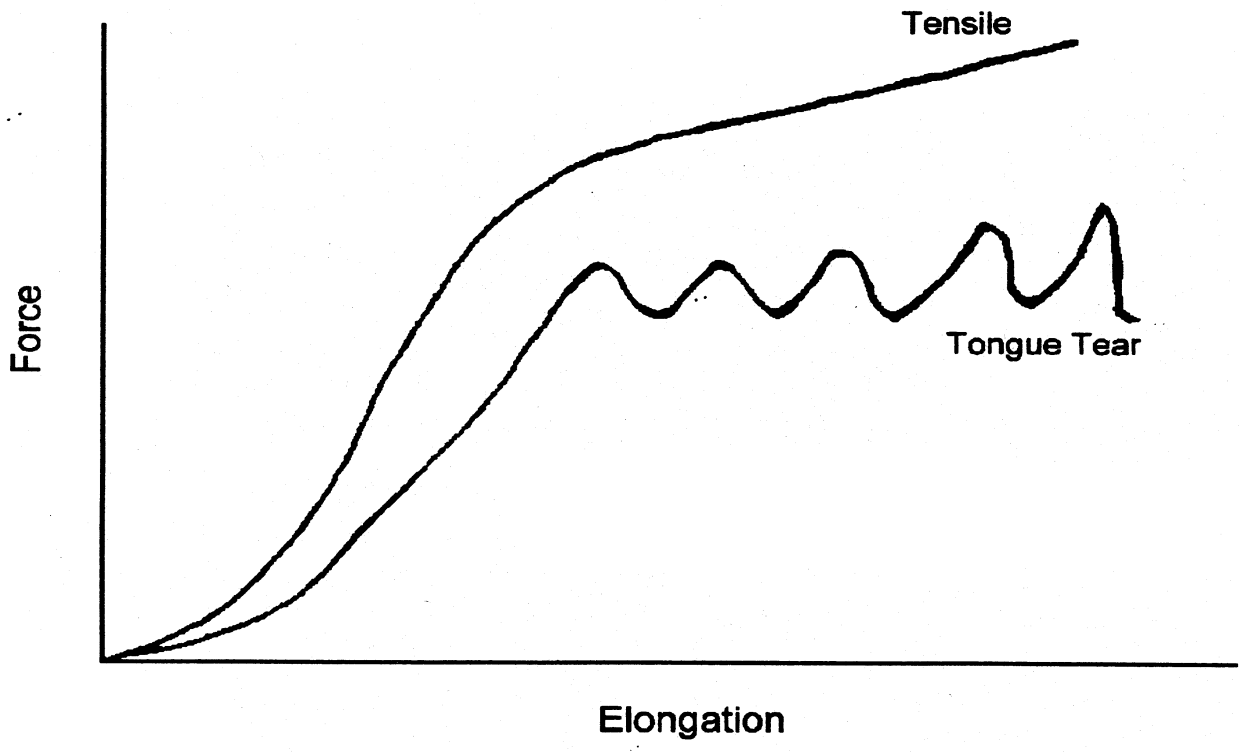

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

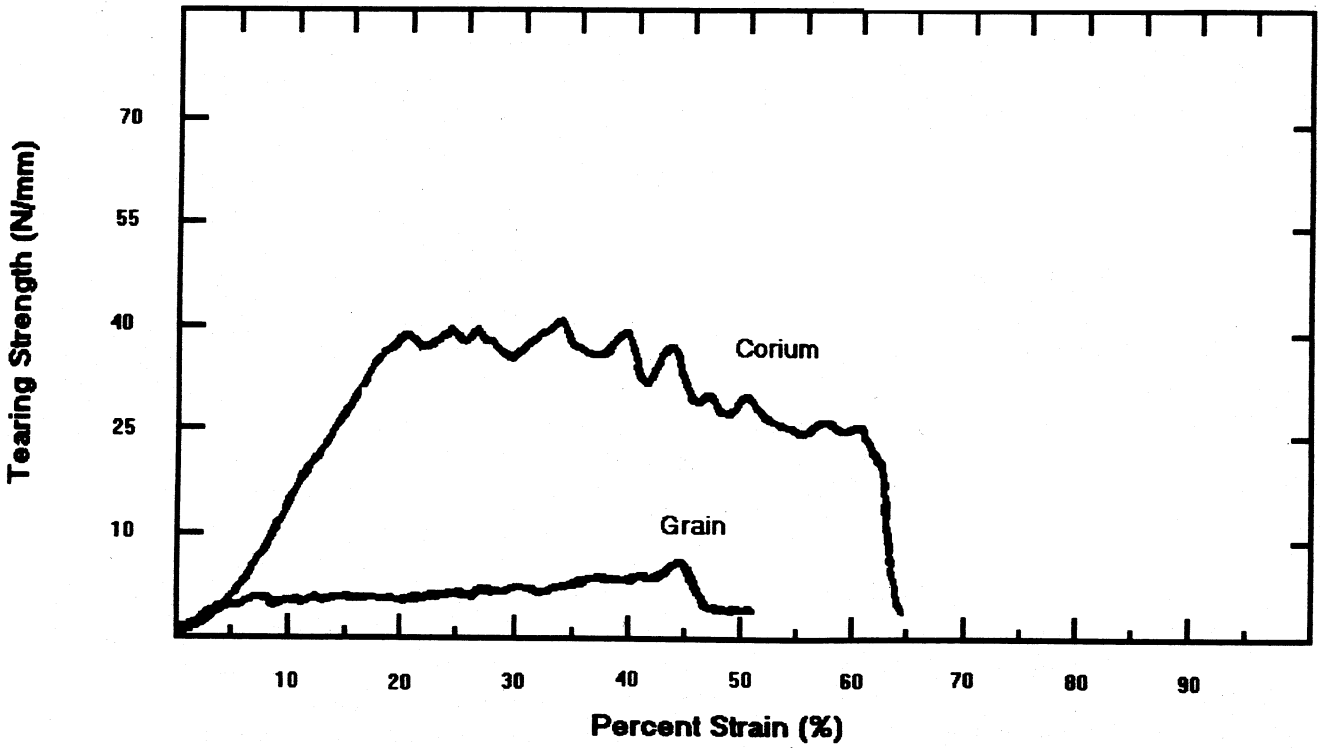

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

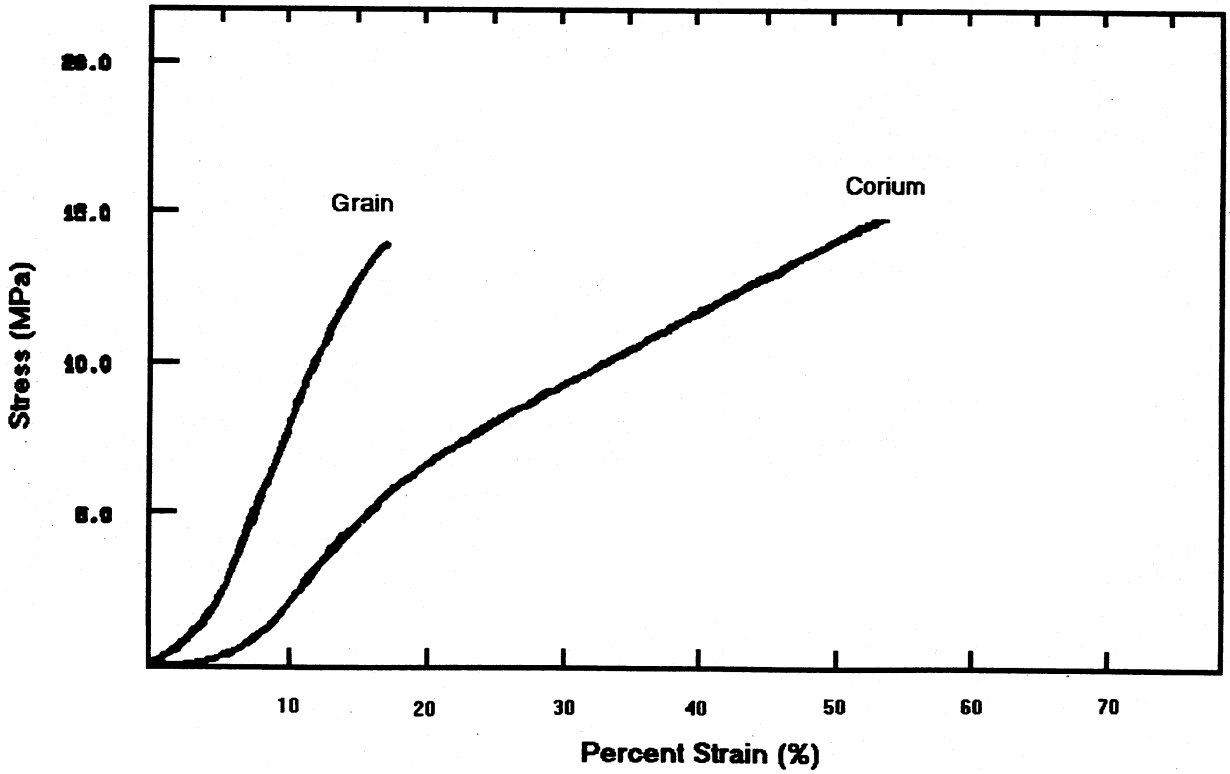

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

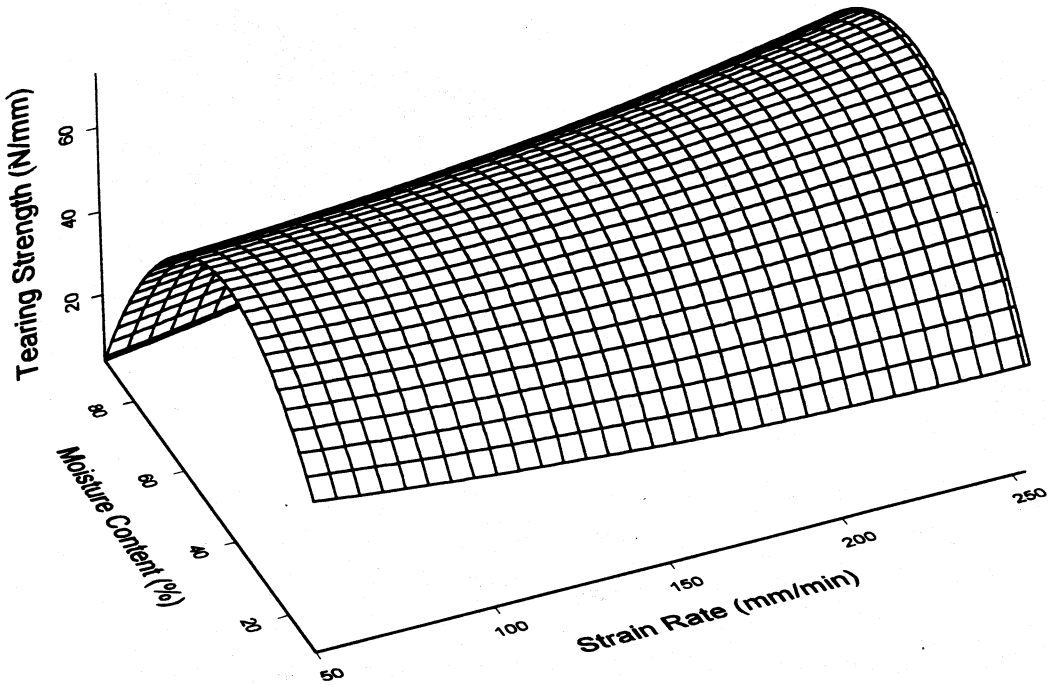

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

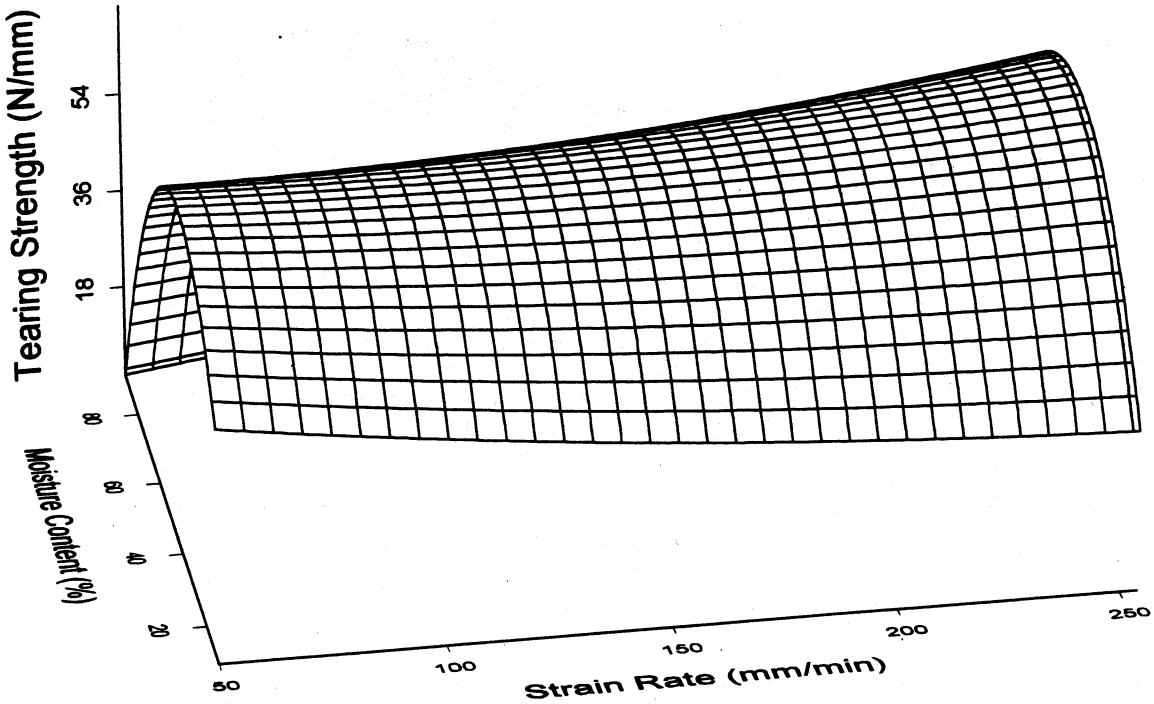

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

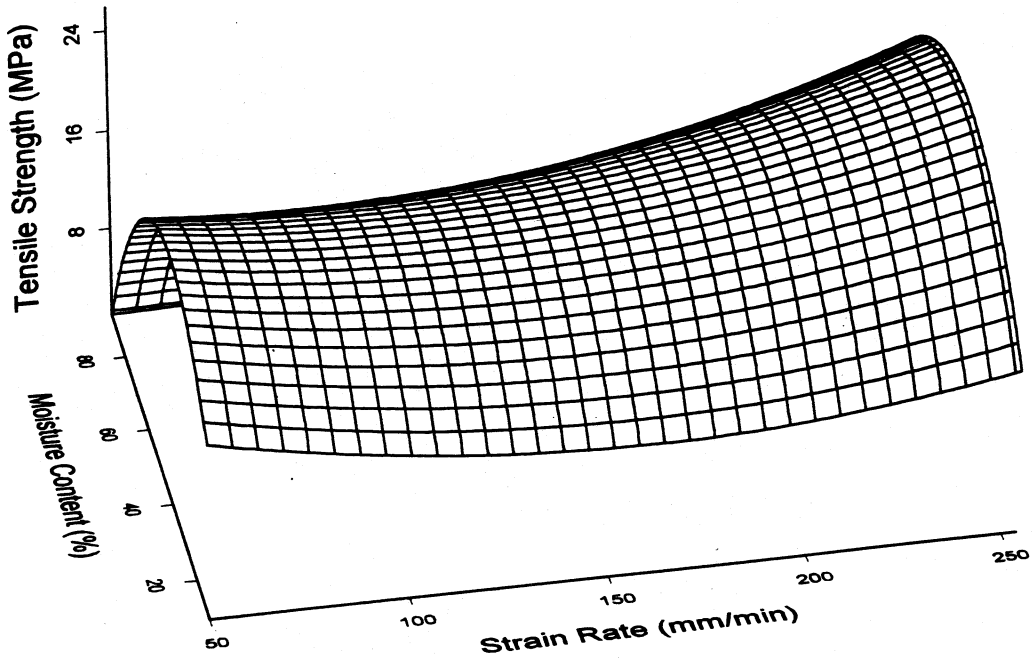

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

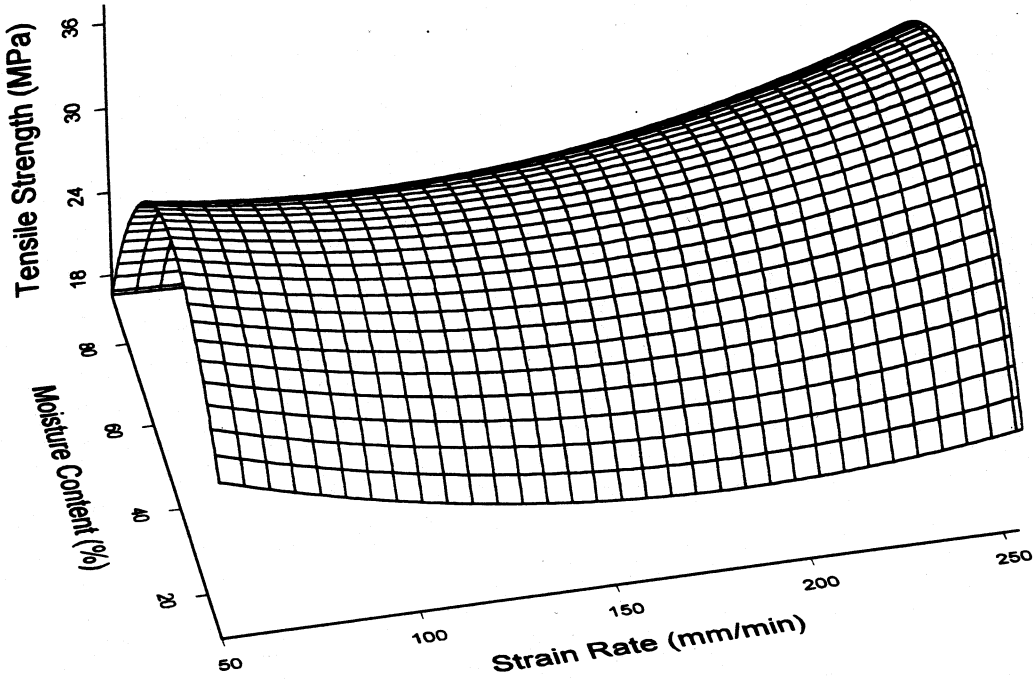

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

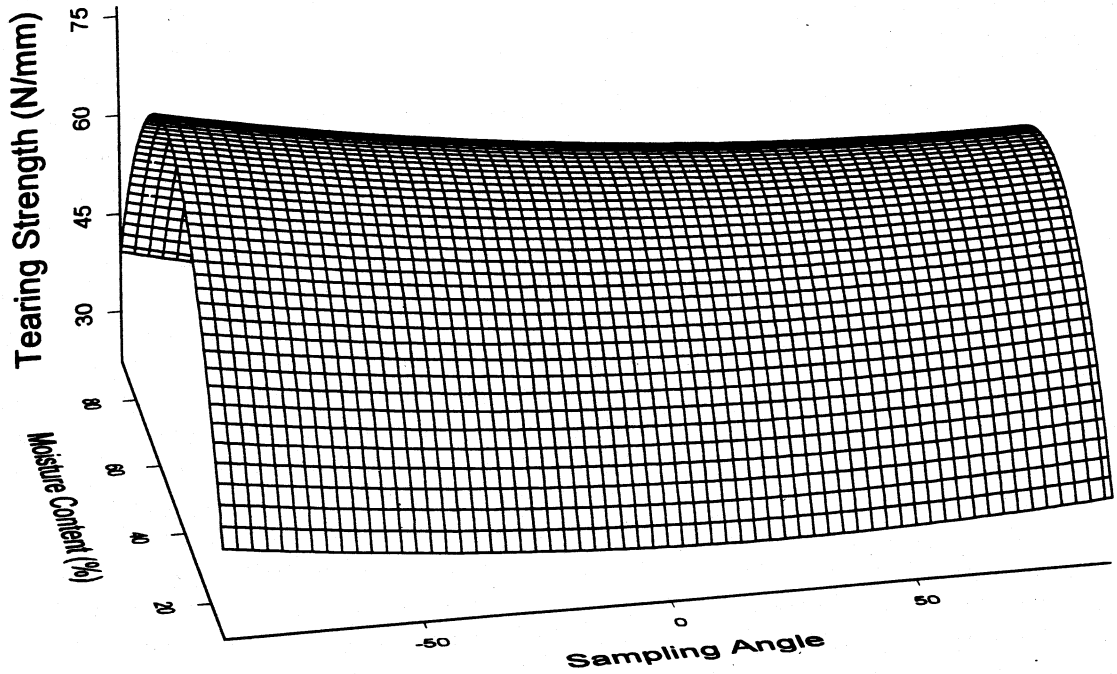

FIGURE 11. — Effect of sampling angle on tearing strength.

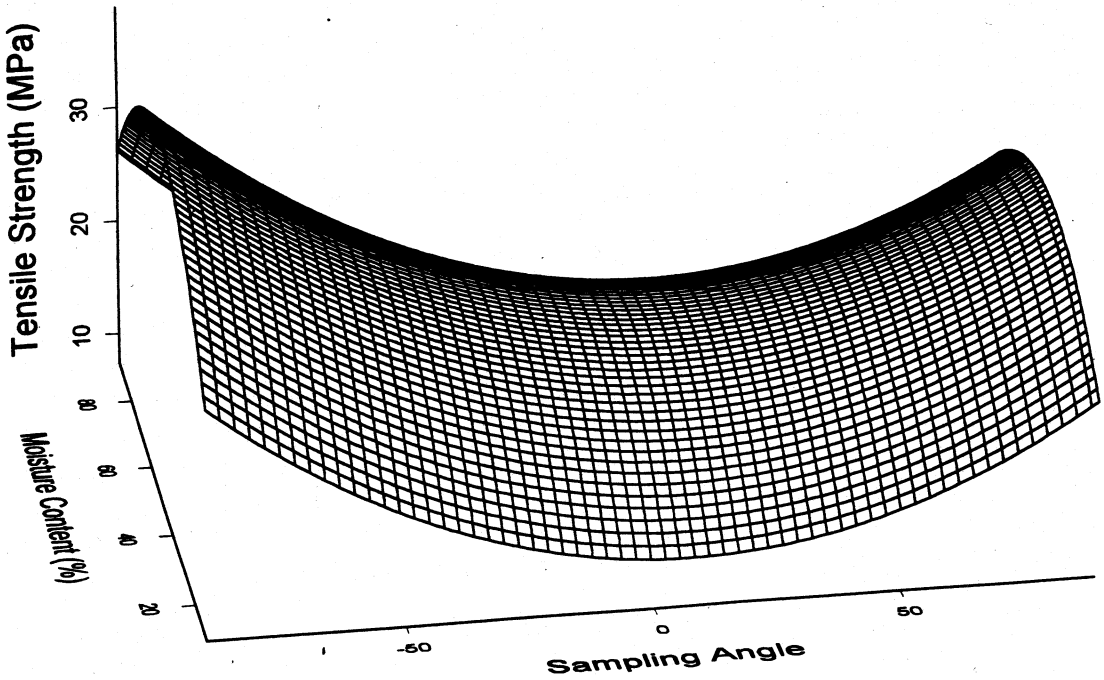

FIGURE 12. — Effect of sampling angle on tensile strength.

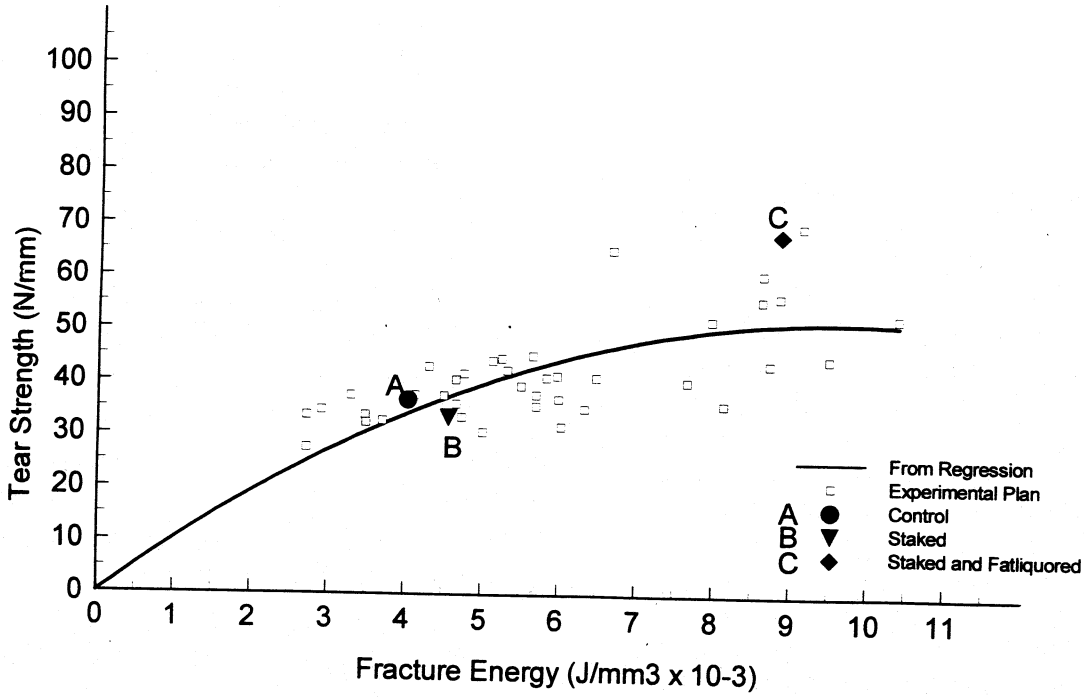

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

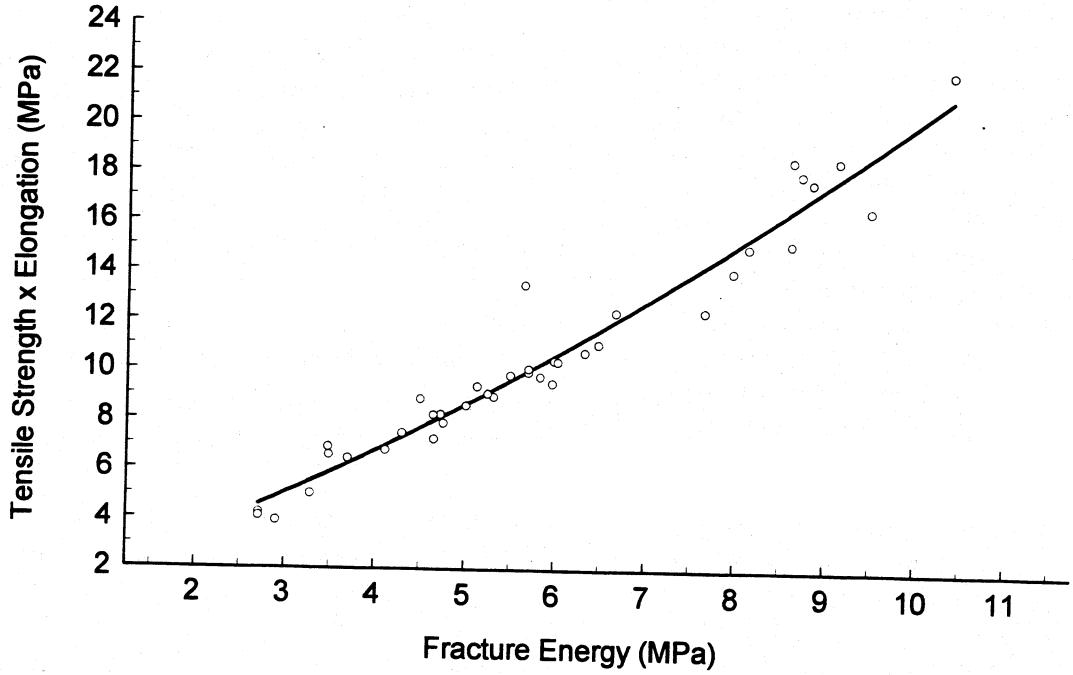

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

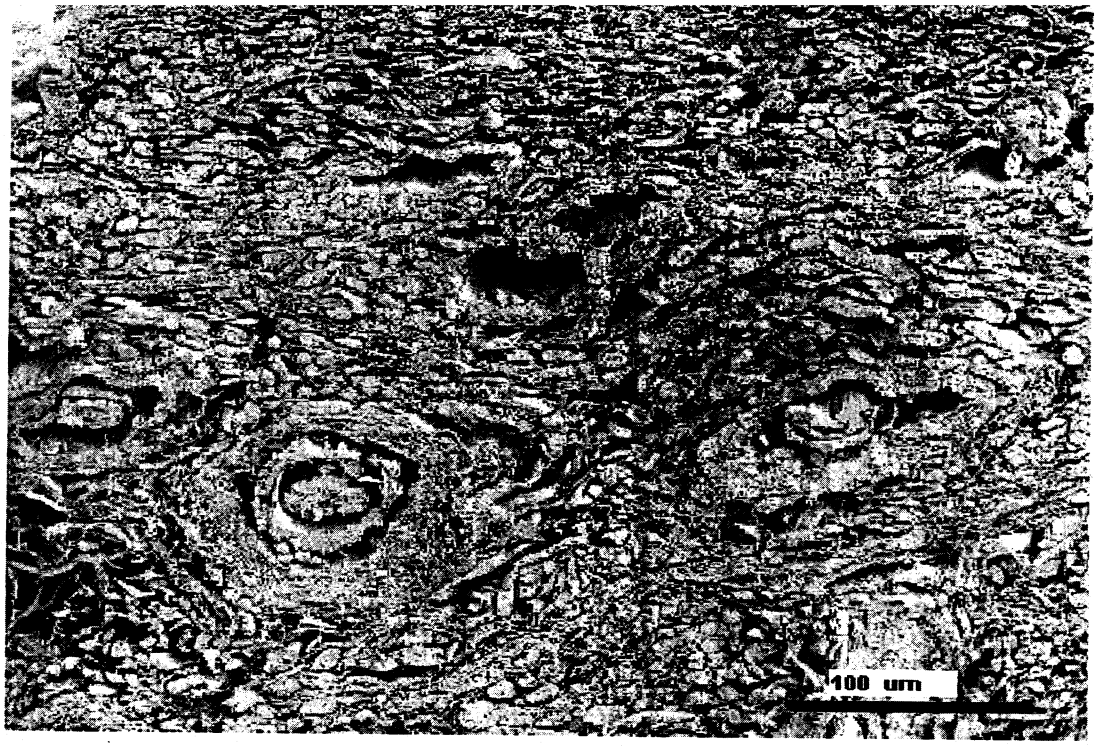

FIGURE 1. — Micrograph showing grain layer with sheet structure.

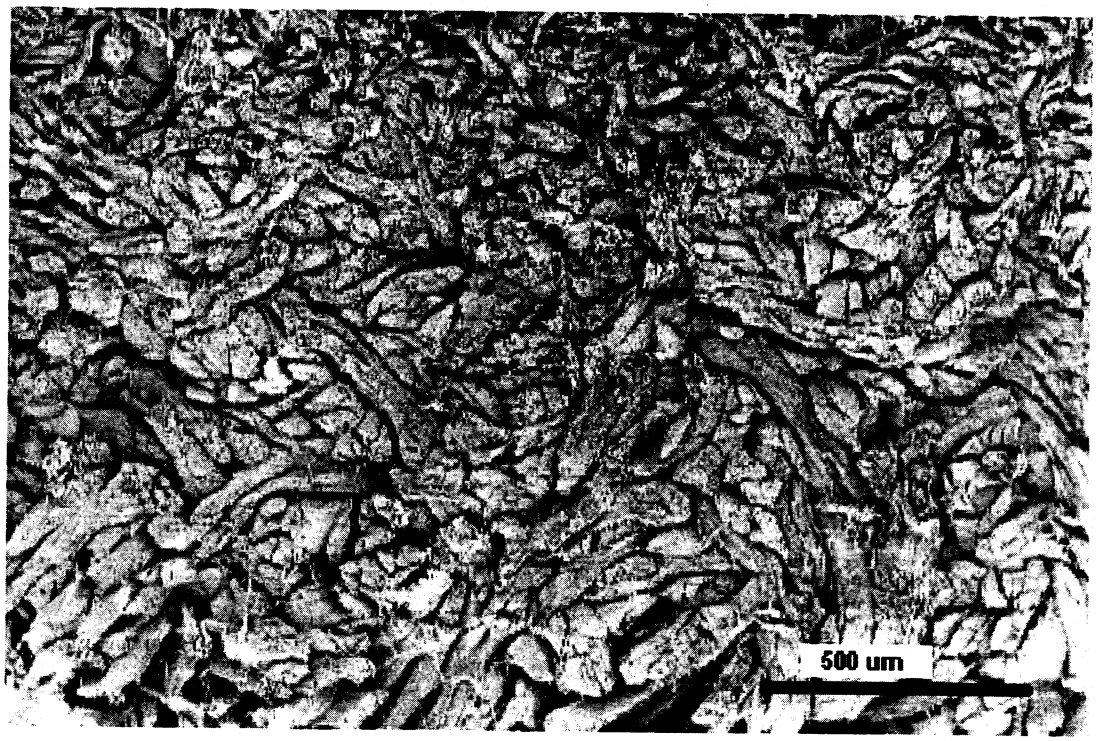

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

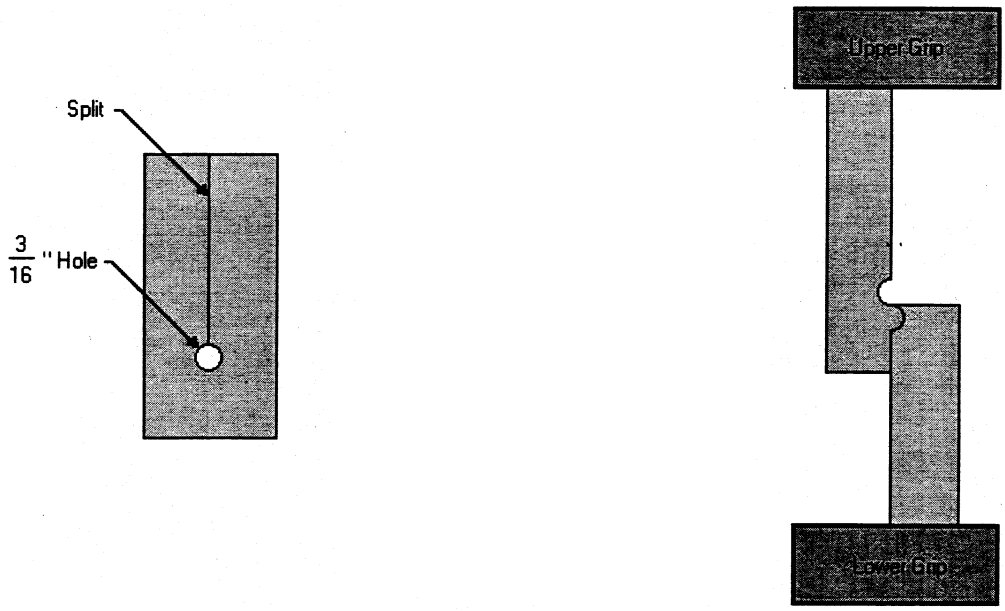

FIGURE 3. — Tear test scheme.

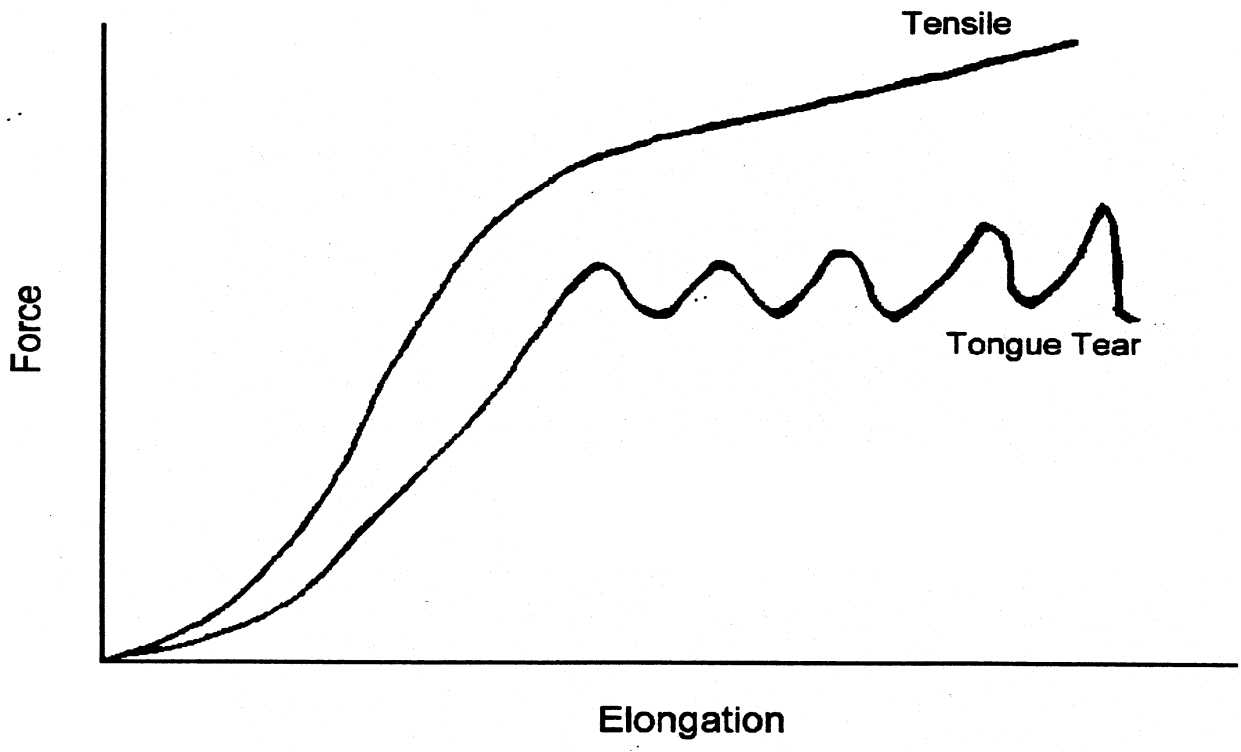

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

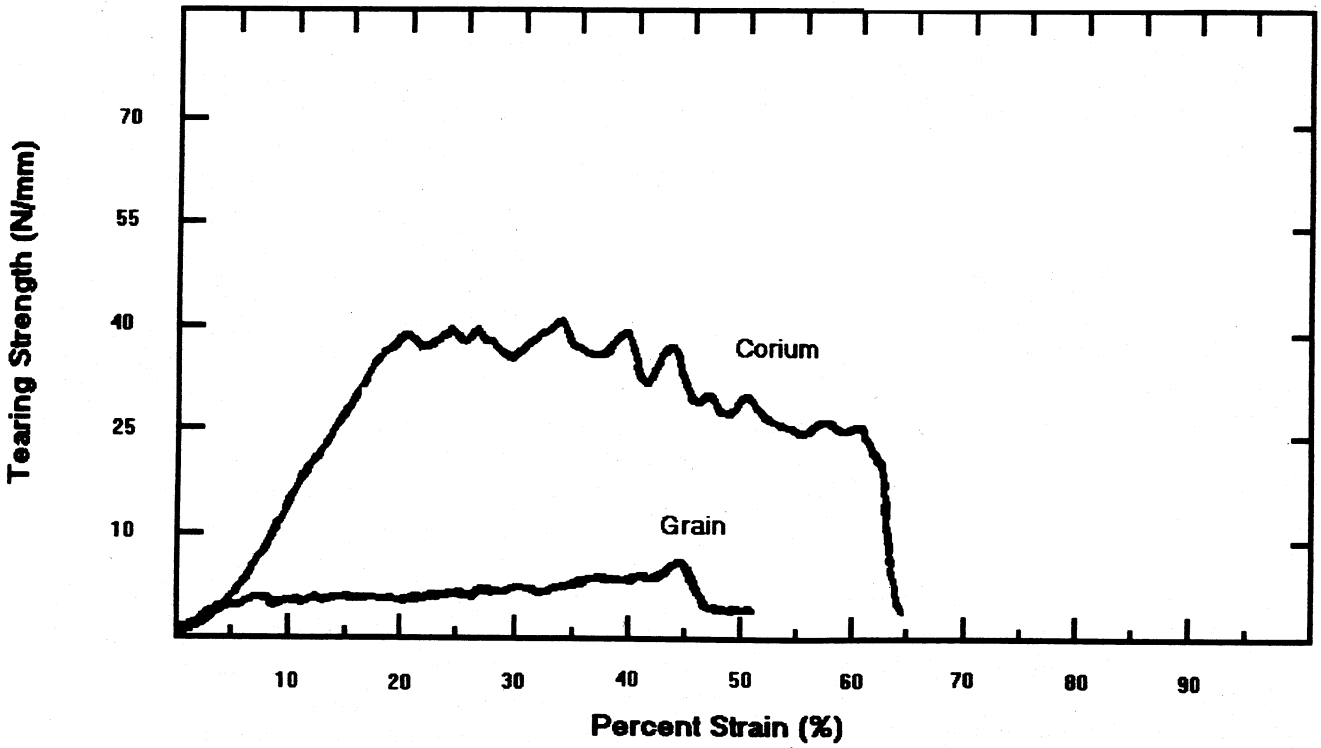

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

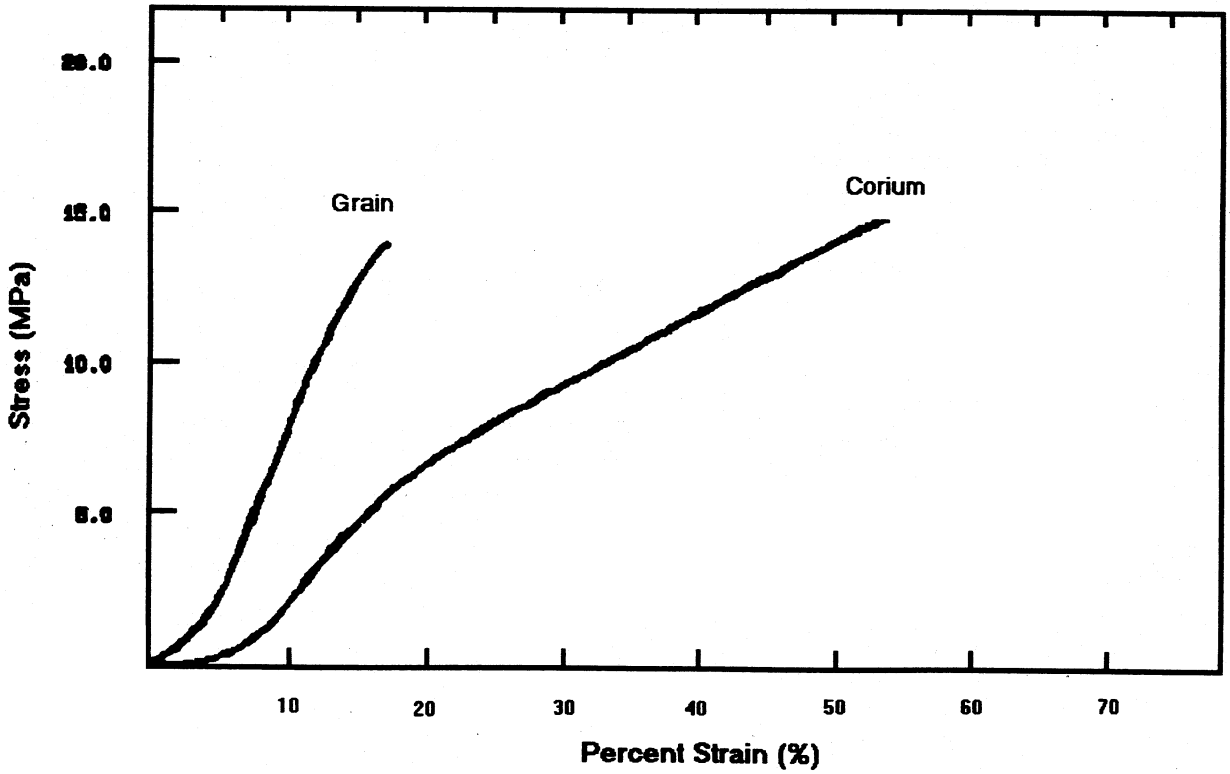

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

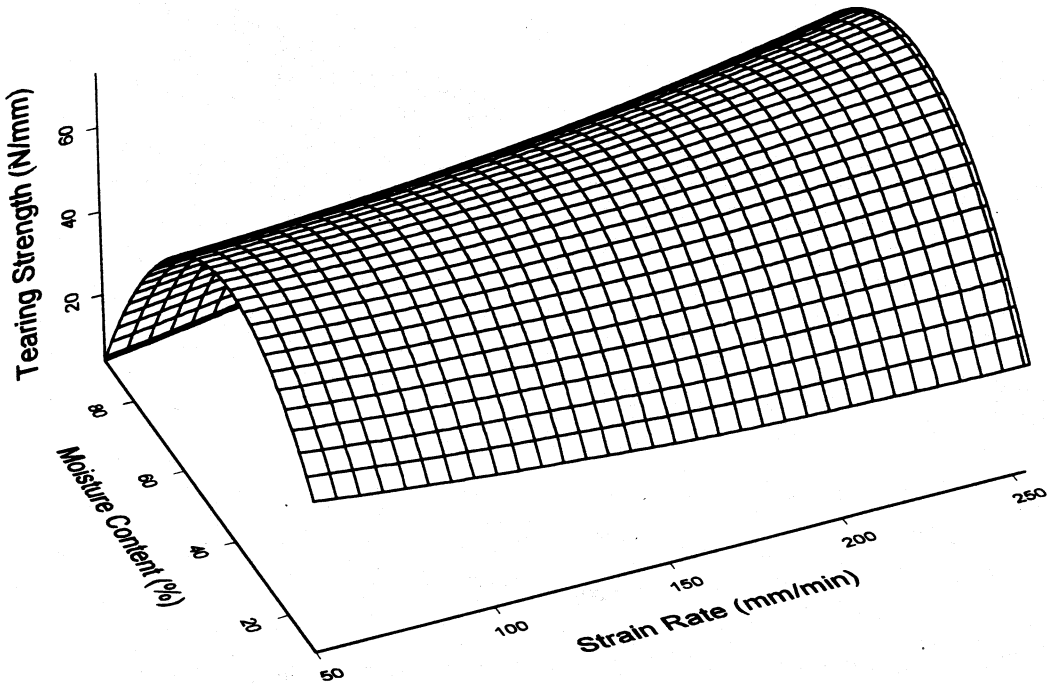

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

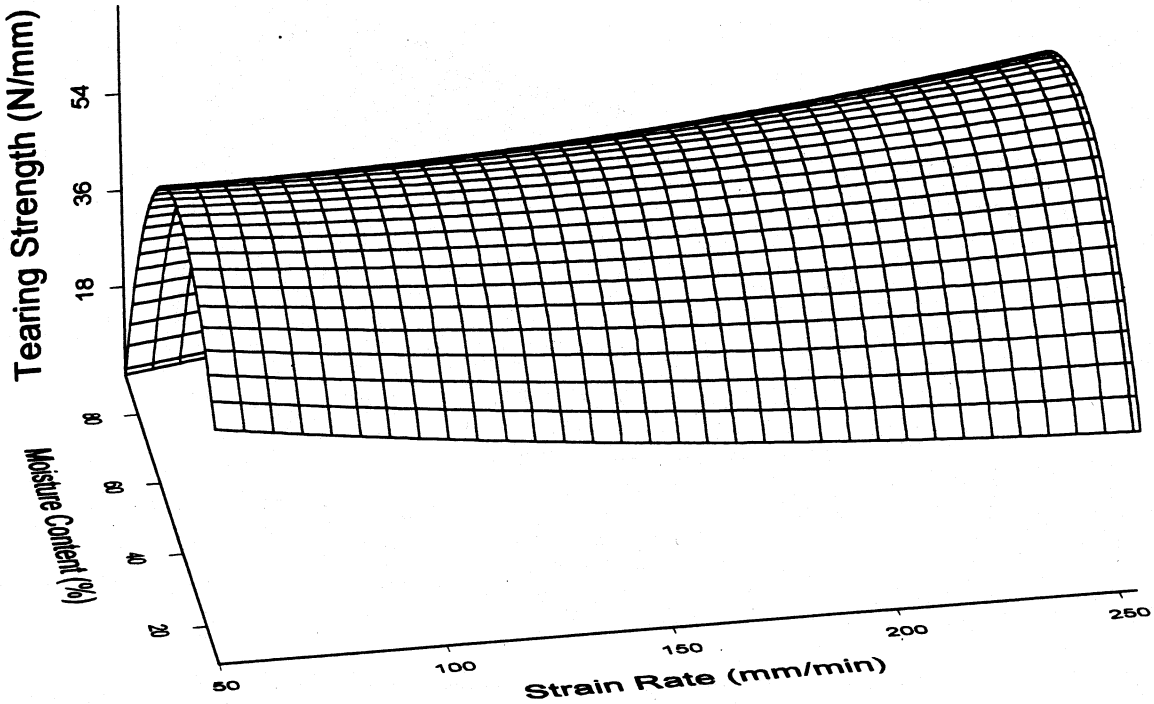

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

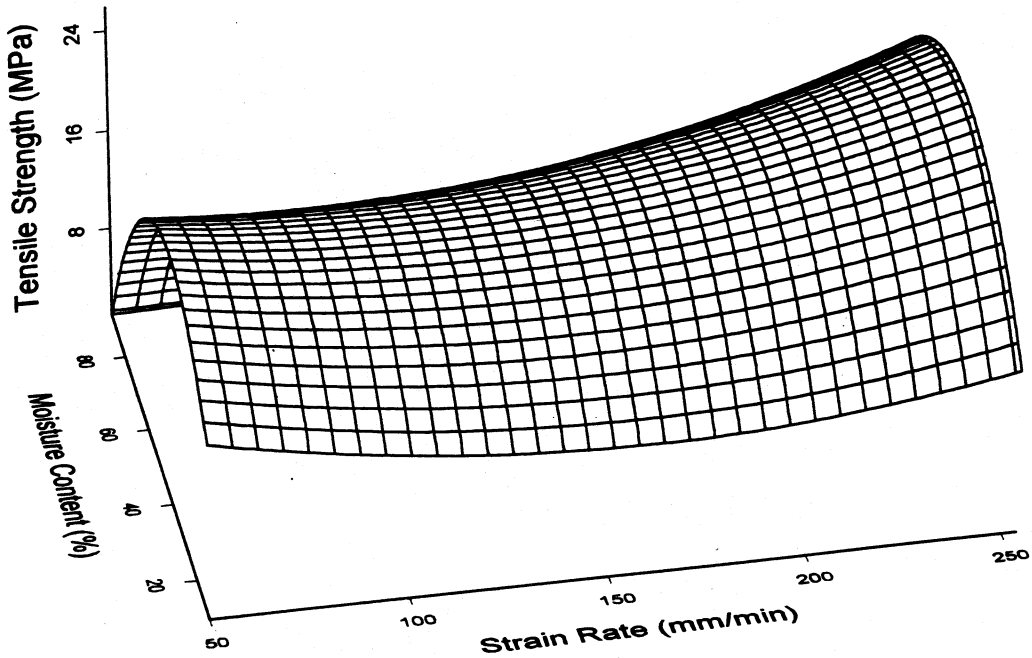

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

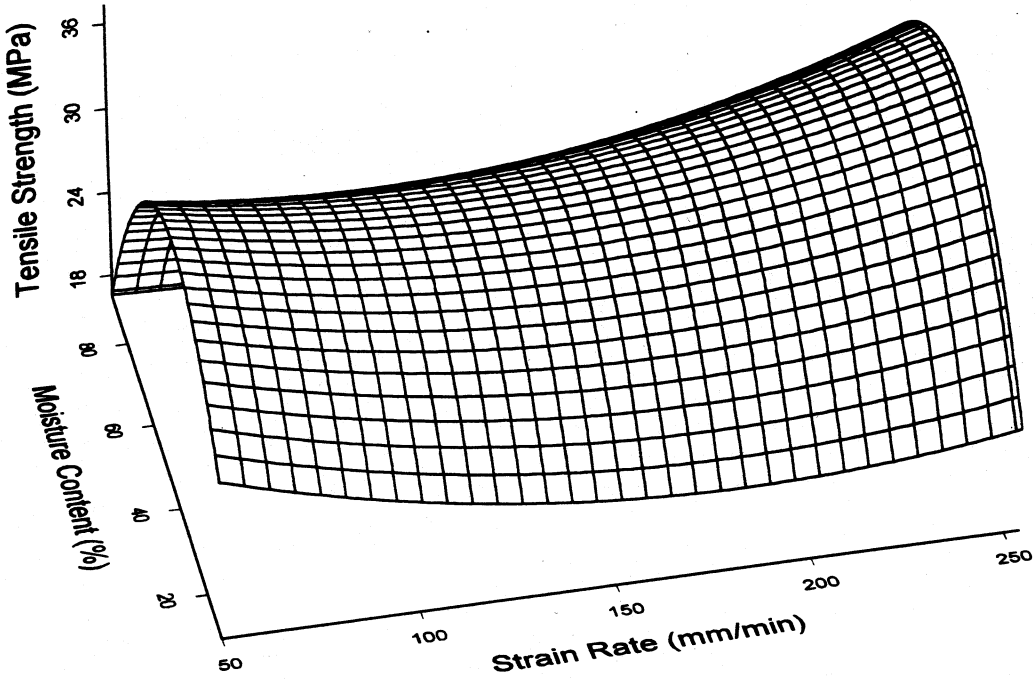

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

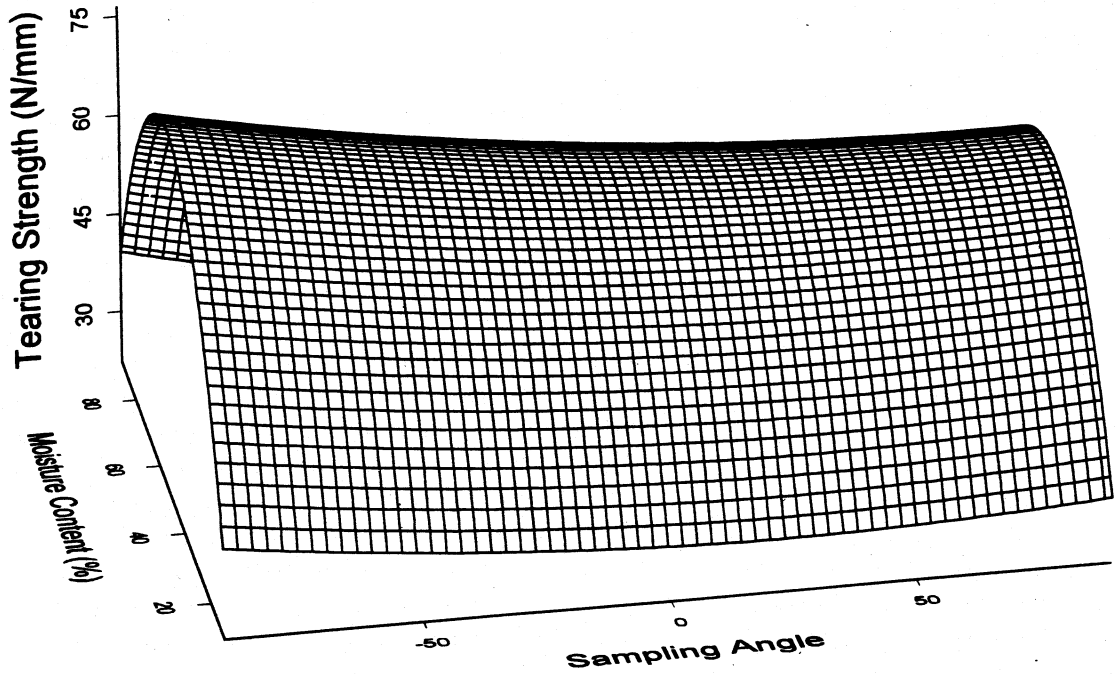

FIGURE 11. — Effect of sampling angle on tearing strength.

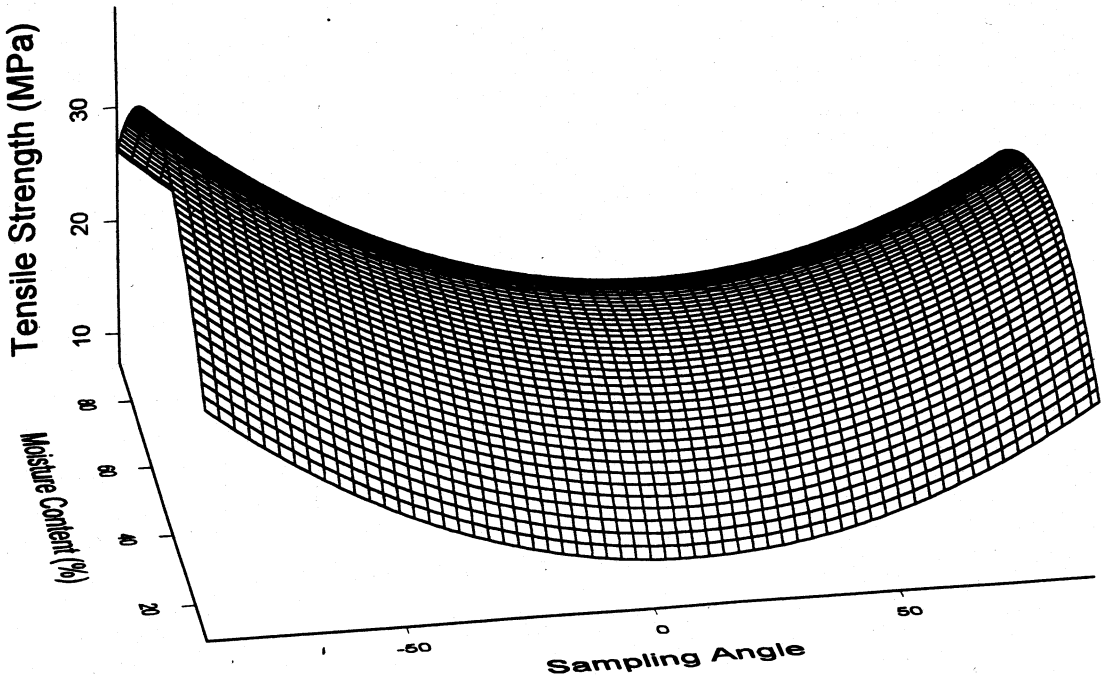

FIGURE 12. — Effect of sampling angle on tensile strength.

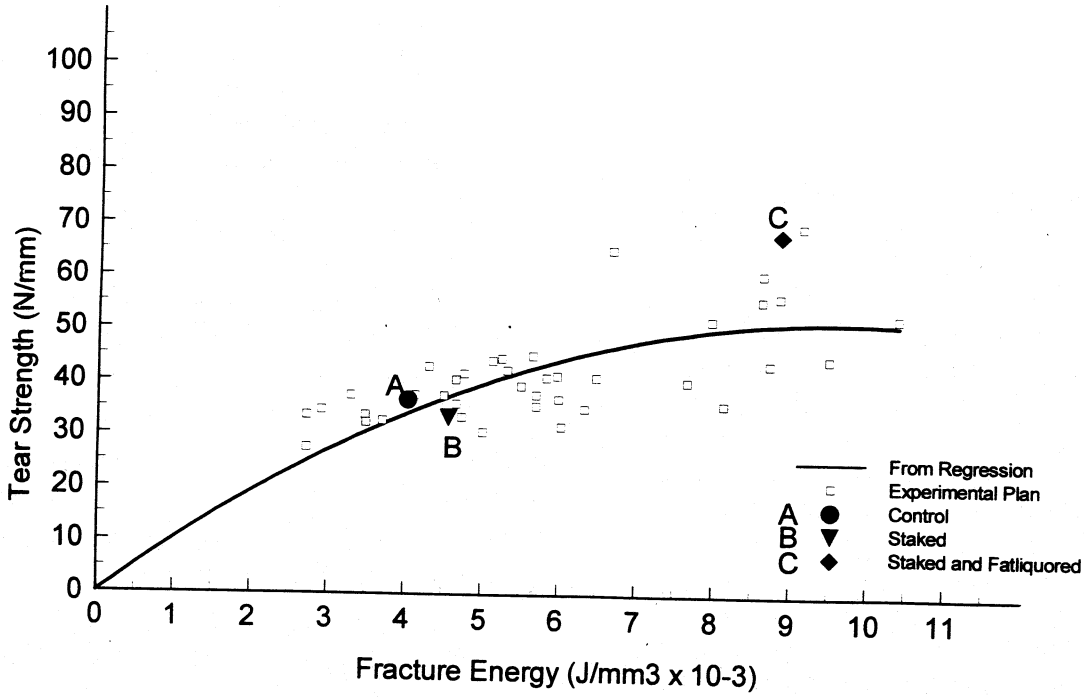

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

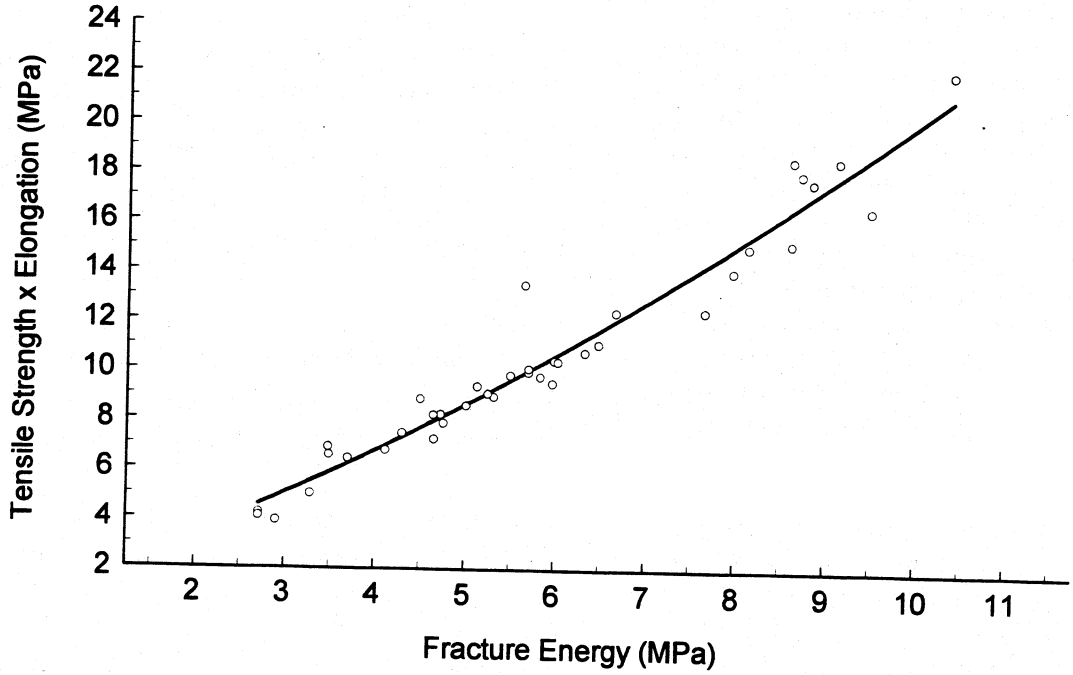

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

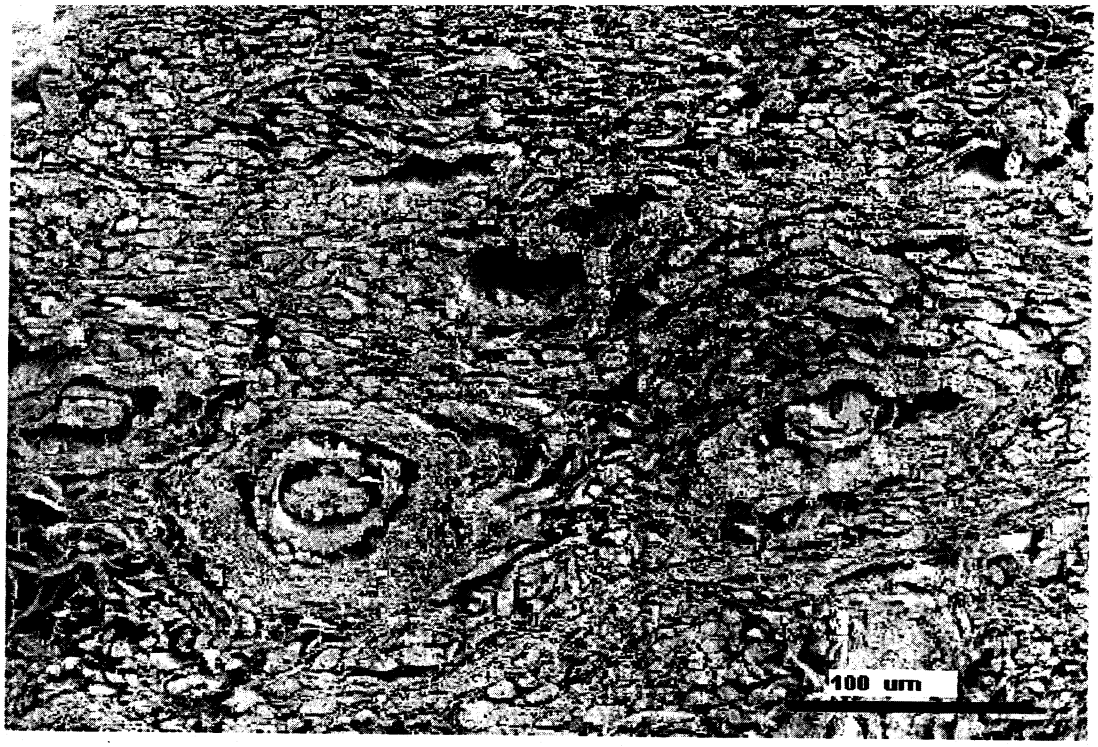

FIGURE 1. — Micrograph showing grain layer with sheet structure.

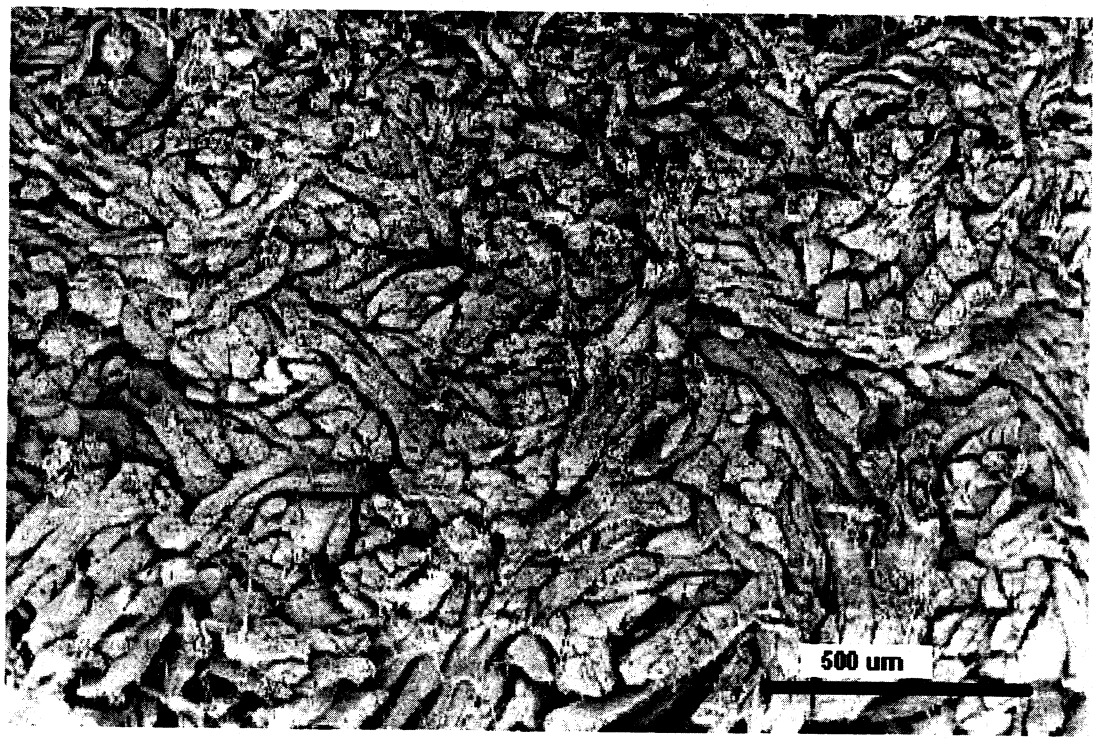

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

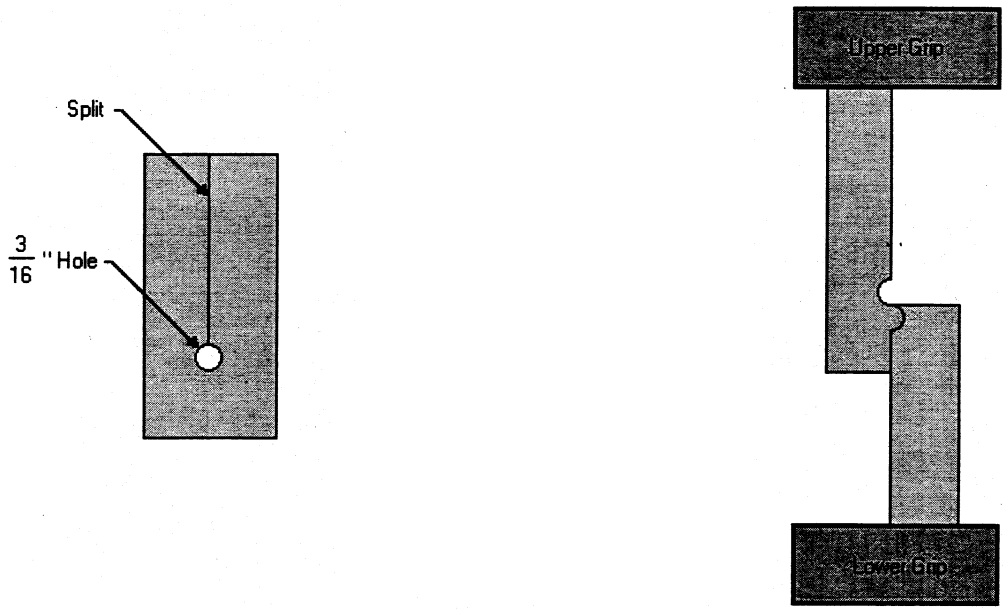

FIGURE 3. — Tear test scheme.

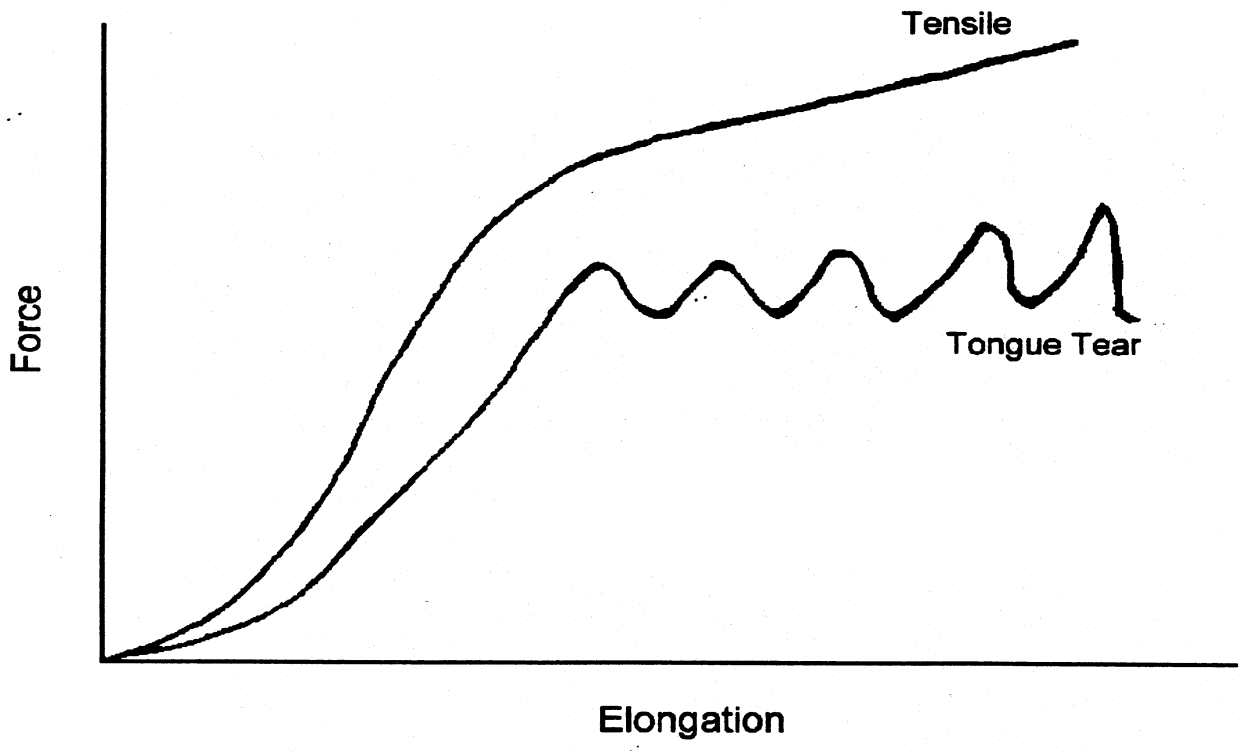

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

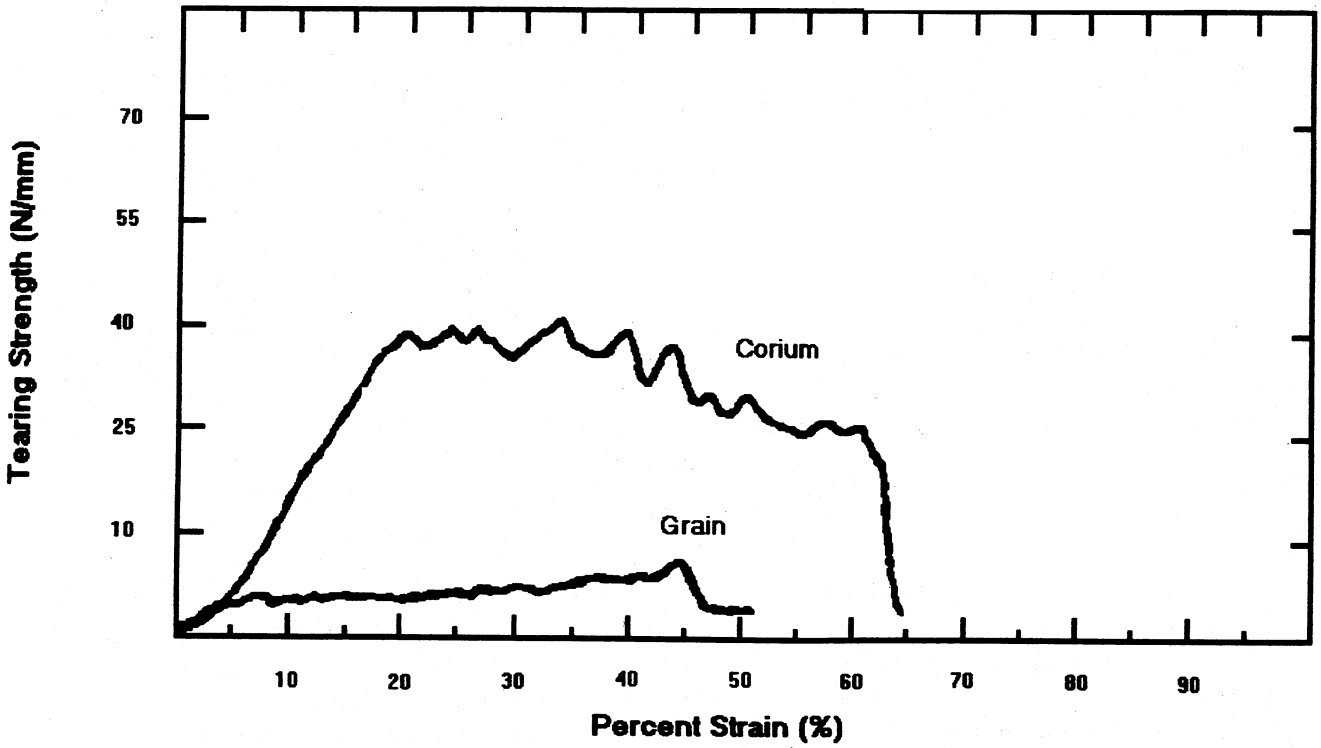

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

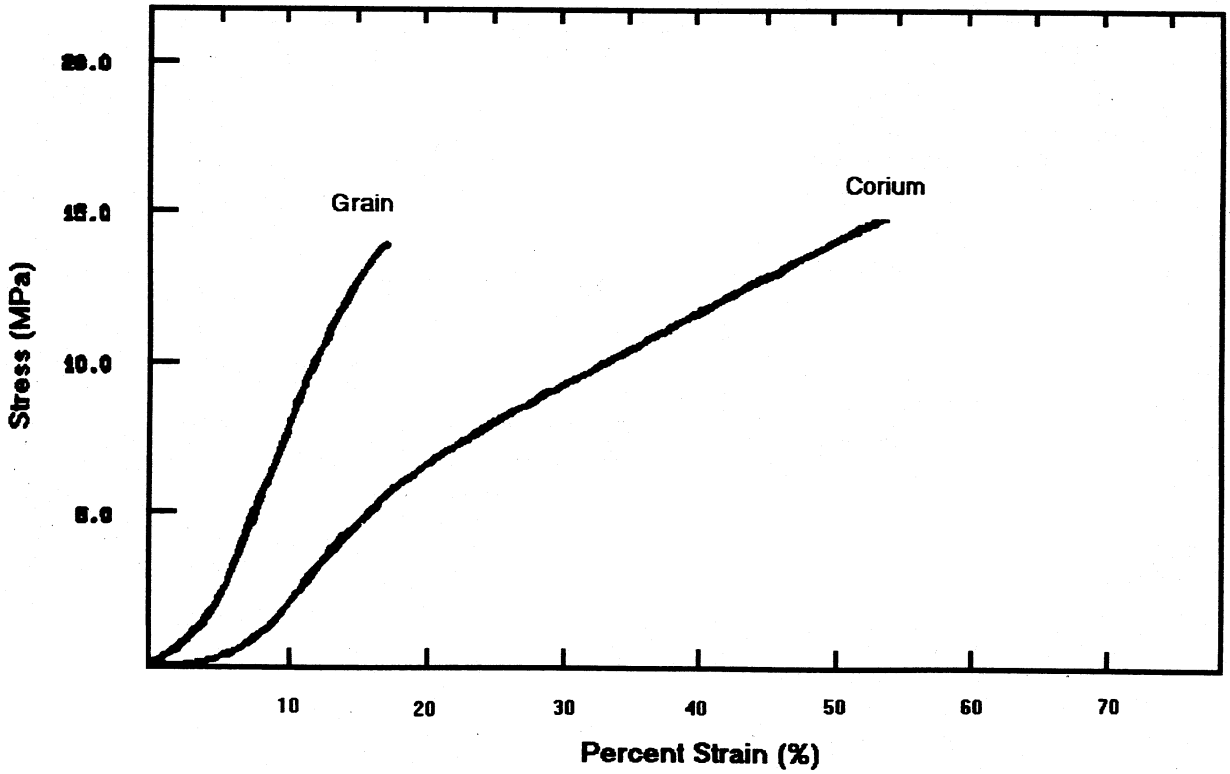

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

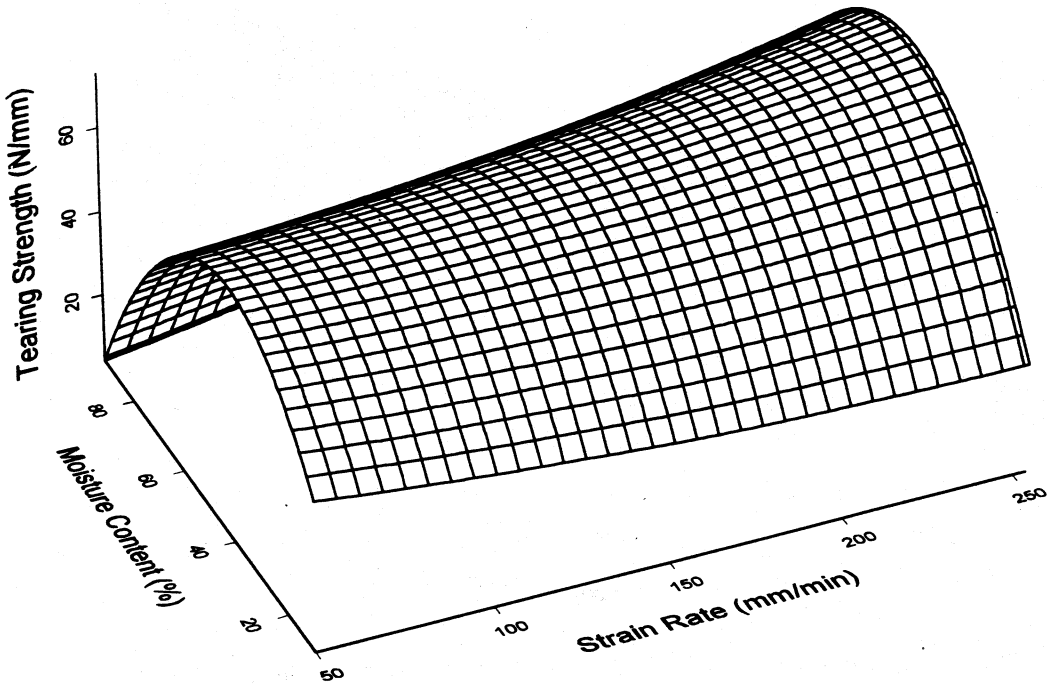

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

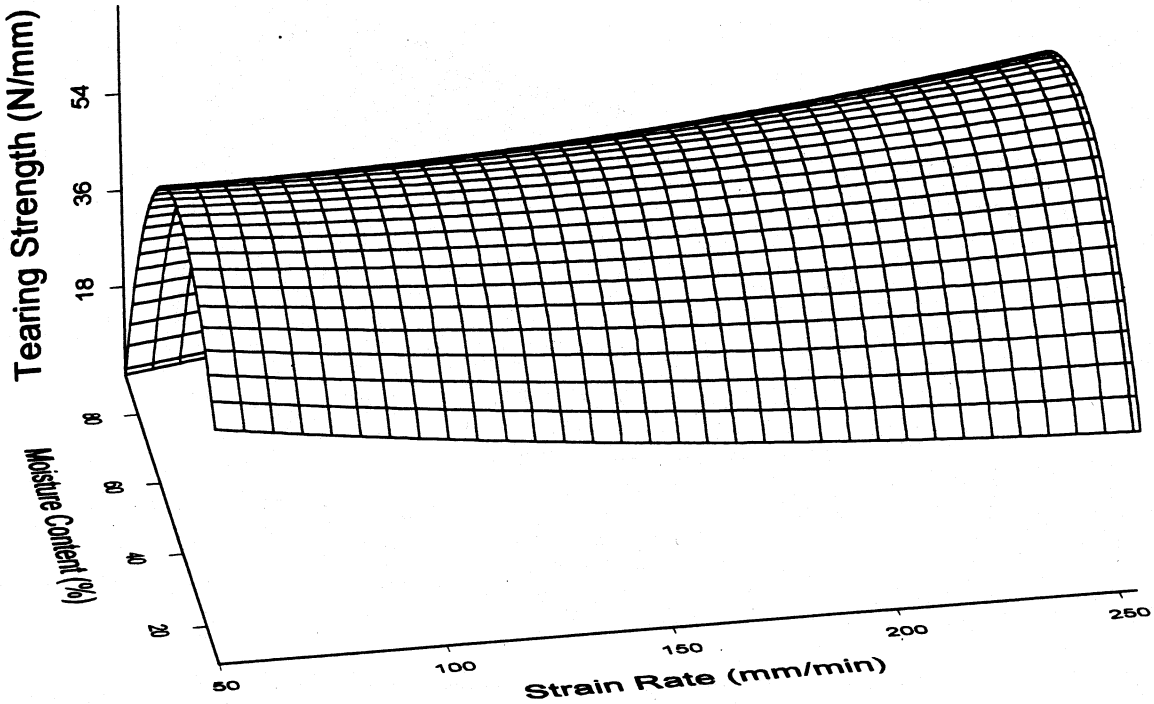

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

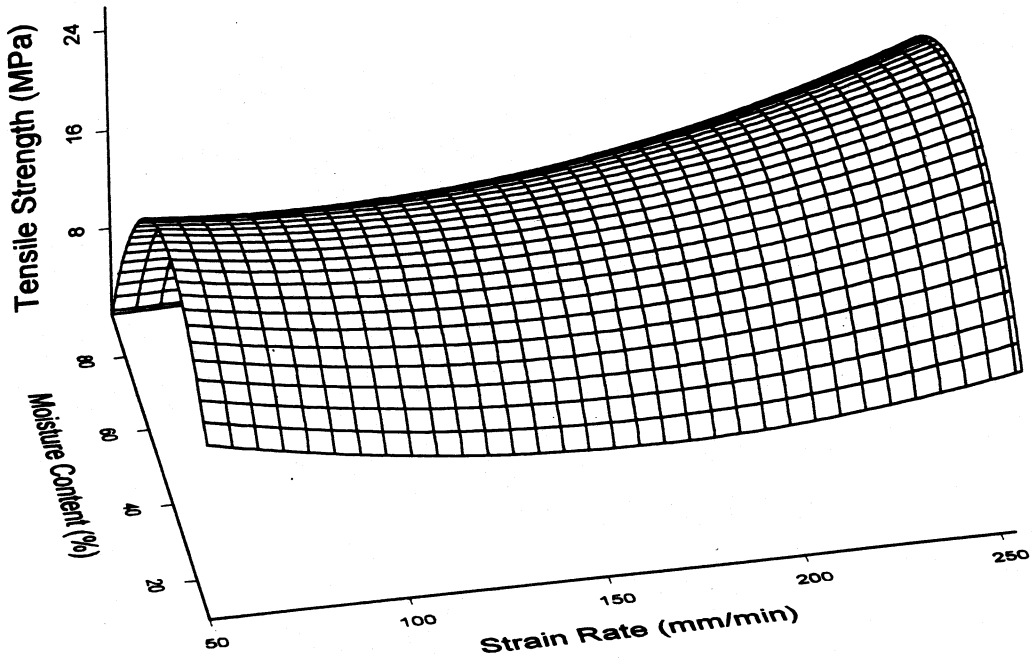

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

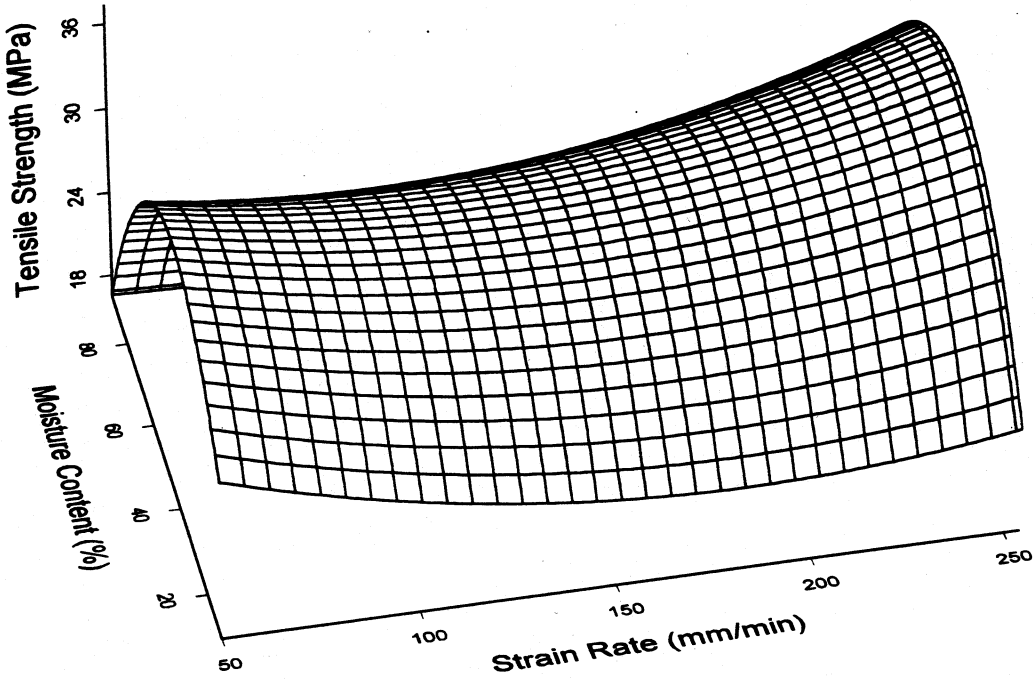

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

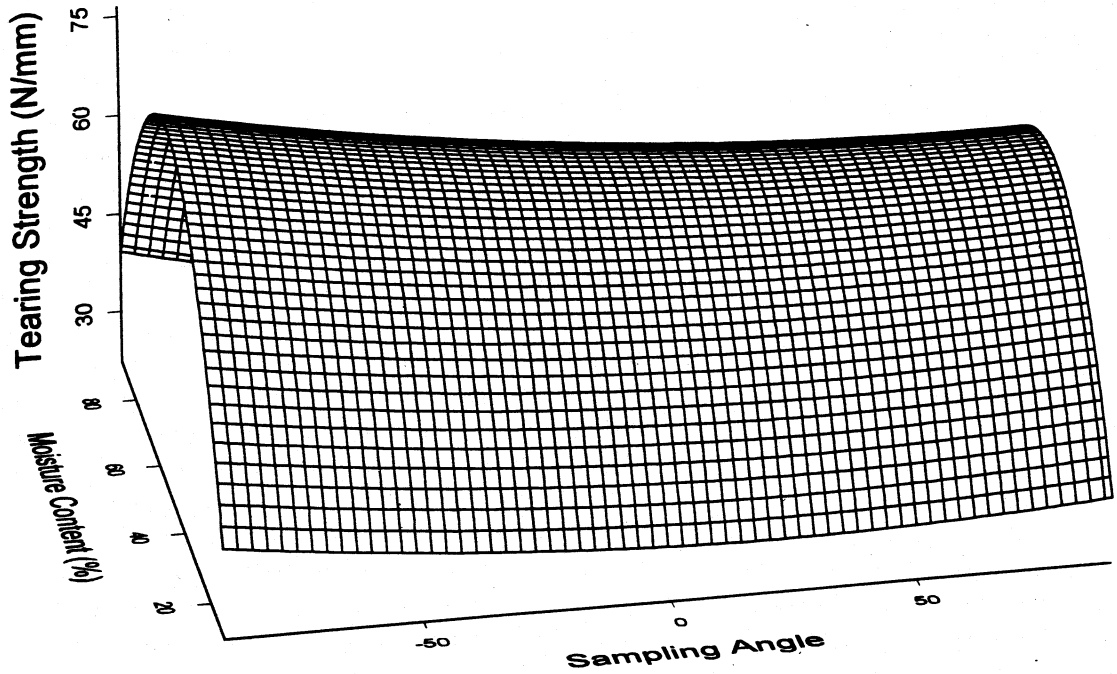

FIGURE 11. — Effect of sampling angle on tearing strength.

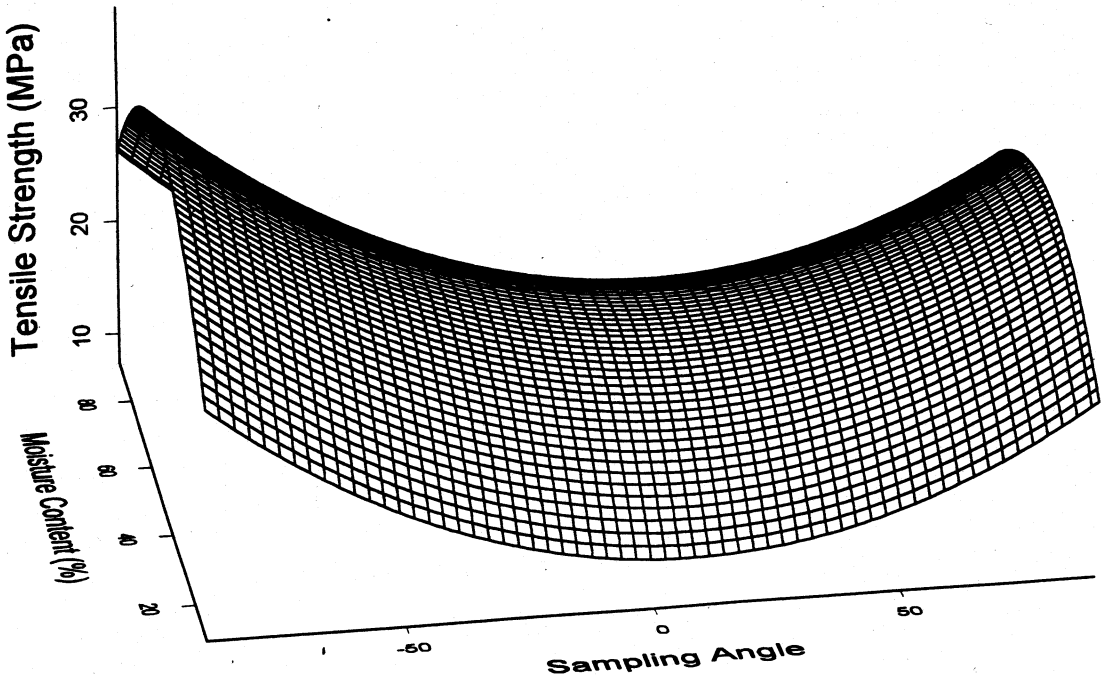

FIGURE 12. — Effect of sampling angle on tensile strength.

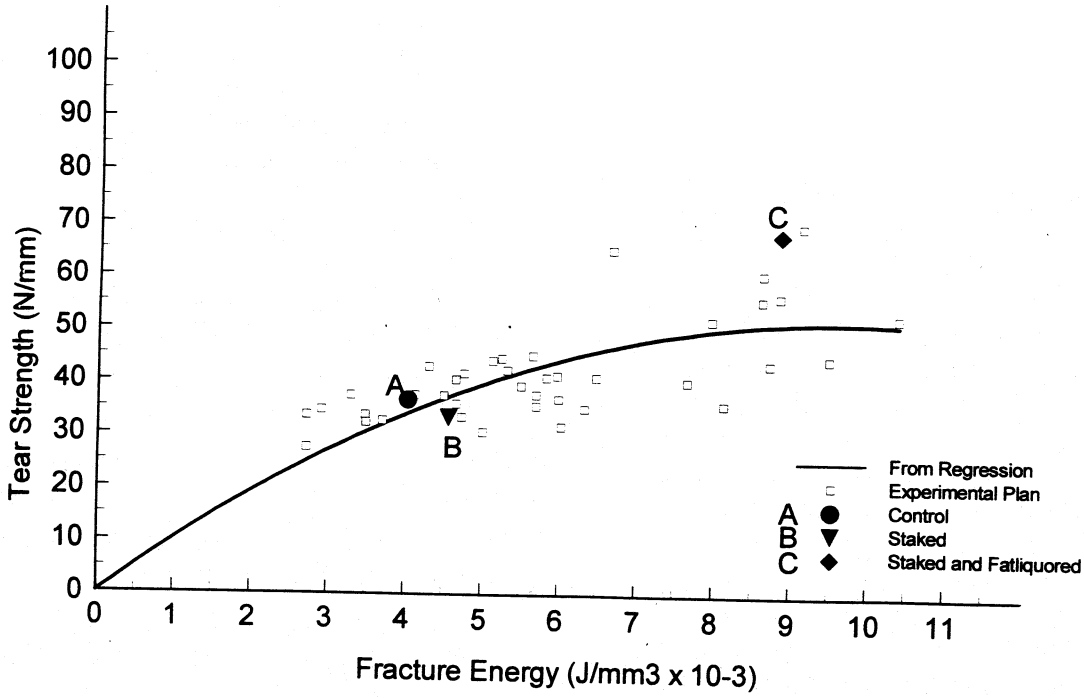

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

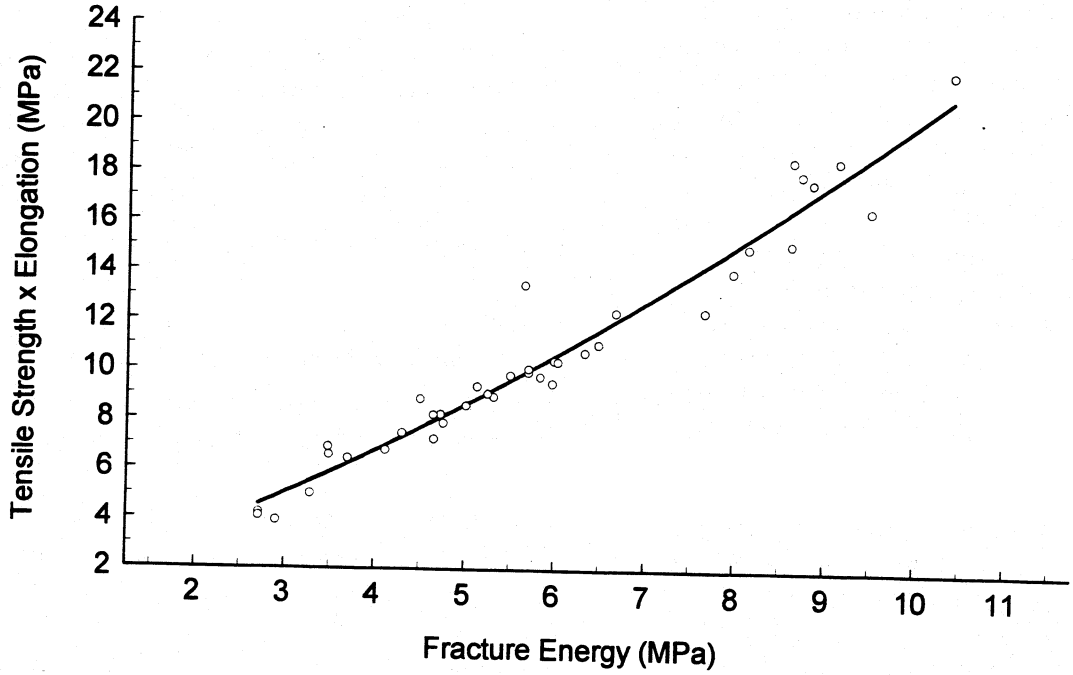

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

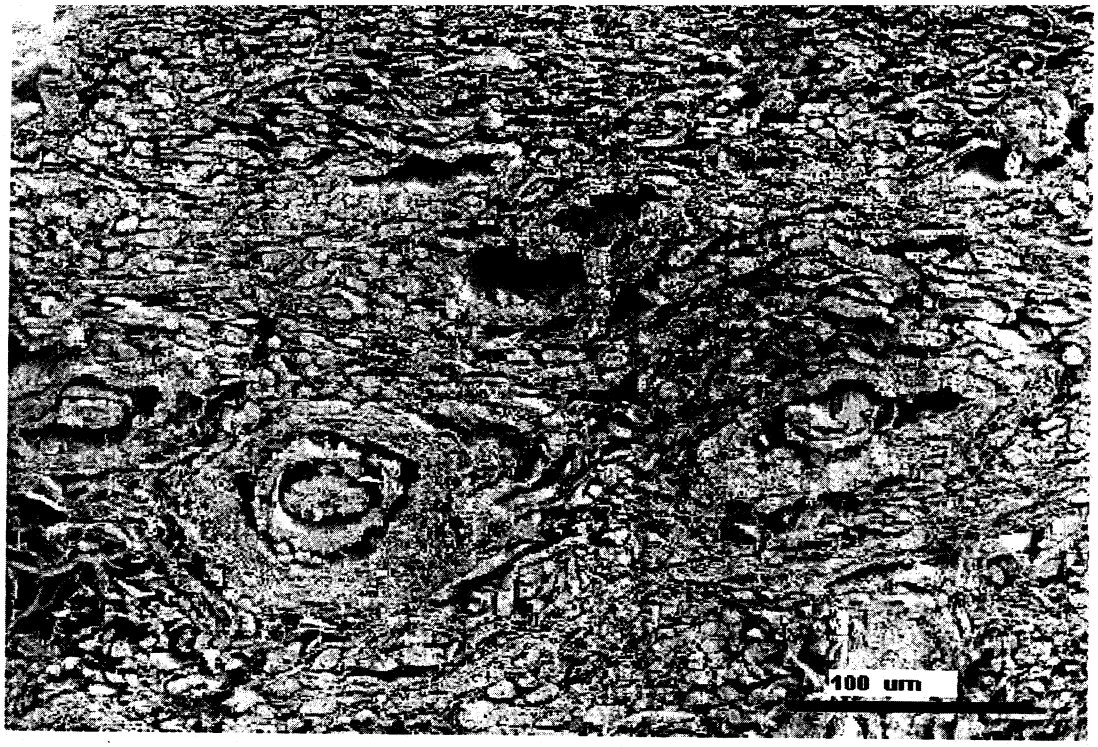

FIGURE 1. — Micrograph showing grain layer with sheet structure.

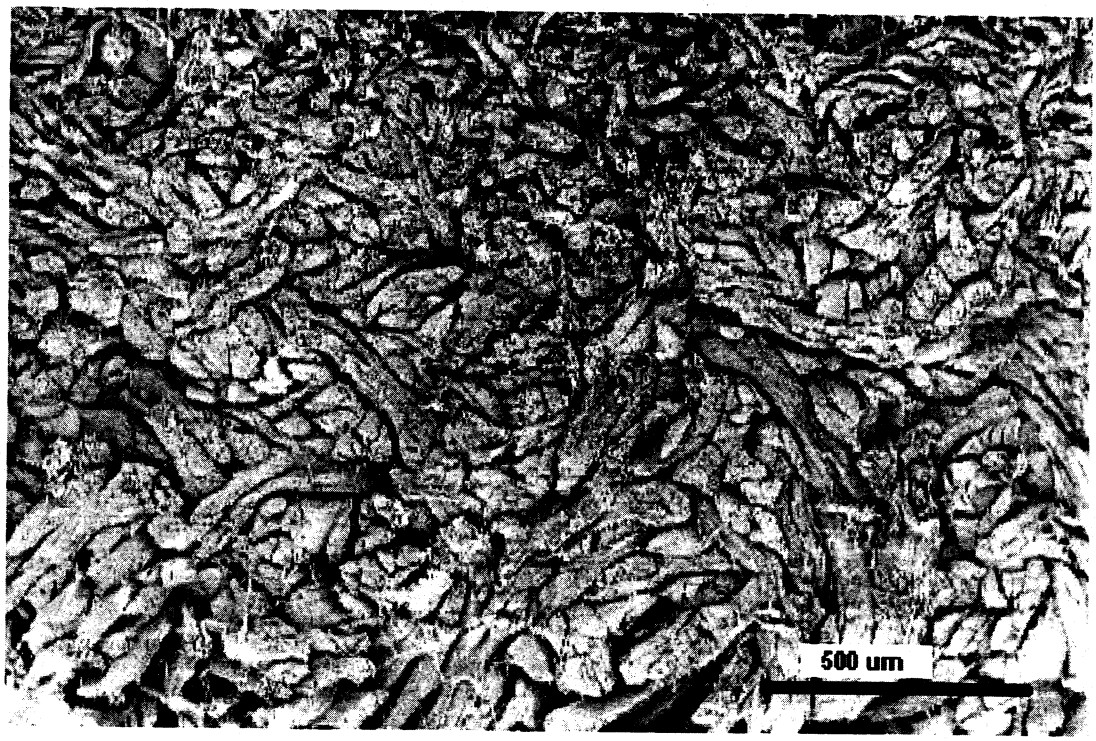

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

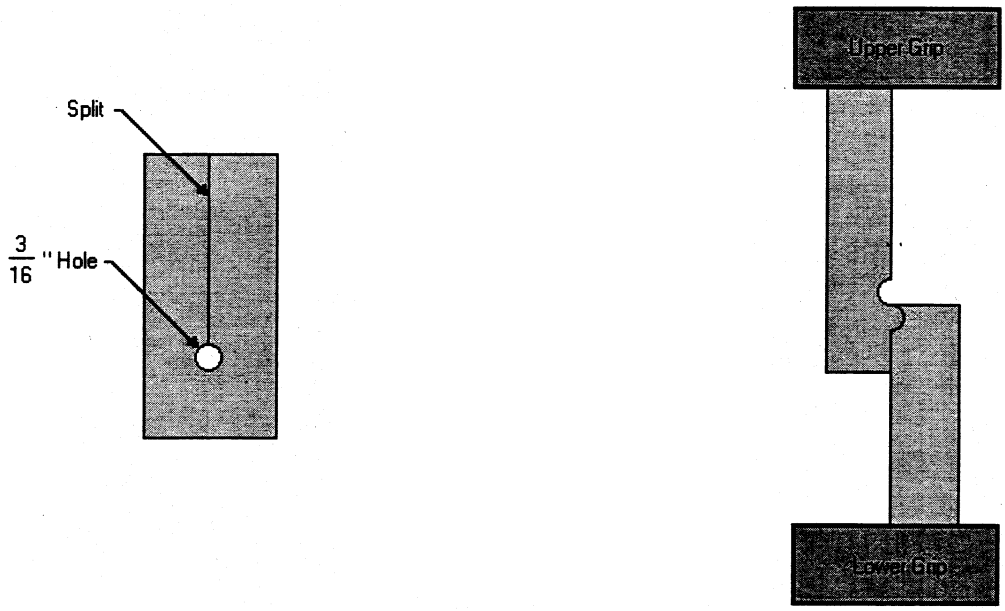

FIGURE 3. — Tear test scheme.

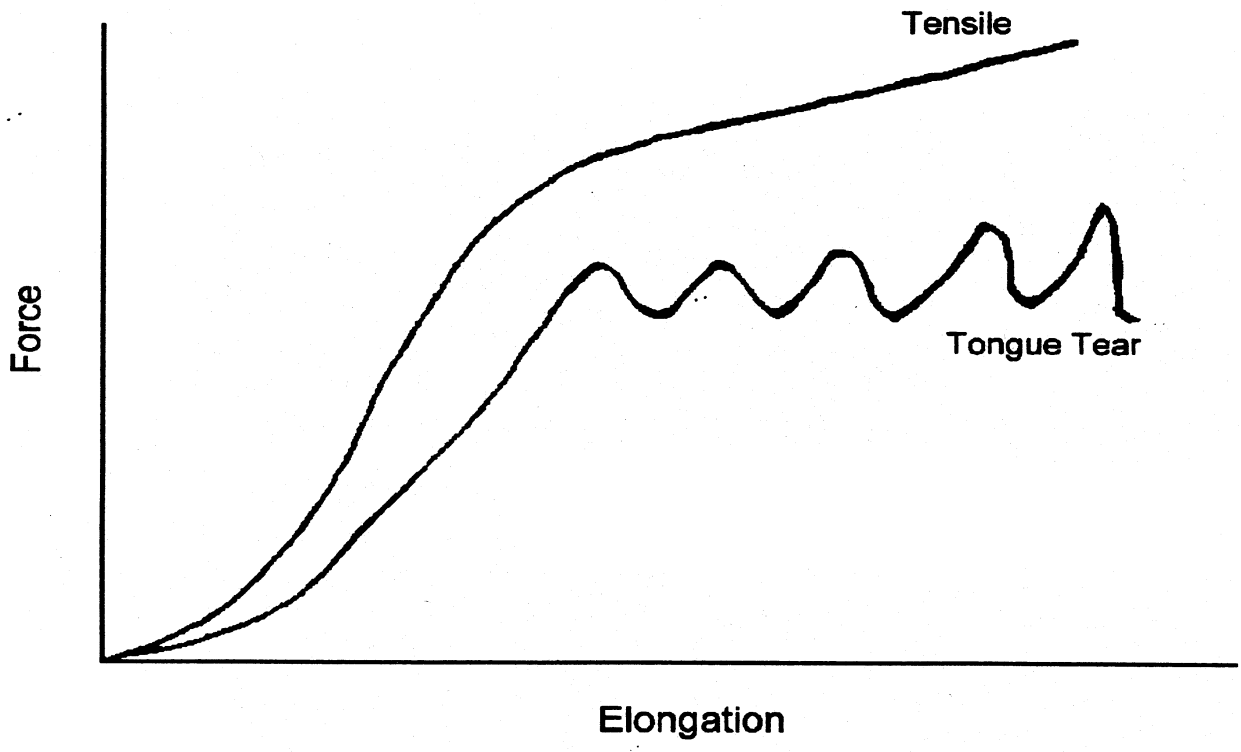

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

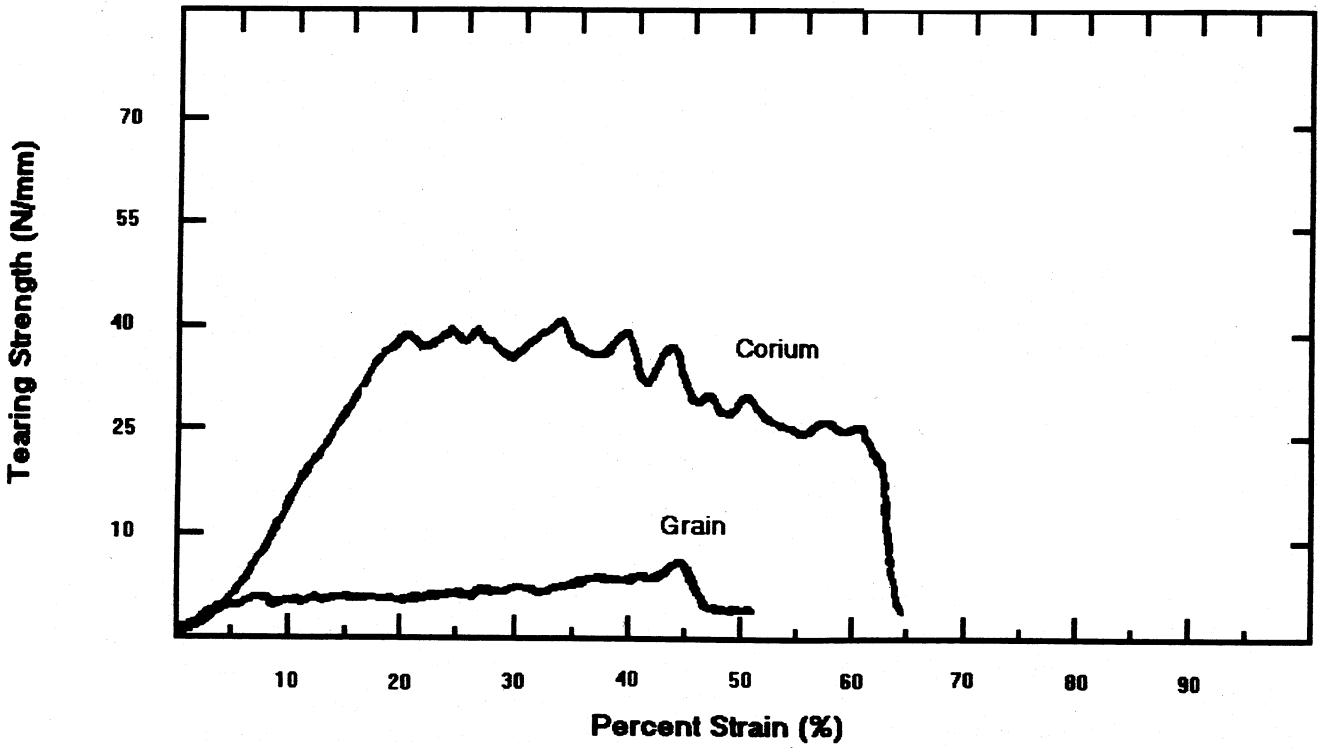

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

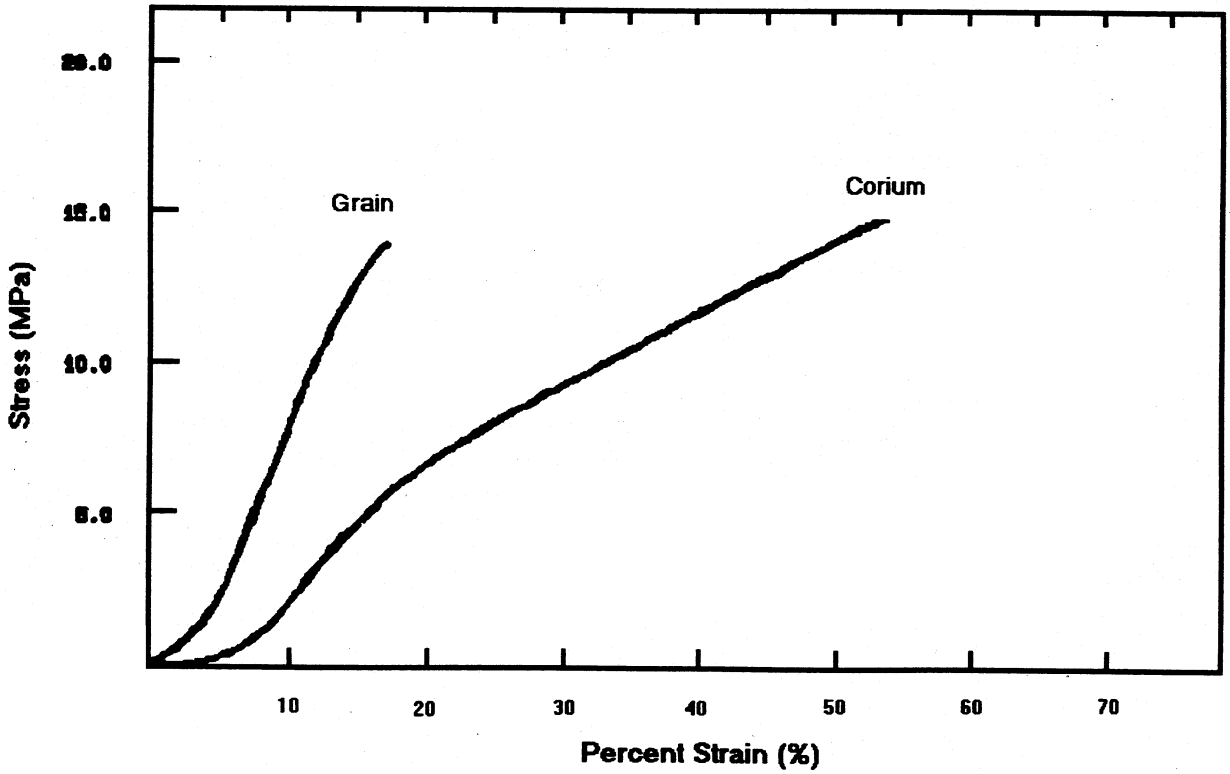

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

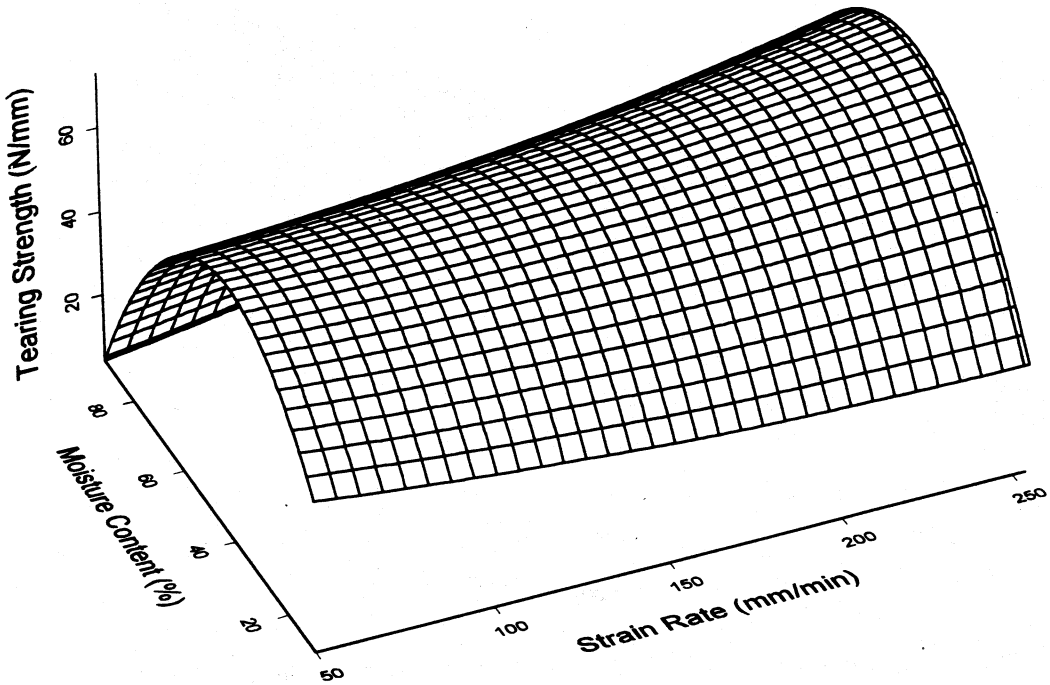

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

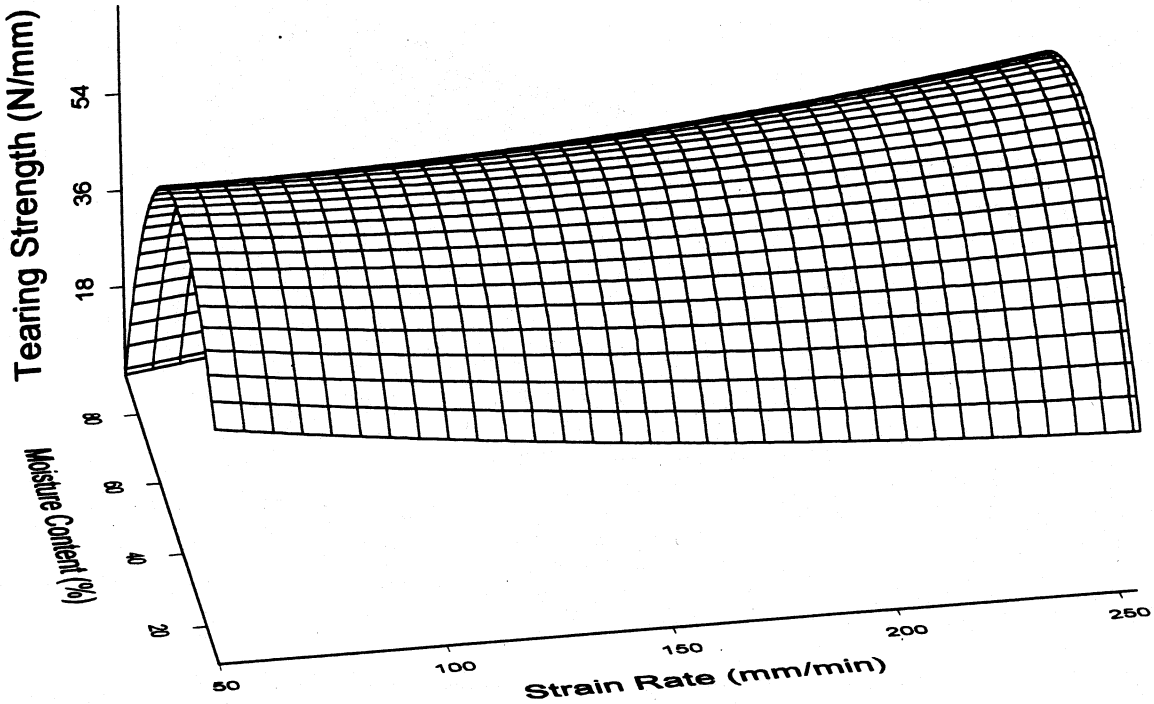

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

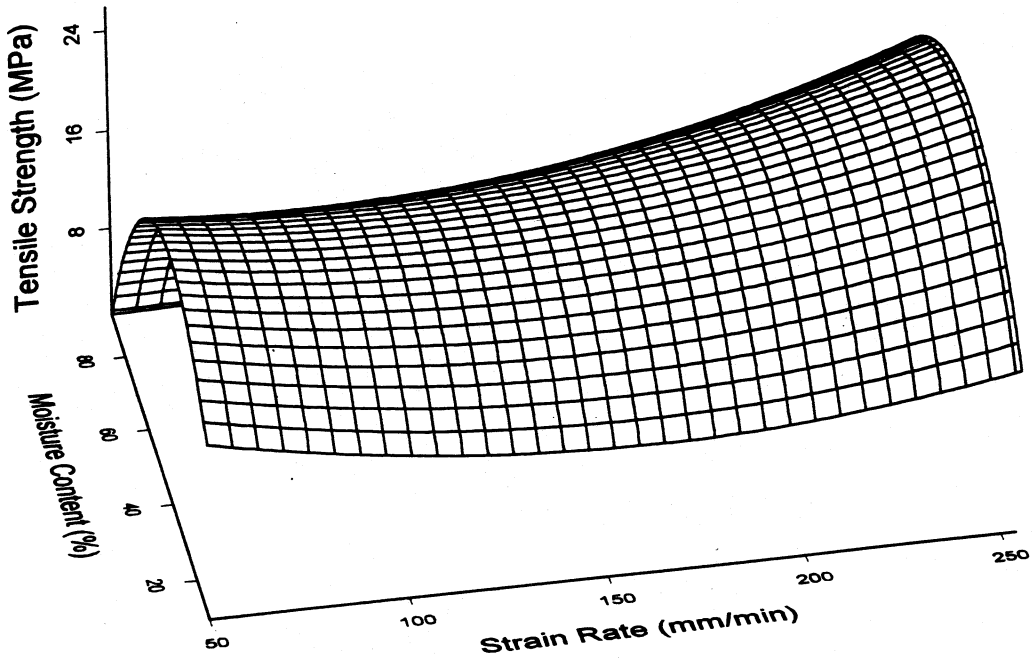

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

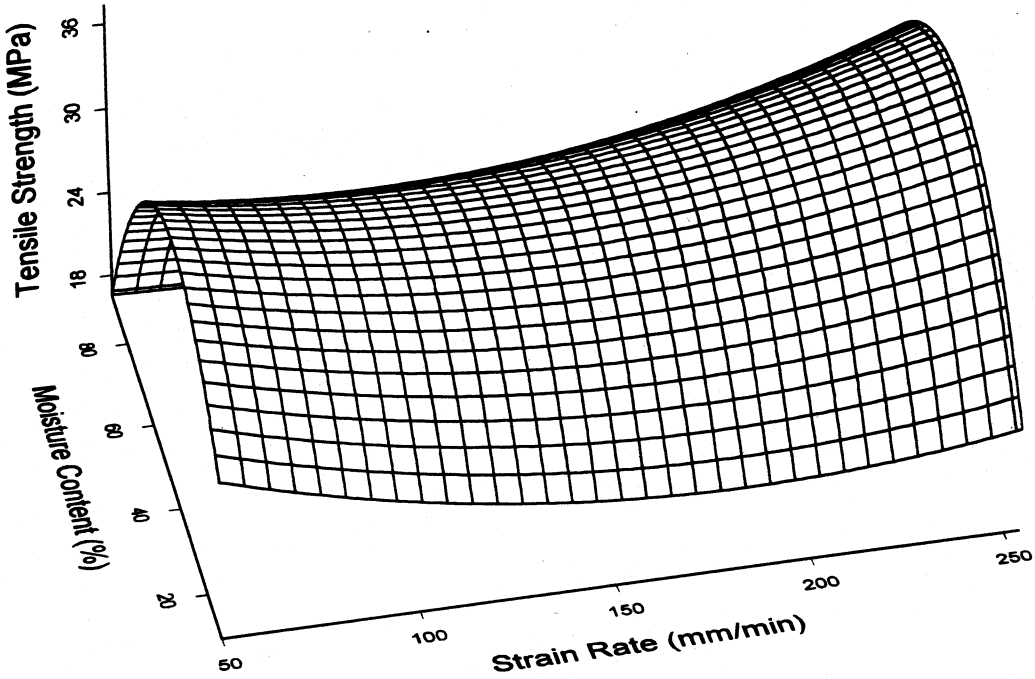

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

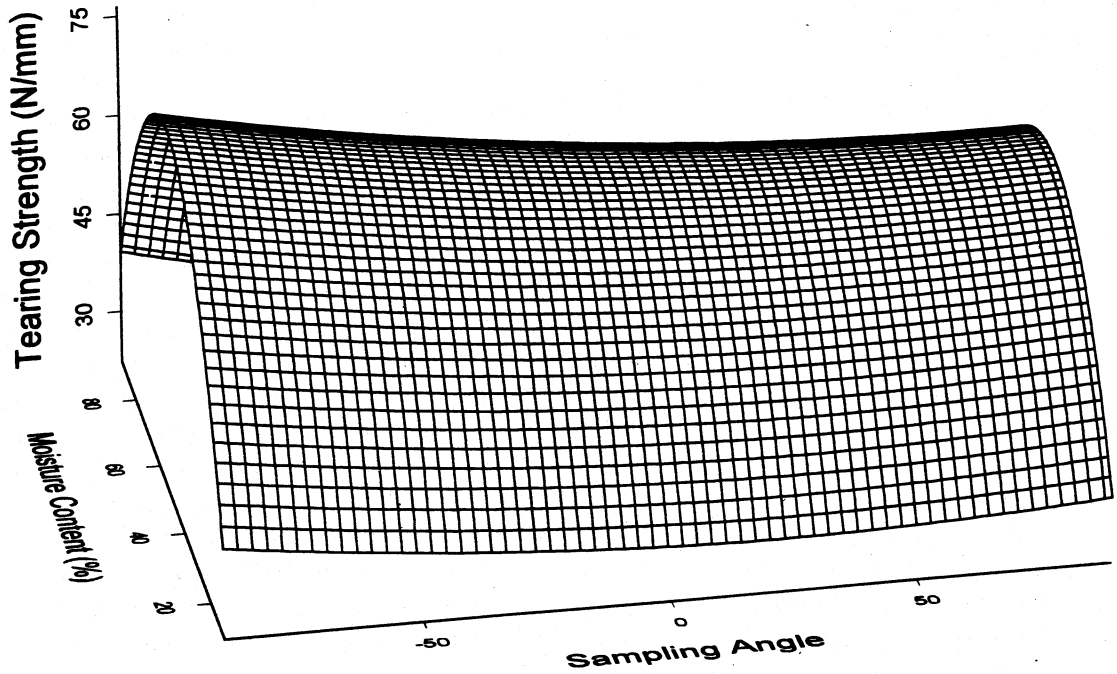

FIGURE 11. — Effect of sampling angle on tearing strength.

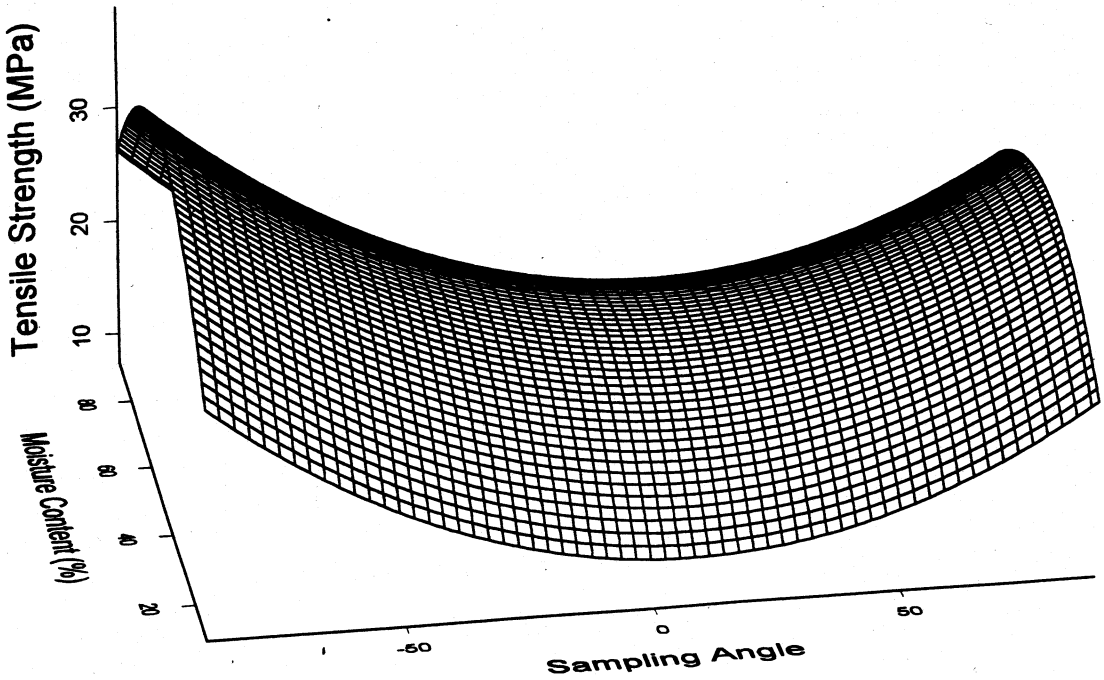

FIGURE 12. — Effect of sampling angle on tensile strength.

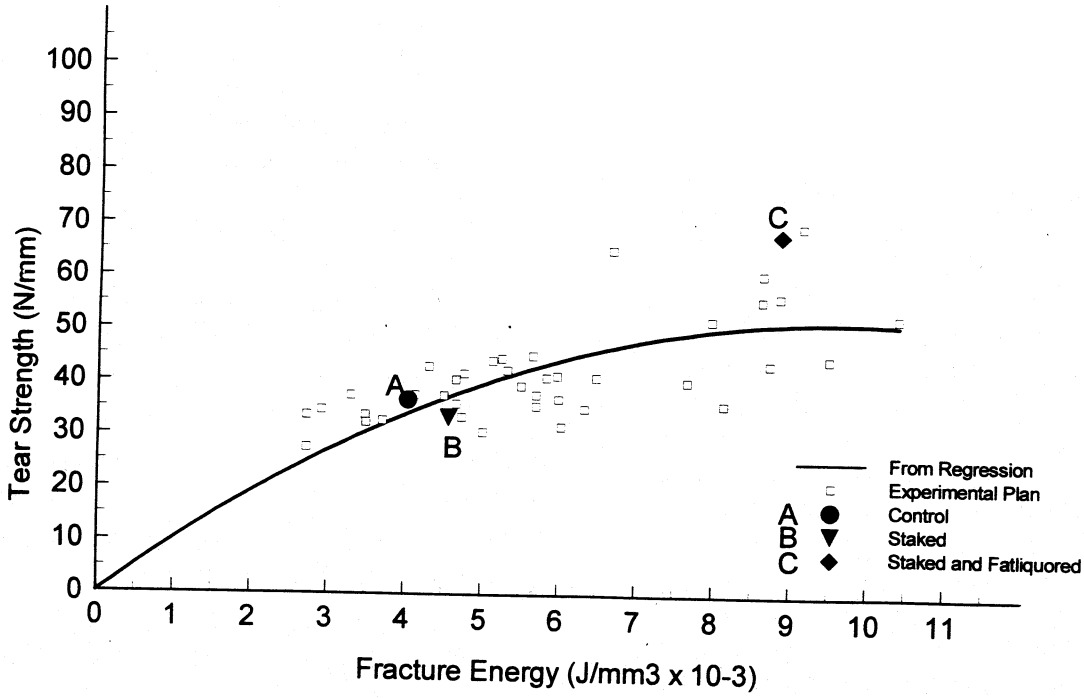

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

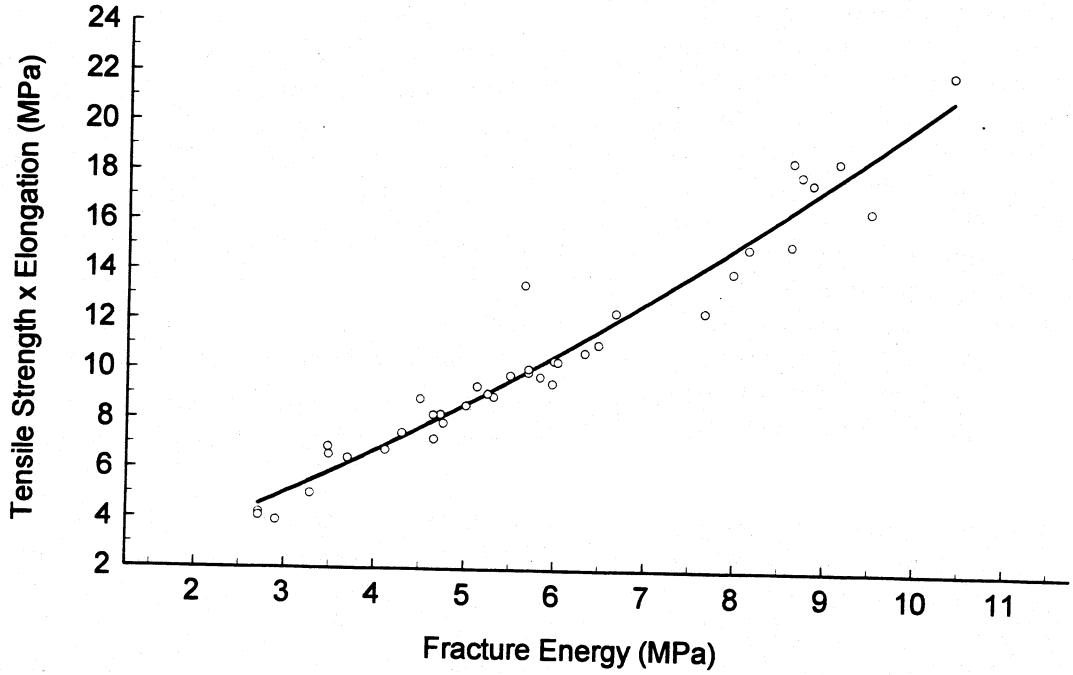

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

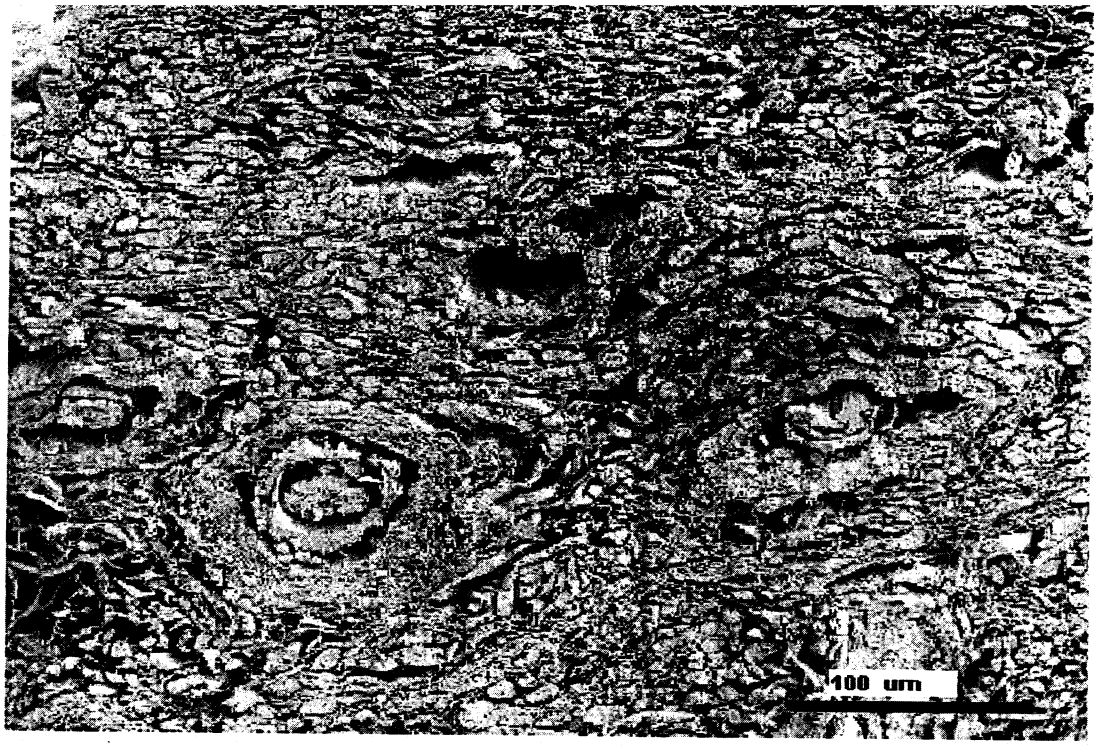

FIGURE 1. — Micrograph showing grain layer with sheet structure.

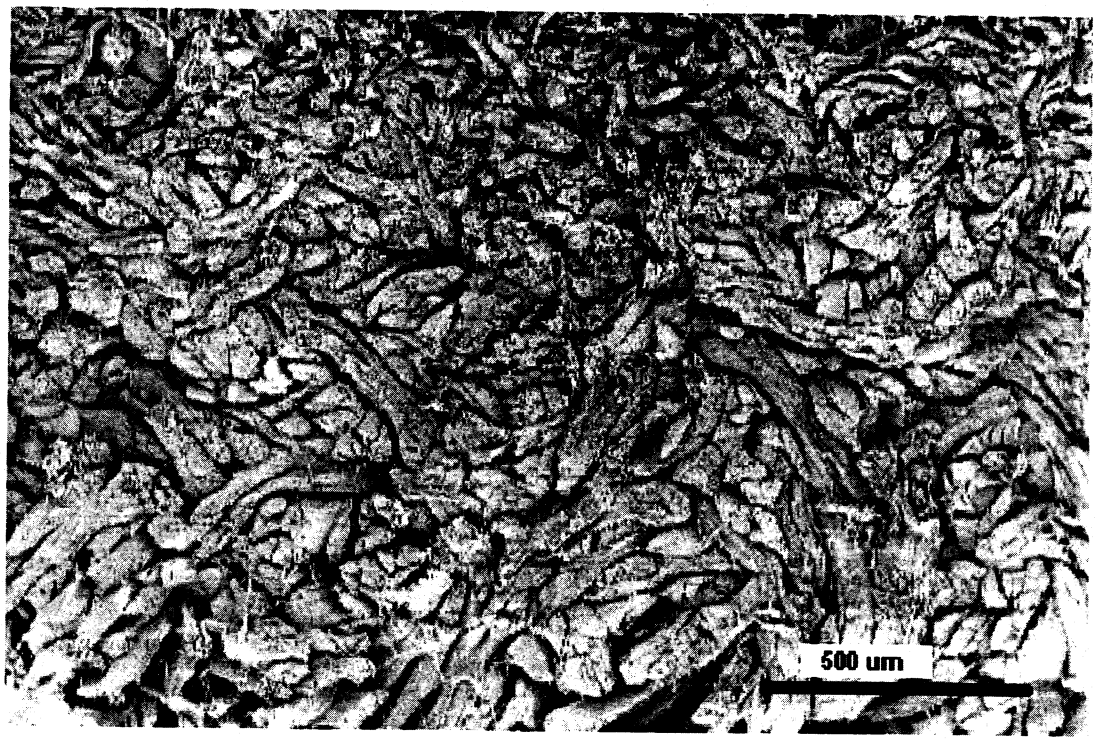

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

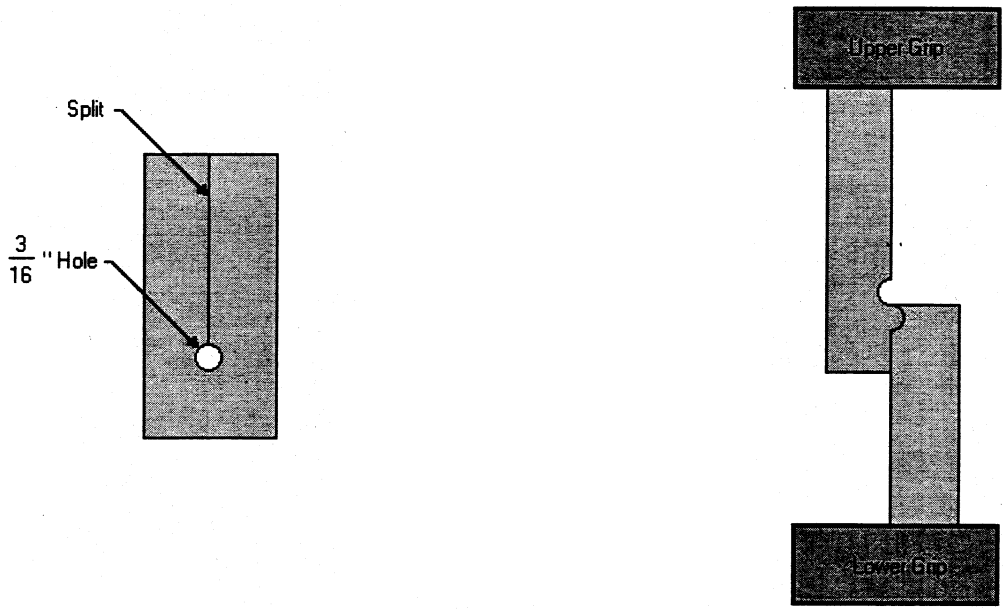

FIGURE 3. — Tear test scheme.

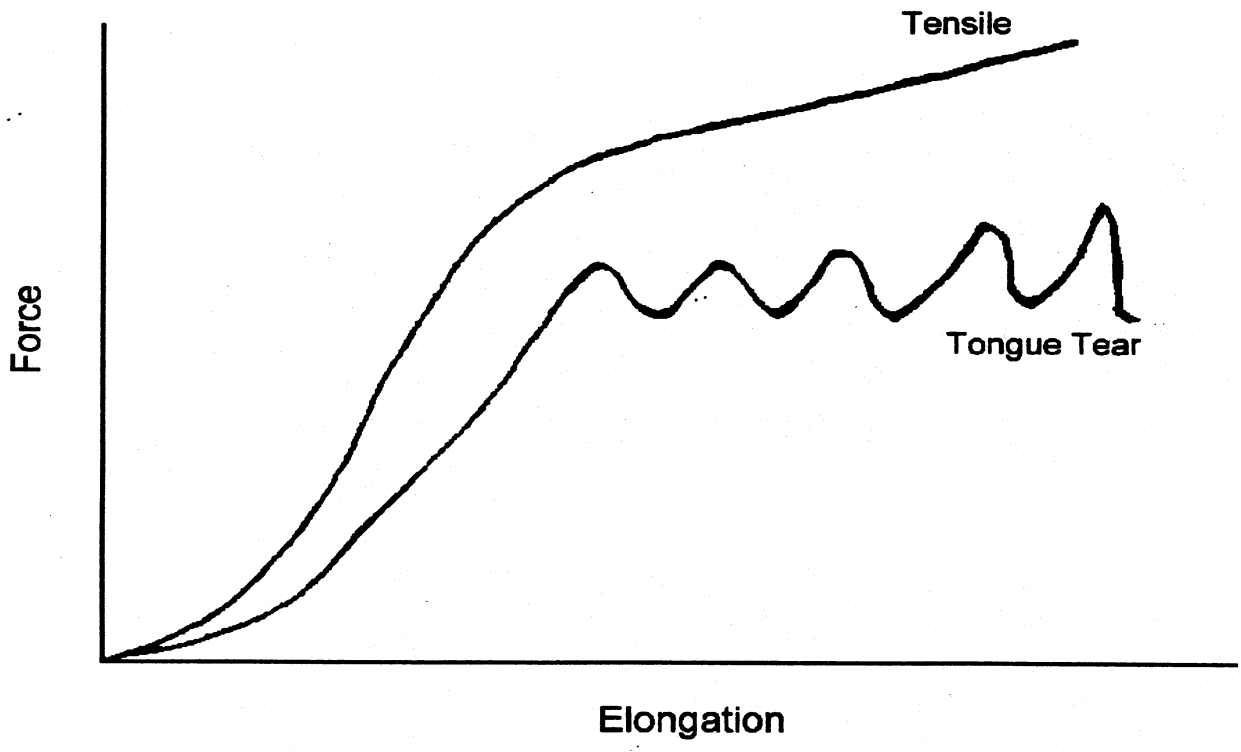

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

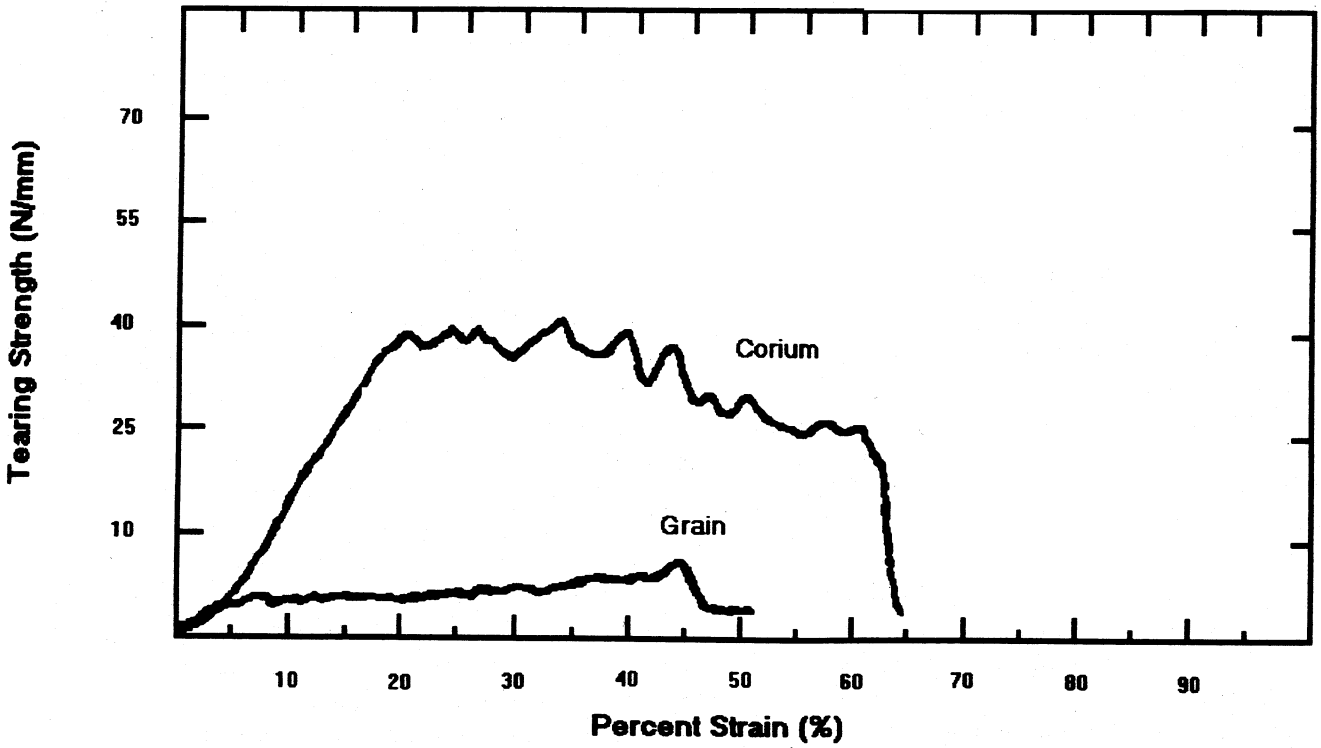

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

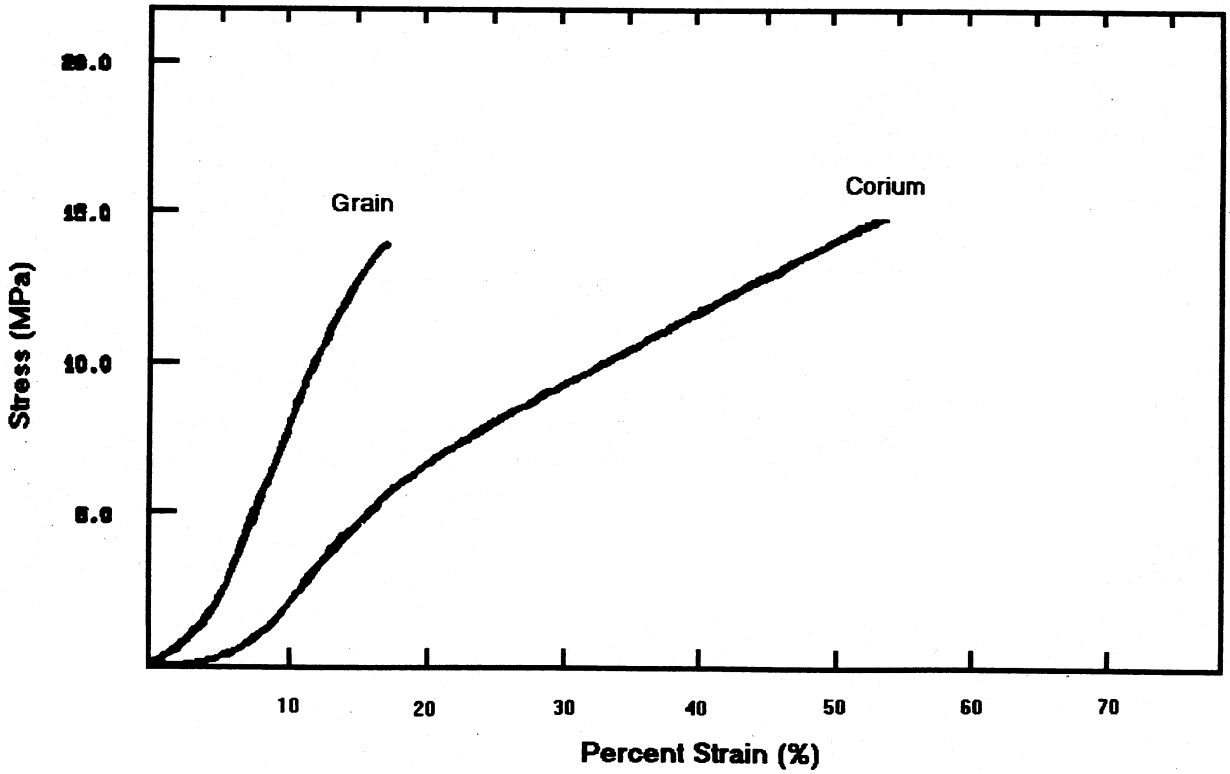

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

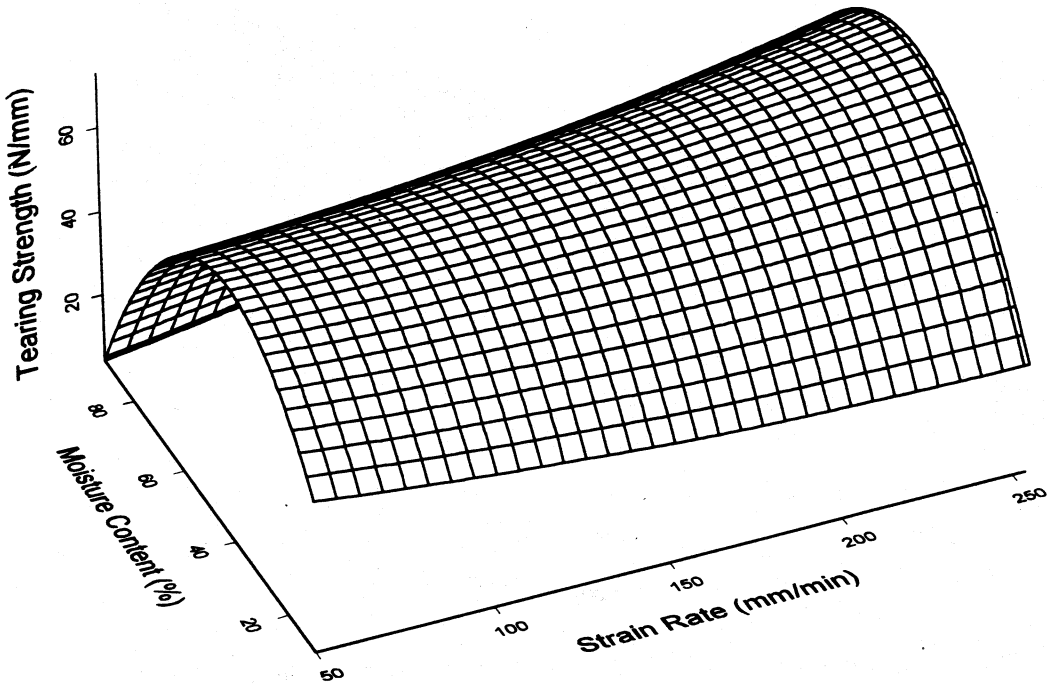

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

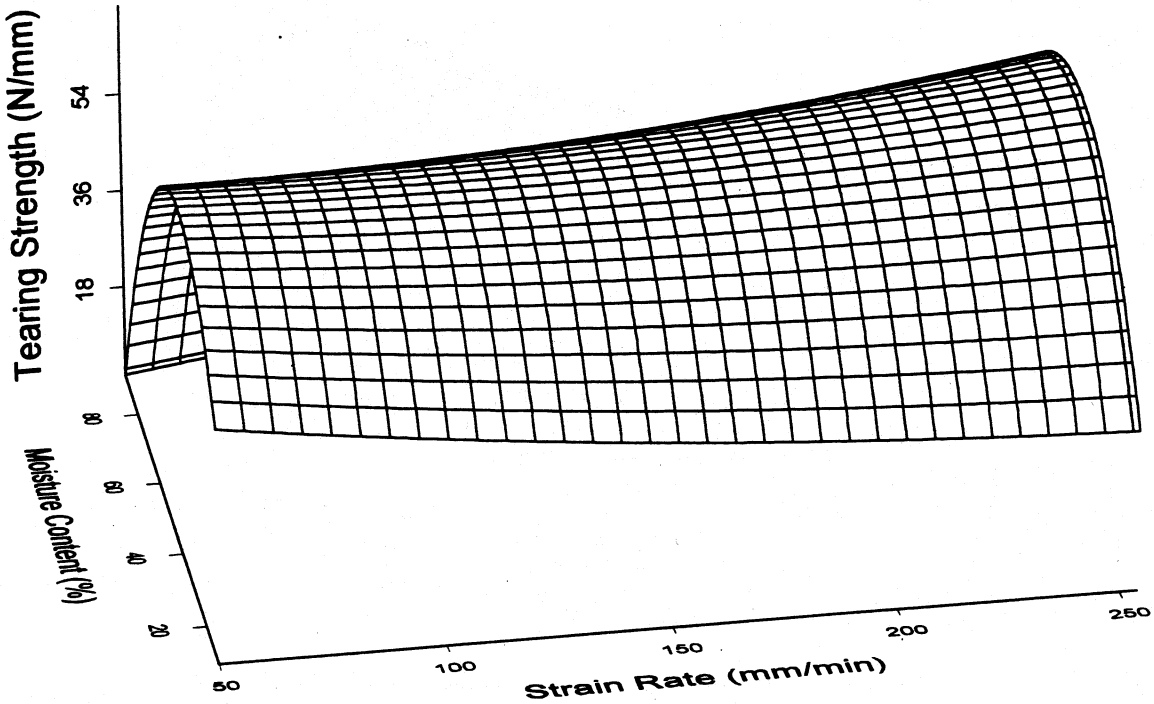

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

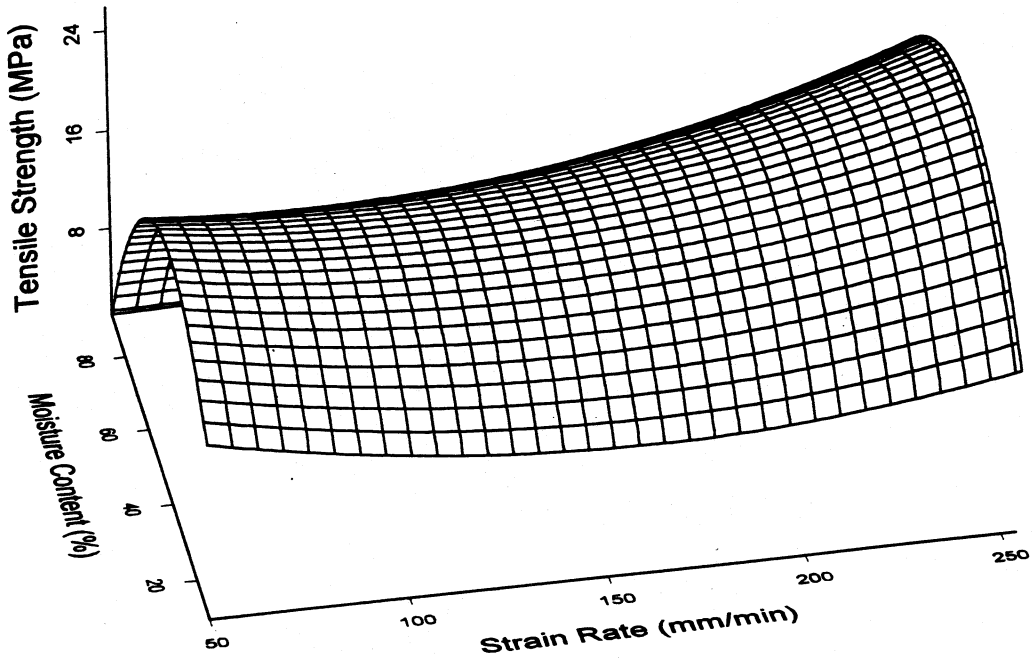

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

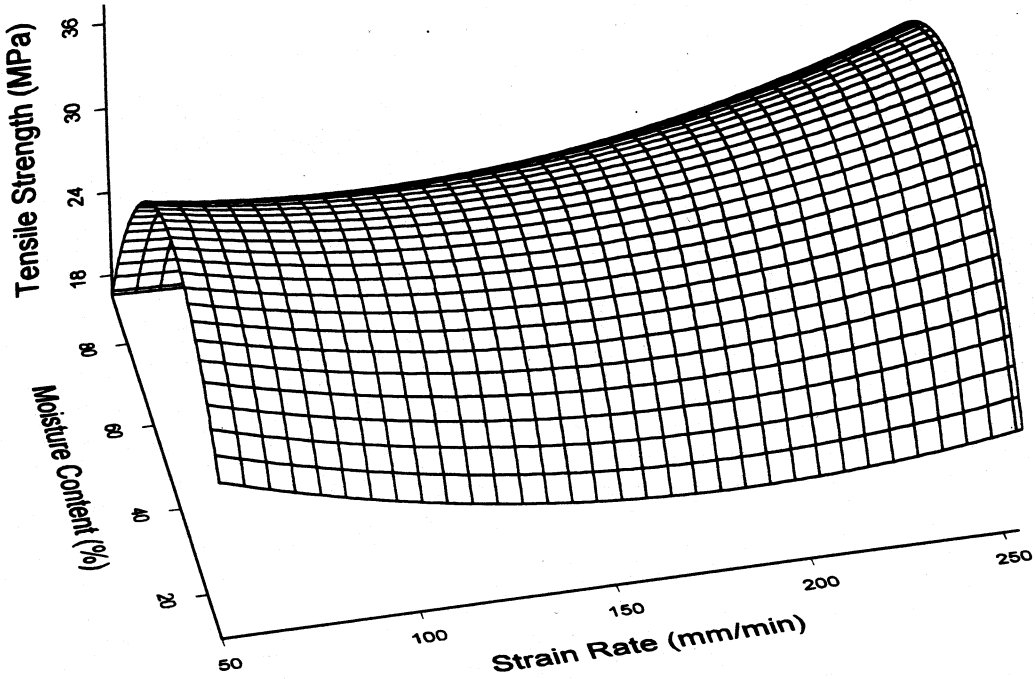

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

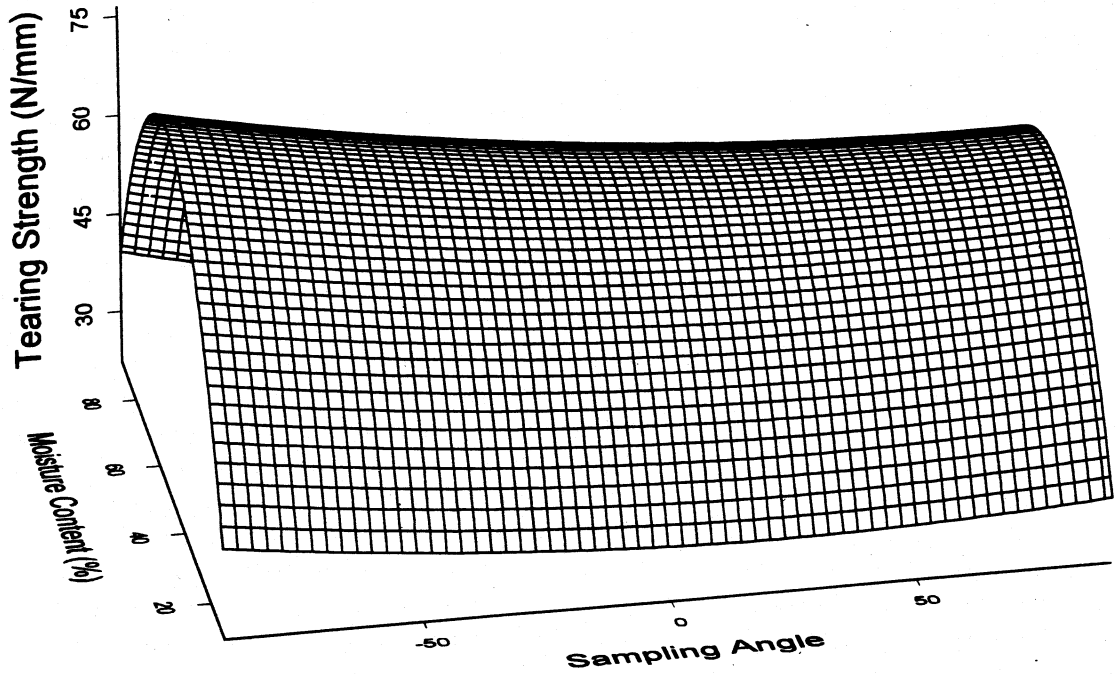

FIGURE 11. — Effect of sampling angle on tearing strength.

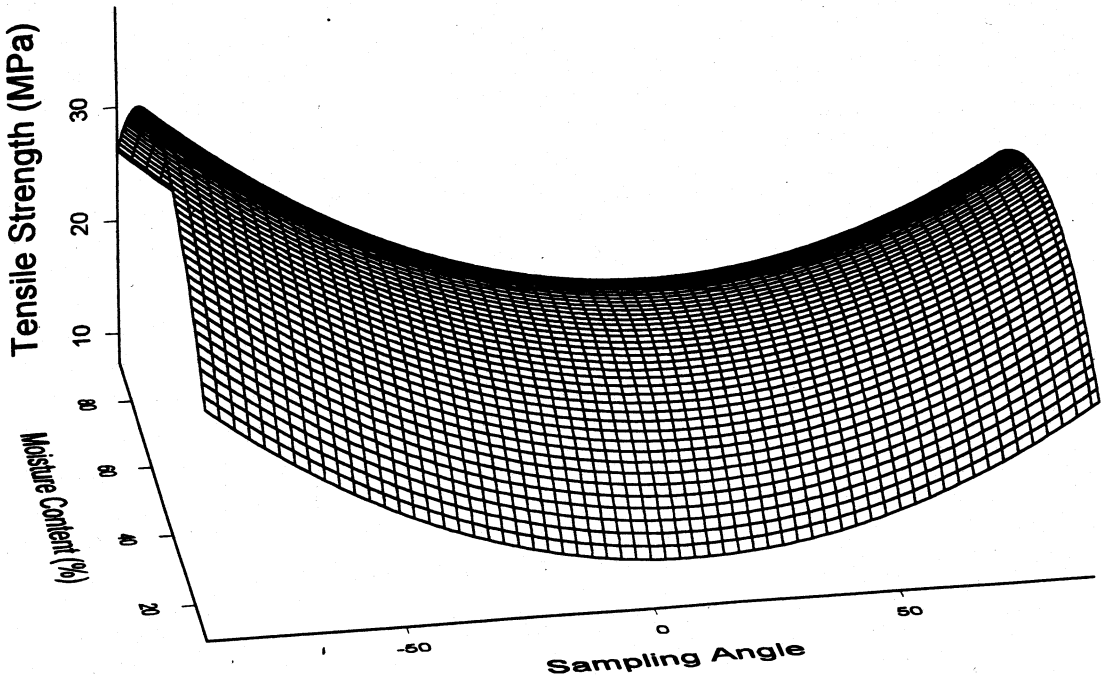

FIGURE 12. — Effect of sampling angle on tensile strength.

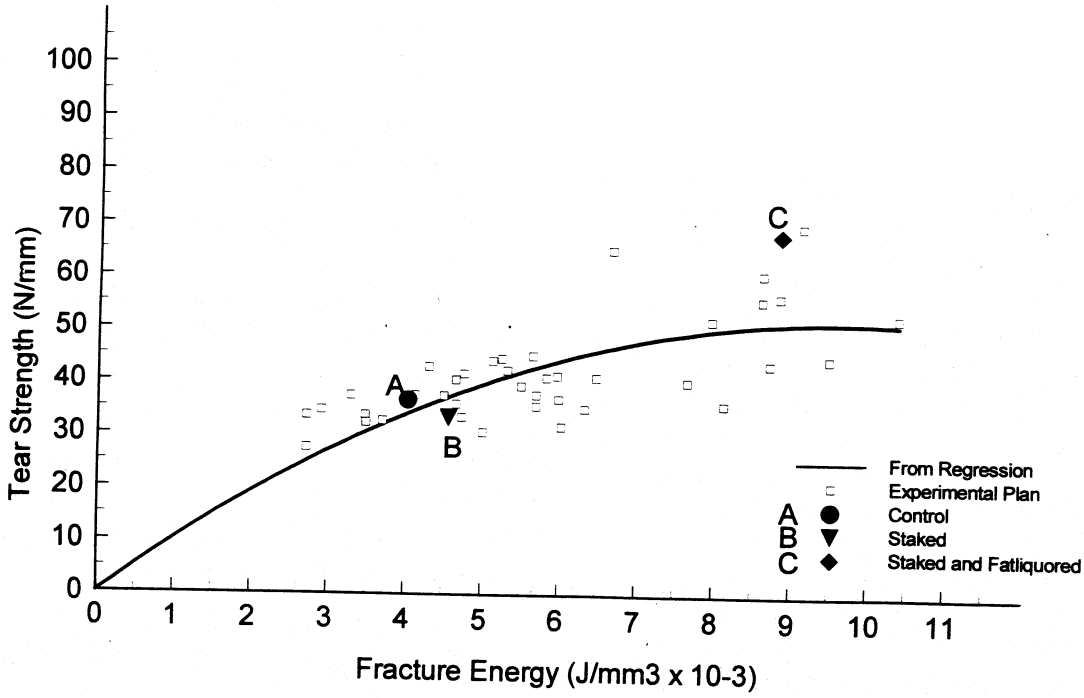

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

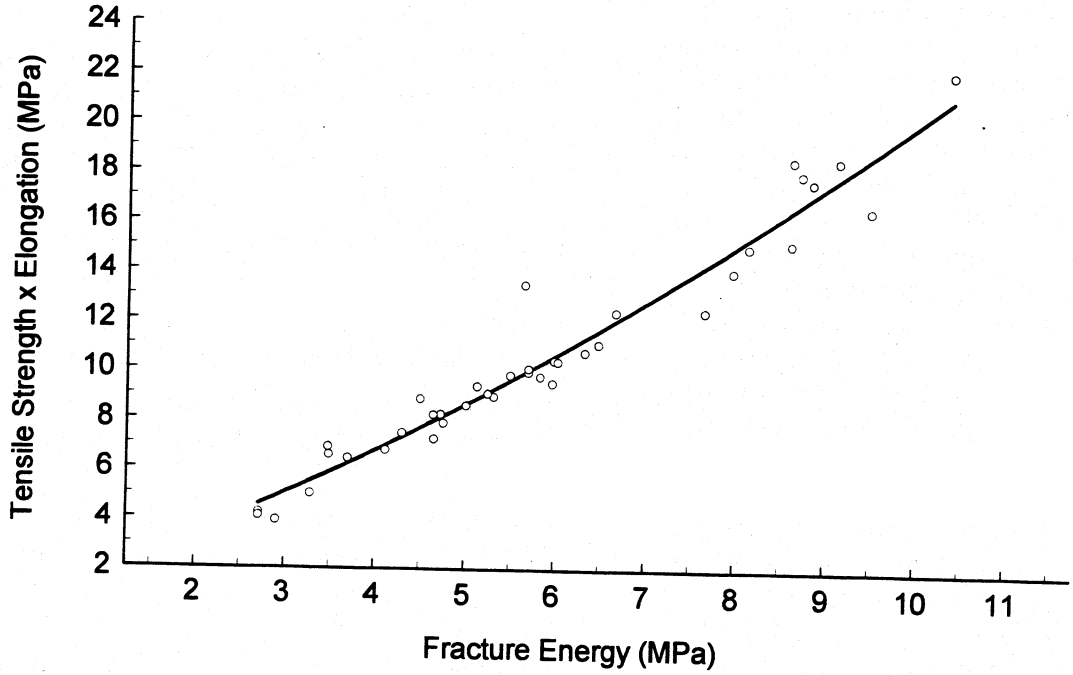

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

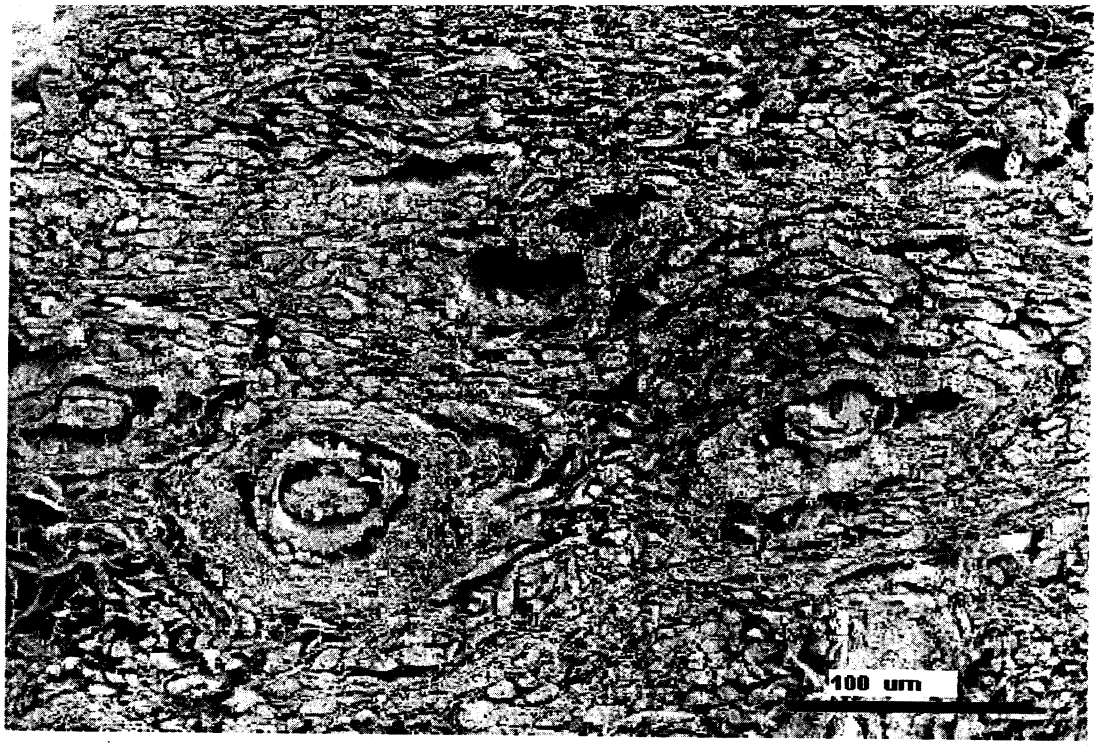

FIGURE 1. — Micrograph showing grain layer with sheet structure.

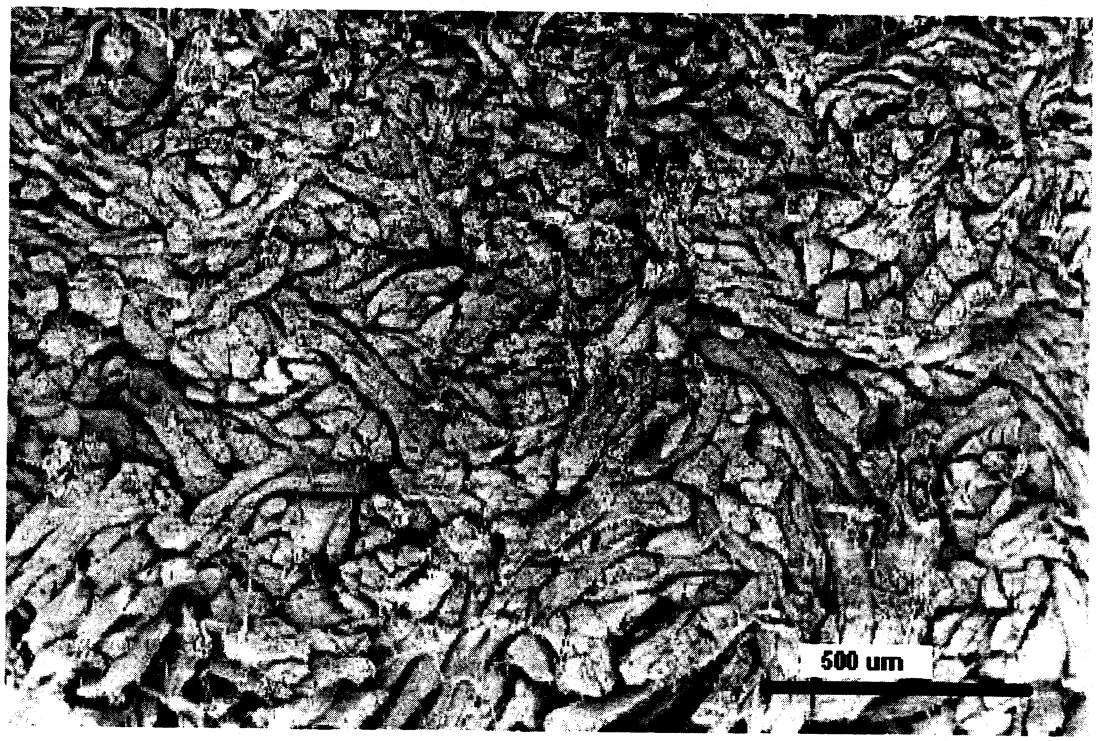

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

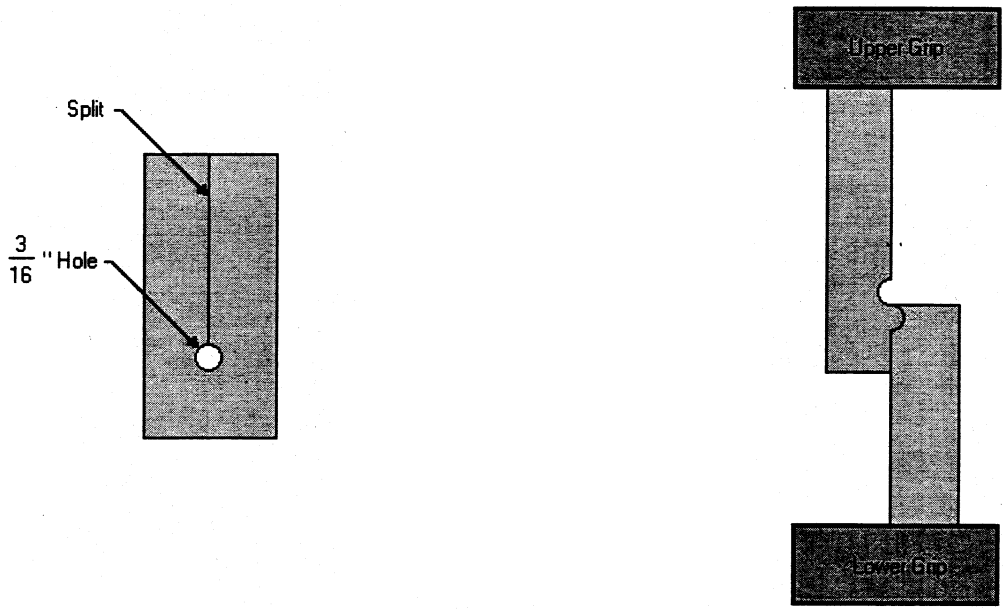

FIGURE 3. — Tear test scheme.

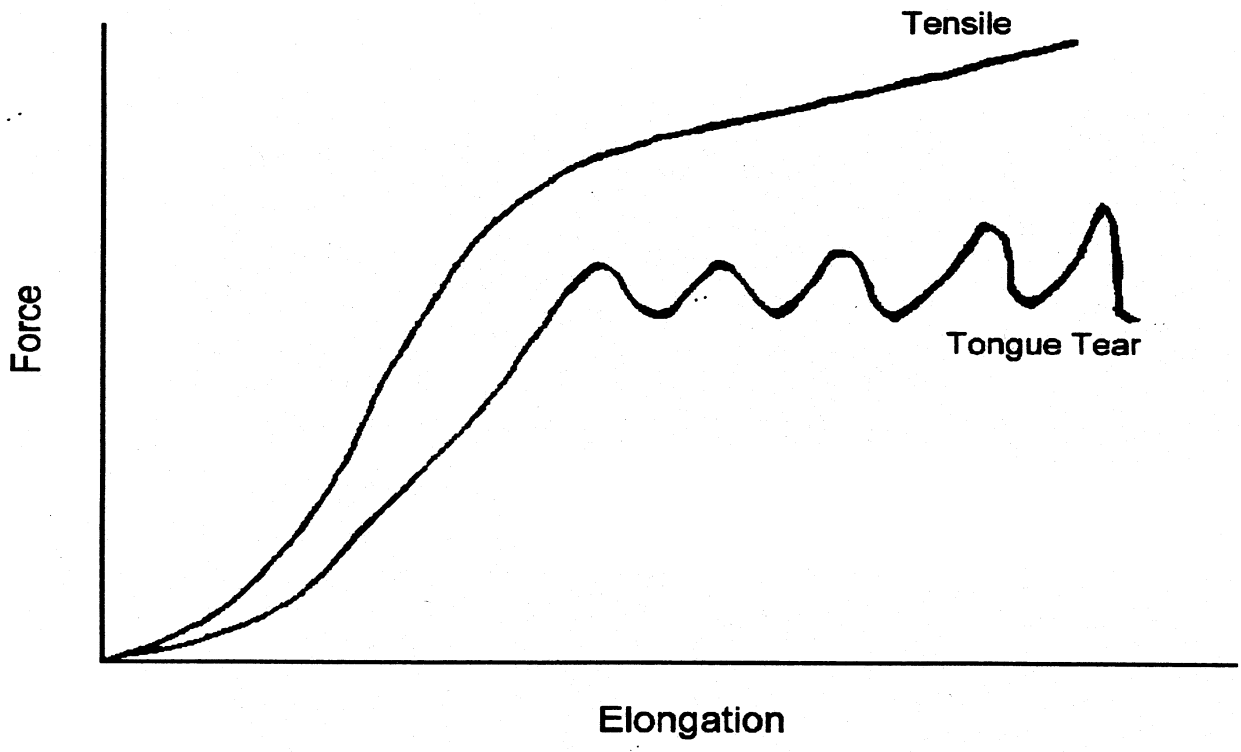

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

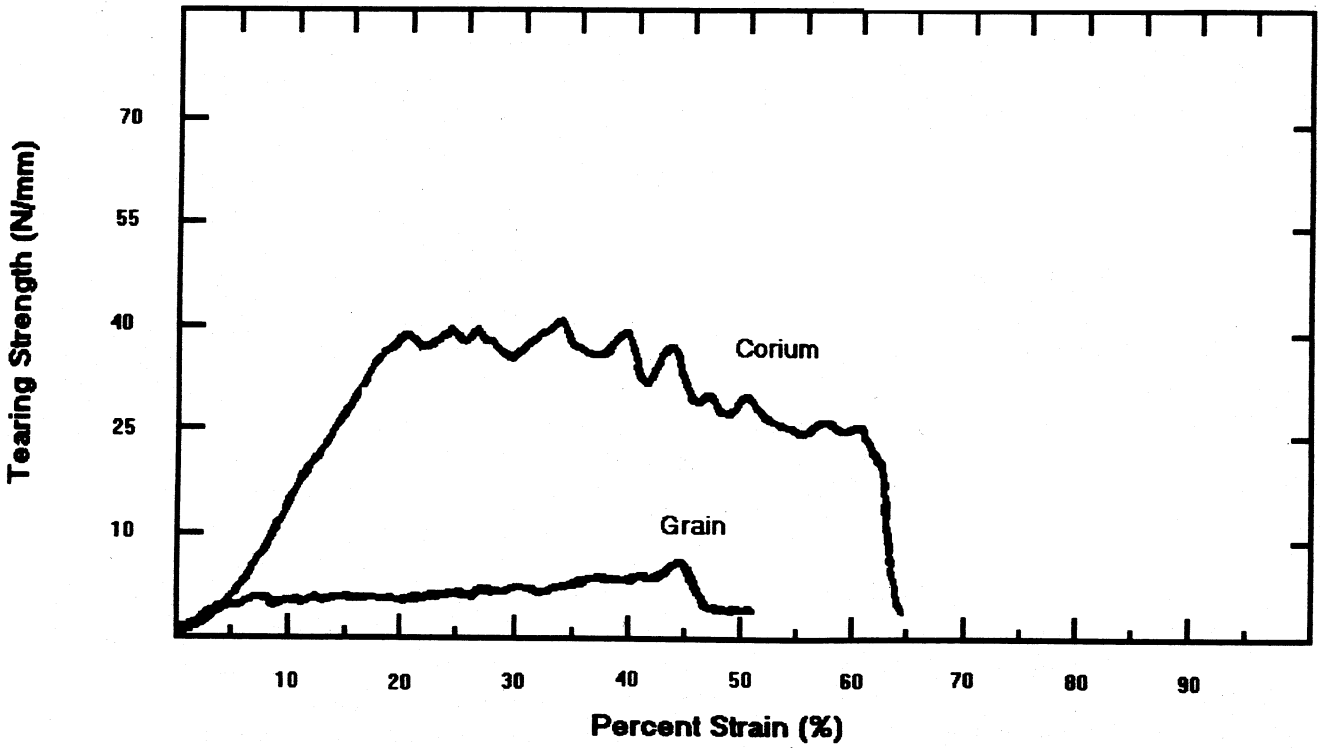

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

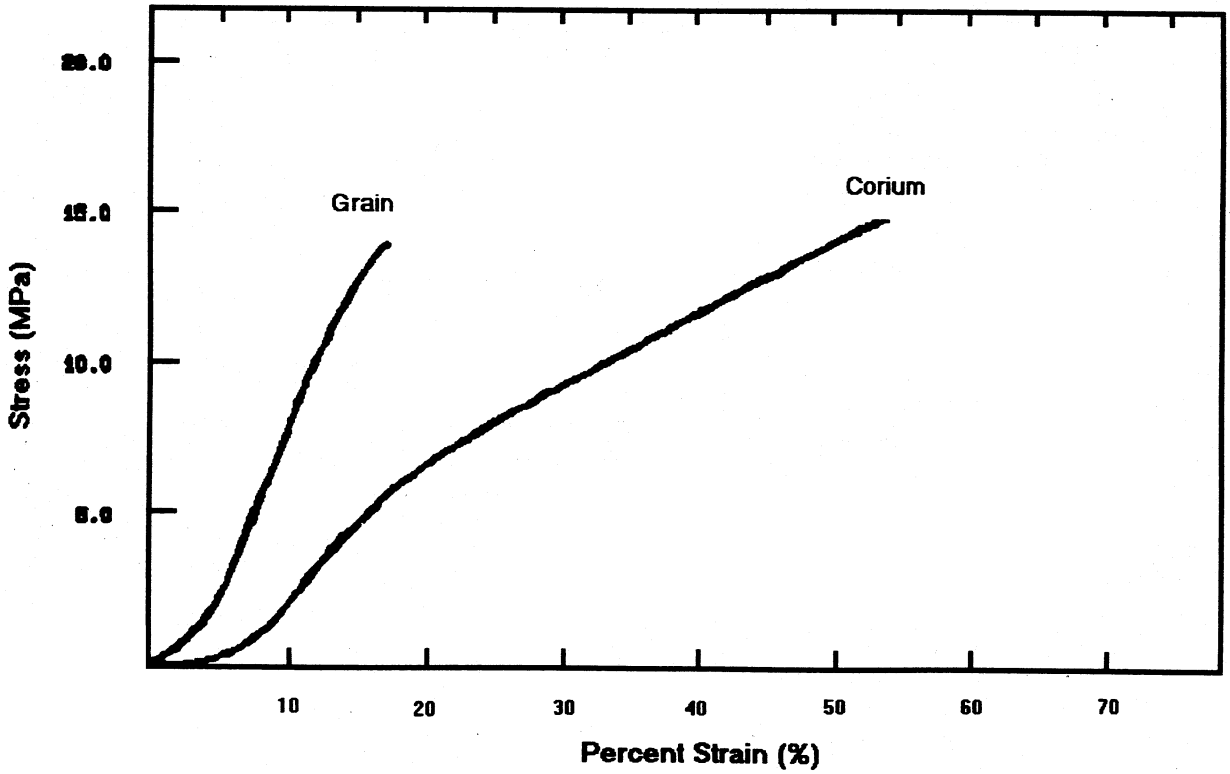

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

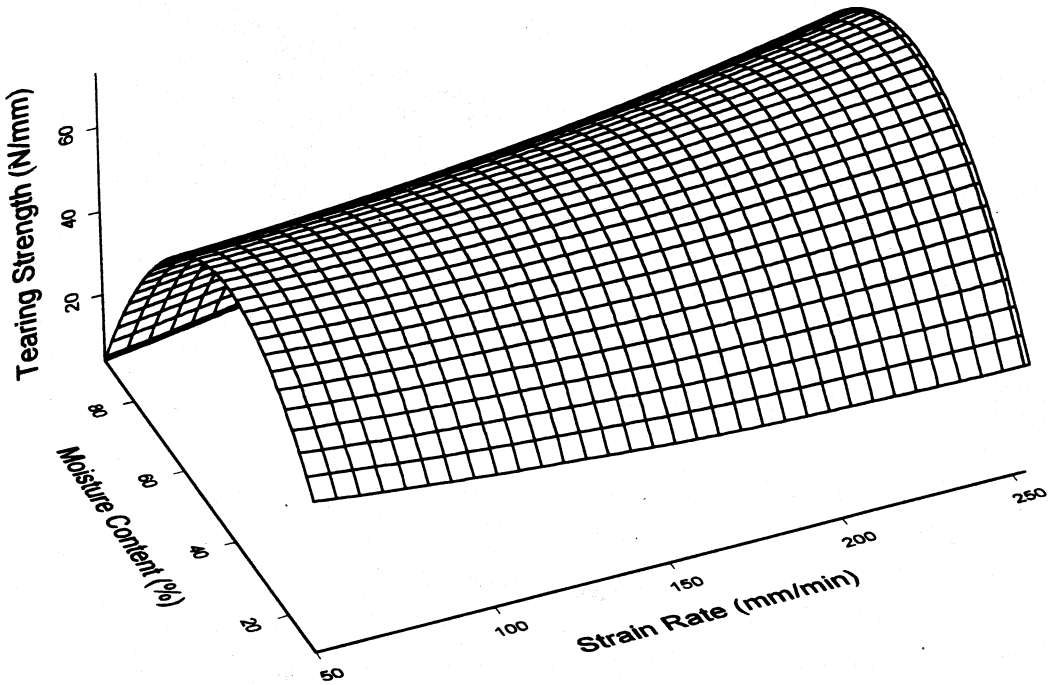

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

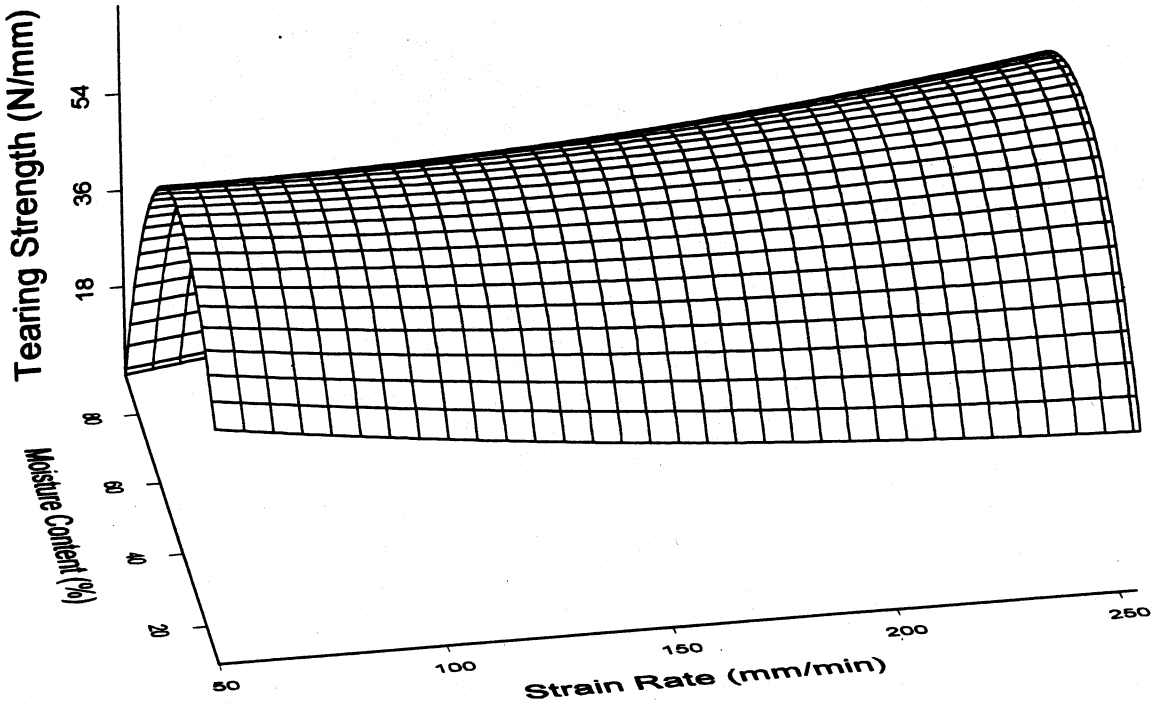

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

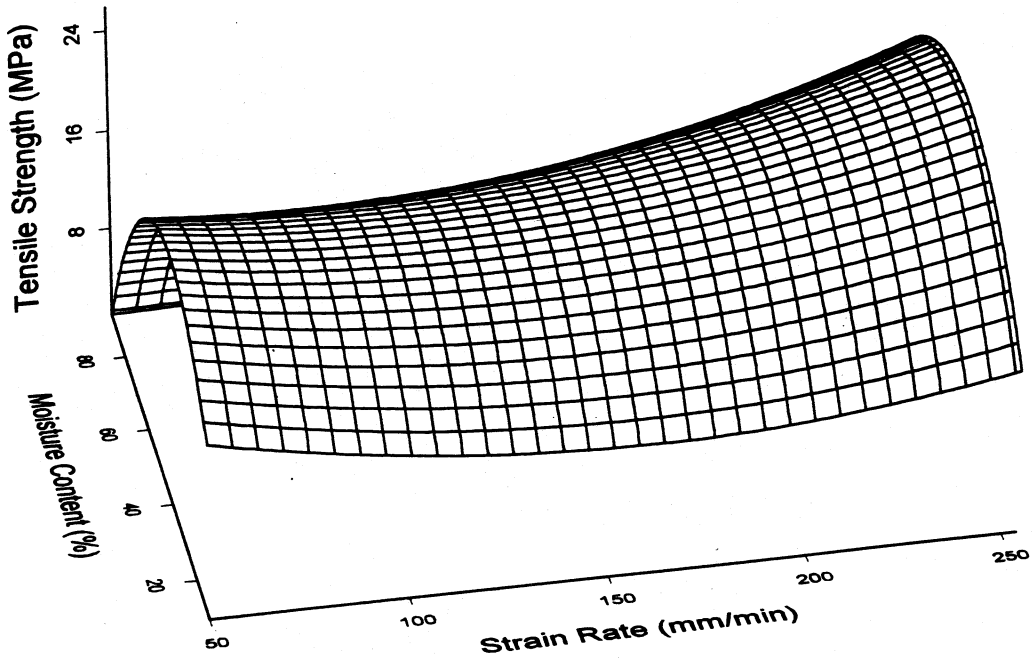

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

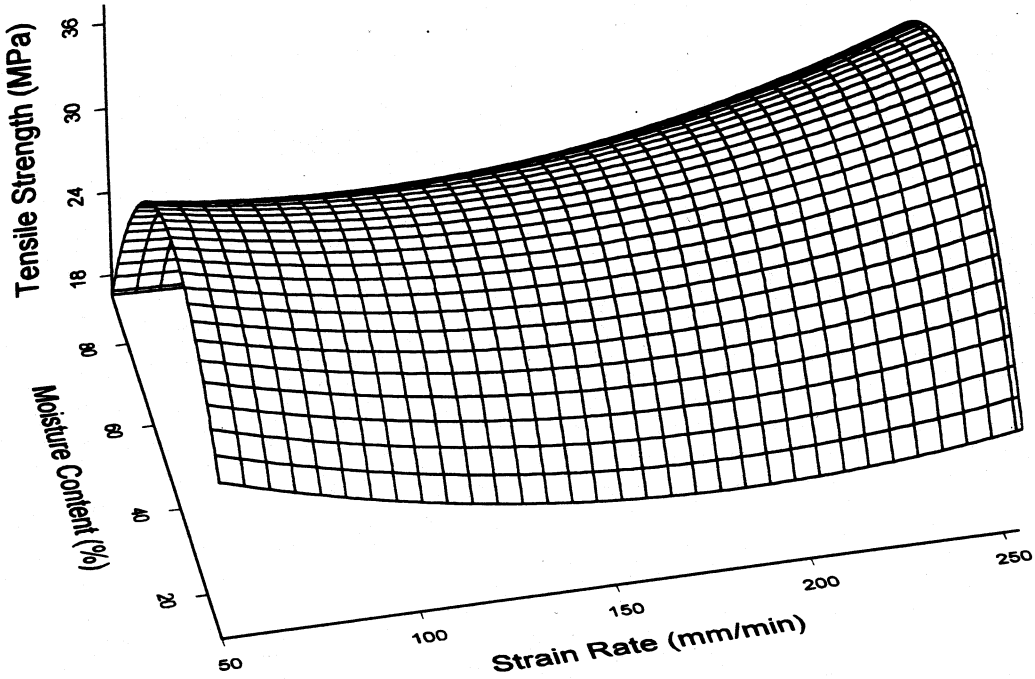

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

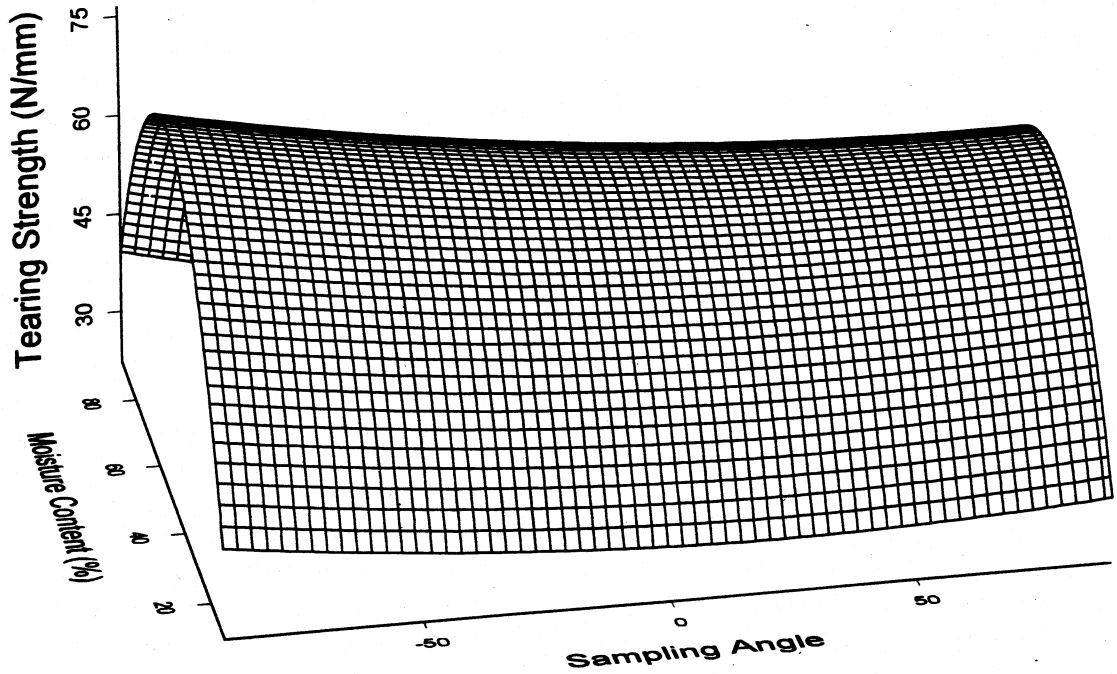

FIGURE 11. — Effect of sampling angle on tearing strength.

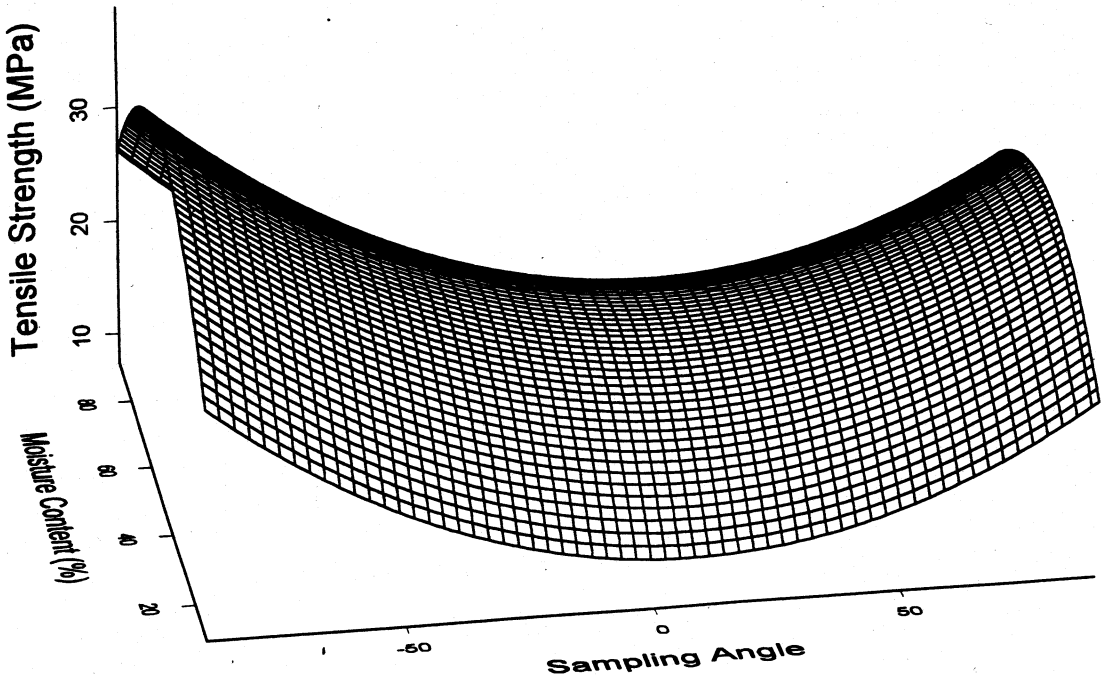

FIGURE 12. — Effect of sampling angle on tensile strength.

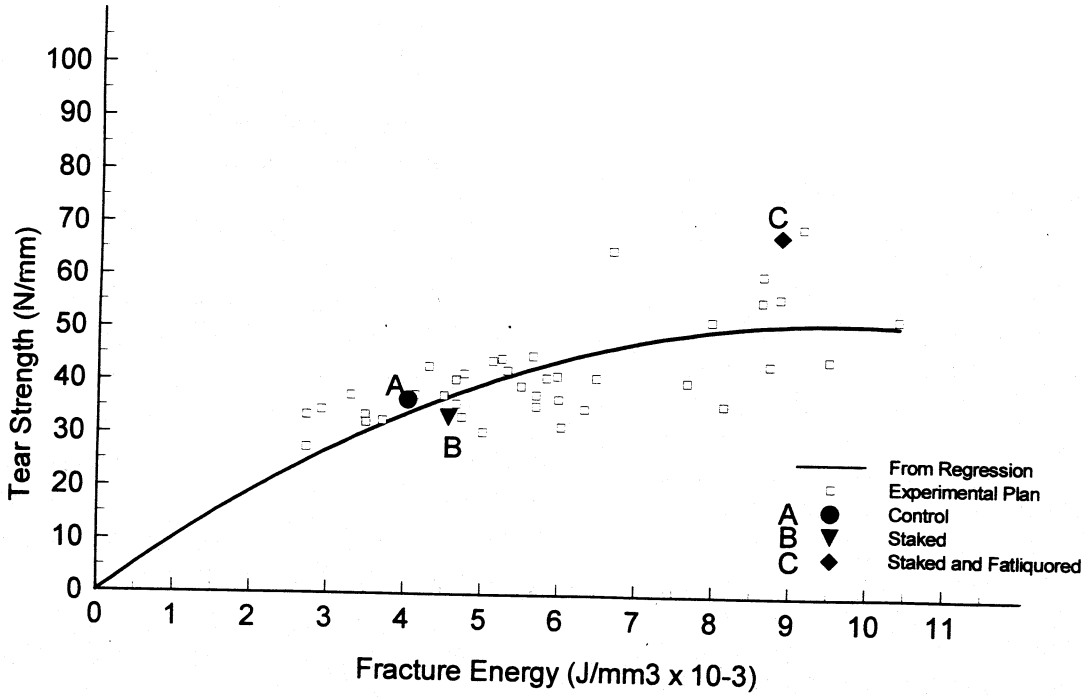

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

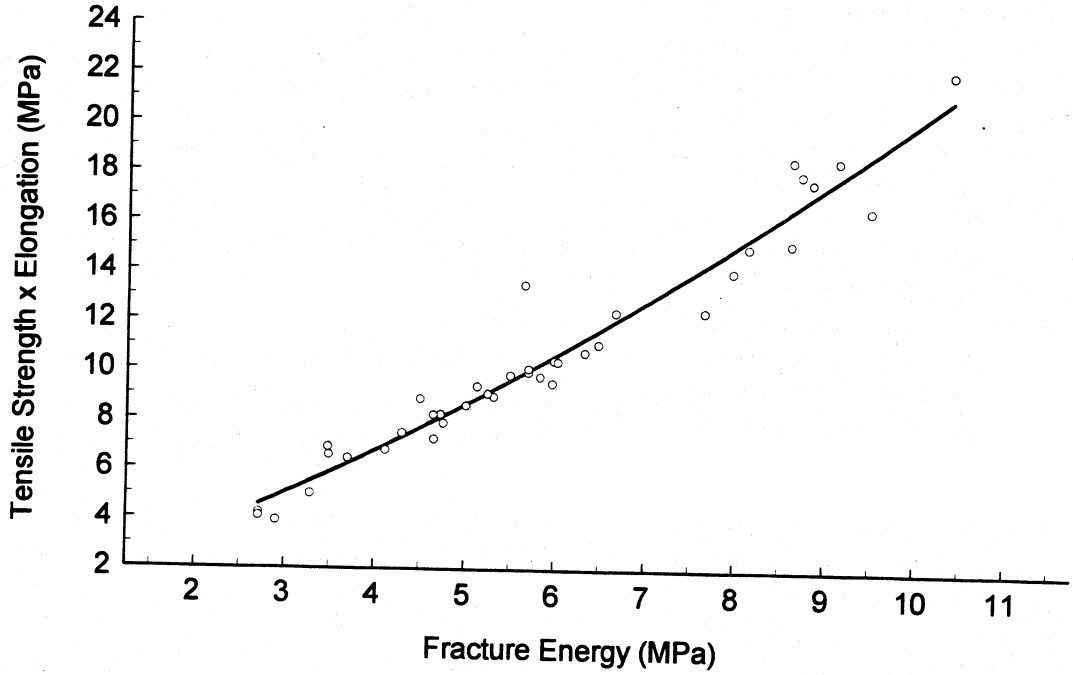

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

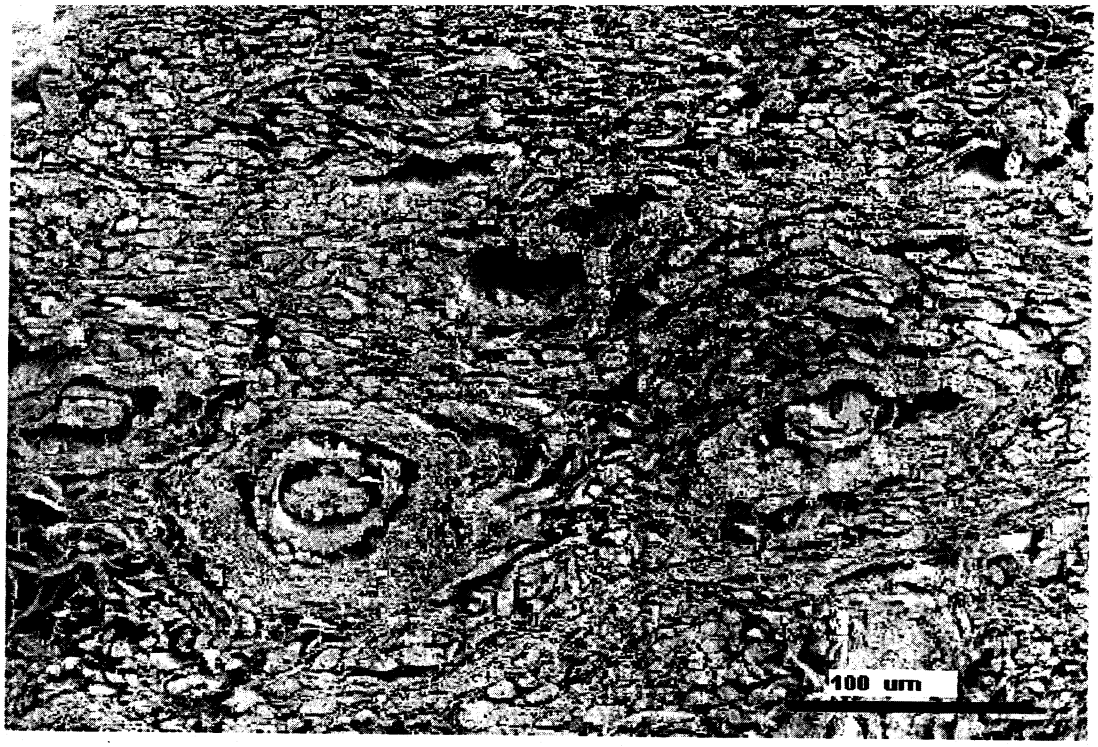

FIGURE 1. — Micrograph showing grain layer with sheet structure.

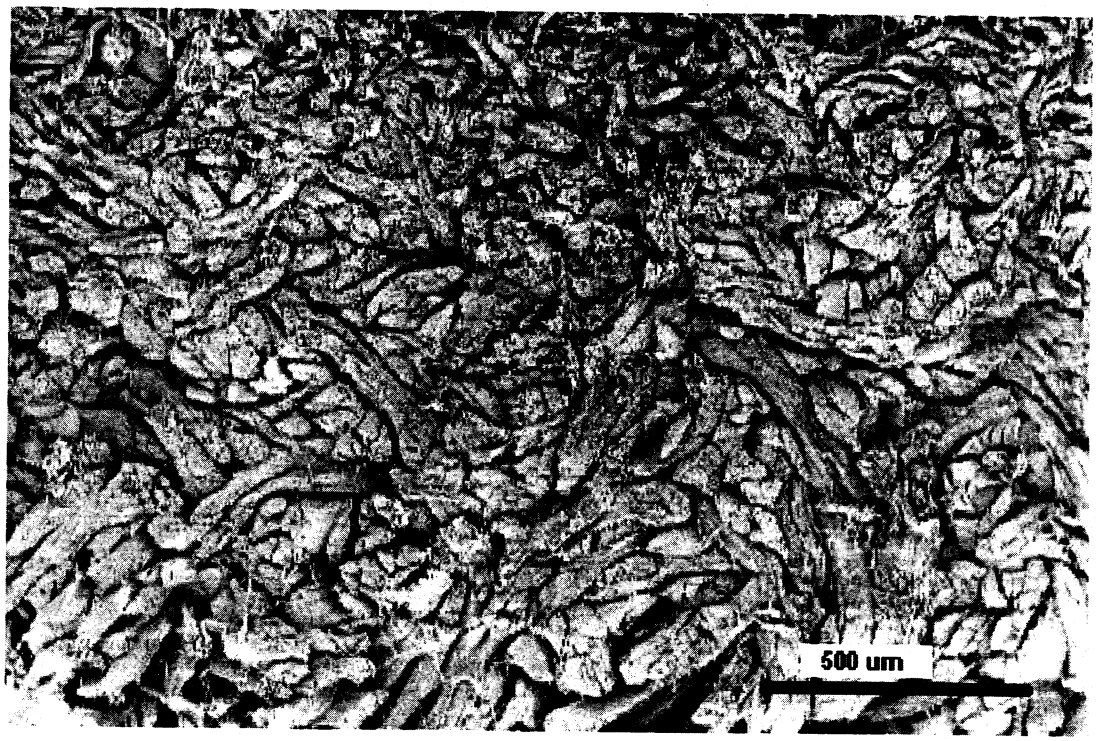

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

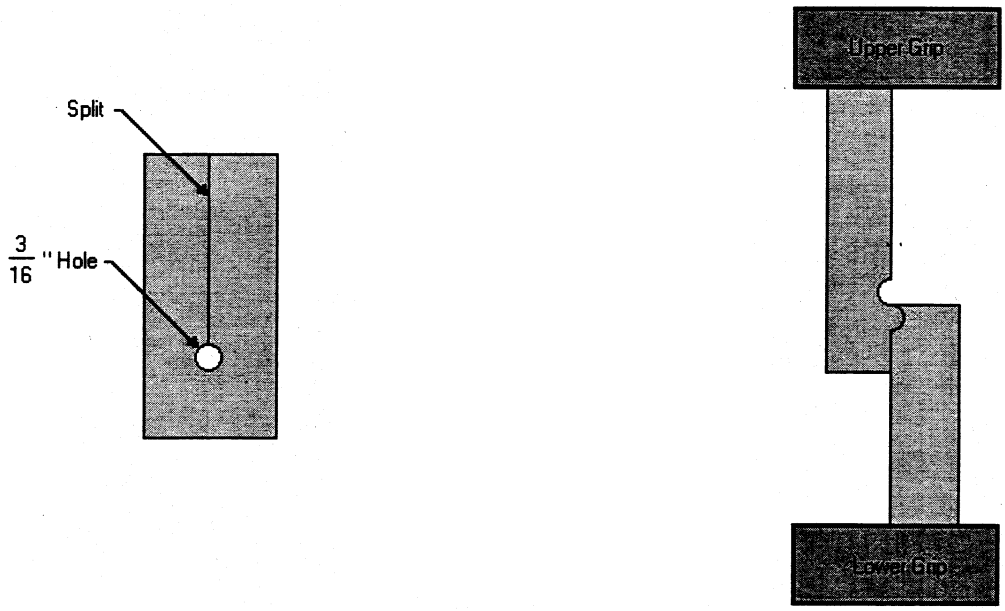

FIGURE 3. — Tear test scheme.

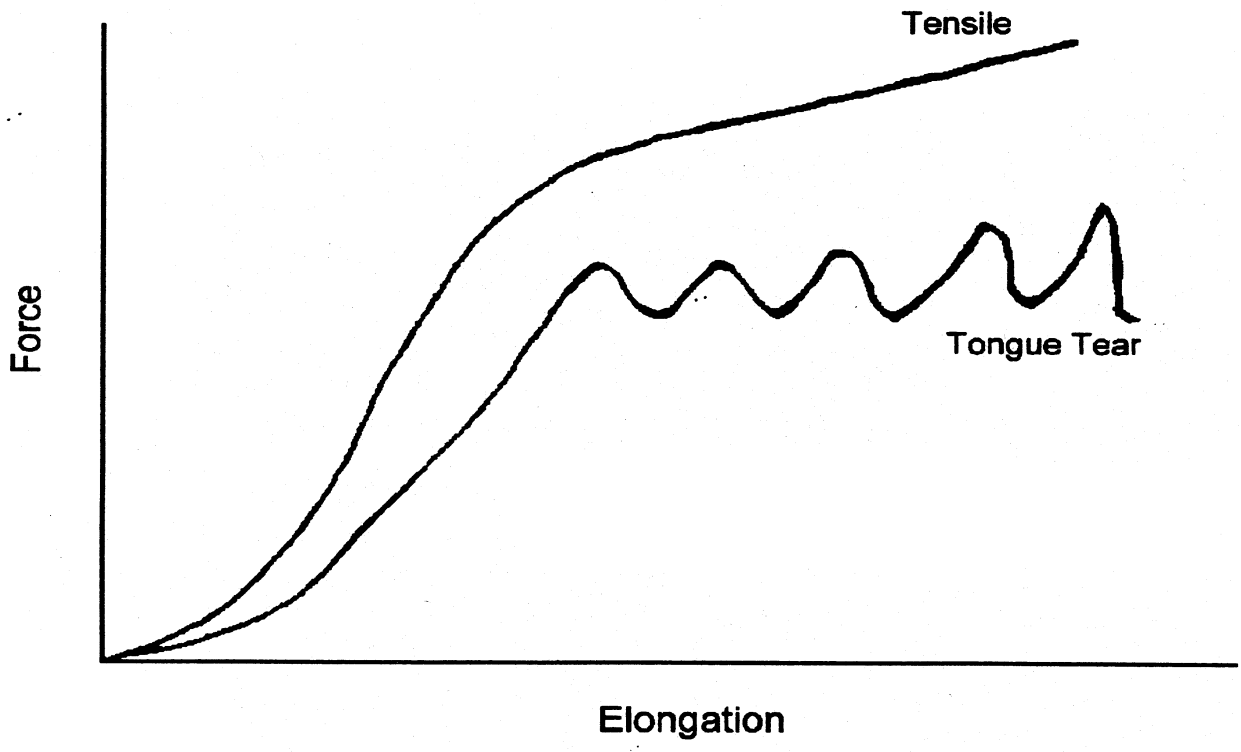

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

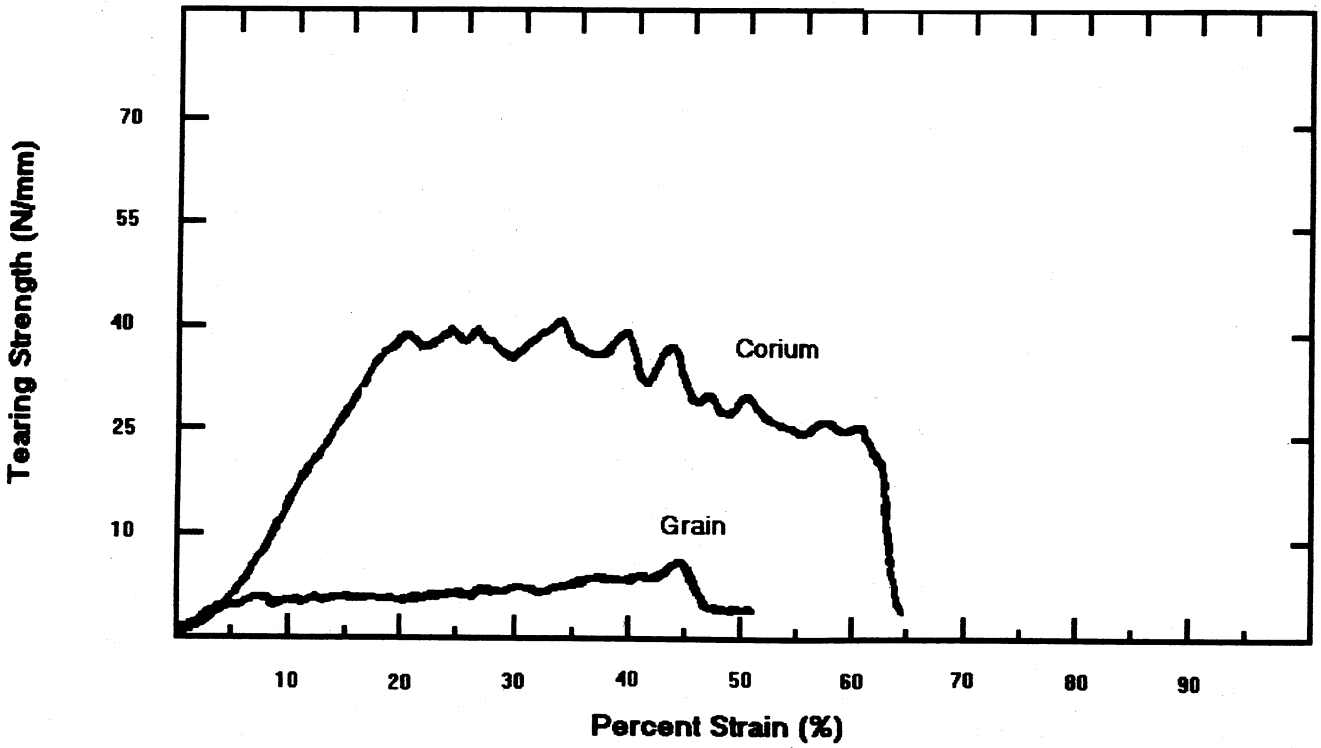

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

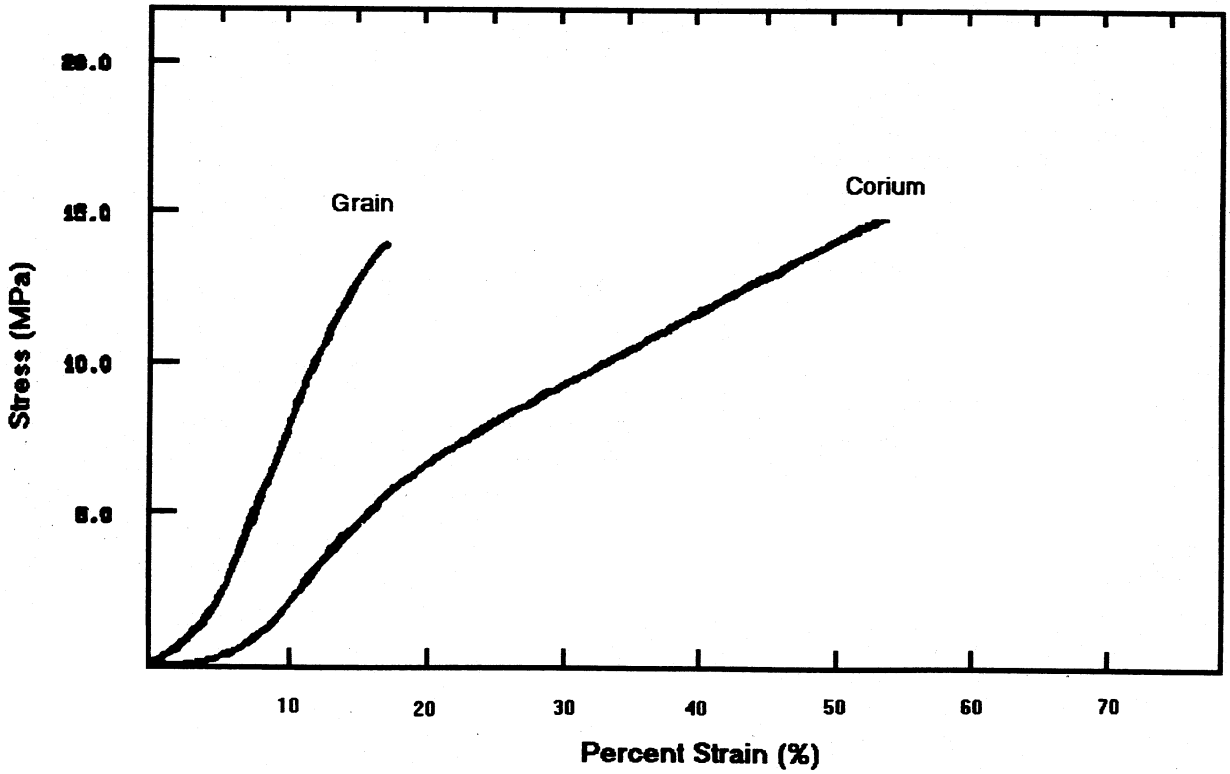

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

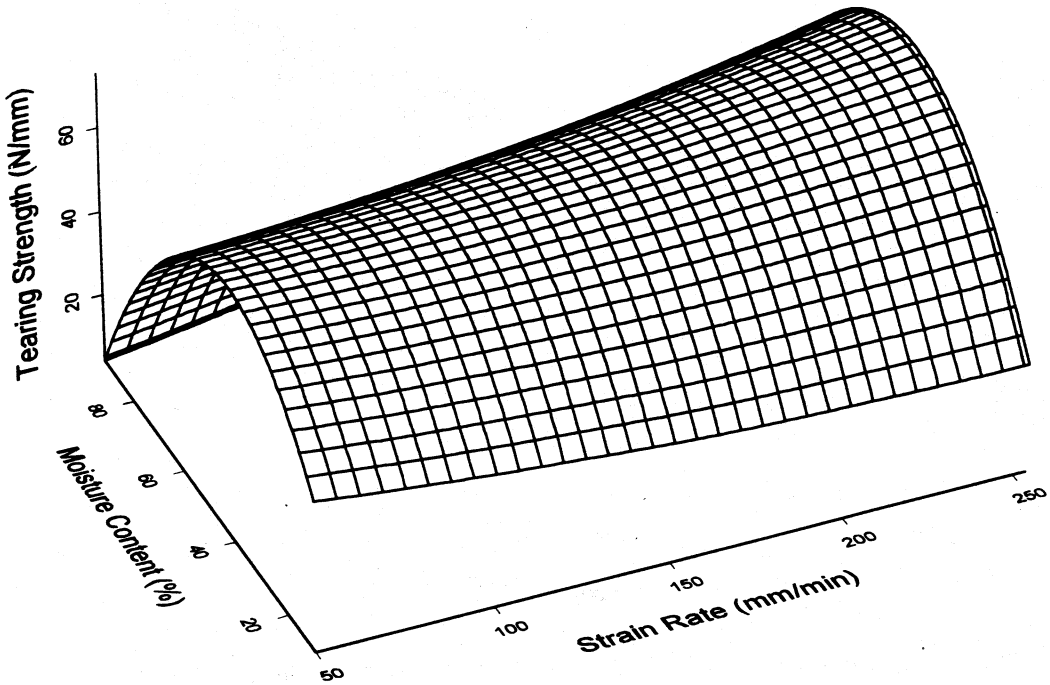

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

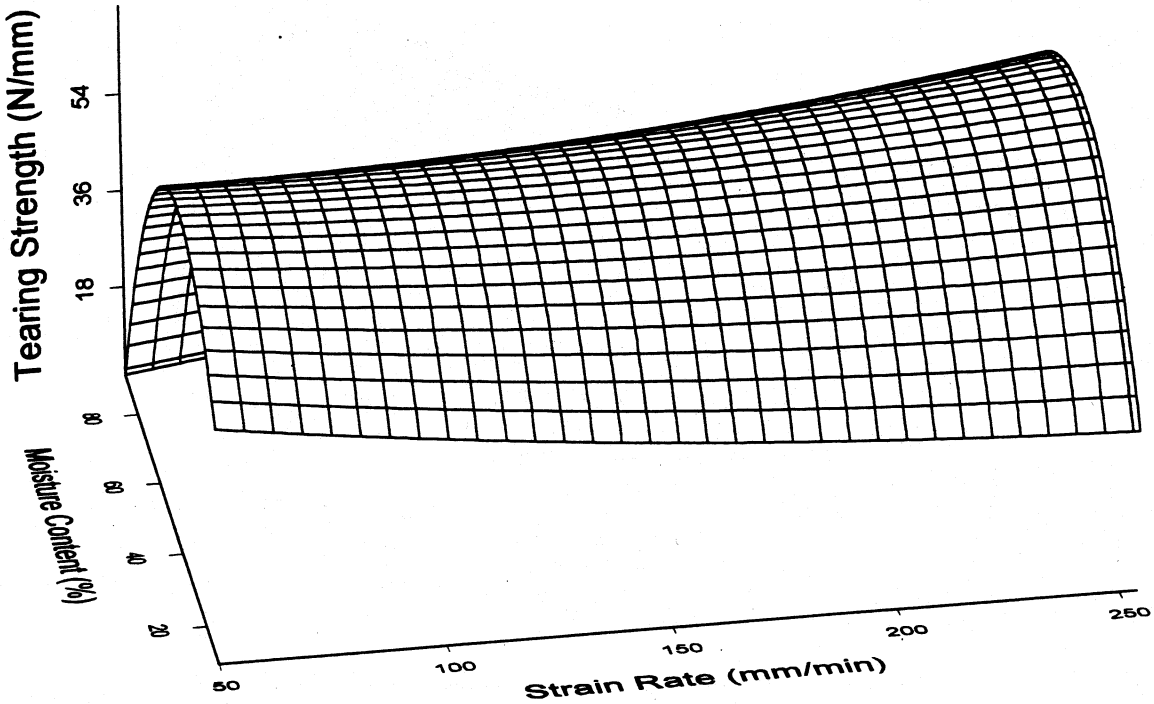

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

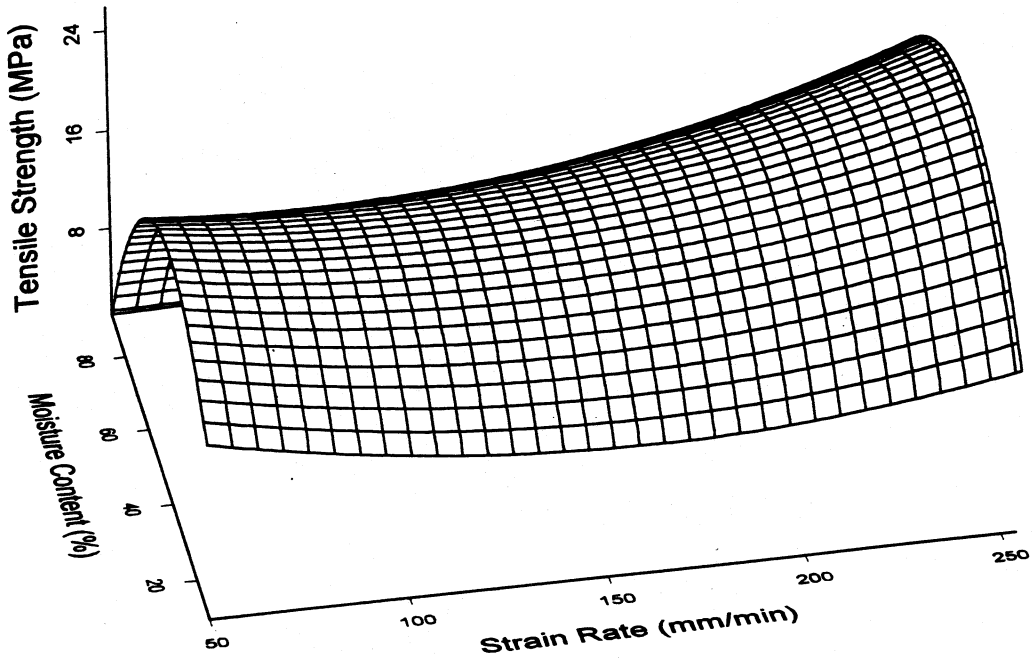

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

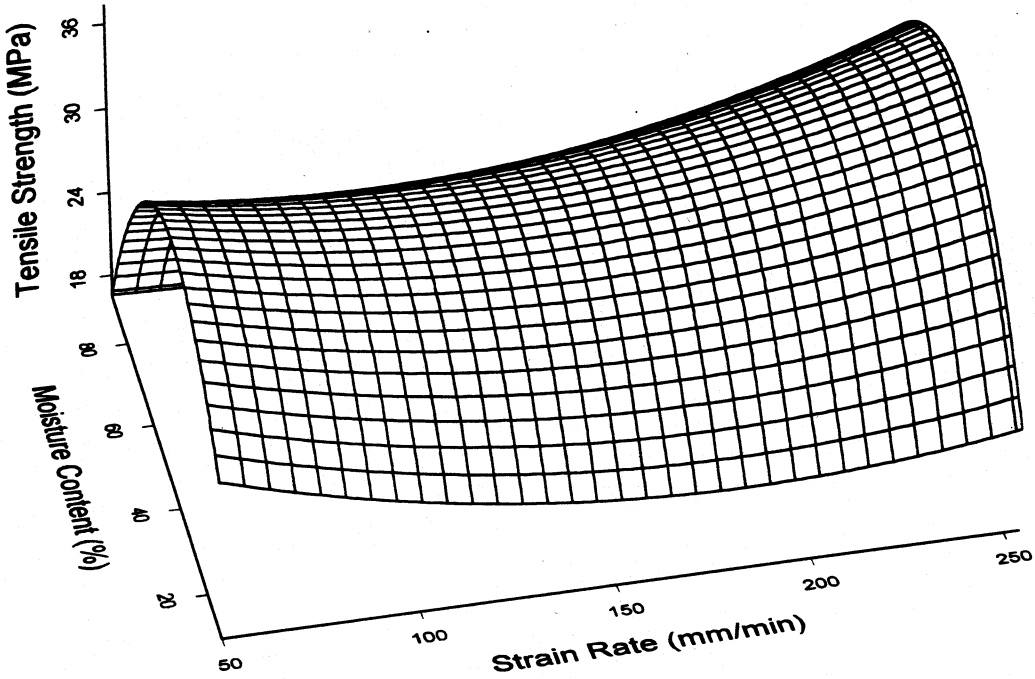

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

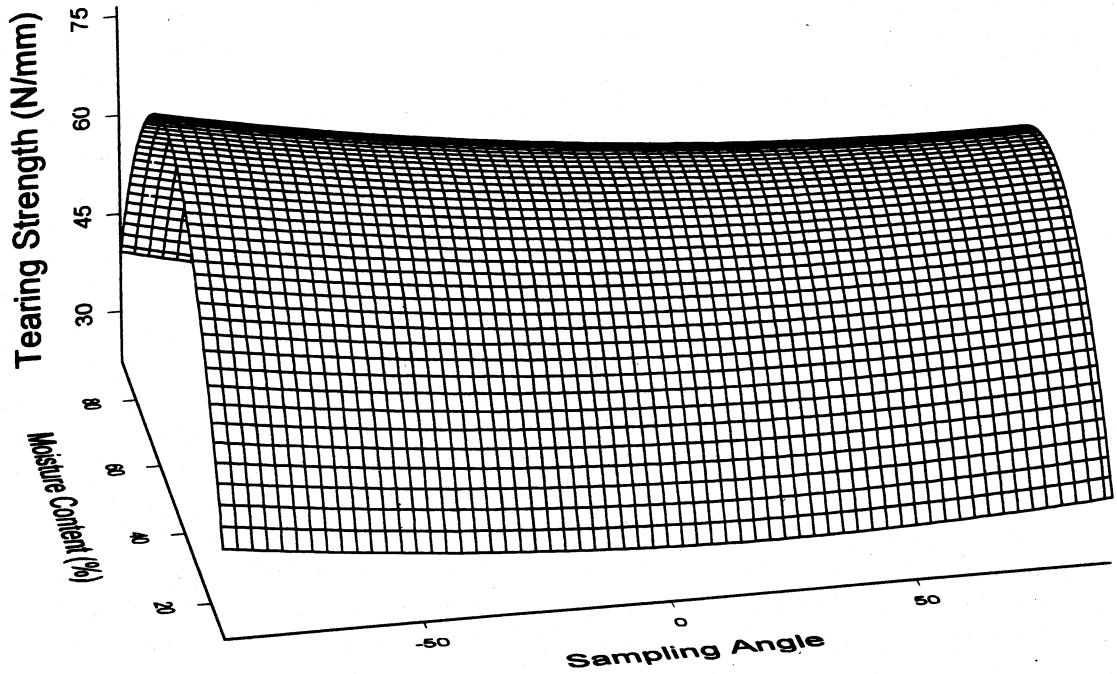

FIGURE 11. — Effect of sampling angle on tearing strength.

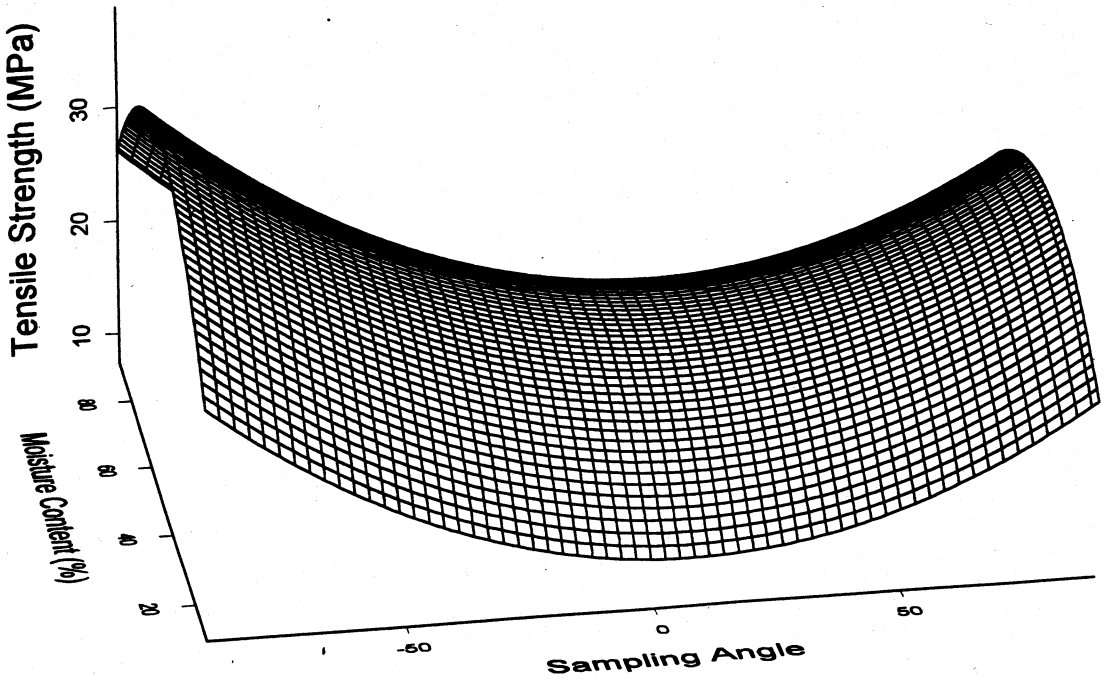

FIGURE 12. — Effect of sampling angle on tensile strength.

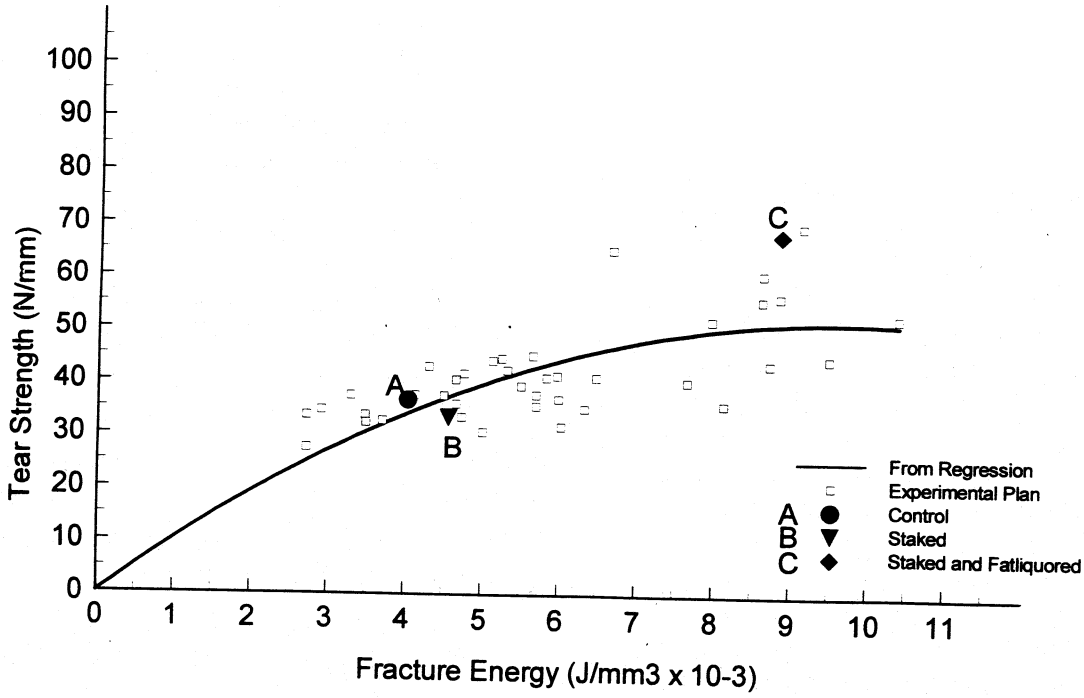

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

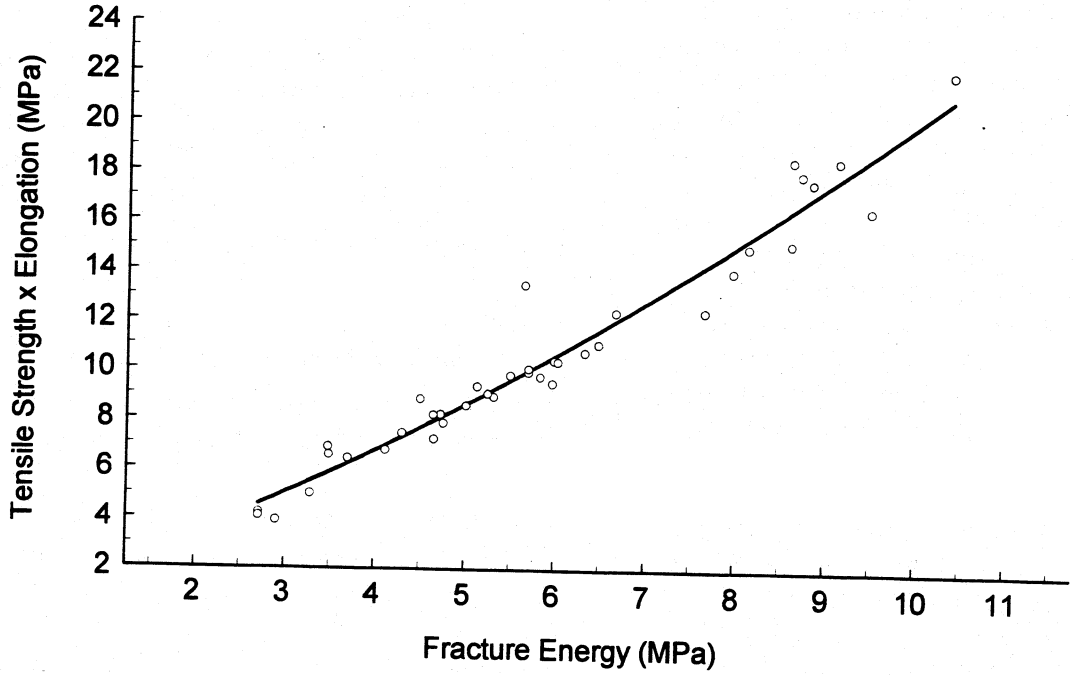

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

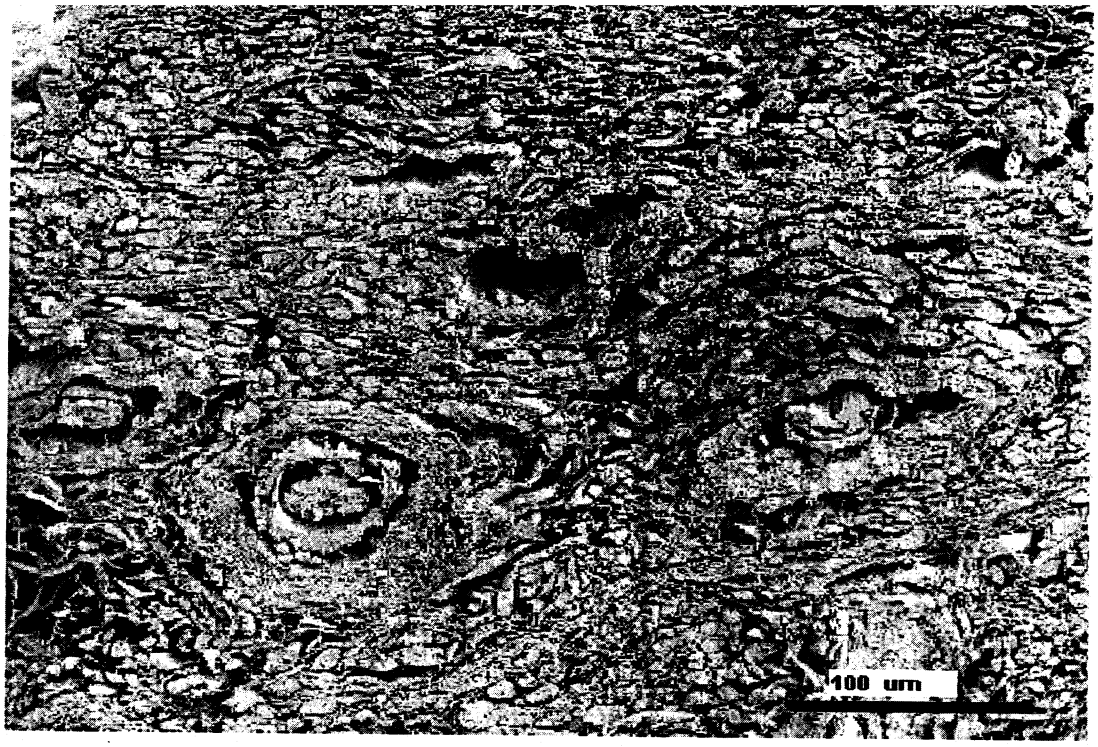

FIGURE 1. — Micrograph showing grain layer with sheet structure.

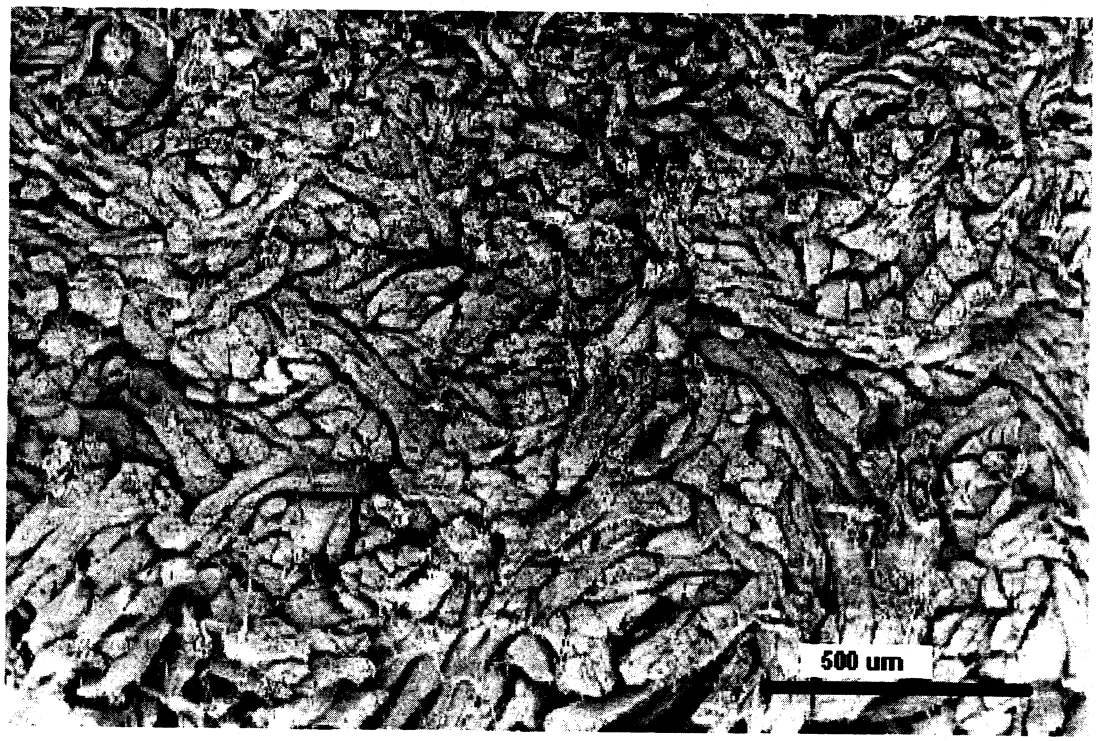

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

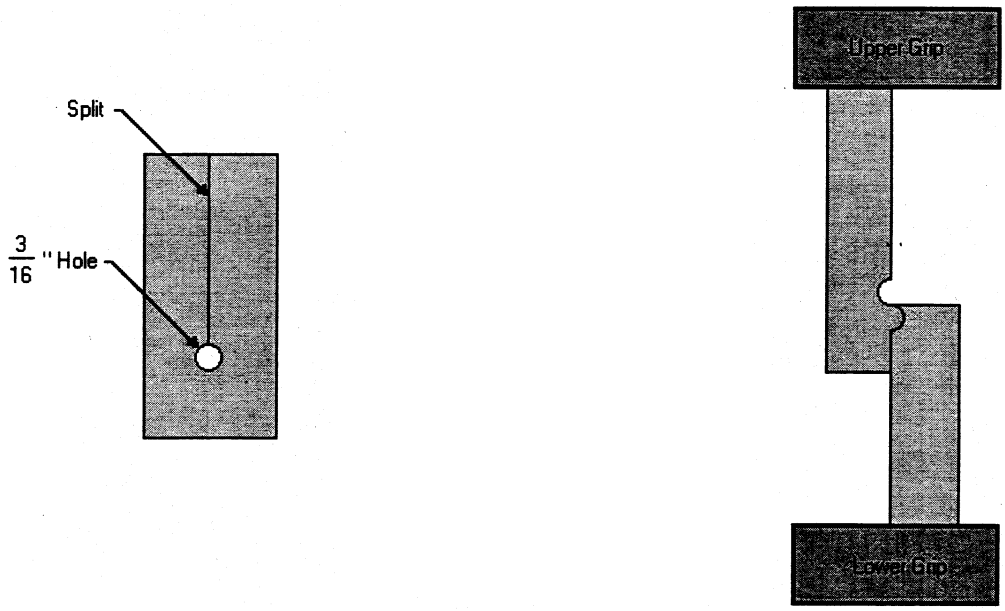

FIGURE 3. — Tear test scheme.

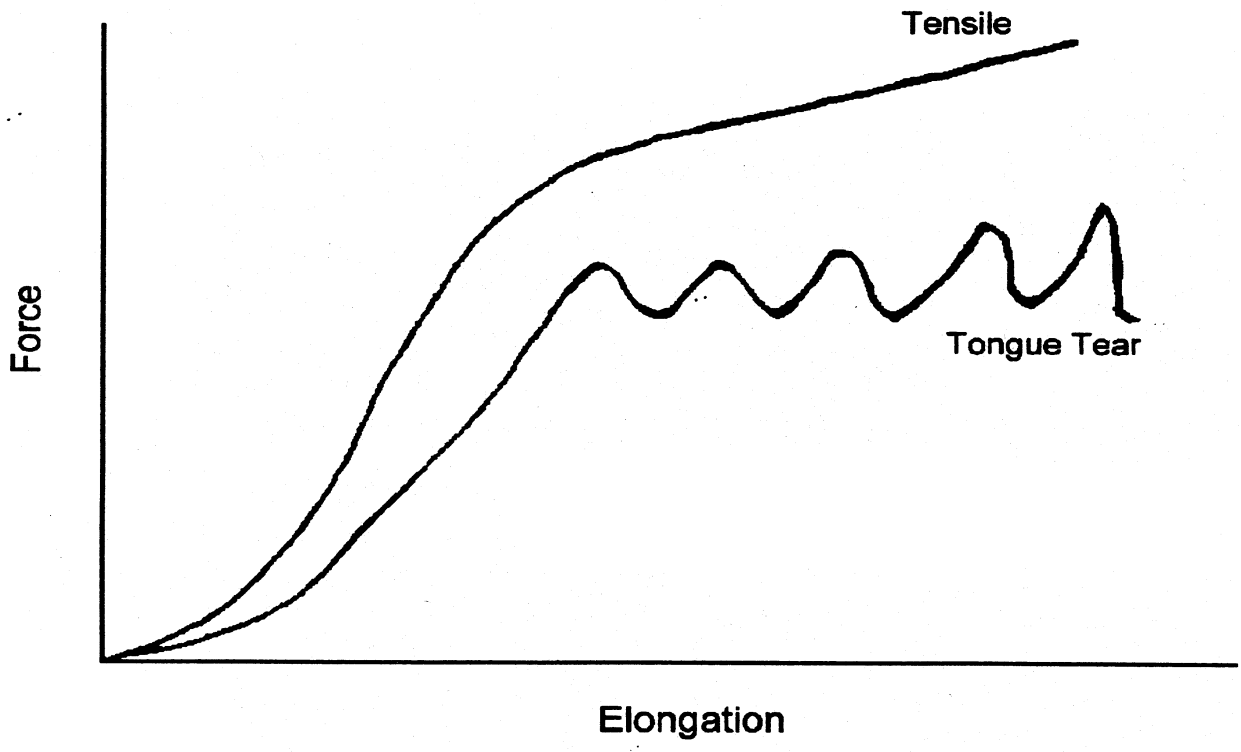

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

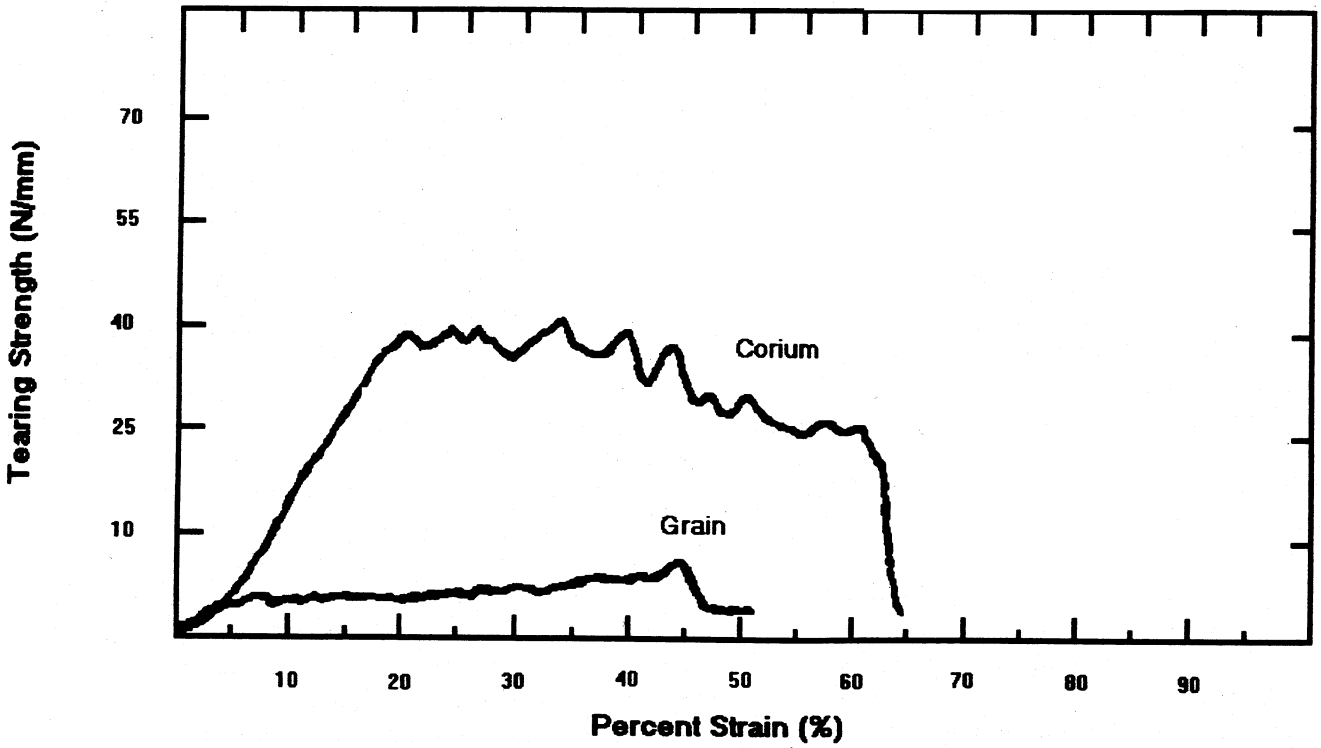

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

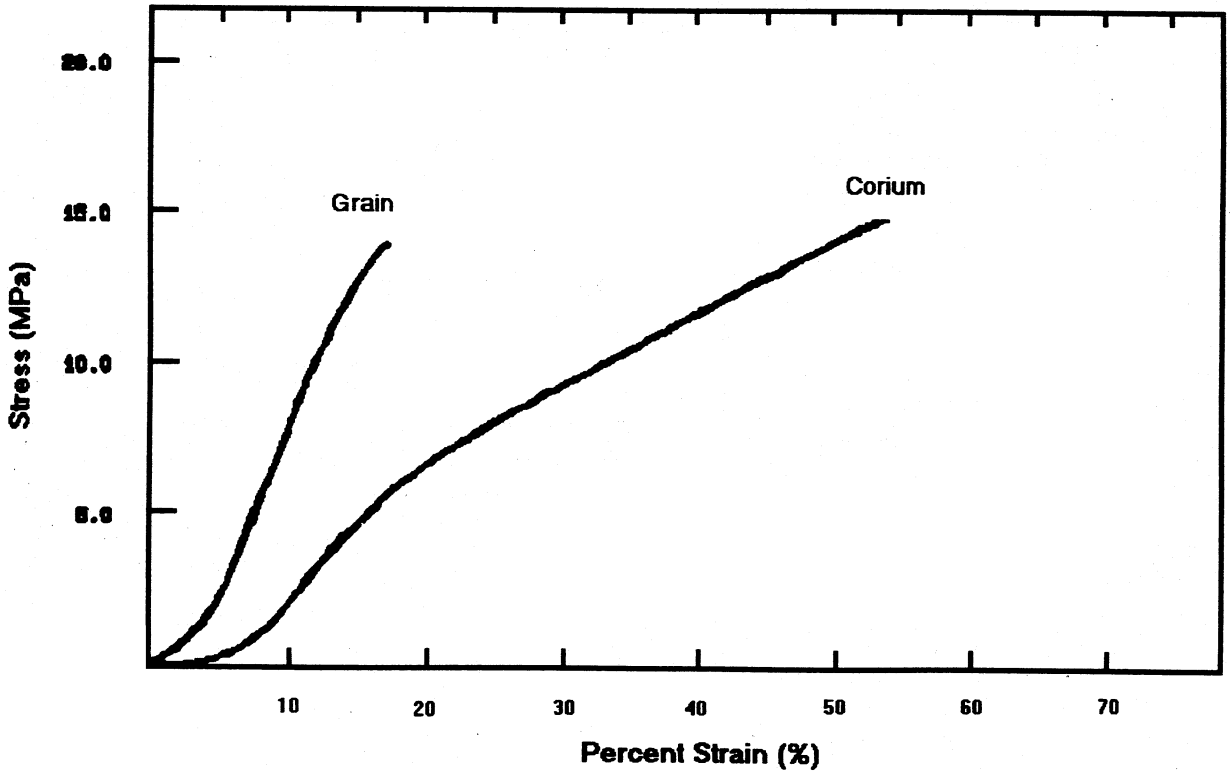

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

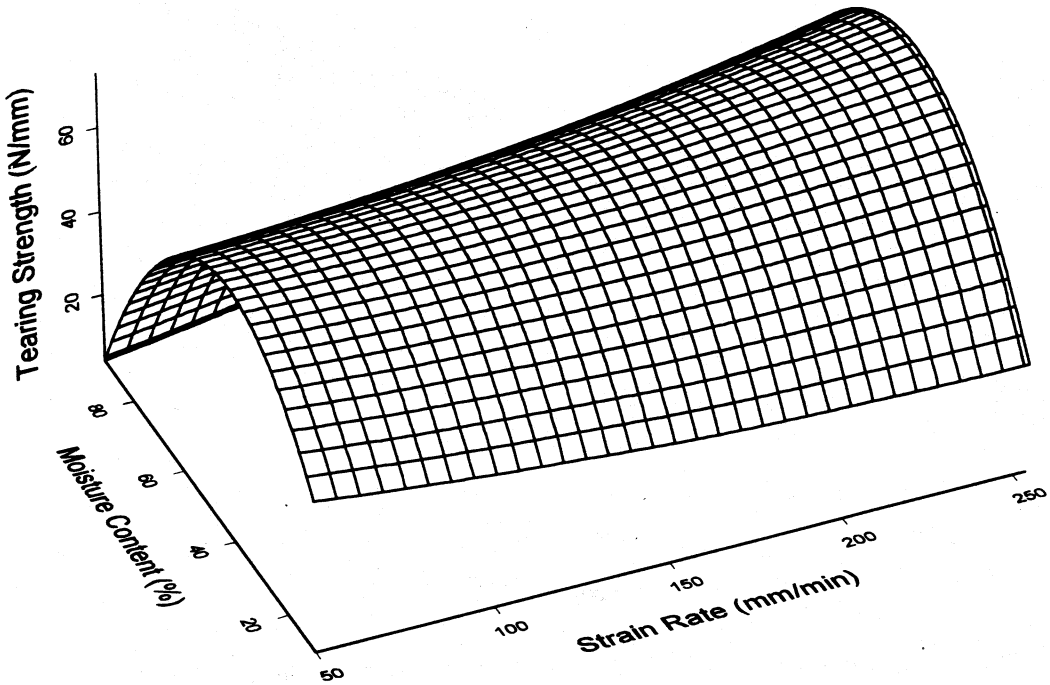

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

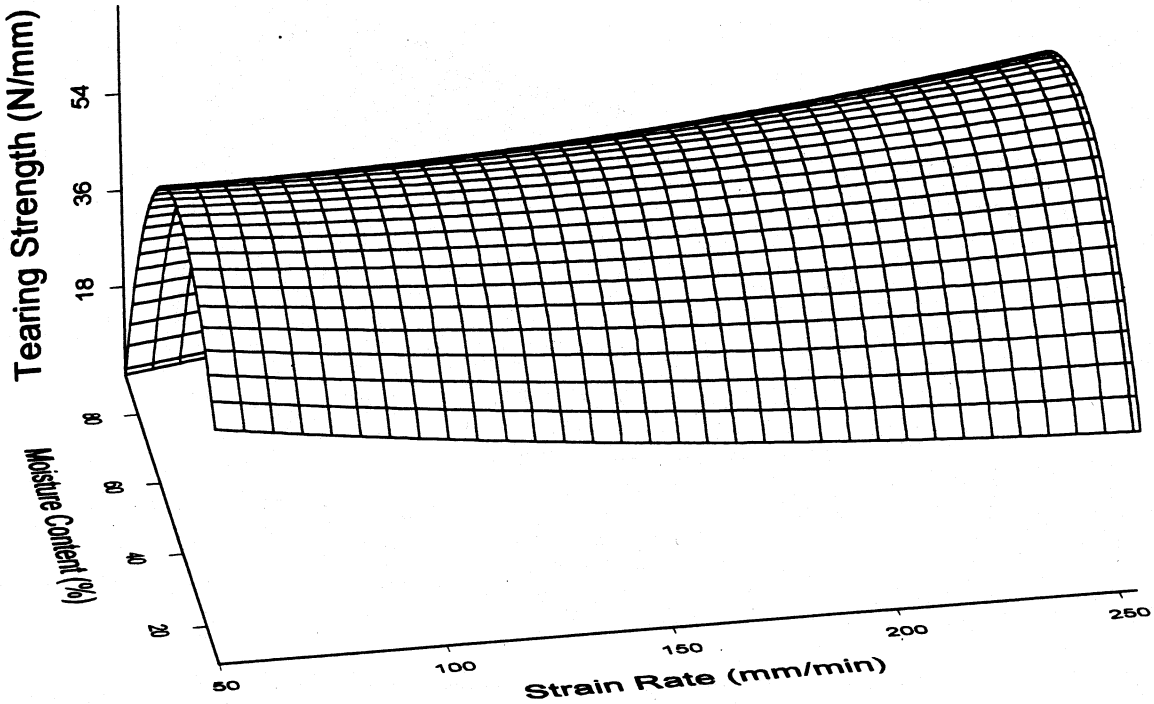

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

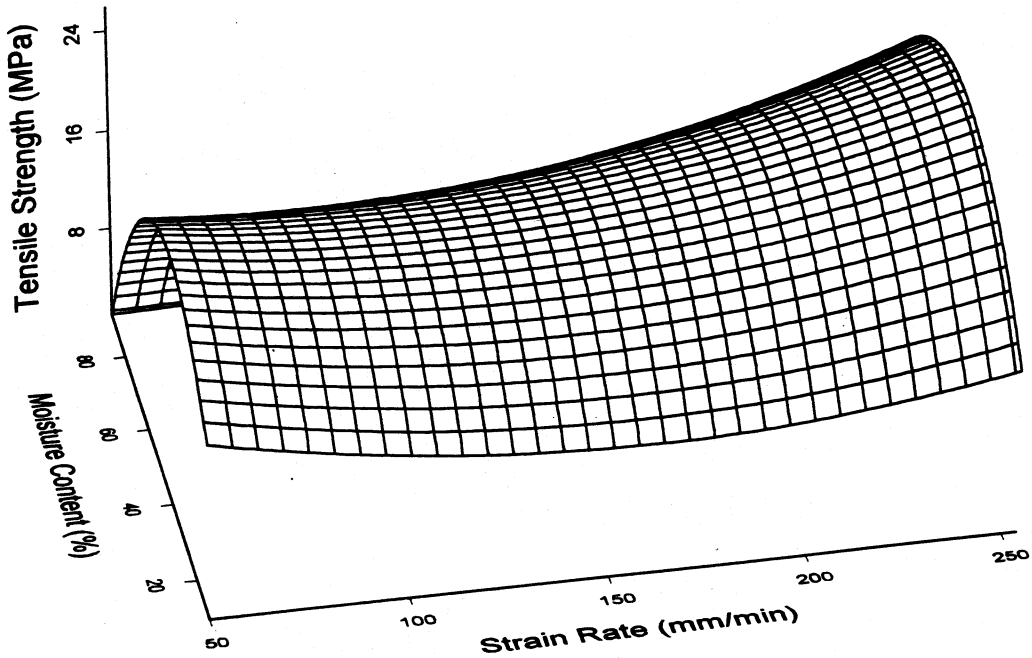

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

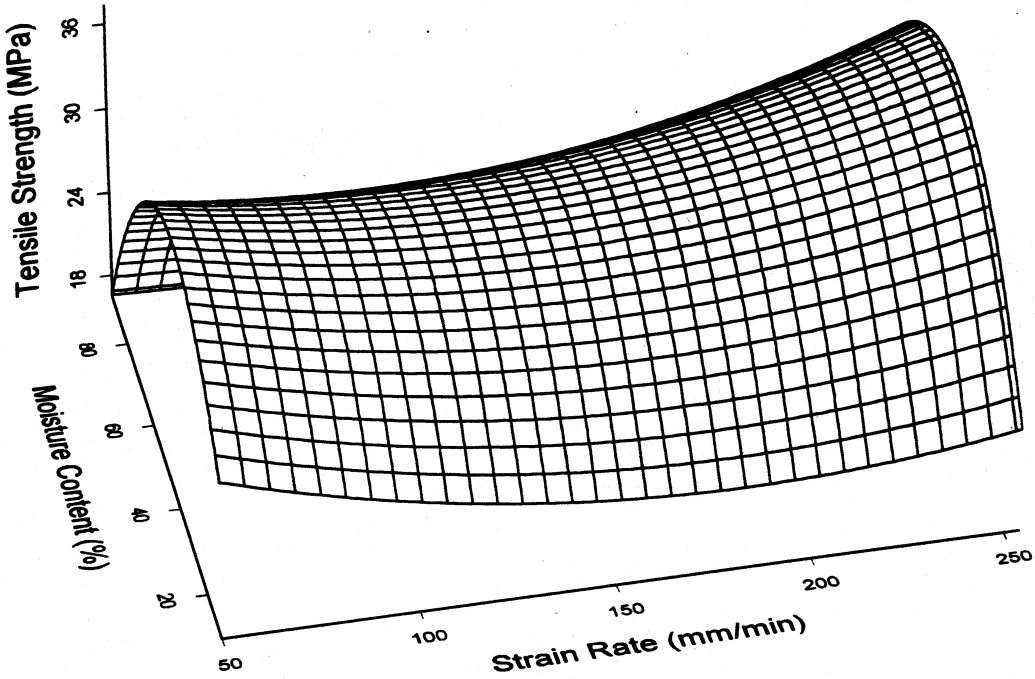

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

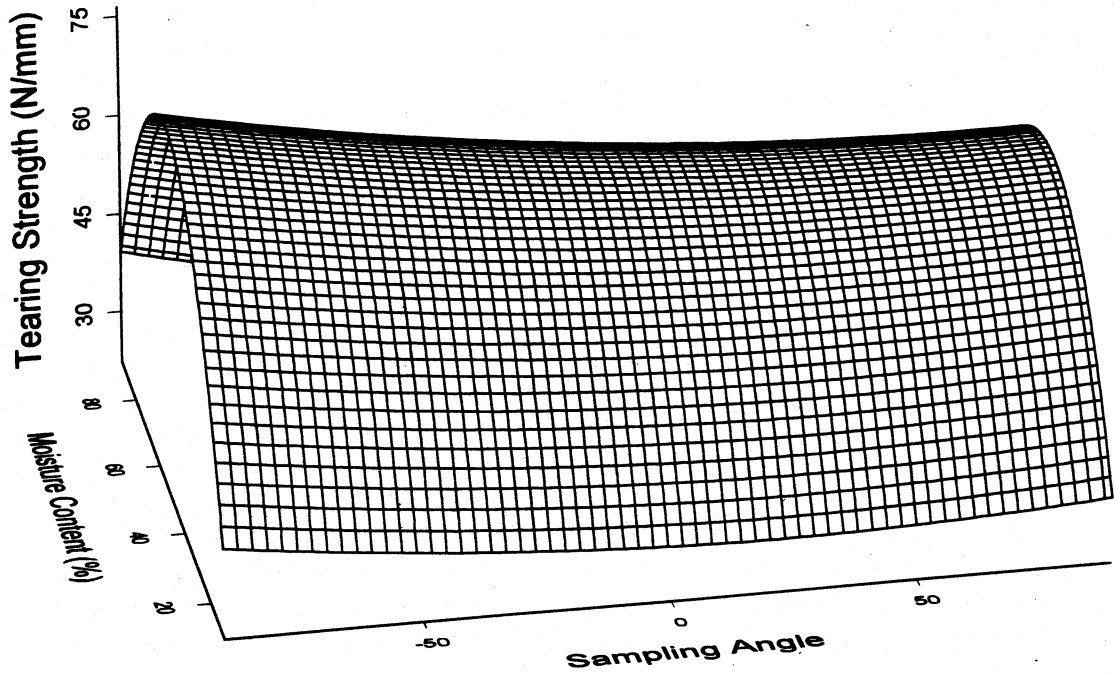

FIGURE 11. — Effect of sampling angle on tearing strength.

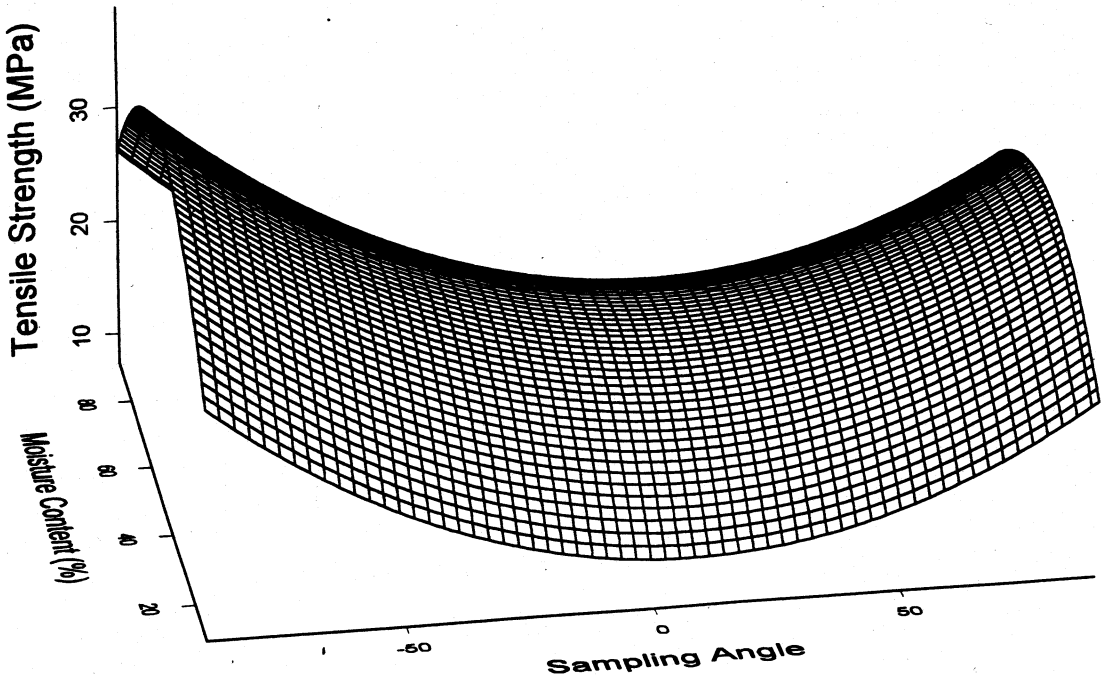

FIGURE 12. — Effect of sampling angle on tensile strength.

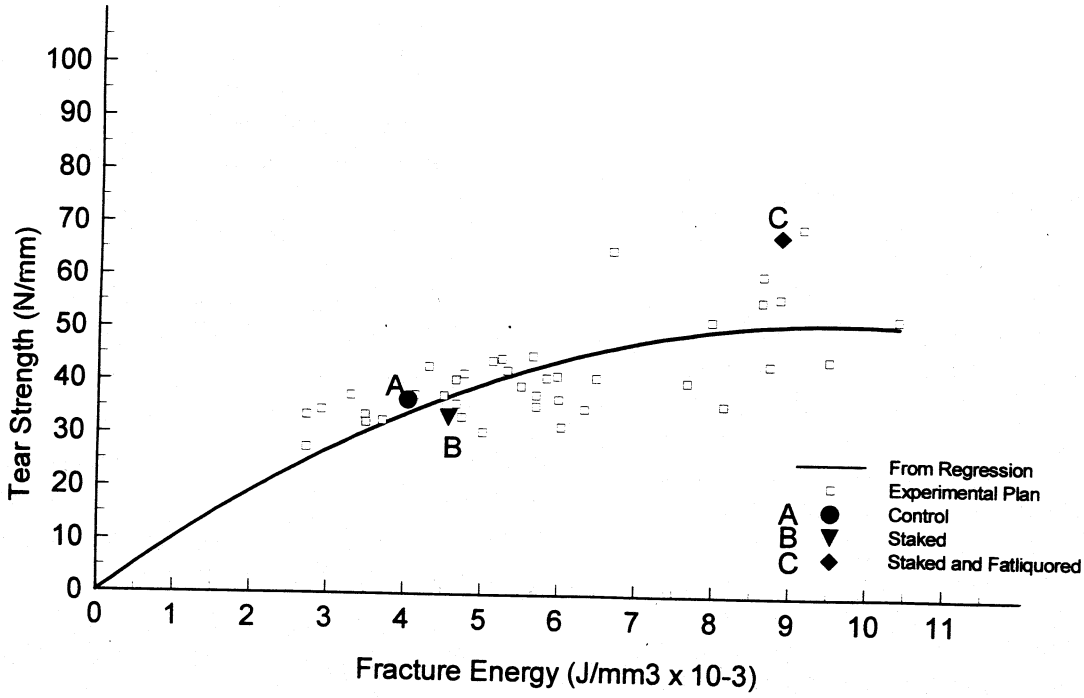

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

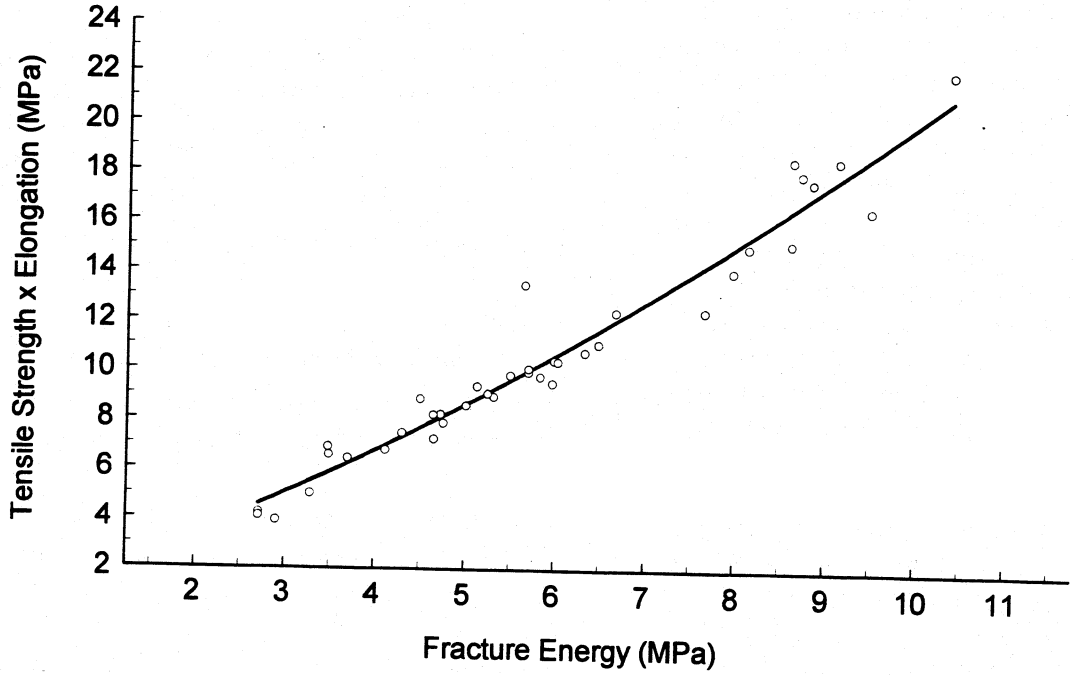

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

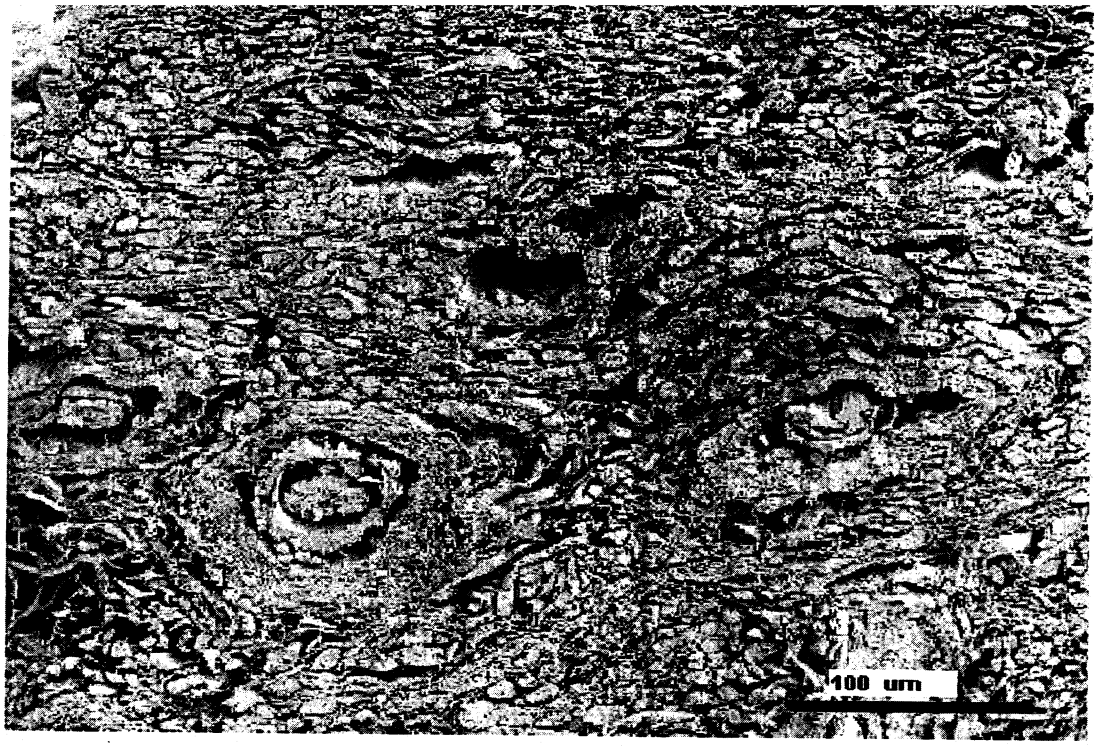

FIGURE 1. — Micrograph showing grain layer with sheet structure.

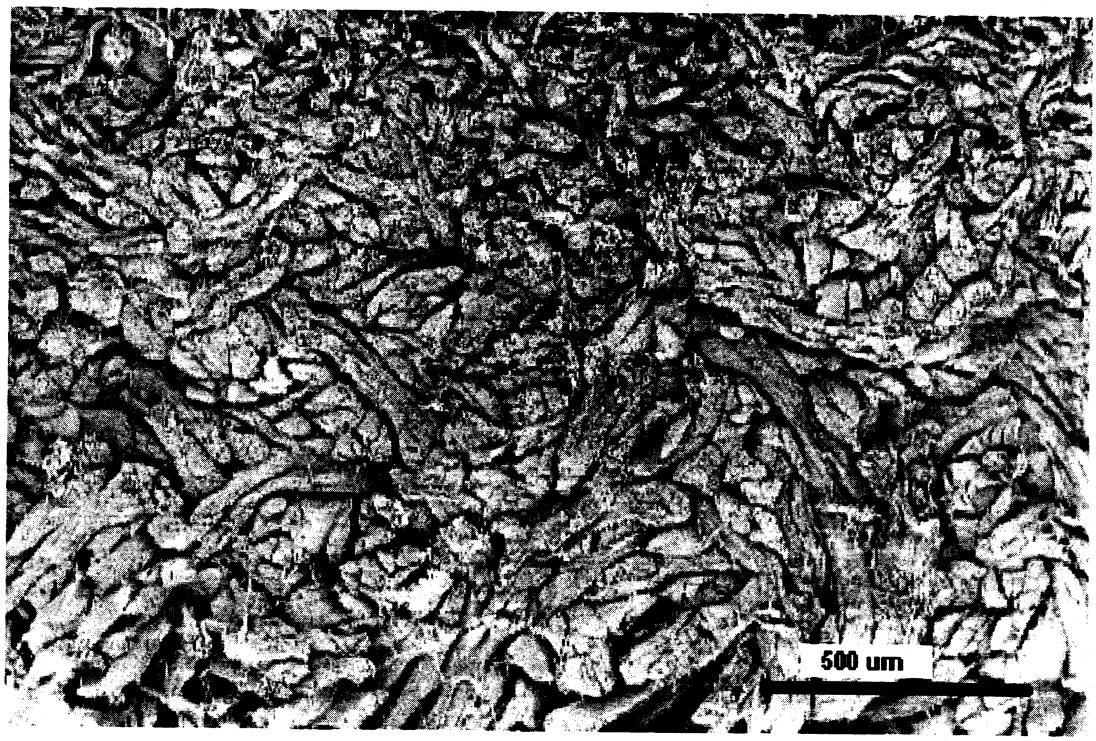

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

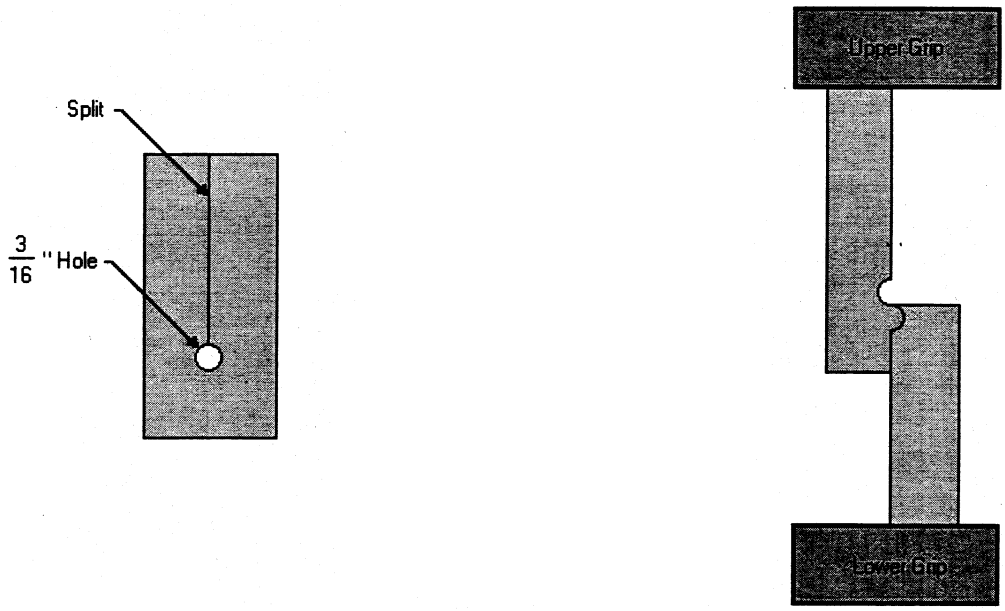

FIGURE 3. — Tear test scheme.

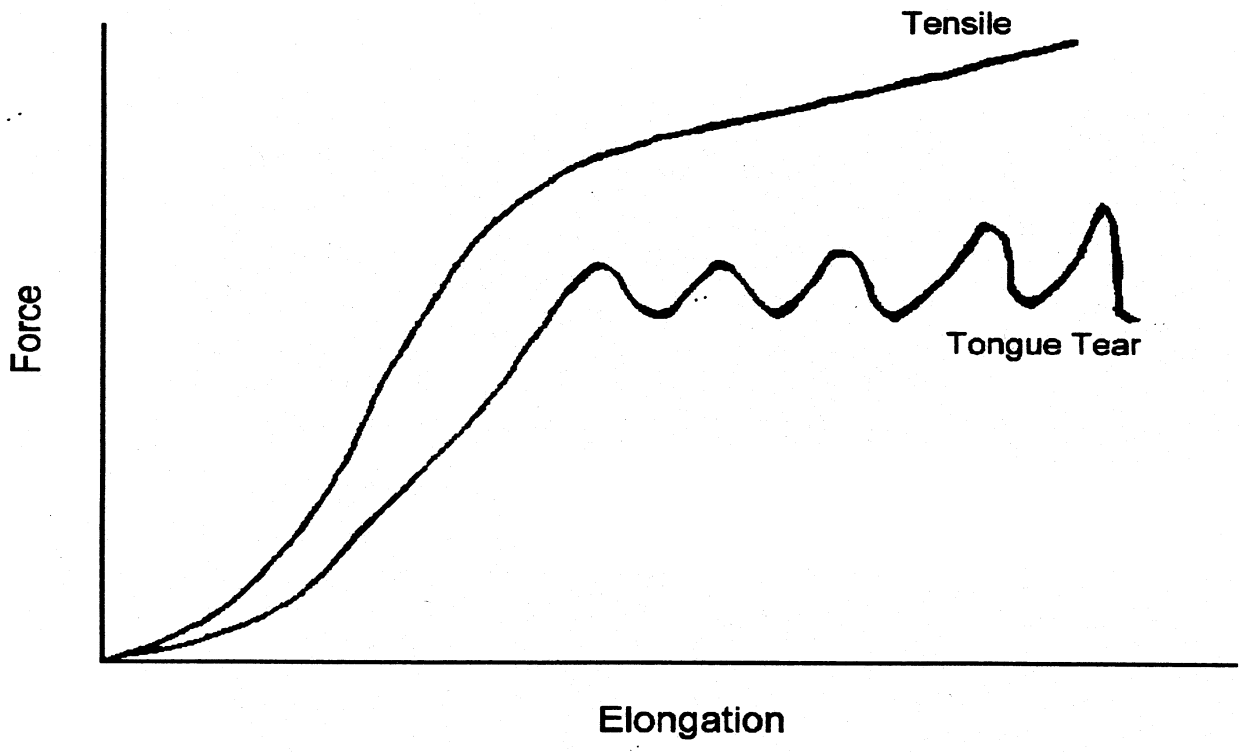

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

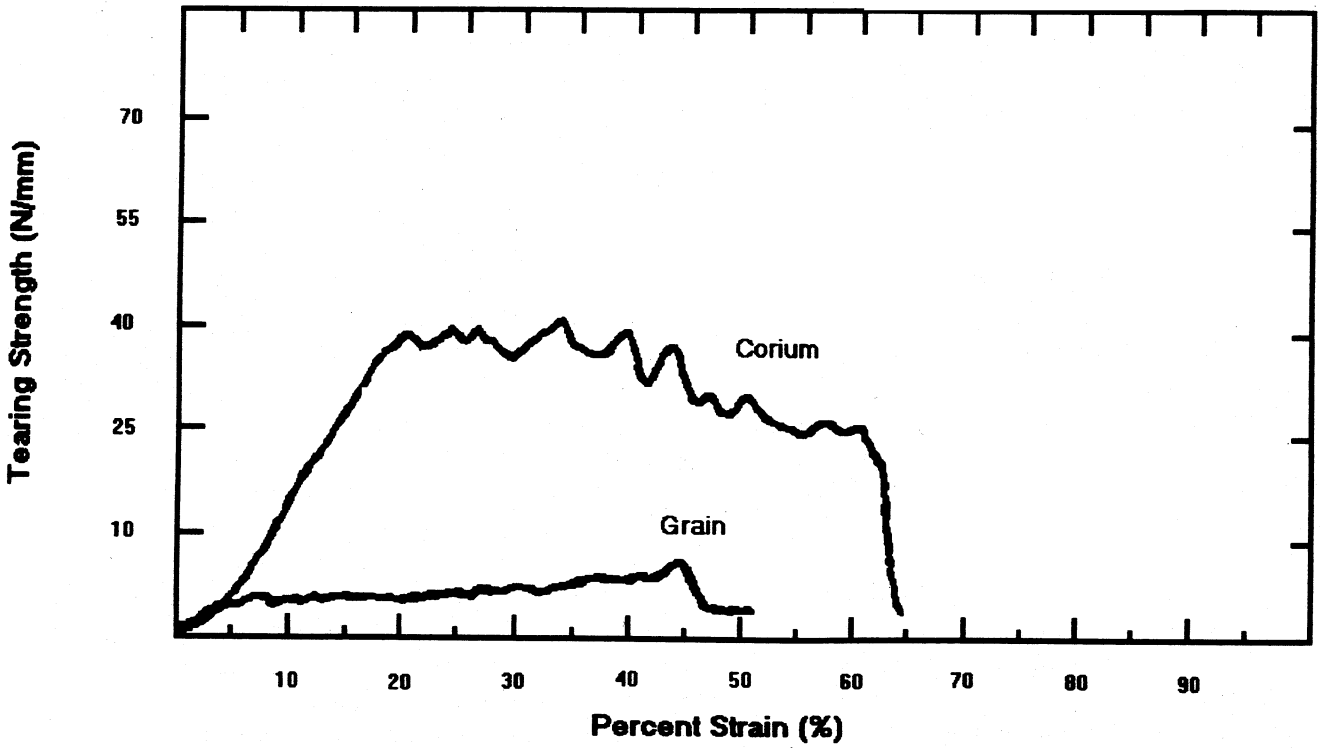

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

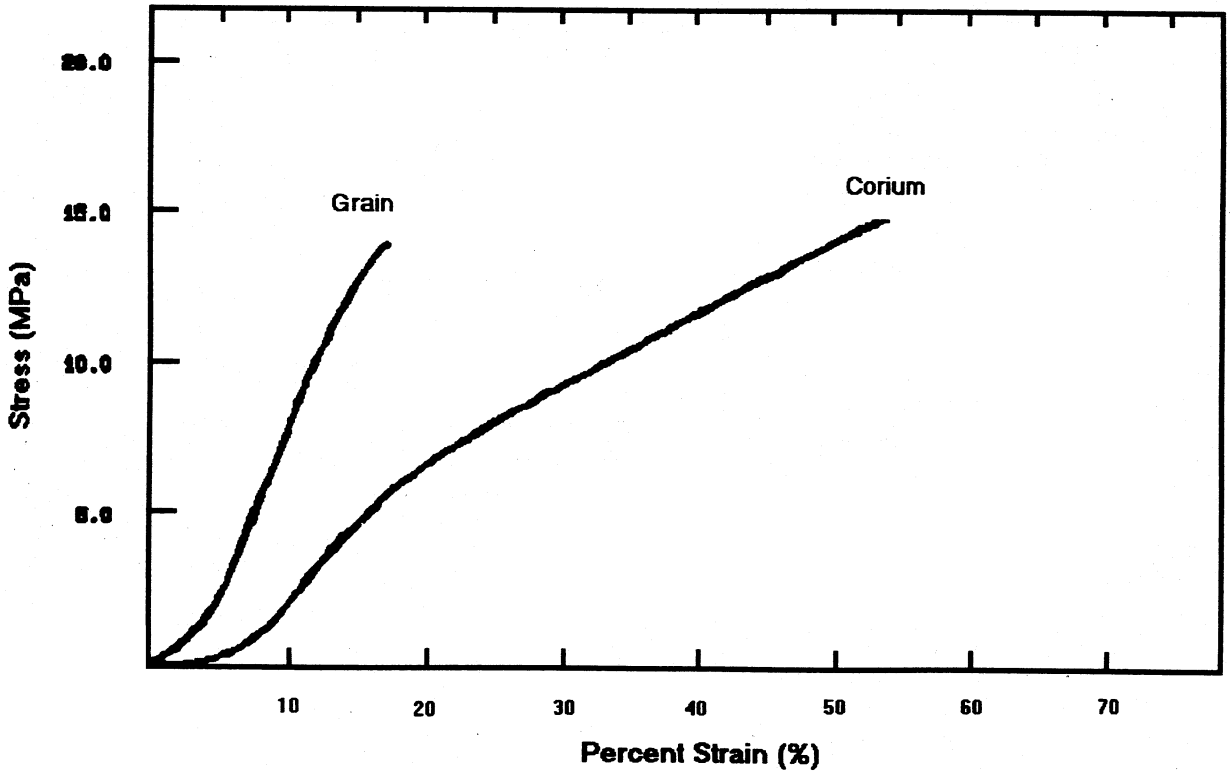

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

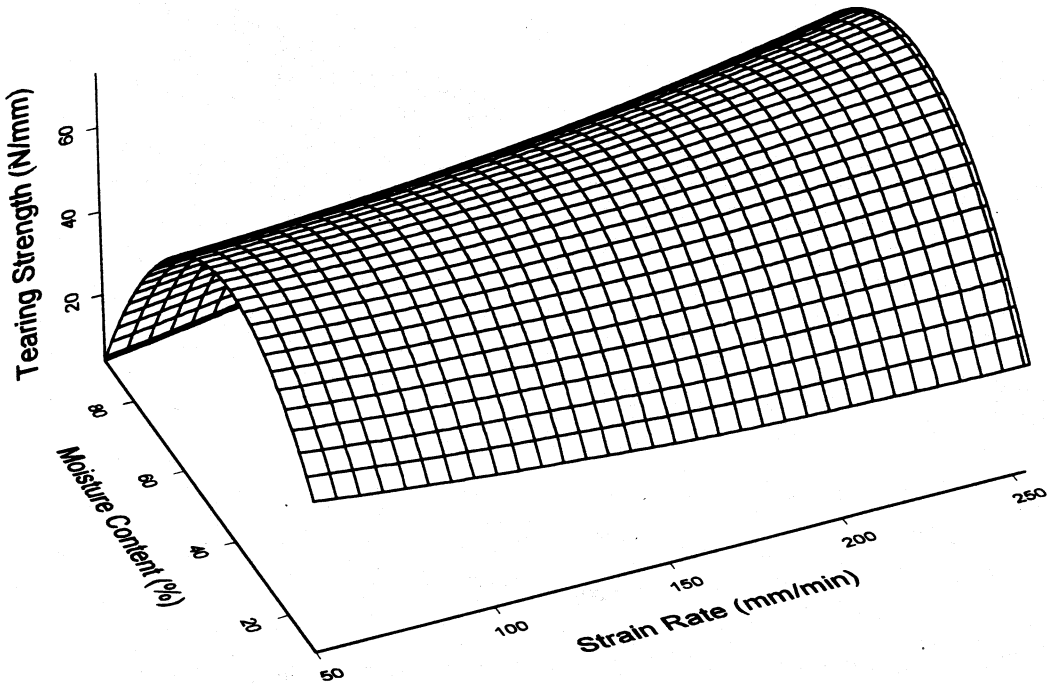

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

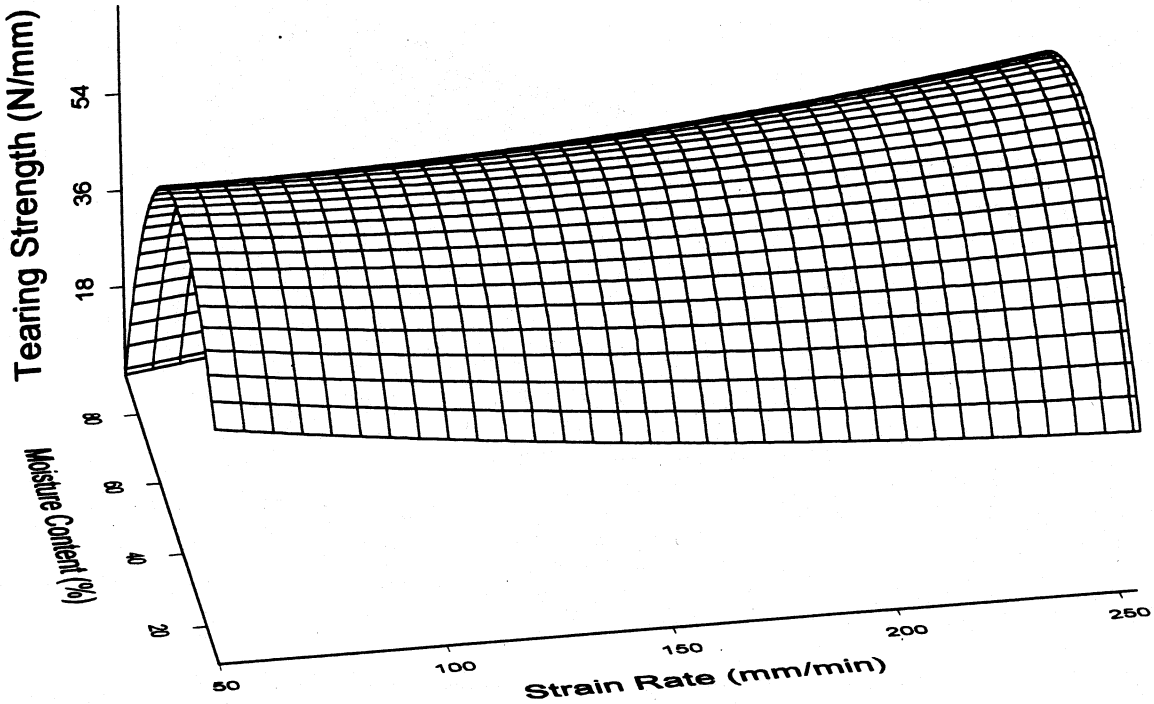

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

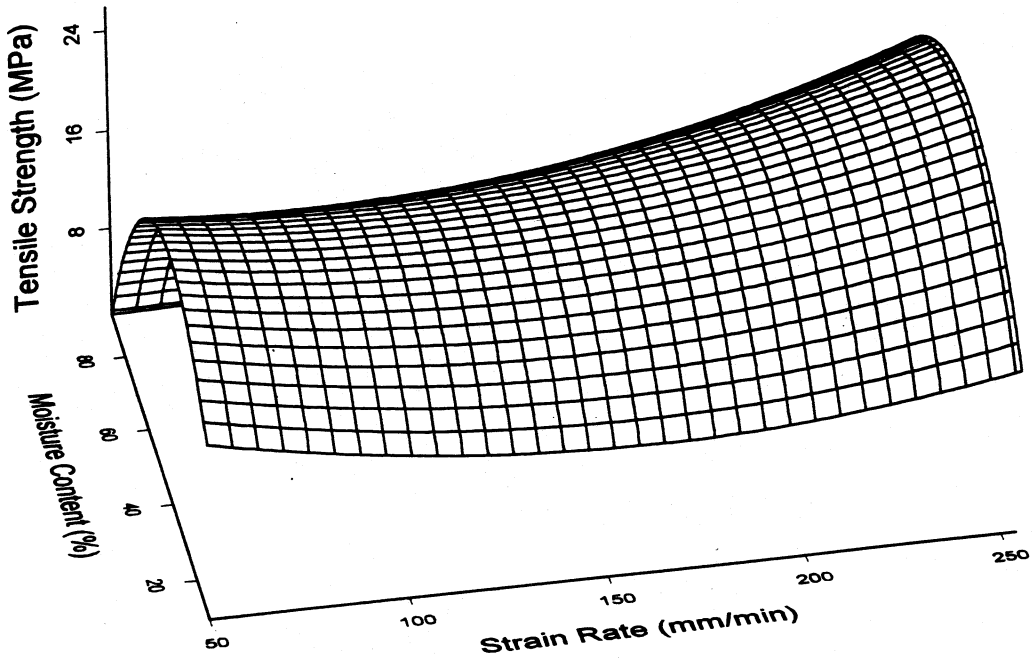

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

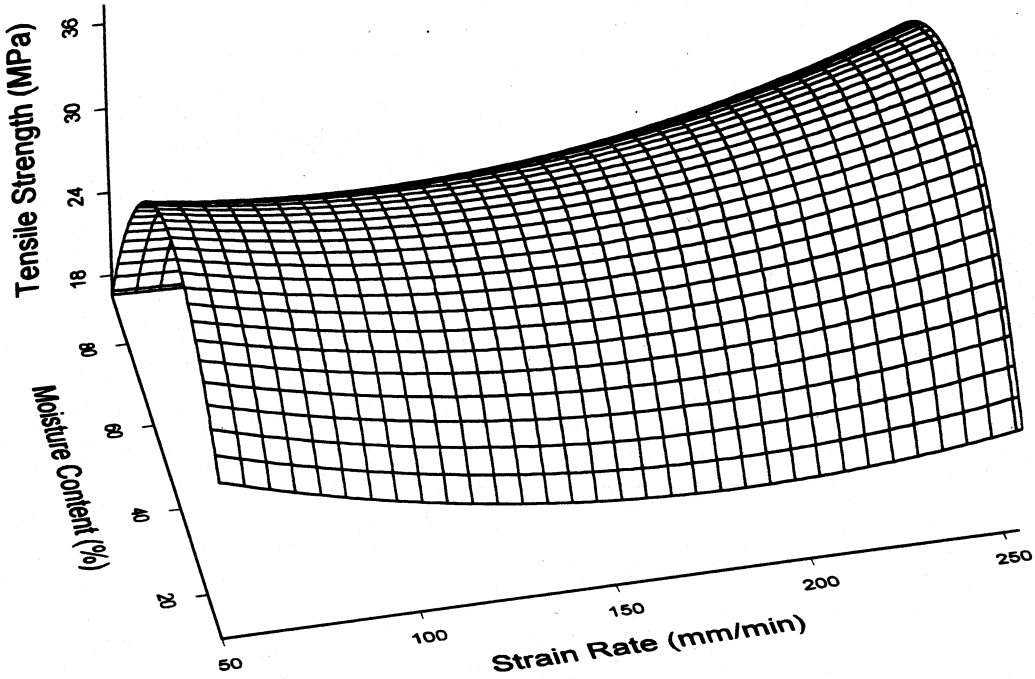

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

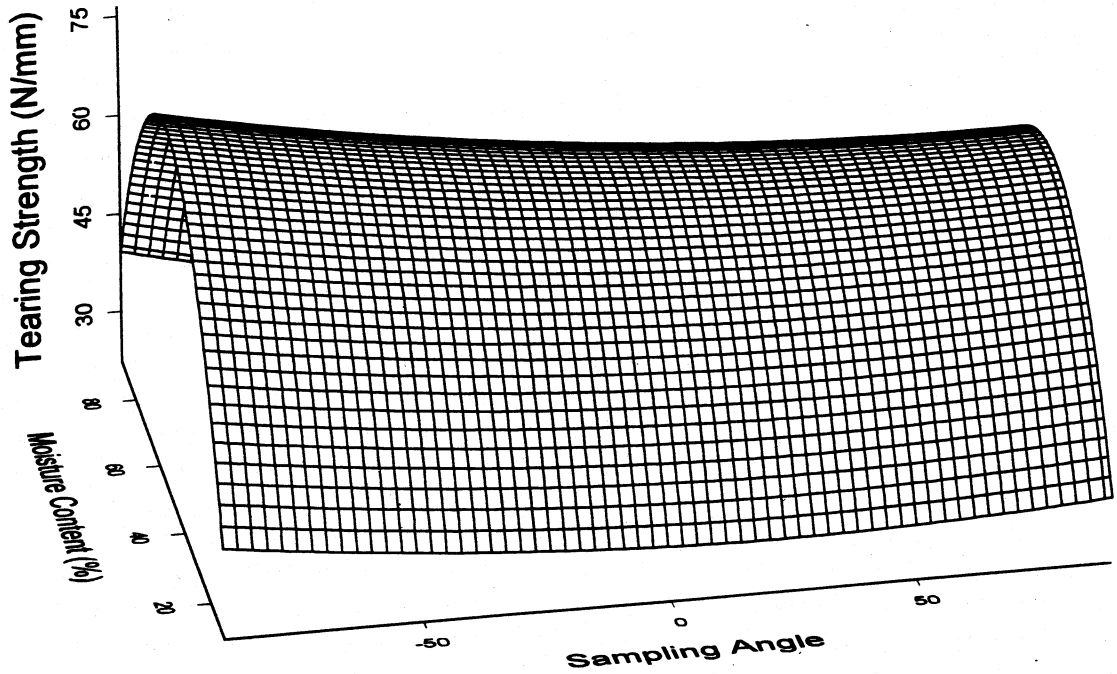

FIGURE 11. — Effect of sampling angle on tearing strength.

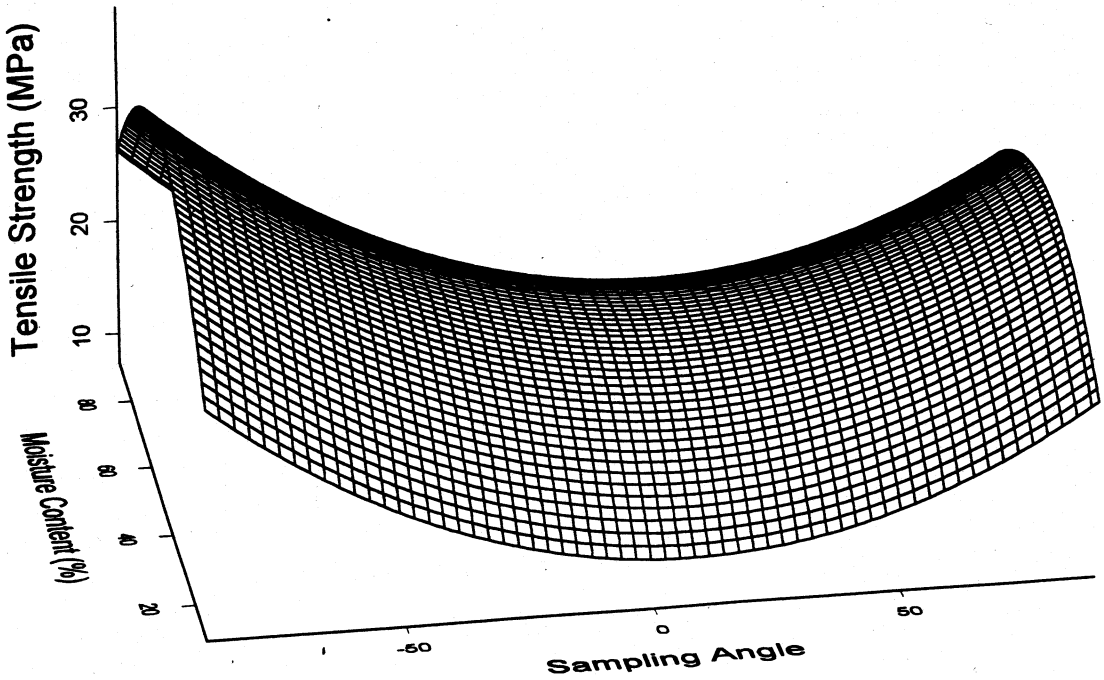

FIGURE 12. — Effect of sampling angle on tensile strength.

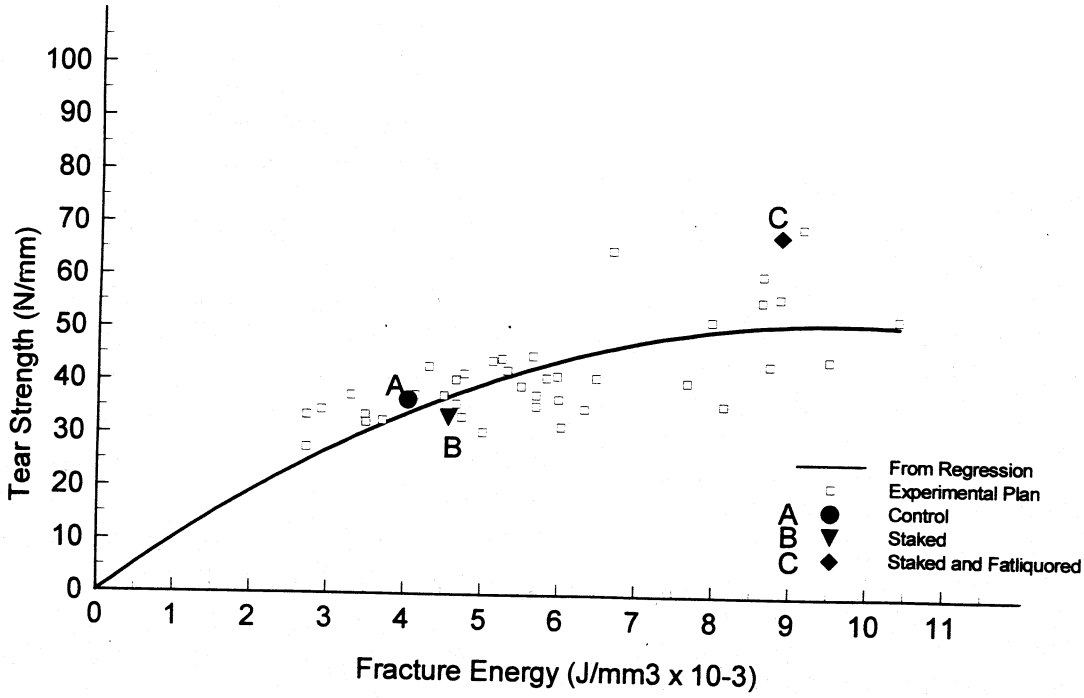

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

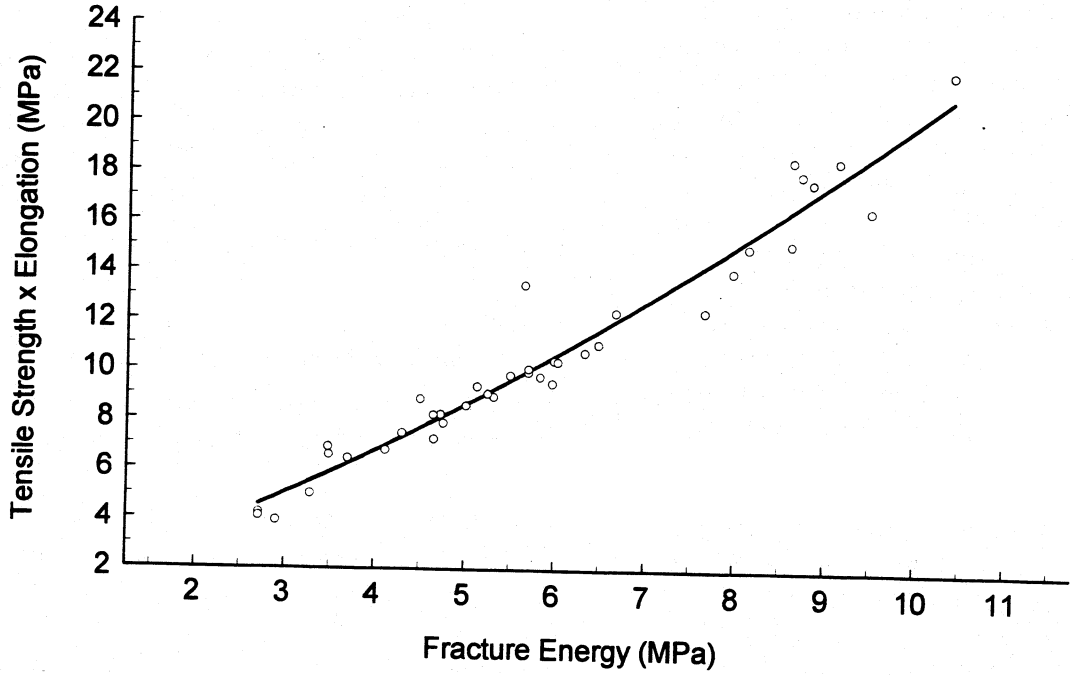

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

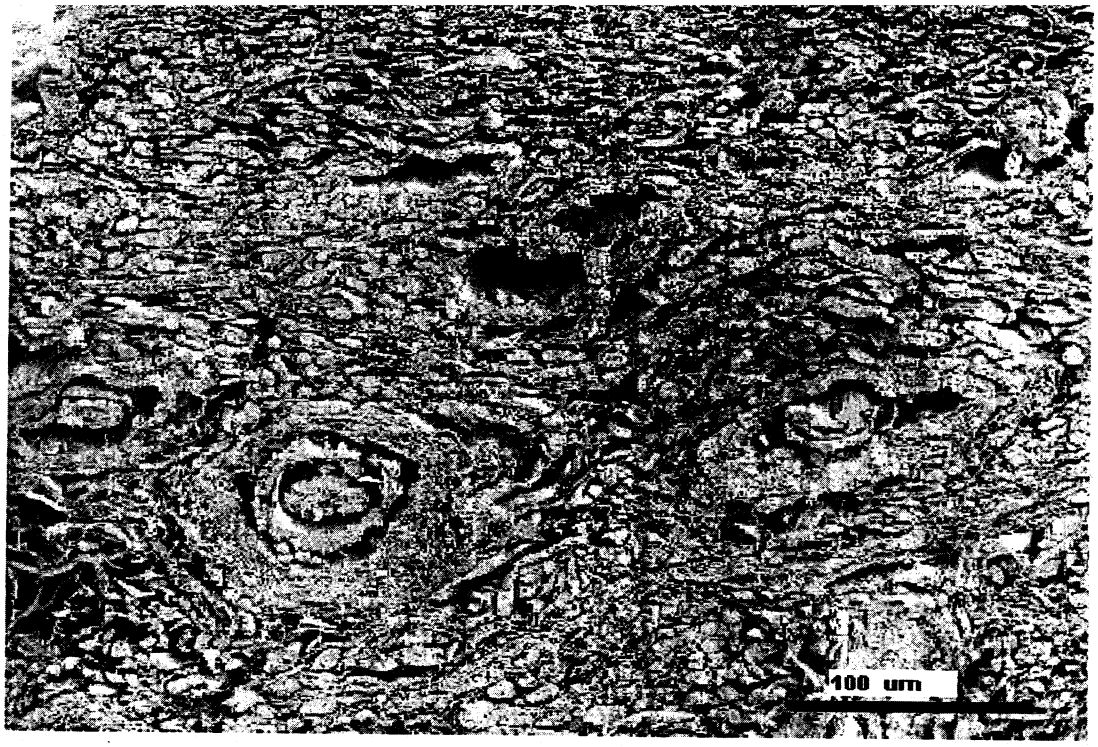

FIGURE 1. — Micrograph showing grain layer with sheet structure.

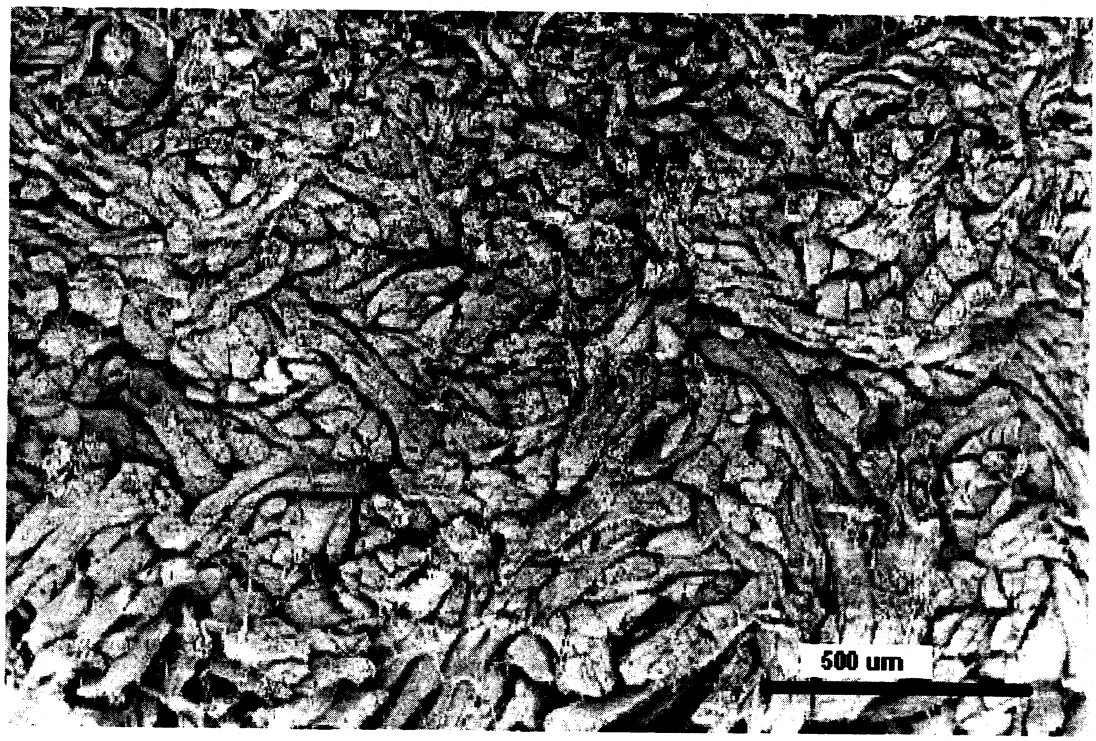

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

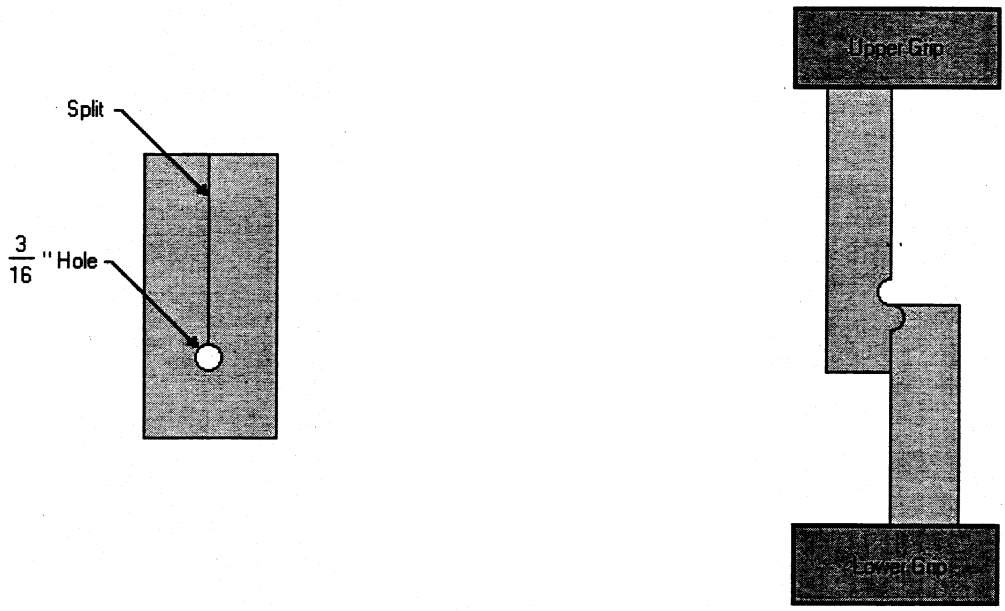

FIGURE 3. — Tear test scheme.

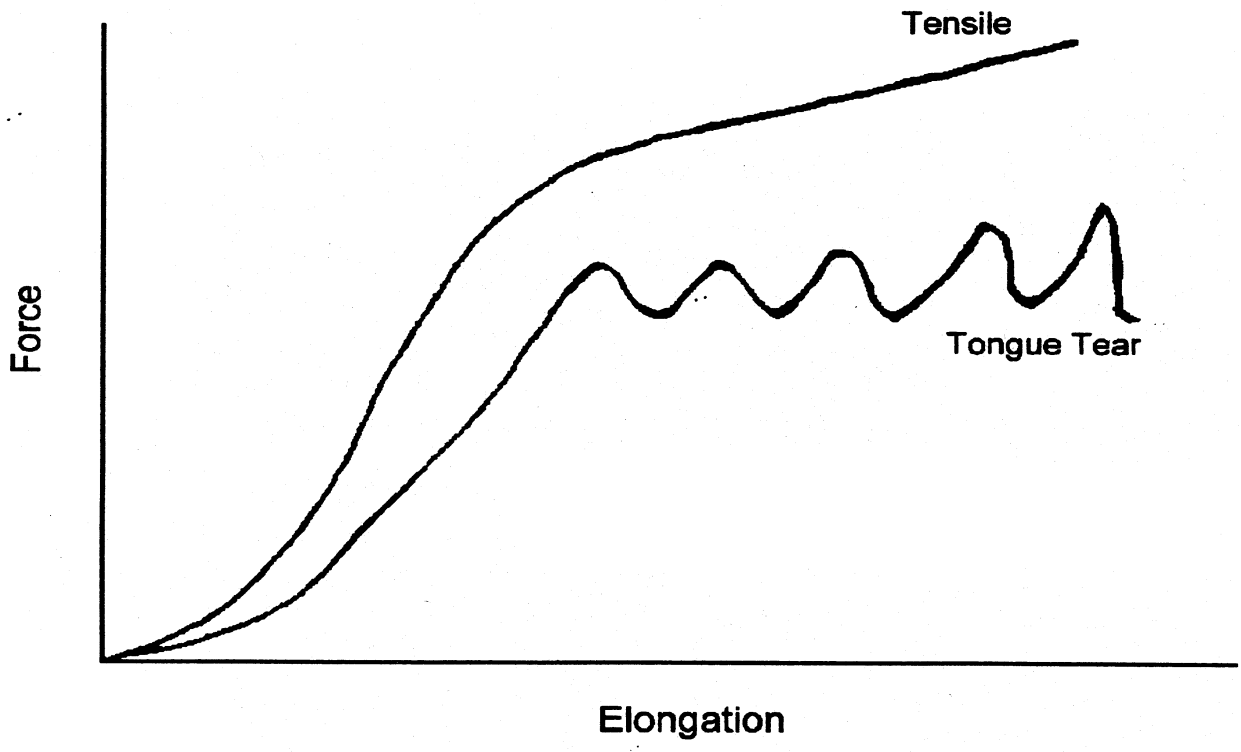

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

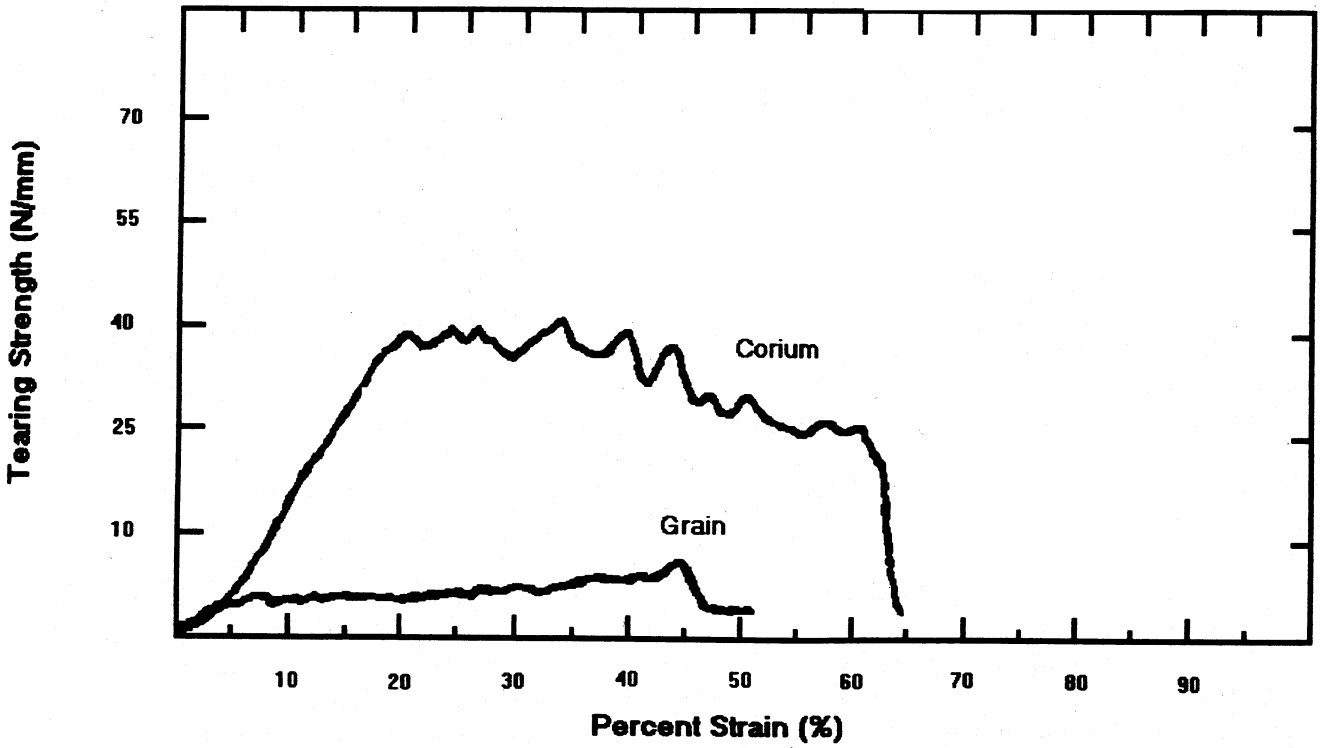

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

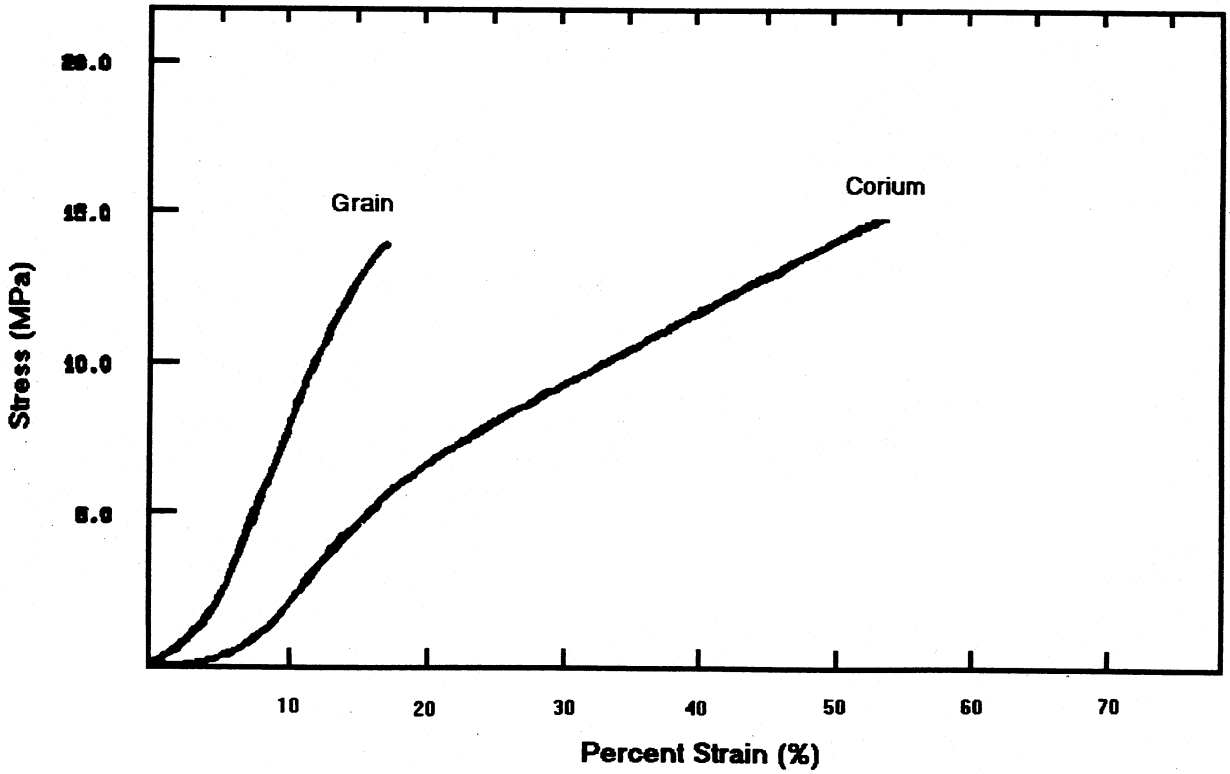

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

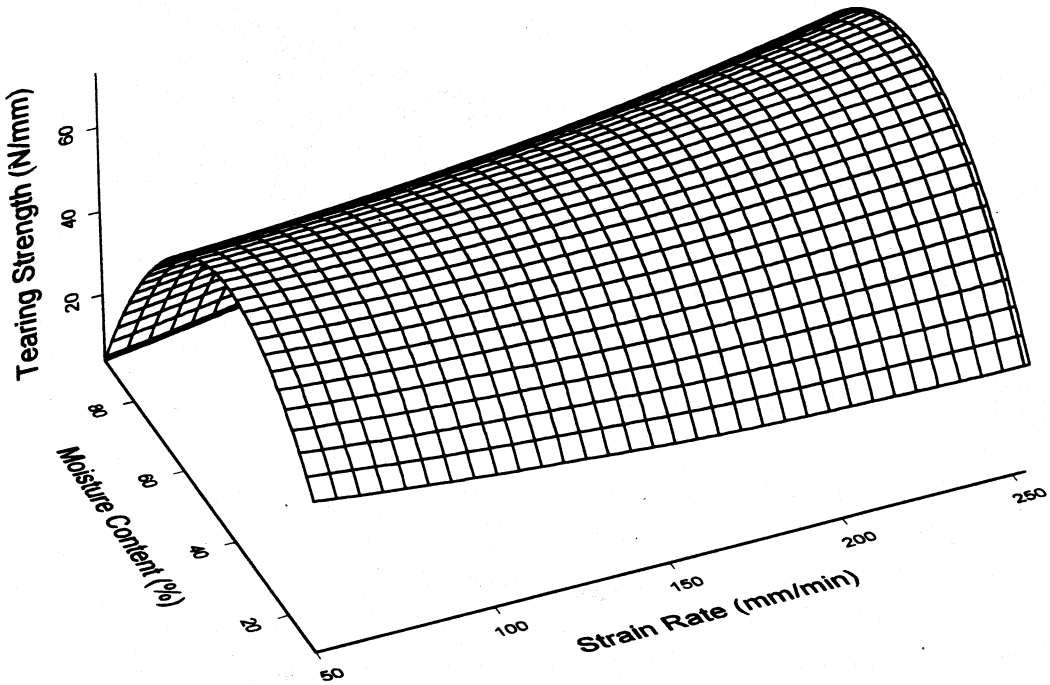

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

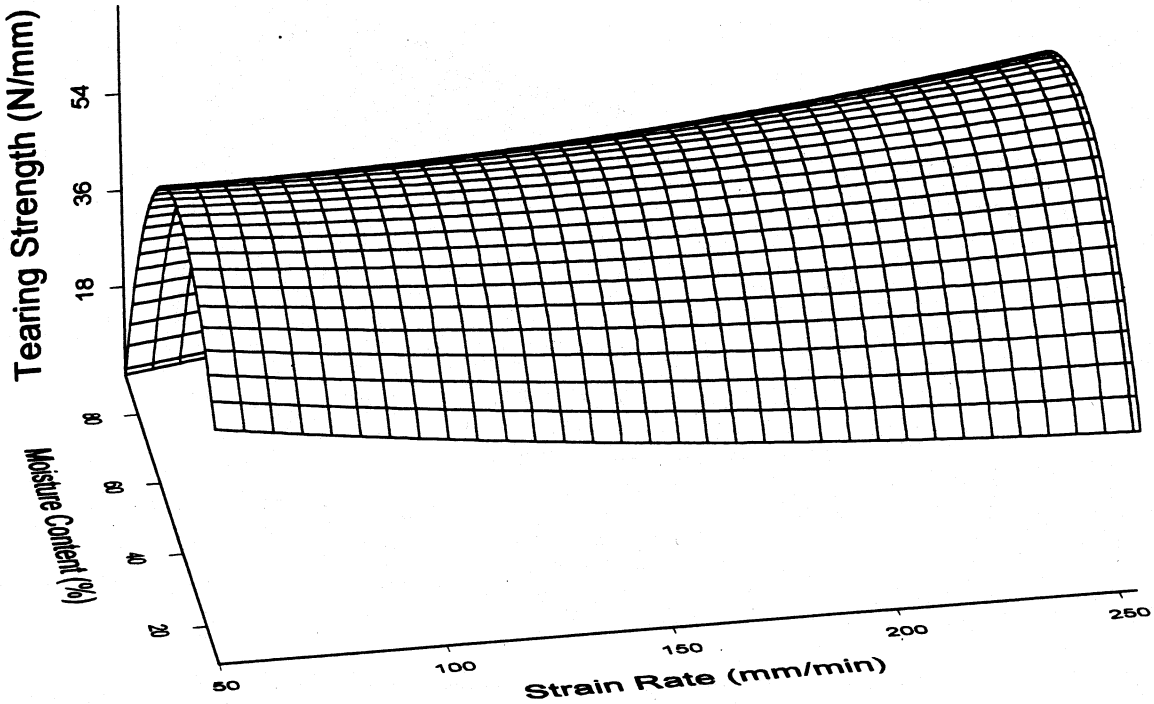

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

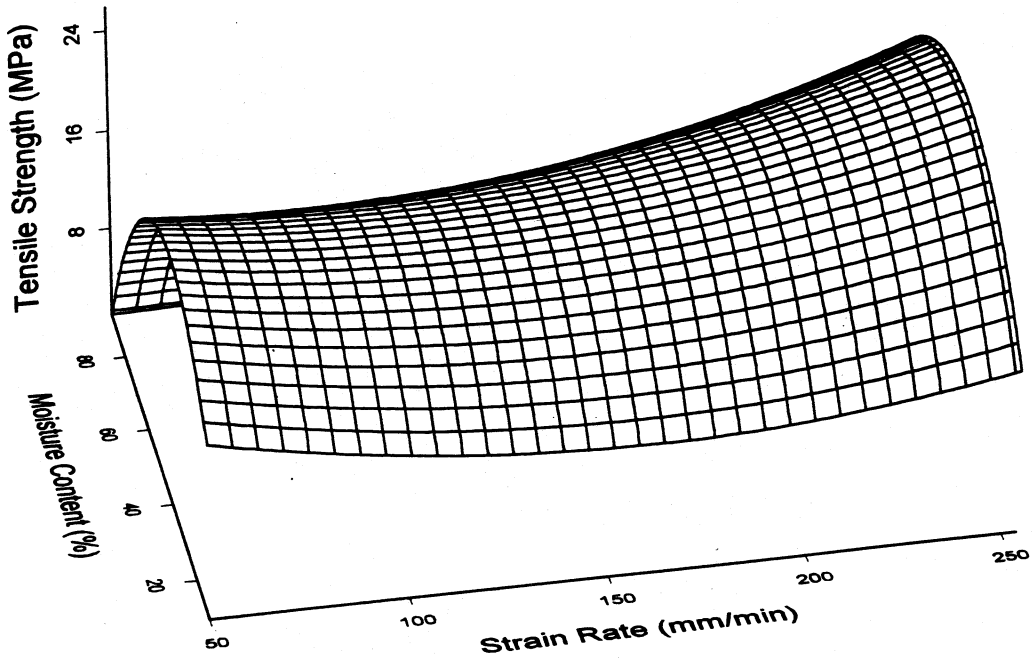

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

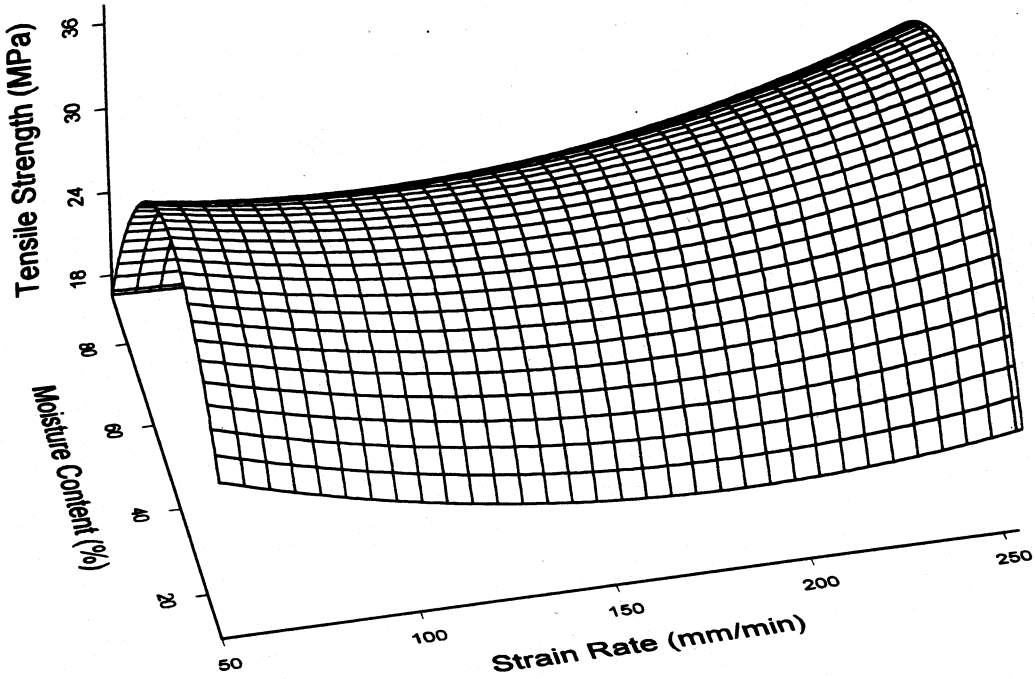

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

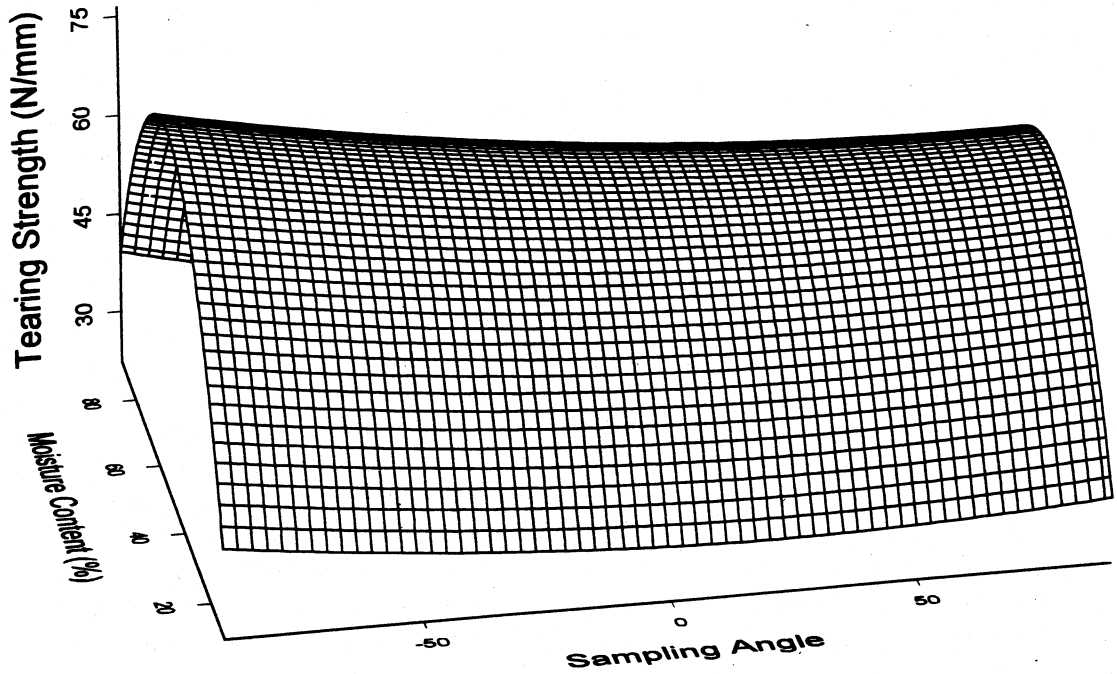

FIGURE 11. — Effect of sampling angle on tearing strength.

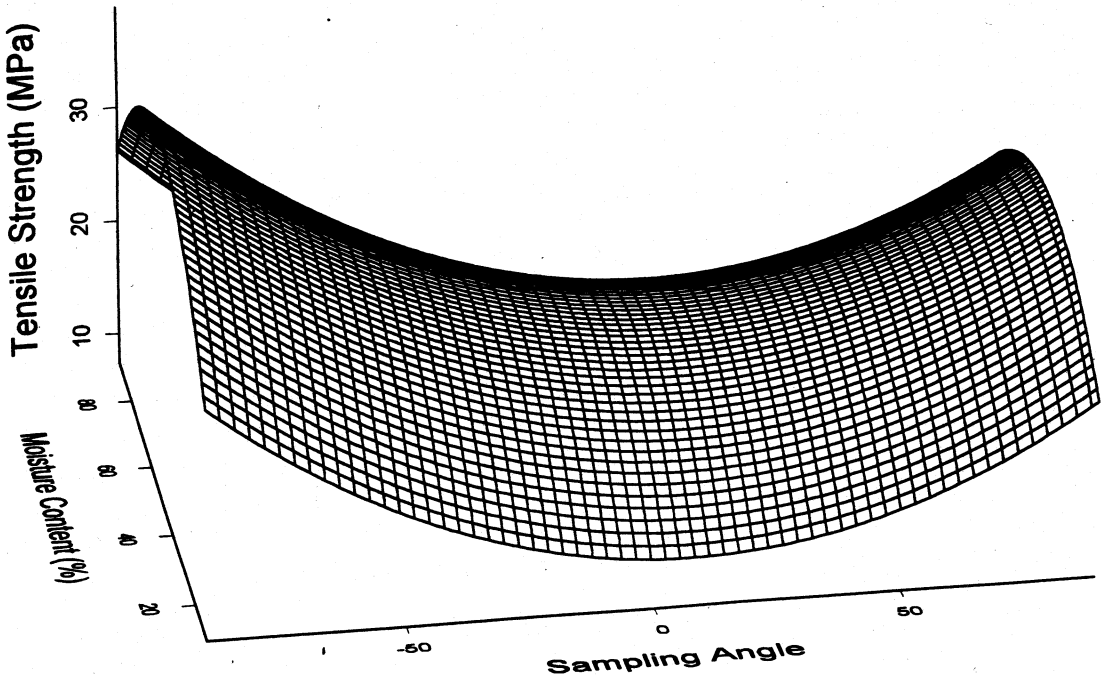

FIGURE 12. — Effect of sampling angle on tensile strength.

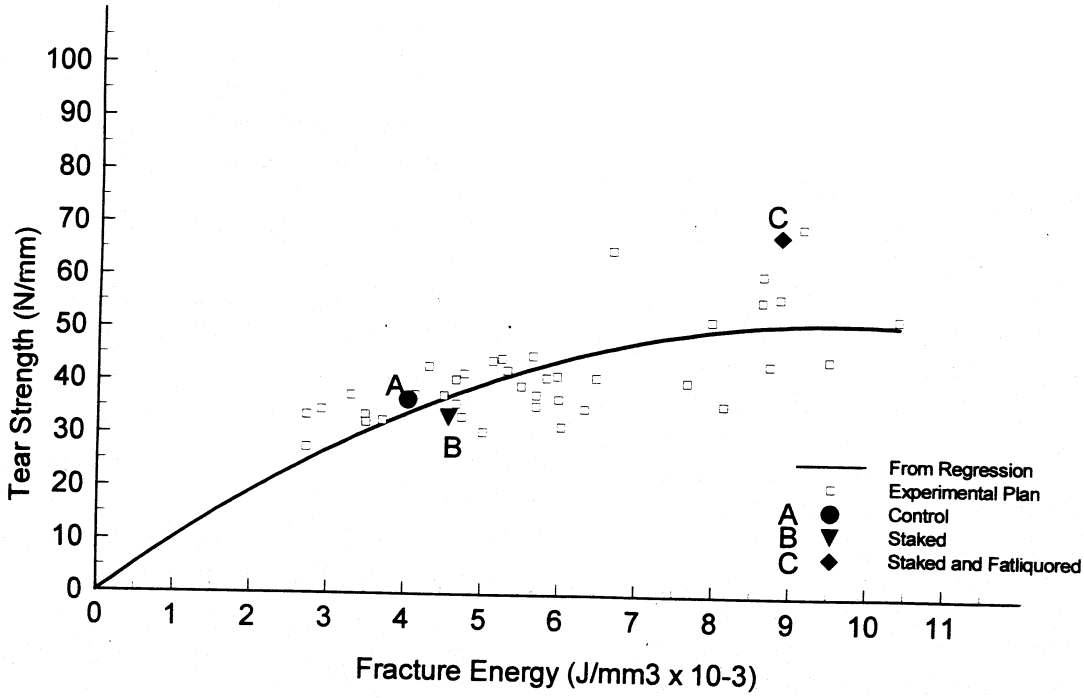

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

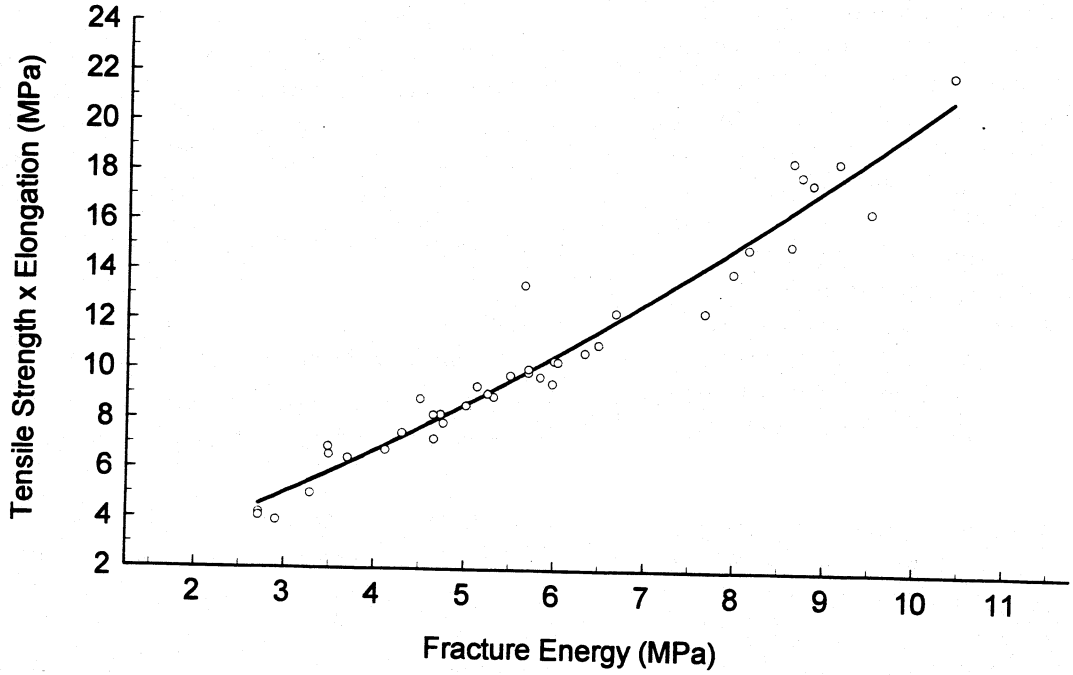

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

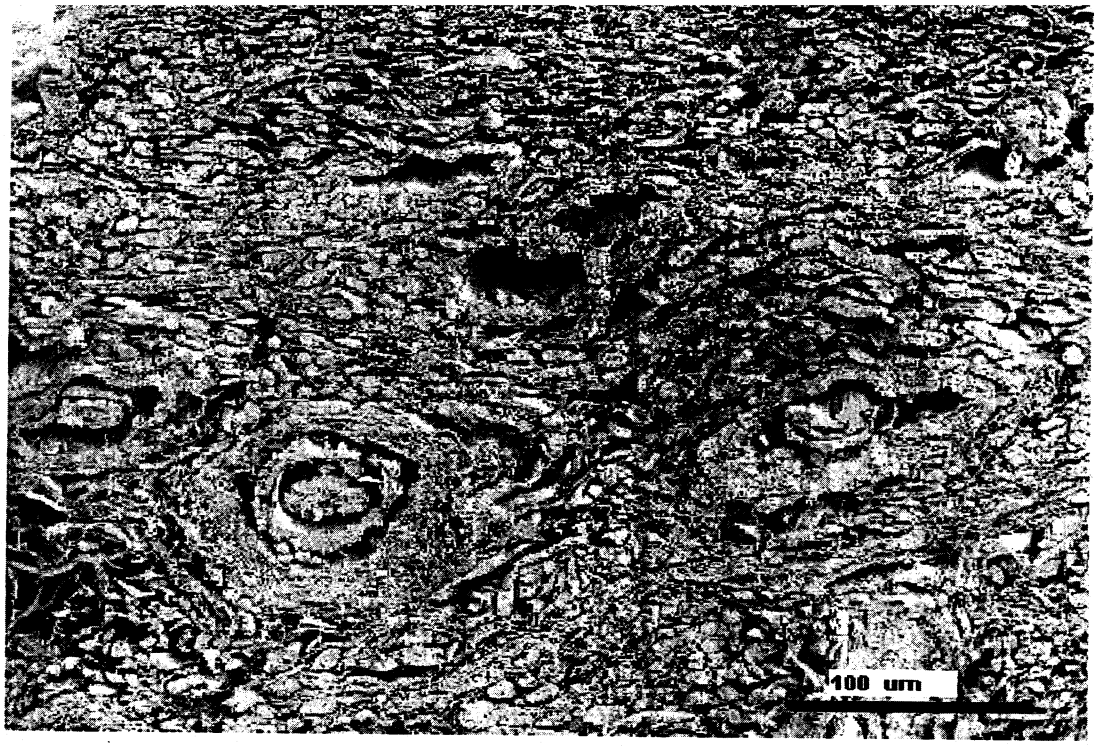

FIGURE 1. — Micrograph showing grain layer with sheet structure.

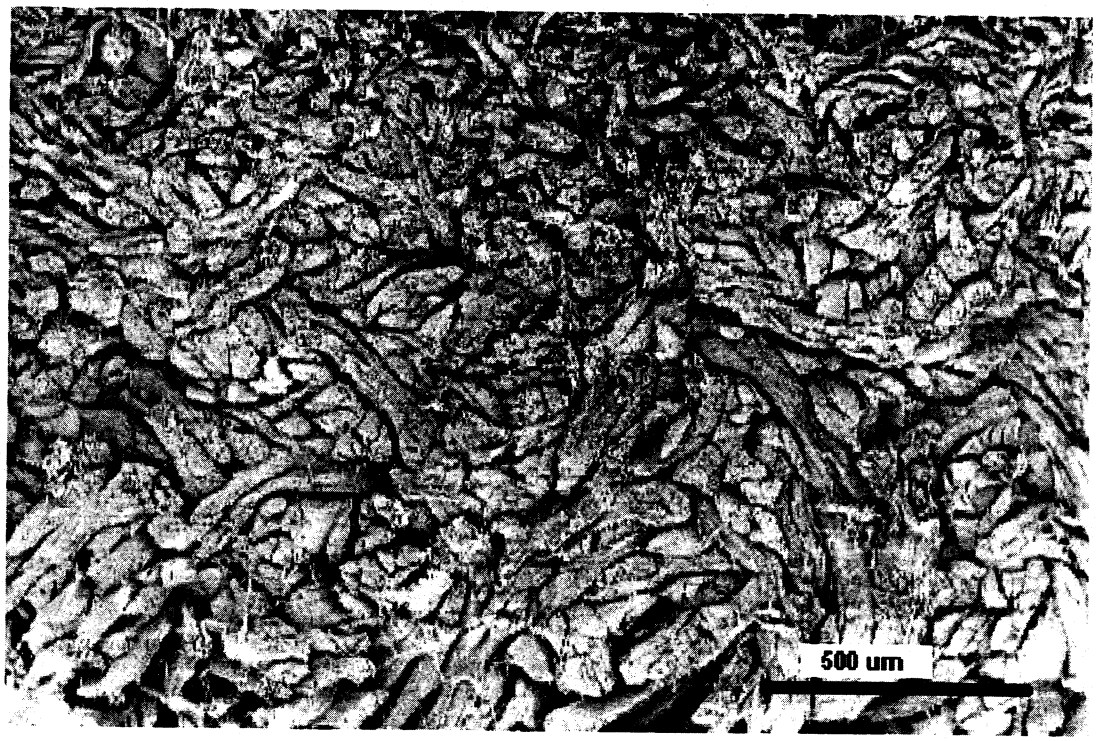

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

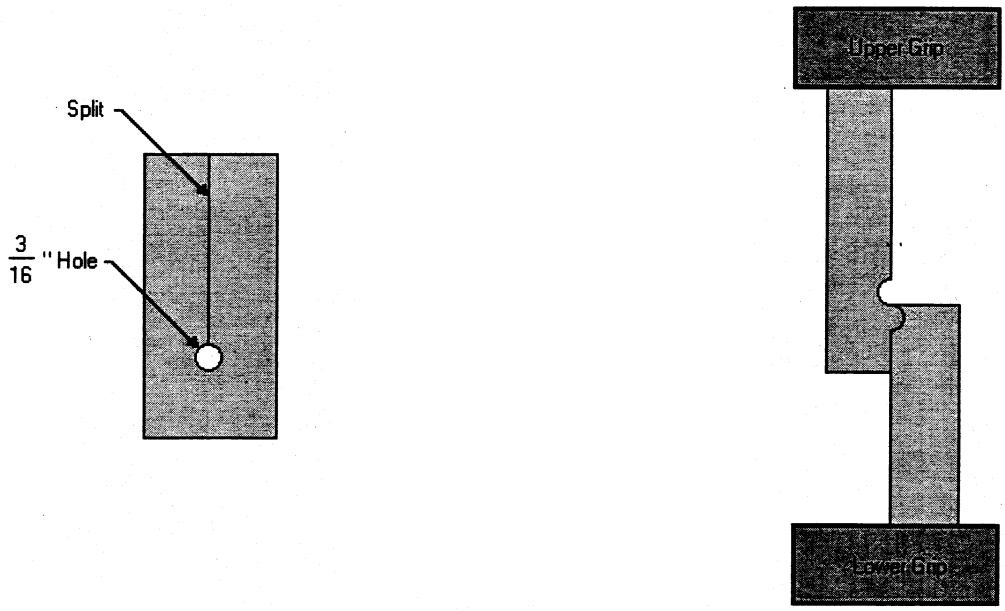

FIGURE 3. — Tear test scheme.

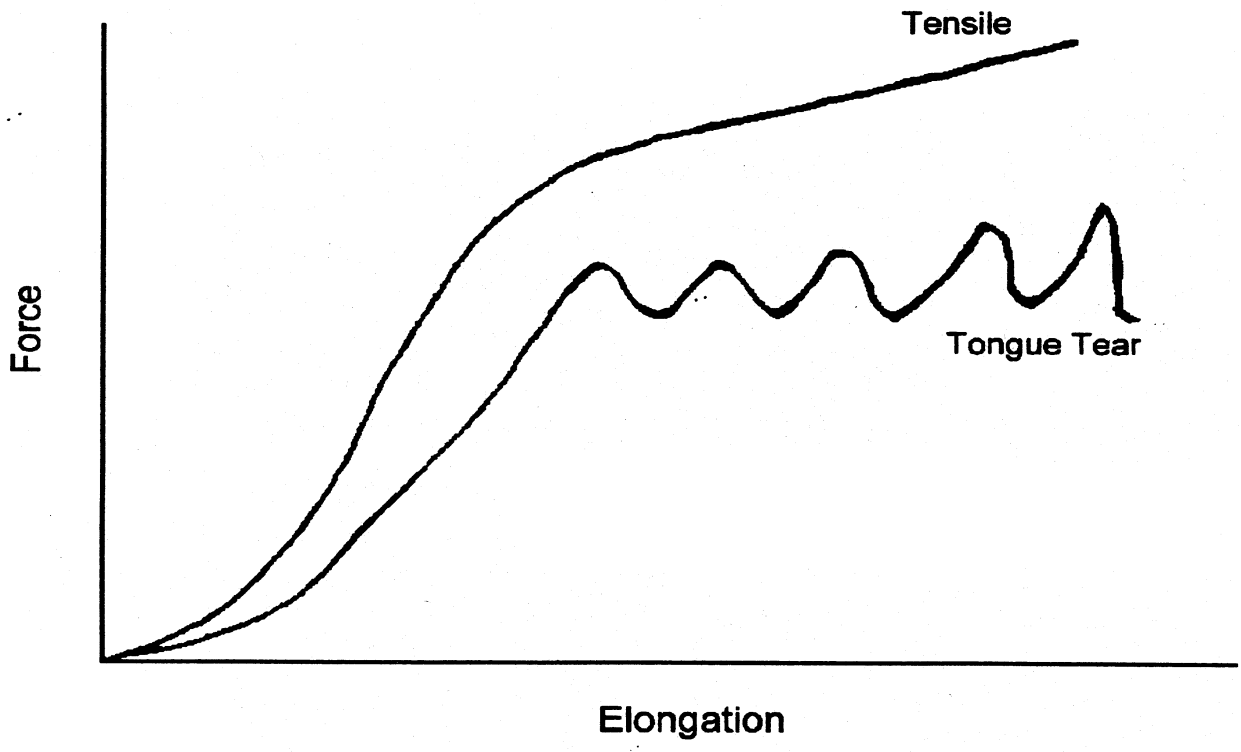

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

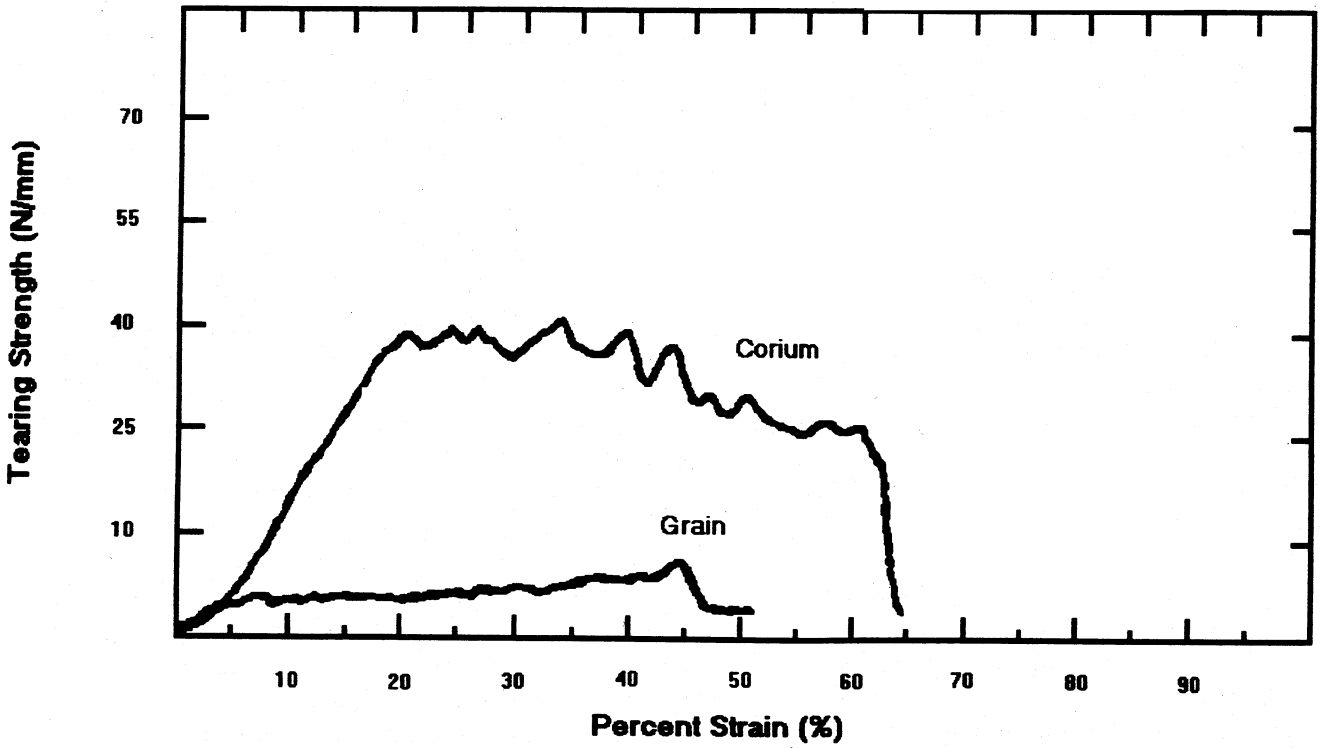

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

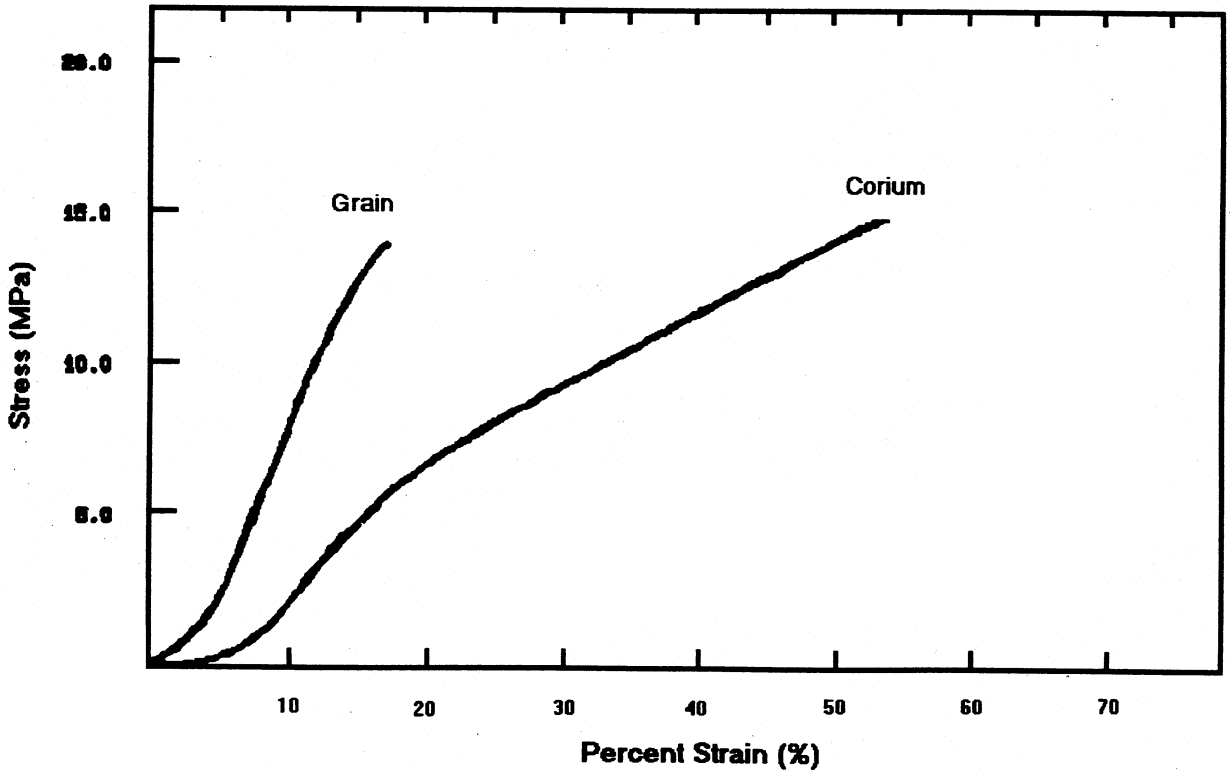

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

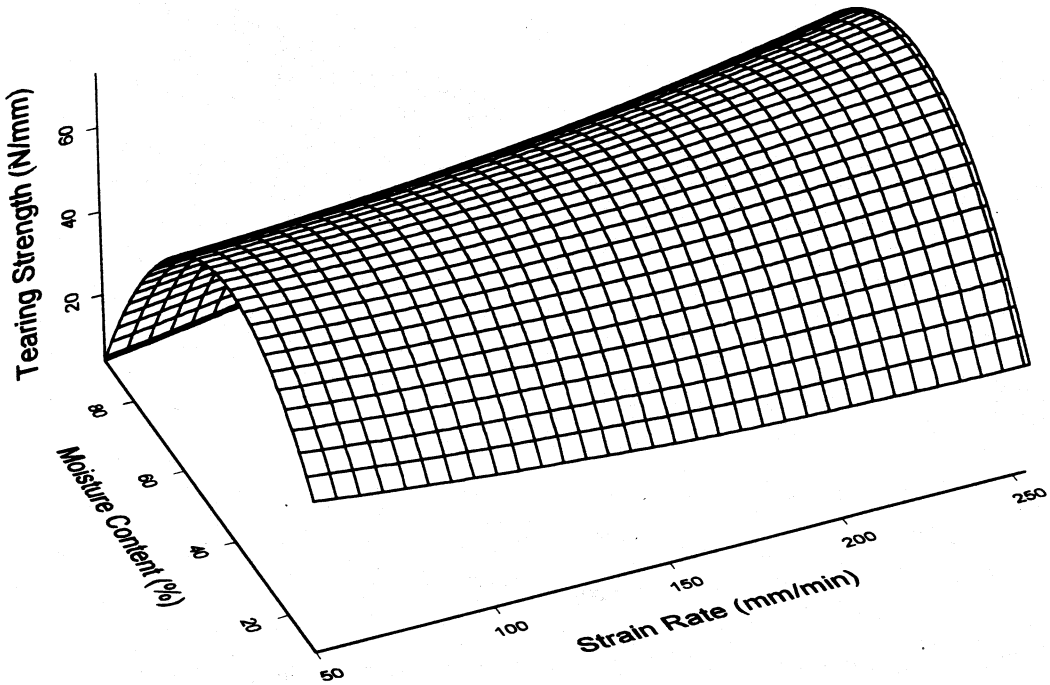

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

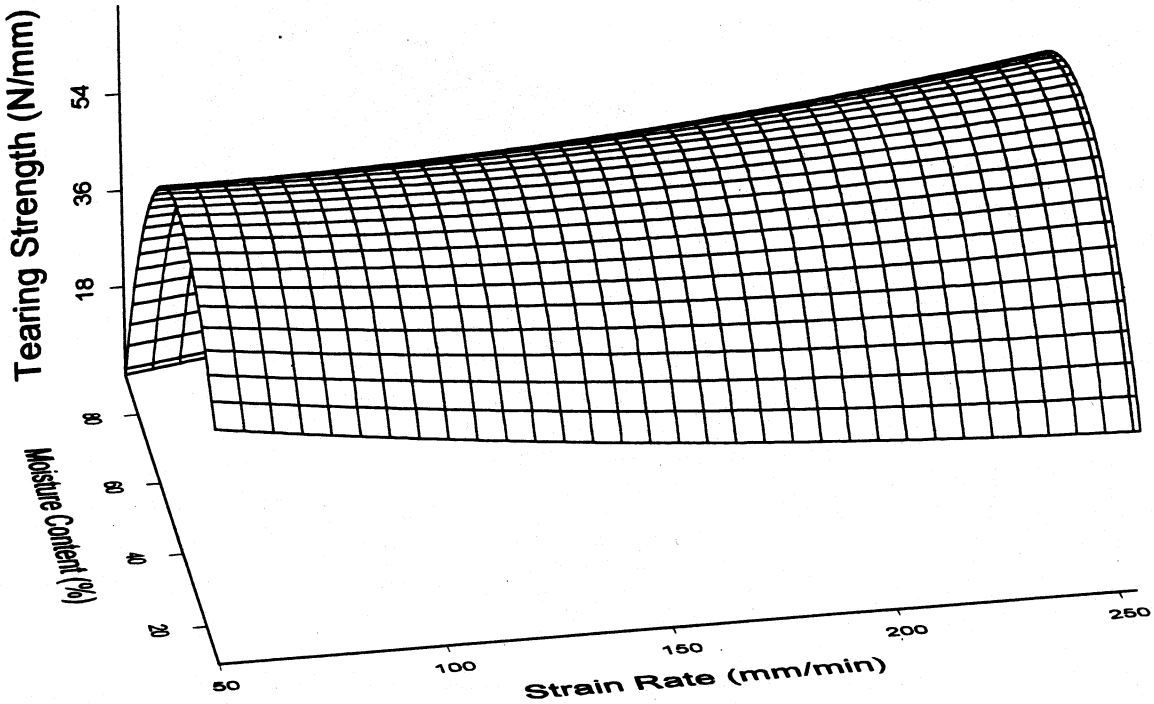

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

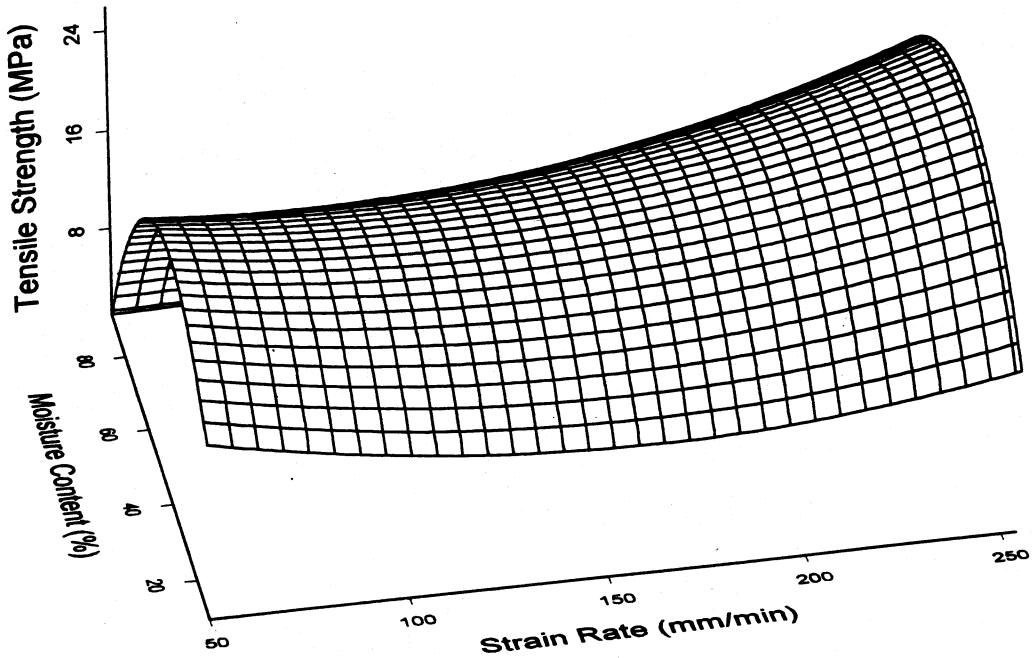

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

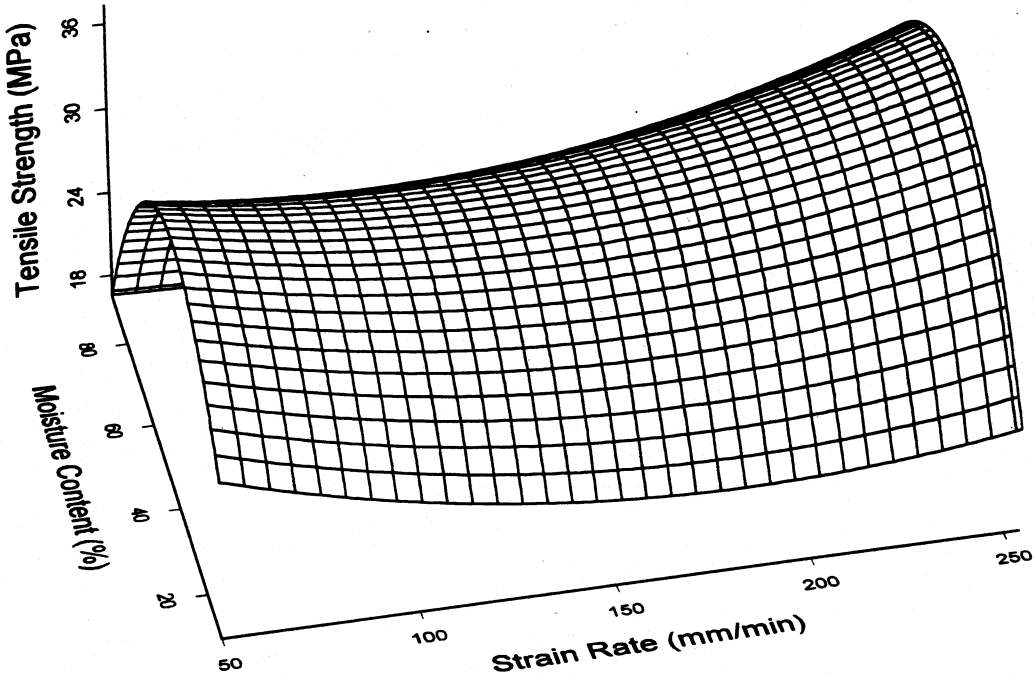

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

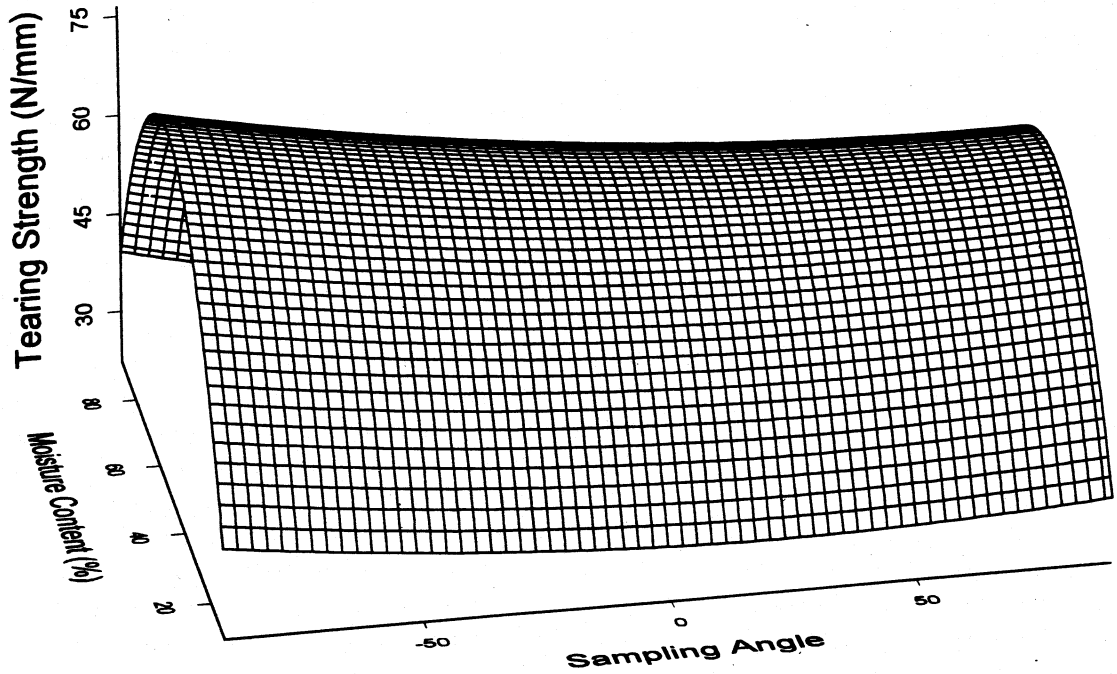

FIGURE 11. — Effect of sampling angle on tearing strength.

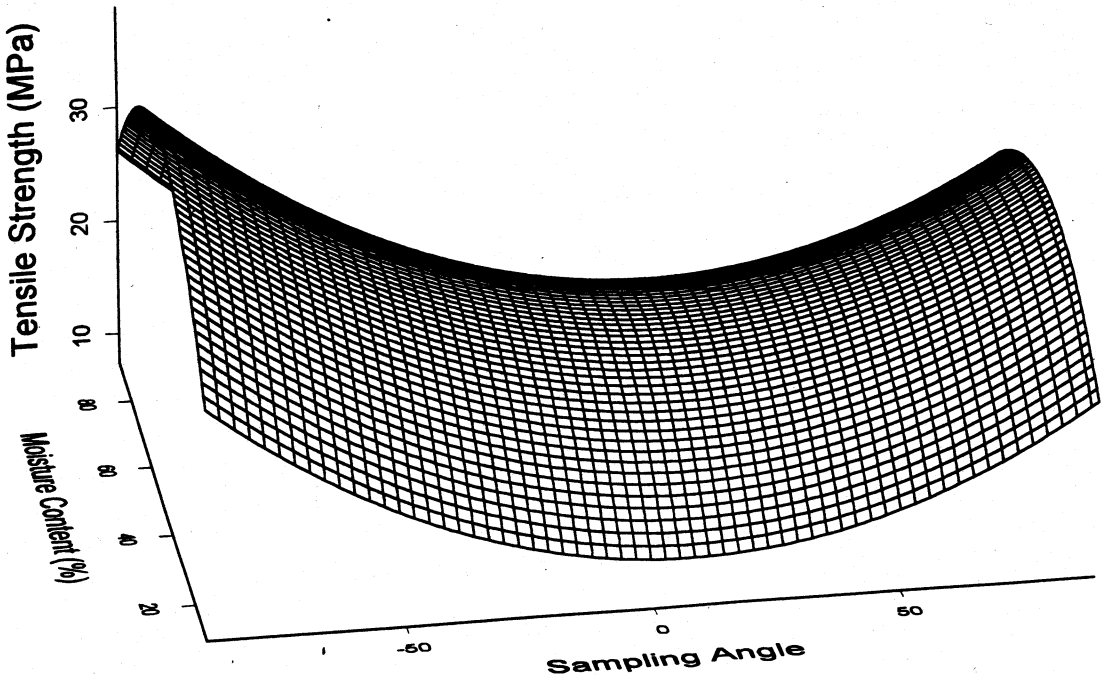

FIGURE 12. — Effect of sampling angle on tensile strength.

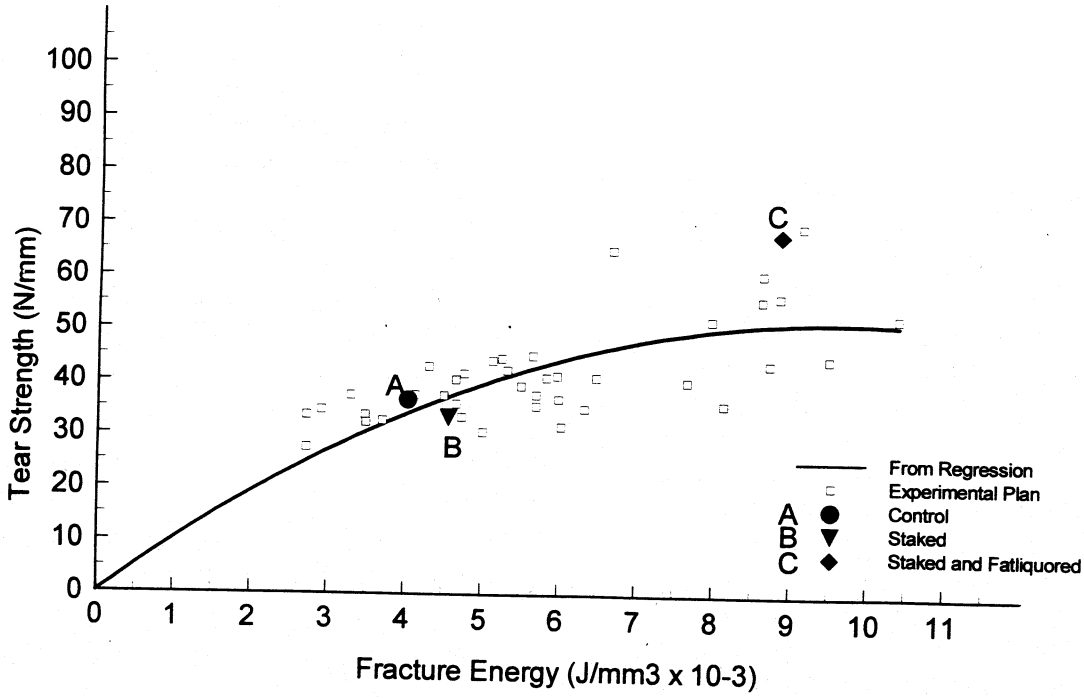

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

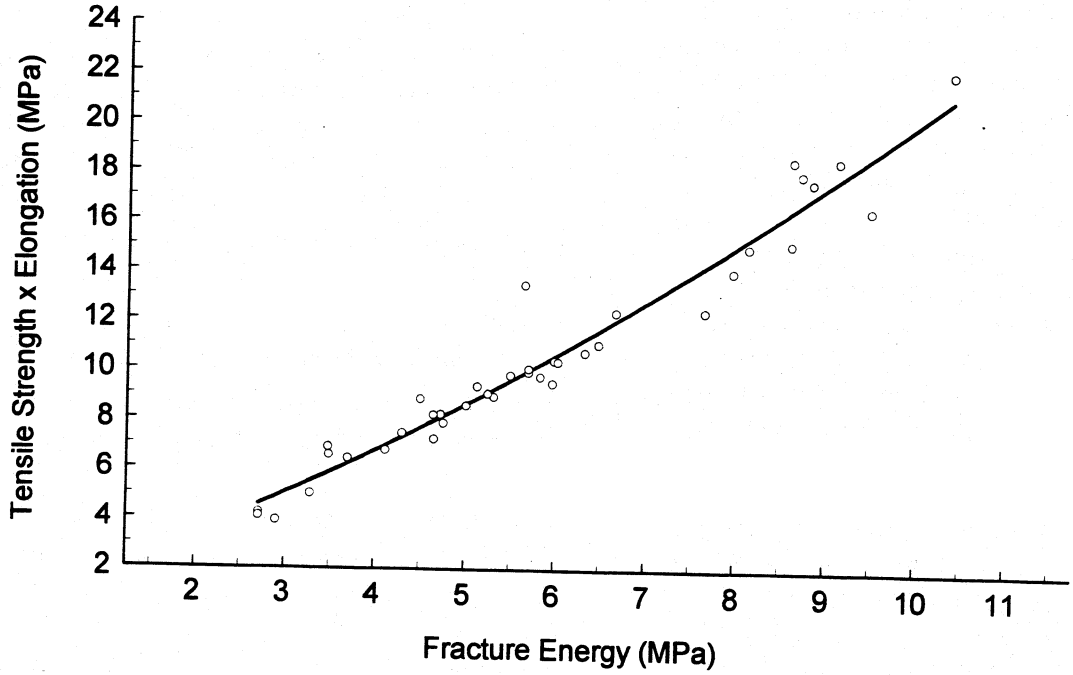

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

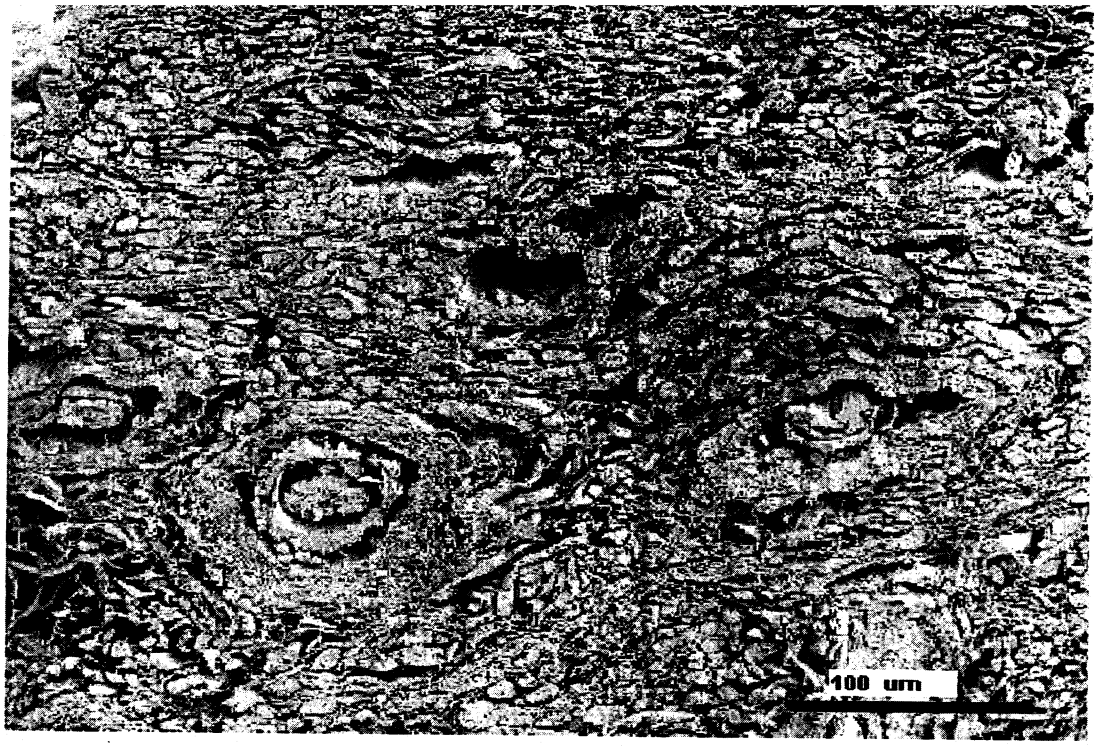

FIGURE 1. — Micrograph showing grain layer with sheet structure.

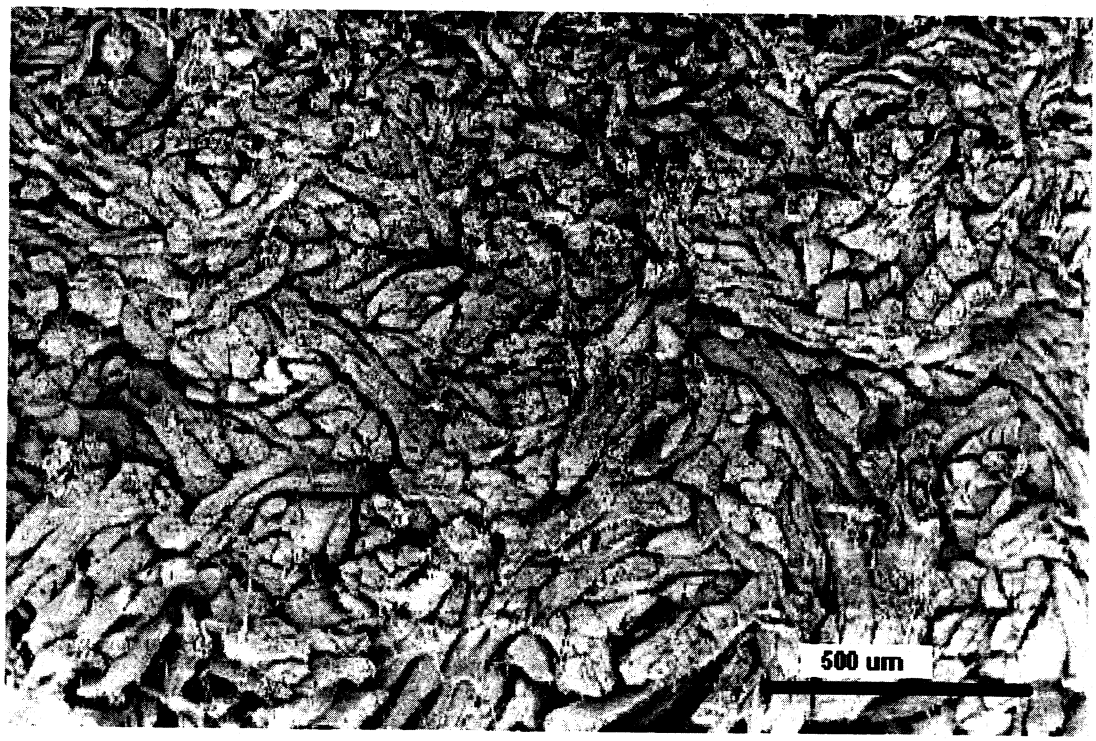

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

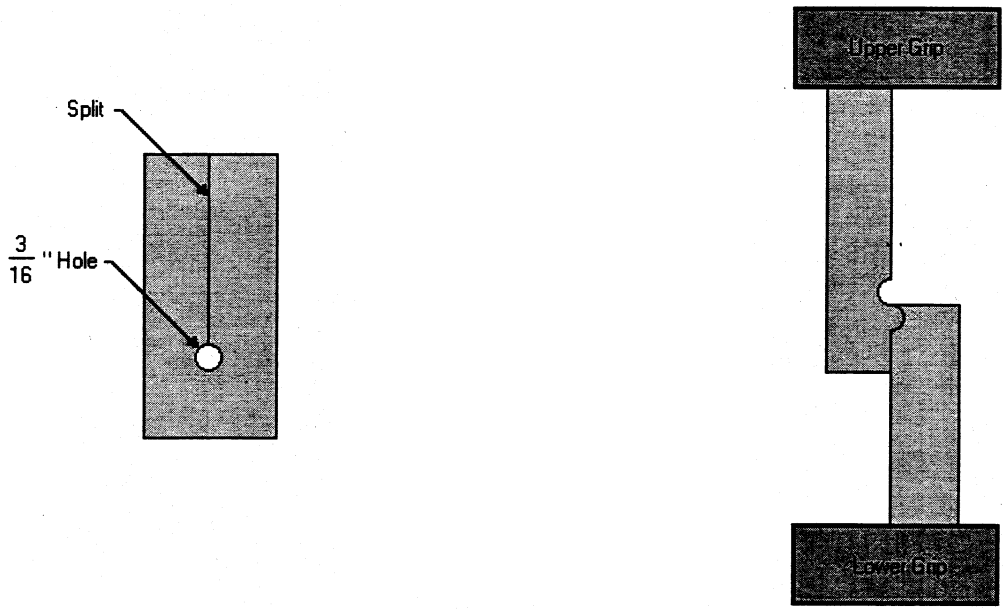

FIGURE 3. — Tear test scheme.

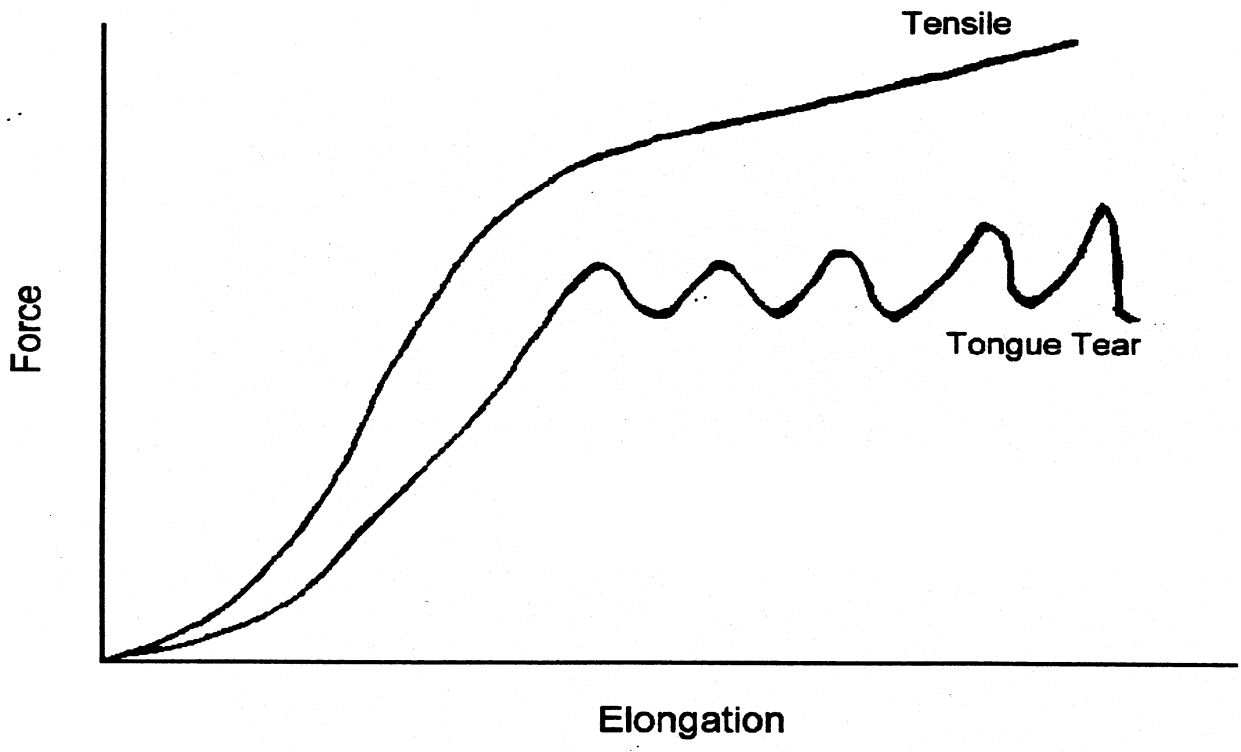

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

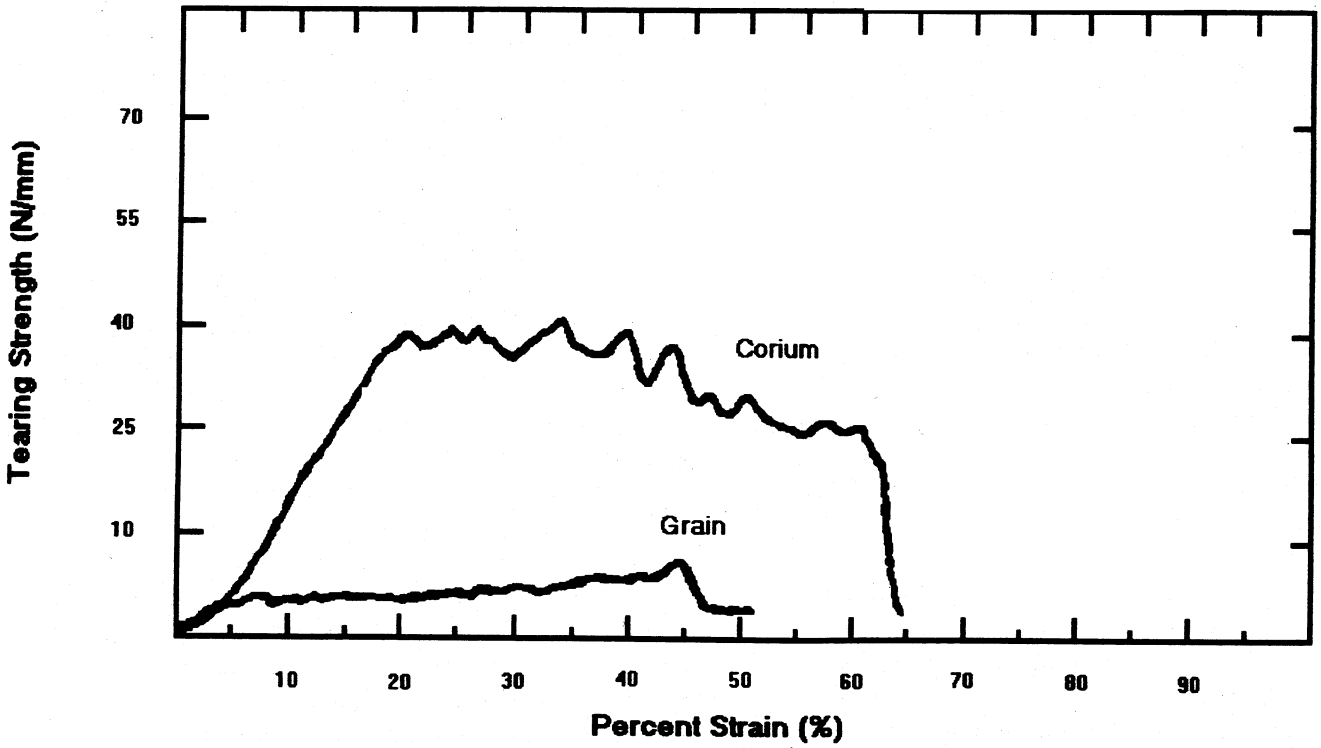

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

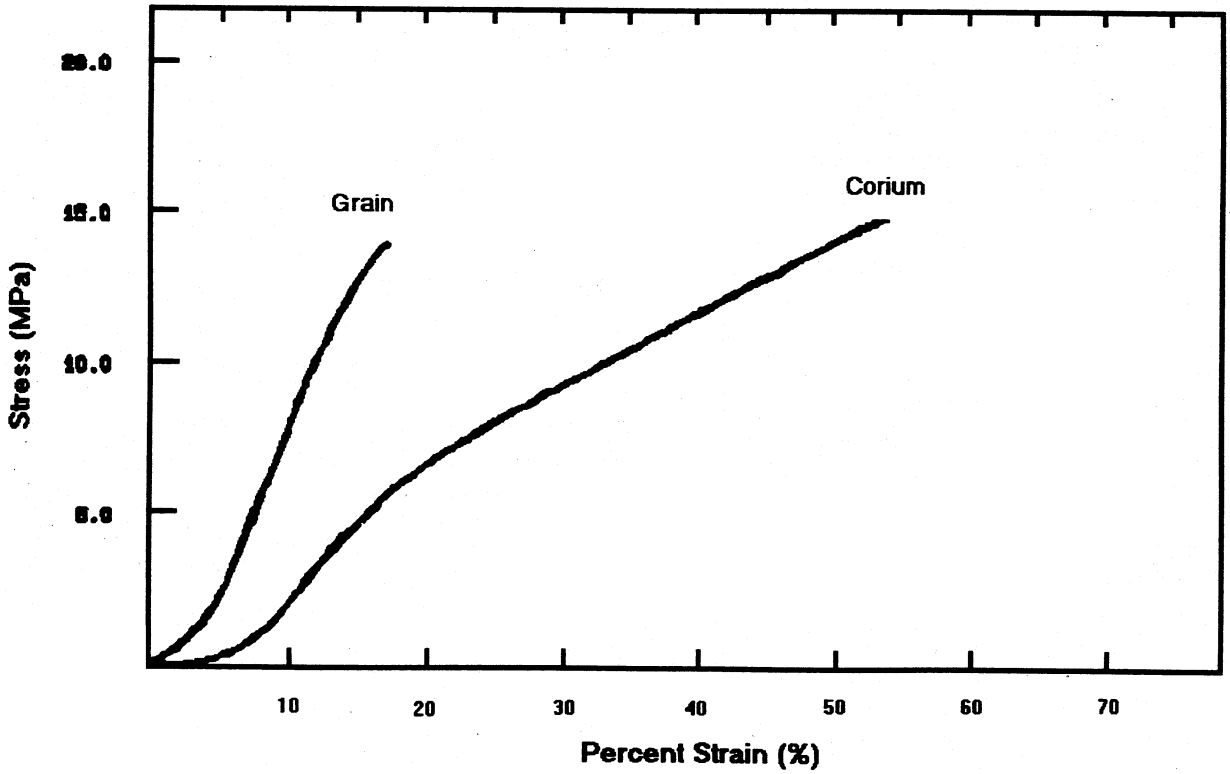

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

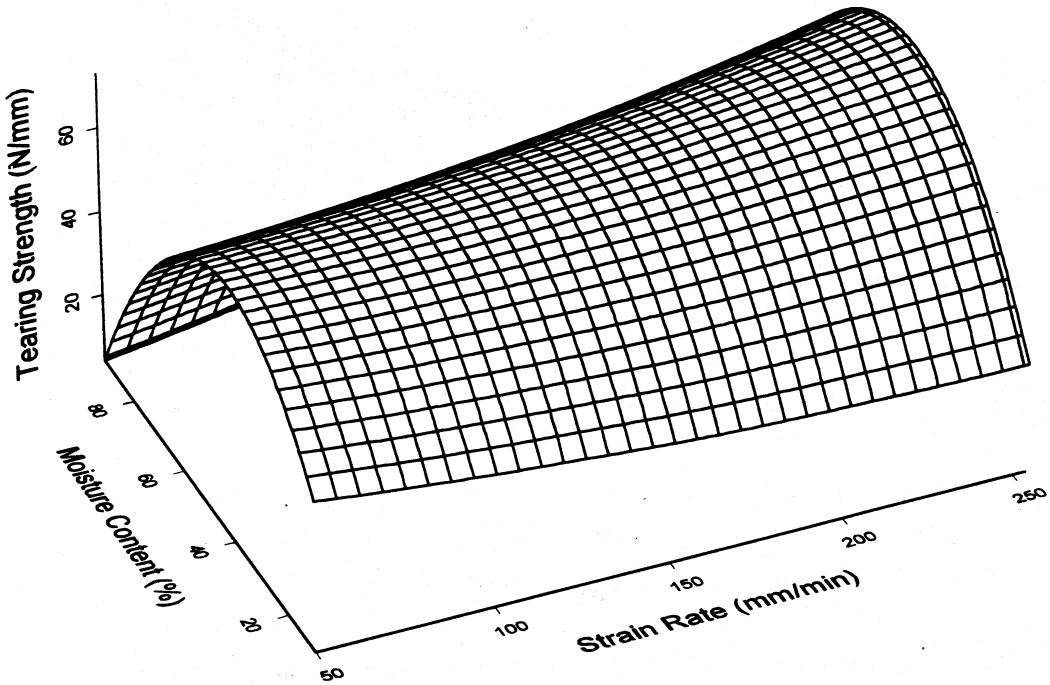

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

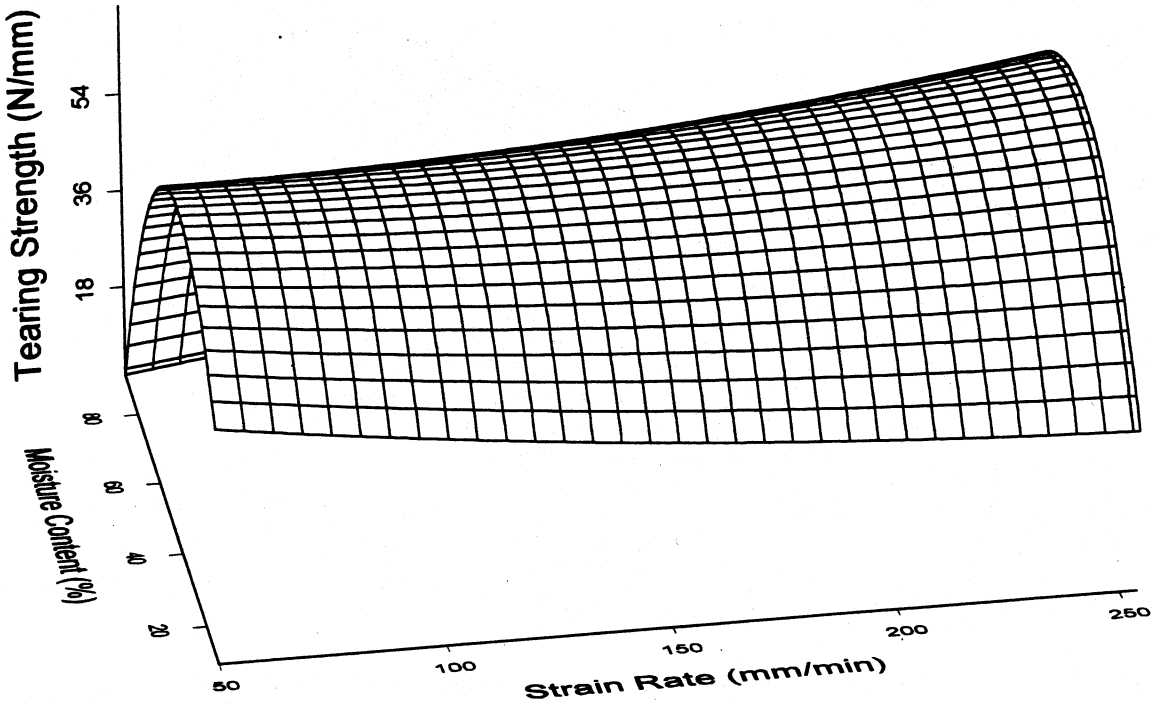

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

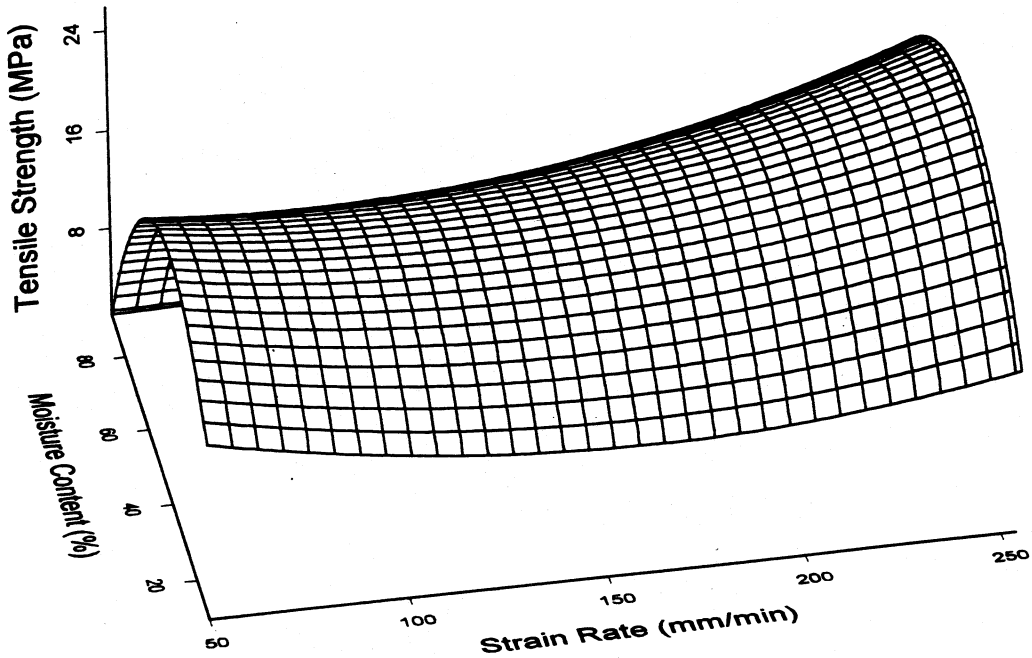

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

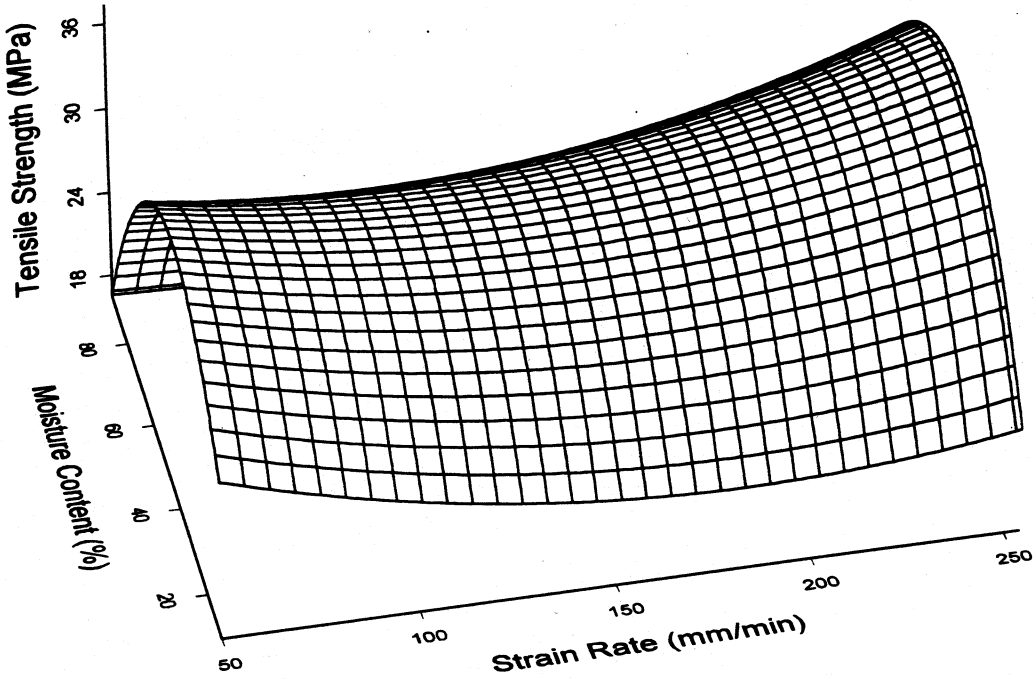

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

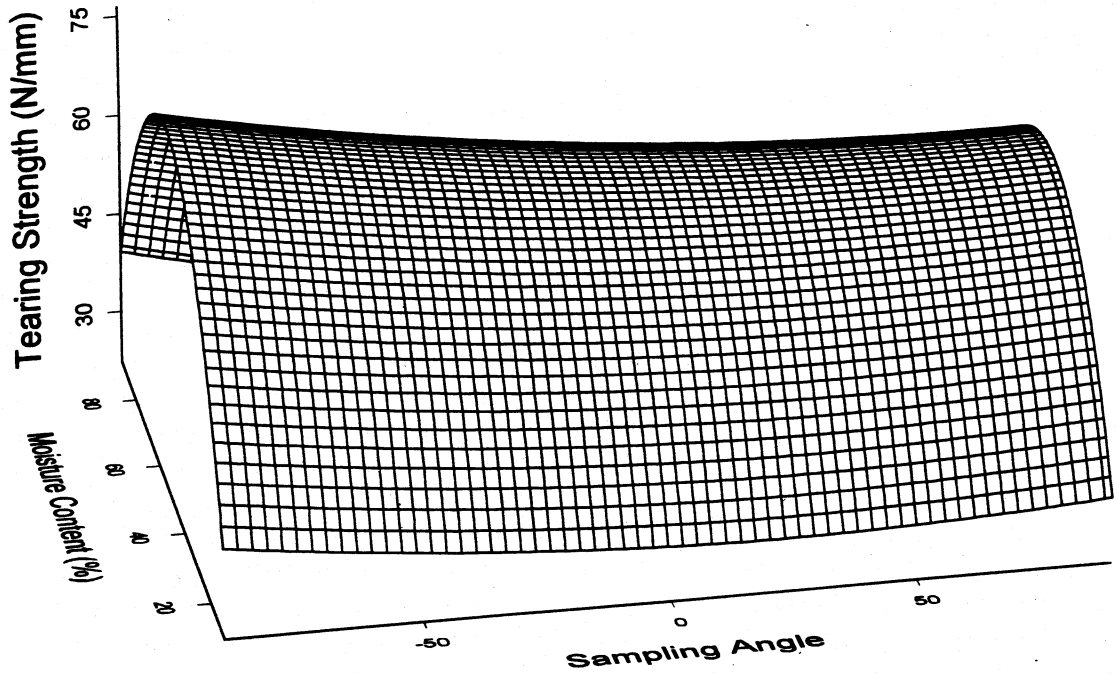

FIGURE 11. — Effect of sampling angle on tearing strength.

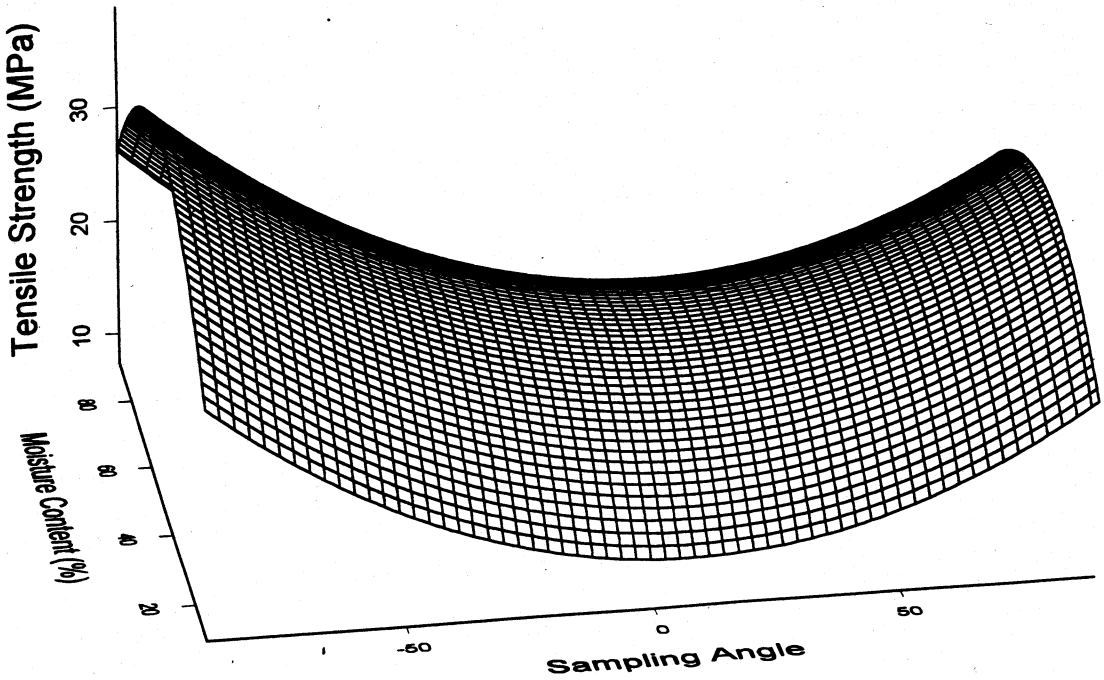

FIGURE 12. — Effect of sampling angle on tensile strength.

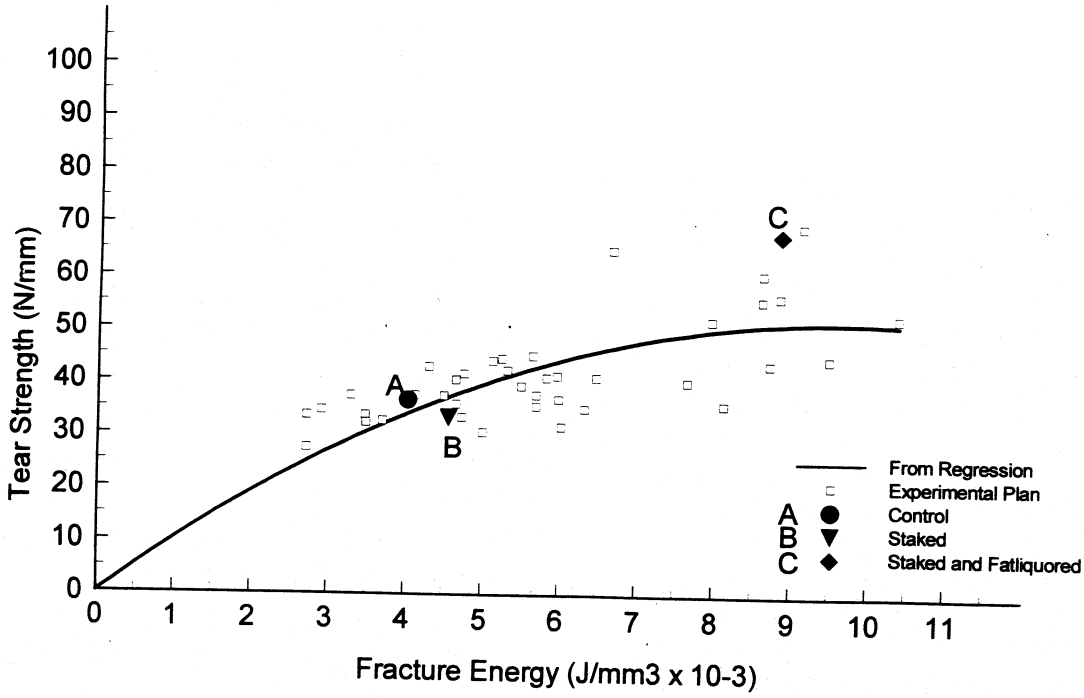

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

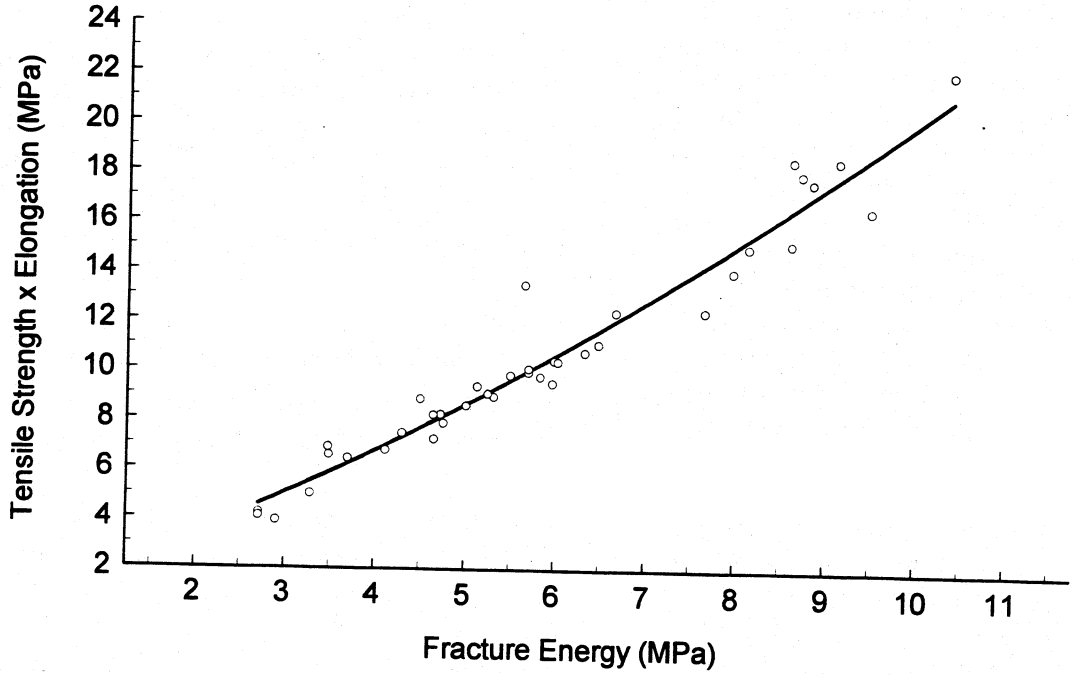

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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Tearing Behavior of Chrome-Tanned Leather

by

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Abstract

Tearing tests were performed along with tensile tests on chrome-tanned leather to clarify the difference between the tearing and tensile behaviors and their fracture mechanisms. For the tearing tests, a unique zigzag fracture pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Observations also showed that strain rate does not significantly affect tearing strength, but slightly affects tensile strength. Both strengths increase with increasing moisture content until certain levels, beyond which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in their response to sampling angle change. Tearing strength showed little variation with the change of sampling angle, whereas the tensile strength was maximum when sampled parallel to the backbone, then steadily decreased when sampling angle deviated from the backbone line. Statistical analysis showed that the tensile strength did not correlate well to tearing strength, whereas a good correlation was observed between fracture energy and tearing strength.

Introduction

The ability to withstand tearing forces is one of the most significant mechanical properties required for leather products, particularly those used for upholstery. Various test methods have been used to determine the tear resistance of leather including buckle tear,[1] slit tear,[2] stitch tear,[3] and tongue tear tests.[4] All these are designed to measure the force required to tear leather, giving an indication of the resistance of leather to tearing. Strictly speaking only the tongue tear test truthfully indicates the tearing strength of leather itself. This test method has also been used for other products such as plastic film, sheet textile fabrics and paper, whereas other test methods are measuring the cutting resistance of leather to either metal, wires or buckles.

In the tannery, one of the frequent questions being asked is why leather strong in tensile strength is not necessarily strong in tear strength. Although some limited investigations[5,6] indicated that a slight correlation existed between tensile strength and tear strength, the relationship between tensile strength and tearing behavior has never been fully exploited. Because of the lack of such knowledge, it is often very difficult for tanners to tailor their processes to produce leather having both good tensile strength and good tear strength.

To gain such important knowledge, we have conducted a systematic study to investigate the relationship between tensile strength and tear strength. Such a study is in line with our ongoing research projects on improving the processing and properties of leather. We hope this investigation will help optimize the leathermaking processes and consequently yield a higher quality of leather, strong in both tensile strength and tear strength.

Experimental

Materials

The standard ERRC process[8] was used to chrome tan a bovine hide, though the resultant leather was air-dried without fatliquoring but conditioned at 23°C and 50% RH for several months. According to ASTM D4704-93,

rectangular samples having a 25.4 x 101.6 mm dimension were cut from the standard test area as described in ASTM D2813-91. These samples, without fatliquoring and staking, were used in statistical modeling as described in the next section. Each sample comprises about 0.6 mm of grain layer as shown in Figure 1, and 1.4 mm of the corium layer, with numerous fiber bundles interwoven together as shown in Figure 2. To study the effects of fatliquoring and staking, the mature bovine hides were chrome-tanned by the same method previously described. The fatliquored samples were prepared with 2% sulfated Reilly-Whiteman (Conshohocken, PA) fatliquor X-76-31. The staked samples were obtained by passing through a Molissa staking machine.[9] Control samples were also prepared without fatliquoring and staking, and were used for comparison. The moisture content reported in this paper is based on sample dry weight as determined by the following equation:

$$\text{Moisture content (\%)} = 100 \times (W-W_o)/W_o \qquad (1)$$

where W is the sample weight, W_o is the dry weight of sample, after vacuum drying at 60°C to constant.

Statistical Modeling

SAS statistical software was used to formulate the relationship between dependent variables such as tearing strength and tensile strength and independent variables including strain rate (x_1), moisture content (x_2), and sampling angle (x_3). Table I is the matrix showing the combinations of coded levels of three factors for each of the thirty-nine experimental conditions. A regression model has the form of a polynomial equation in which the variables are presented as their linear and quadratic terms as well as their bifactorial cross products:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \qquad (2)$$

where y is response such as tearing strength or tensile strength and b's are the corresponding regression coefficients of the polynomial equation.[10] These coefficients along with analysis of variance can be obtained readily by using SAS software version 6.12 with a microcomputer. The levels of the coded variables x_1, x_2, and x_3 were obtained by means of the following formulae, where x_1' (mm/min), x_2' (%), and x_3' (degree, °), are the variables with original scales:

$$x_1 = (x_1'-200)/100$$
$$x_2 = (x_2'-13)/2 \qquad (3)$$
$$x_3 = (x_3'-0)/45$$

The sampling angle designated as 0° is the direction perpendicular to back bone line, whereas the direction parallel to the back bone line was designated as 90°.

Tearing and Tensile Tests

The tongue tearing strength was measured according to ASTM standard test method D4704-93 entitled "Standard Test Method for Tearing Strength, Tongue Tear of Leather" as illustrated in Figure 3. This method determines the force required to tear the leather between two tongues formed by splitting the leather perpendicular to its surface. To normalize results from various samples, we divided the value by the thickness of samples to present the tearing strength with the SI unit of N/mm.

To minimize the experimental errors because of sample changes, the tensile strength was measured for the legs separated by the tongue tear tests. They were measured right after the tearing test. Therefore, these two tests were performed with exactly the same independent variables. The tensile strength of leather was measured at 23°C and 50% RH with a gauge length of 40 mm. An Instron tensile testing machine, model 1122, was used throughout this work. All the data were calculated and collected through the use of Instron series IX automated materials testing system version V.

Measurement of the Fracture Energy

The fracture energy is defined as the energy needed to break the leather. If we consider a leather sample subjected to an extensional force *F*, increasing in length by a small elongation, *dl*, the total energy needed to break the leather (fracture energy) will be:

$$= \int_0^{\text{breaking}} F \cdot dl \qquad (4)$$

This value is the area under the force-elongation curve (Figure 4). The force-elongation curve can be readily converted to the so called A"stress-strain curve" by simply dividing force by the cross-sectional area of the test sample for the former, and dividing elongation by the original length of the test samples for the latter. If the thickness and original length of the samples are relatively constant as in this study, then these curves essentially have the same pattern. Therefore, the term "stress-strain curve" may be exchangeable with "force-elongation curve" for describing tensile behavior. We use the term "force-elongation curve" because it is easier to relate to the energy data, *F. dl*. Other things being equal, the fracture energy of leather will be

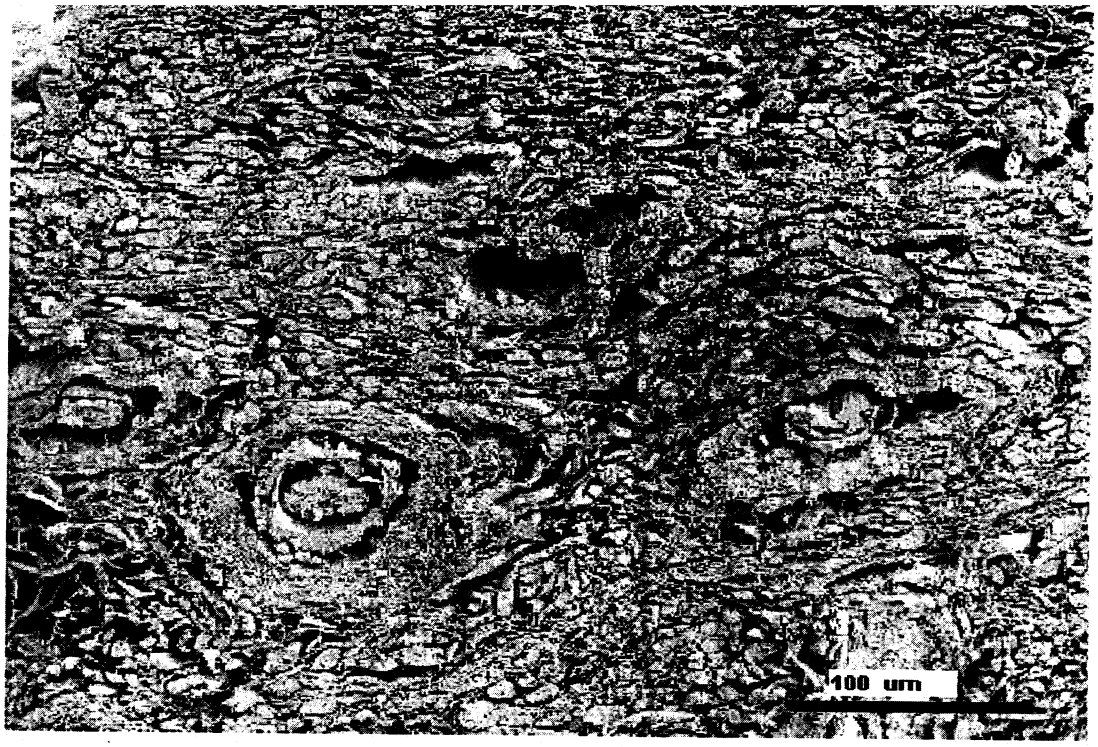

FIGURE 1. — Micrograph showing grain layer with sheet structure.

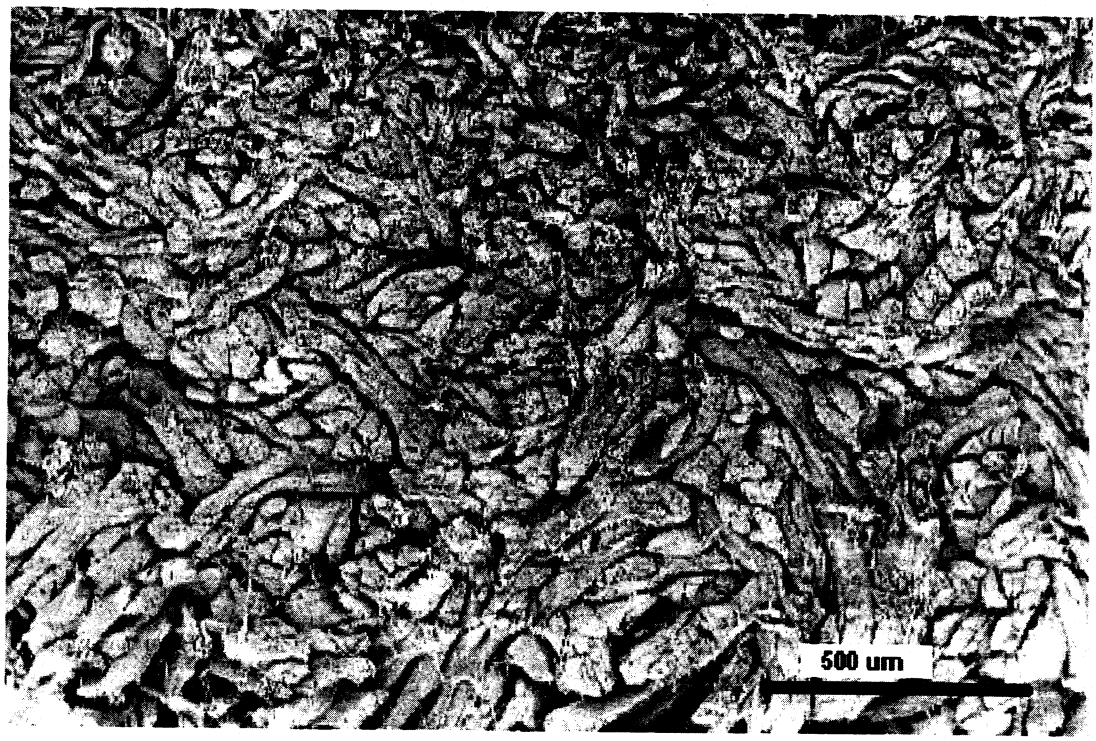

FIGURE 2. — Micrograph showing corium layer with interwoven structure.

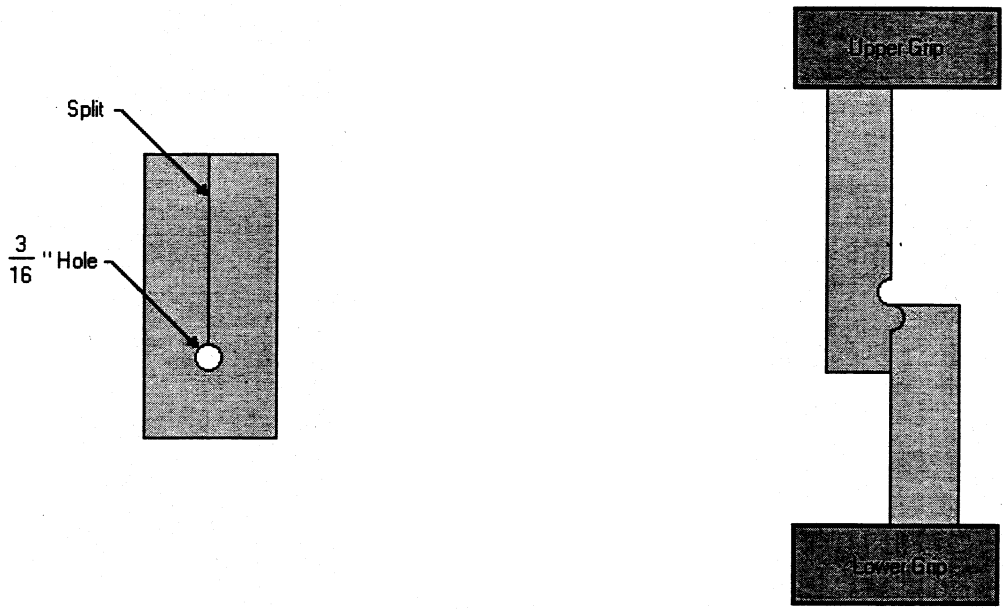

FIGURE 3. — Tear test scheme.

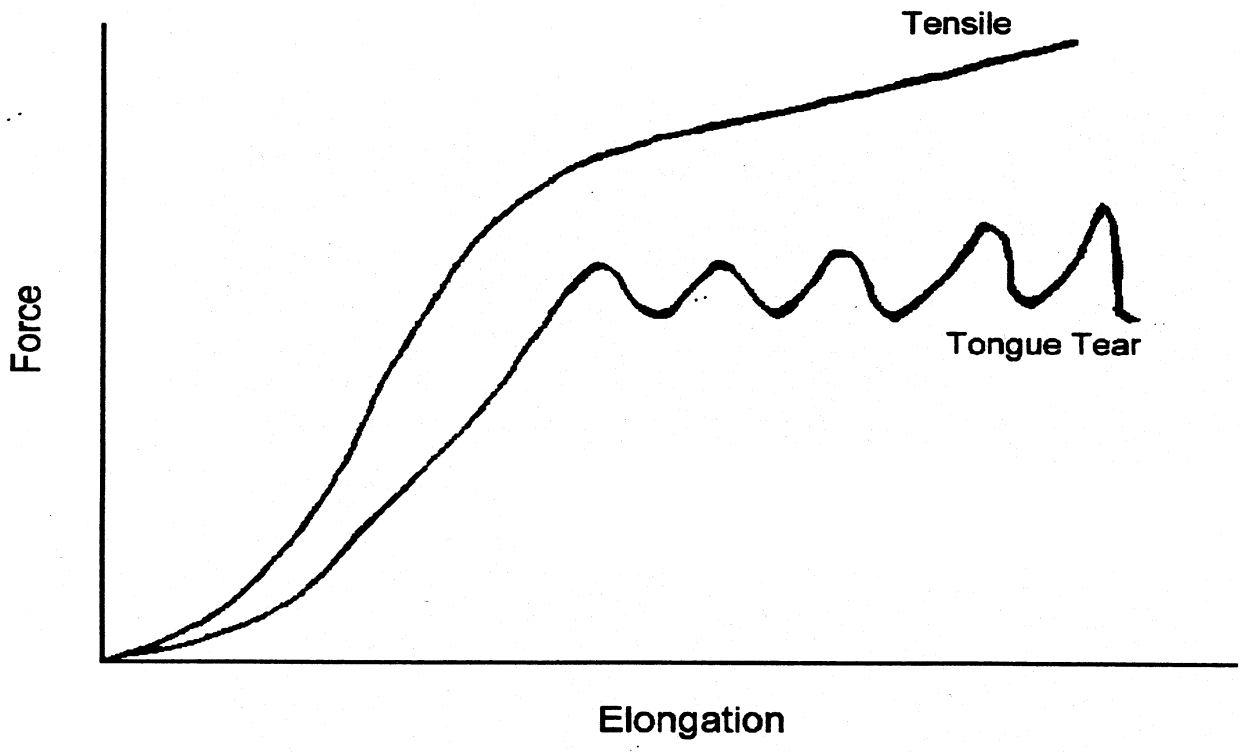

FIGURE 4. — Force-elongation curves for tongue tear tests and for tensile tests.

proportional to its cross-sectional area (because of the effect on the force needed) and to its length (because of the effect on the elongation). Therefore, the fracture energy is dependent on volume. To compare different samples, we divided the value of Equation 4 by the volume of the tested area, which is between the clamps of the Instron tester, to present the fracture energy with the SI unit of J/mm^3.

Results and Discussion

The experimental results were presented in a quantitative way for this study by using the method of multiple regression along with variance analysis to establish mathematical models[7] and to assess their validity. With the aid of a microcomputer and statistical software such as the SAS program, the task has been made easier. It has also made calculations more reliable and rapid. Major independent variables such as strain rate, moisture content, and sampling angle, which affect tearing strength and tensile strength, were investigated. The effects of the fatliquoring and staking processes on these two strengths were also included in the study. Finally, an attempt was made to correlate the tearing strength to the fracture energy determined by the integration of the area under the tensile stress-strain curves.

Force-Elongation Curves

The mechanisms of the fracture process by tensile and tearing can be best elucidated with the force-elongation curves. For leather tensile tests, this curve as shown in Figure 4 has been described and analyzed by various investigators.[11, 12, 13] The force increases slowly with elongation until the leather sample reaches the catastrophic failure point and fractures. Force-elongation curves have not been reported for tearing tests previously. Their significant difference from tensile tests is illustrated in the lower curve of Figure 4, demonstrating that a J shaped curve proceeds first until the initiation of tearing as the tearing force reaches a critical value. The tearing propagated with a fluctuation in the tearing force, revealing a zigzag pattern.[14] This behavior is attributed to the variation of shear resistance associated with heterogeneity in the leather fibrous structure with interwoven fiber bundles. It is evident that shear resistance decreases for less interwoven regions and increases for denser interwoven regions.

Although this report generally treats the tearing behavior of leather as described below it is interesting to note that tearing behavior shows a significant difference between grain and corium layers. The tearing force fluctuation is less for the grain layer than for the corium layer, as demonstrated in curves A and B respectively in Figure 5. This agrees with the micrographs presented in Figures 1 and 2, where the grain layer shows the fibers forming a sheet-like layer with very little connection in between, whereas the corium shows an intense network structure with fiber bundles interwoven together. Figure 5 also clearly demonstrates that the grain layer has a much poorer tearing strength than the corium layer. Obviously this is associated with their structure difference as described earlier. This is in contrast to tensile tests, in which less difference was observed in tensile strength between grain and corium layers, as shown in Figure 6. The breaking elongation of the corium layer, however, is much greater than that of the grain layer. The tensile tests measure the maximum tensile stress across the cross-sectional area of fiber bundles to fracture the samples, so that the degree of association between fiber bundles will not yield significant differences in tensile strength. However, in the tearing test where the shearing force is the dominant force to fracture the samples, the degree of association between fibers bundles becomes a very important factor to determine the fracture resistance, i.e., tearing strength. Consequently, the corium layers with interwoven structure yield much greater tearing resistance.

Regression Model and Analysis of Variance

Table II shows the matrix of test results corresponding to experimental matrix listed on Table I. Table III shows the regression coefficients of the statistical model, corresponding t values, and significant levels for each coefficient. A second order regression model can be expressed as follows:

Y (tearing strength, N/mm) =

$$35.76 - 1.94\,x_1 + 3.46\,x_2 - 1.00\,x_3 + 2.24\,x_1^2 - 0.09\,x_2^2 + 0.86\,x_3^2 + 0.52\,x_1x_2 - 0.74\,x_1x_3 - 0.08\,x_2x_3. \quad (5)$$

Y (tensile strength, MPa) =

$$13.18 + 2.64\,x_1 + 1.01\,x_2 - 1.18\,x_3 + 3.02\,x_1^2 - 0.03\,x_2^2 + 3.28\,x_3^2 + 0.16\,x_1x_2 - 0.69\,x_1x_3 + 0.04\,x_2x_3. \quad (6)$$

As indicated in Table IV for the analysis of variance, both the linear and quadratic terms give a significant mean square. The correlation coefficients are 0.87 and 0.89 for tearing strength and tensile strength, respectively. It is evident that the quadratic model as shown in Equations 5 and 6 fits the data fairly well.

Strain Rate

The current test procedure described in ASTM only uses one strain rate (cross-head speed), which is 254 mm/min. However, it is well known that the rate of stretching (strain rate) has profound effects on the results of mechanical properties testing.[15,16]

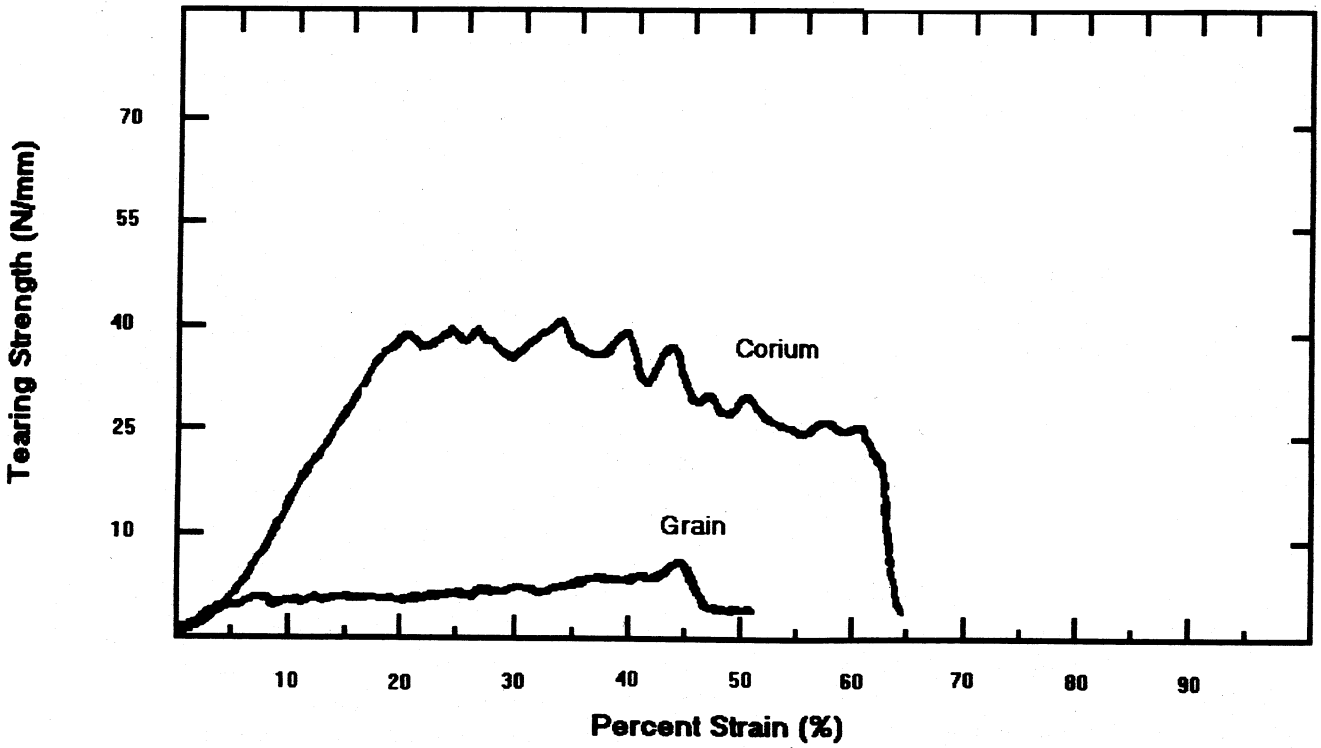

FIGURE 5. — Stress-strain curves for grain and corium layers in tongue tear tests.

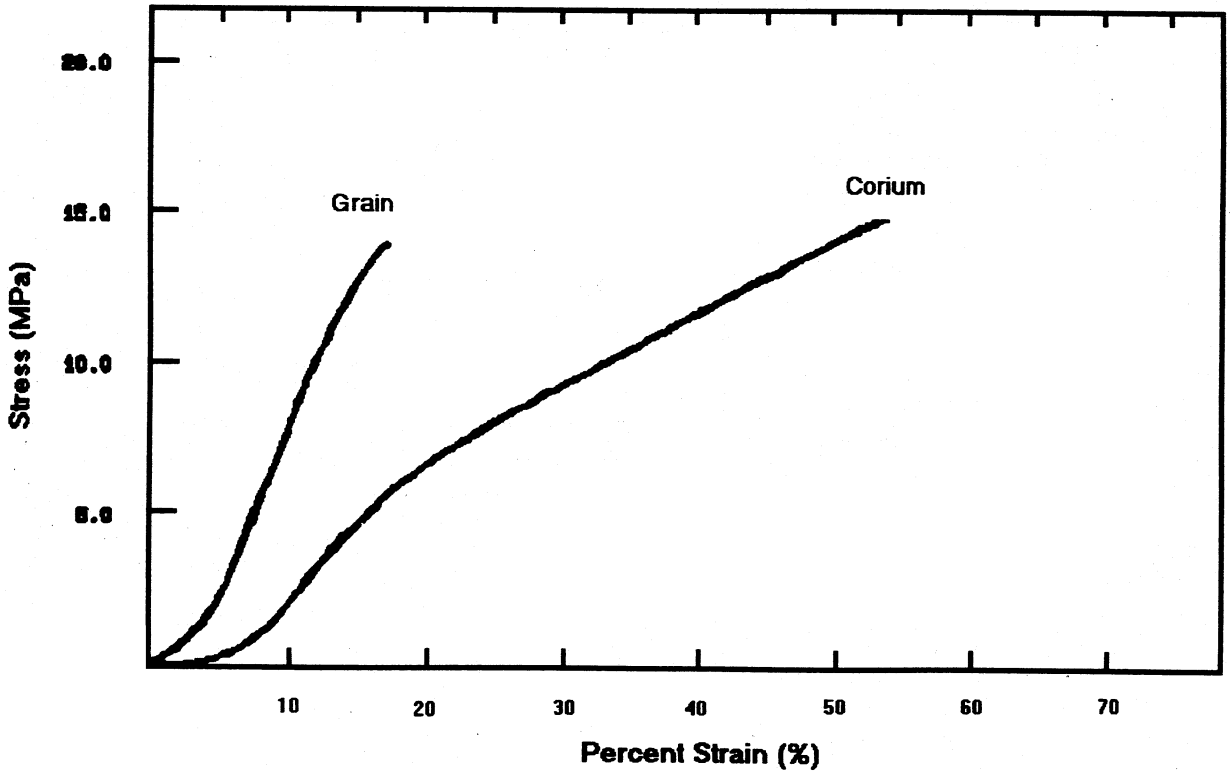

FIGURE 6. — Stress-strain curves for grain and corium layers in tensile tests.

TABLE I
Experimental Plan

Run	Coded Variables X1	X2	X3	Uncoded Variables Strain Rate (mm/min)	Moisture Content (%)	Sampling Angle (°)
1	0.54	1	-1	254	15	-45
2	0.54	0	-1	254	13	-45
3	0.54	0.5	0	254	14	0
4	0.54	0.5	0	254	14	0
5	0.54	1	-1	254	15	-45
6	0.54	0	0	254	13	0
7	0.54	0.5	1	254	14	45
8	0.54	0.25	1	254	13.5	45
9	0.54	0.25	2	254	13.5	90
10	0.54	39.5	-2	254	92	-90
11	0.54	37.5	1	254	88	45
12	-1.5	26	0	50	65	0
13	-1.5	16	2	50	45	90
14	-1.5	4	0	50	21	0
15	-1.5	0.25	0	50	13.5	0
16	-1	1	1	100	15	45
17	-1	0.25	1	100	13.5	45
18	-1	0.25	-1	100	13.5	-45
19	-1	-1.5	0	100	10	0
20	-1	-1.5	0	100	10	0
21	0	16.5	0	200	45	0
22	0	14.5	2	200	42	90
23	0	6.5	0	200	26	0
24	0	4.5	-2	200	22	-90
25	0	1.5	0	200	16	0
26	0	1	0	200	15	0
27	0	1	0	200	15	0
28	0	1	0	200	15	0
29	0	1	0	200	15	0
30	0	0.75	1.68	200	14.5	76
31	0	0.75	-1.68	200	14.5	-76
32	0	0.5	0	200	14	0
33	0	0.5	0	200	14	0
34	0	0.5	0	200	14	0
35	0	0	0	200	13	0
36	0	-1.5	2	200	10	90
37	0	-1.5	0	200	10	0
38	0	-1.5	0	200	10	0
39	0	-1.5	-2	200	10	-90

TABLE II
Results

Tearing Strength (N/mm)	Tensile Strength (MPa)	Fracture Energy (J/cm^3)
51.85	25.58	7.97
35.19	24.31	6.33
36.93	14.92	5.99
41.03	16.51	6.48
44.67	27.09	9.50
35.63	14.27	5.70
40.45	14.87	4.65
30.60	13.05	5.01
36.00	26.25	8.14
52.50	27.14	10.40
43.60	19.58	8.73
45.10	17.87	5.65
56.30	32.84	8.85
44.50	16.78	5.25
41.57	14.34	4.76
37.71	18.80	5.70
37.54	15.21	4.12
40.30	24.09	7.66
27.50	1.09	2.72
34.60	10.74	2.91
60.60	23.31	8.63
69.60	35.25	9.14
65.10	19.75	6.67
55.70	32.17	8.62
39.35	15.55	5.50
33.64	10.52	3.48
44.04	13.27	5.13
31.72	15.95	6.03
32.25	9.87	3.49
33.42	16.56	4.73
42.86	15.96	4.30
40.98	16.33	5.83
32.67	11.36	3.70
37.41	12.18	4.50
42.31	17.36	5.32
37.40	12.76	3.29
33.60	12.17	2.72
35.90	23.86	4.66
41.30	27.54	5.97

TABLE III
Regression Coefficients

TEARING STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t for H_O: Parameter = 0	Probability > | t |
Intercept	1	35.76	1.37	26.03	0.00
X_1	1	1.94	2.52	0.77	0.45
X_2	1	3.46	0.41	8.41	0.00
X_3	1	-1.00	0.93	-1.08	0.29
X_1^2	1	2.24	2.49	0.90	0.37
$X_2 X_1$	1	0.52	0.16	3.24	0.00
X_2^2	1	-0.09	0.01	-7.39	0.00
$X_3 X_1$	1	-0.74	1.11	-0.67	0.51
$X_3 X_2$	1	-0.08	0.07	-1.12	0.27
X_3^2	1	0.86	0.54	1.60	0.12

TENSILE STRENGTH

Parameter	Degrees of Freedom	Regression Coefficient	Standard Error	t* for H_O**: Parameter = 0	Probability > | t |
Intercept	1	13.18	0.88	15.04	0.00
X_1	1	2.64	1.60	1.65	0.11
X_2	1	1.01	0.26	3.86	0.00
X_3	1	-1.18	0.59	-1.99	0.06
X_1^2	1	3.02	1.59	1.90	0.07
$X_2 X_1$	1	0.16	0.10	1.60	0.12
X_2^2	1	-0.03	0.01	-3.56	0.00
$X_3 X_1$	1	-0.68	0.71	-0.96	0.35
$X_3 X_2$	1	0.04	0.05	0.76	0.45
X_3^2	1	3.28	0.34	9.58	0.00

* H_O = null hypothesis

** t = Student≈s t = (regression coefficient / standard error)

TABLE IV
Analysis of Variance for Second-Order Model

ARING STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	959.72	0.25	10.38	0.00
adratic	3	1608.81	0.41	17.40	0.00
›ssproduct	3	365.29	0.09	3.95	0.02
.al Regress	9	2933.82	10.58	10.58	0.00

:NSILE STRENGTH

gression	Degrees of Freedom	Sum of Squares	R-Square	F *	Probability > F
ıear	3	205.36	0.10	5.46	0.00
adratic	3	1359.64	0.68	36.16	0.00
›ssproduct	3	43.36	0.02	1.15	0.34
.al Regress	9	1608.36	0.80	14.26	0.00

= variance ratio

:ures 7 and 8 are 3-D plots of response surfaces of ring strength according to Equation 5 for the 0° and 90° npling angles, respectively. They clearly show that the ıin rate has very little effect on the tearing strength. The tistical analysis as mentioned earlier indicated that the ıin rate is not a significant factor in determining the ring strength. In tearing tests the stress concentrates at a row area and involves only small scale movement of er bundles, so that the resistance to fracture is strongly ociated with the local density of the fibrous network. It reasonable to expect that strain rate will not change the istance to tearing fracture because the change of strain e accompanies very little change in fiber bundle friction d stress distribution during a tearing test. This is quite ferent from tensile tests, where force acts on a wide ›ss-sectional area of fiber bundles and the strain rate ınge normally accompanies a large scale change in fiber ndle friction and stress distribution.

nsile tests, as shown in Figures 9 and 10, are derived ›m Equation 6 for 0° and 90° sampling angles, respec-ely. For both cases, they clearly show that the tensile ength decreases with strain rate at the beginning; then ıen the rate reaches around 150 mm/min the tensile ength increases with strain rate. This behavior may be plained by the effects of stress concentration and genera-n of local heat. At strain rates between 50 mm/min and 150 mm/min, the effect of stress concentration could play an important role in the fracture mechanism. As strain rate increases, the fiber bundles in the leather probably do not have sufficient time to slip and adjust themselves in the stretching direction, and the corresponding stress does not uniformly distribute across the test samples. Stress concentrates at certain regions and consequently causes premature fracture. At a strain rate above 150 mm/min, however, the increased friction between fiber bundles may generate sufficient local heat to soften the surface of fiber bundles and make the fiber bundles slip among each other easily; consequently they are able to adjust themselves into better load-bearing positions, thus increasing the tensile strength.

Moisture Content

For both tearing tests and tensile tests, leather strength shows an increase with increasing moisture content until reaching a certain level, as demonstrated in Figures 9 and 10. The behavior of water's functioning as a lubricant is well known.[17] Water eases the movement of fibers and decreases the frictional resistance of fibers when leather is subjected to a force. Moreover, Kronick and Page[18] have linked the effects of moisture content on fiber adhesion in leather. They demonstrated that as water content increased, less acoustic emission was observed from leather when it was subjected to a tensile stress. This is because water

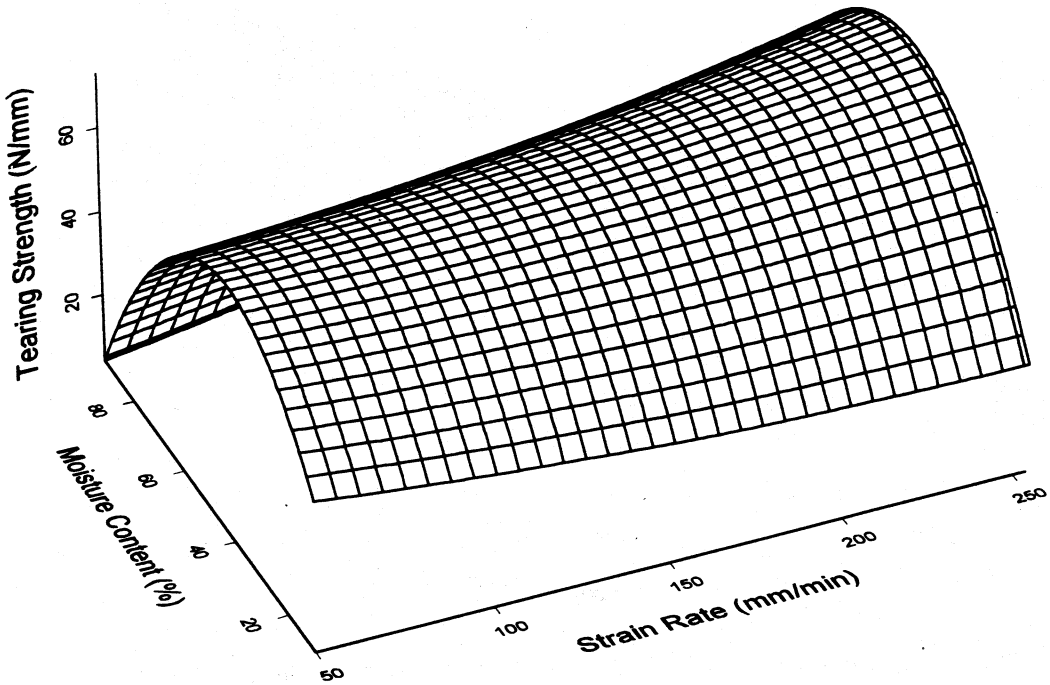

FIGURE 7. — Effect of strain rate and moisture content on tearing strength for sampling angle at 0°.

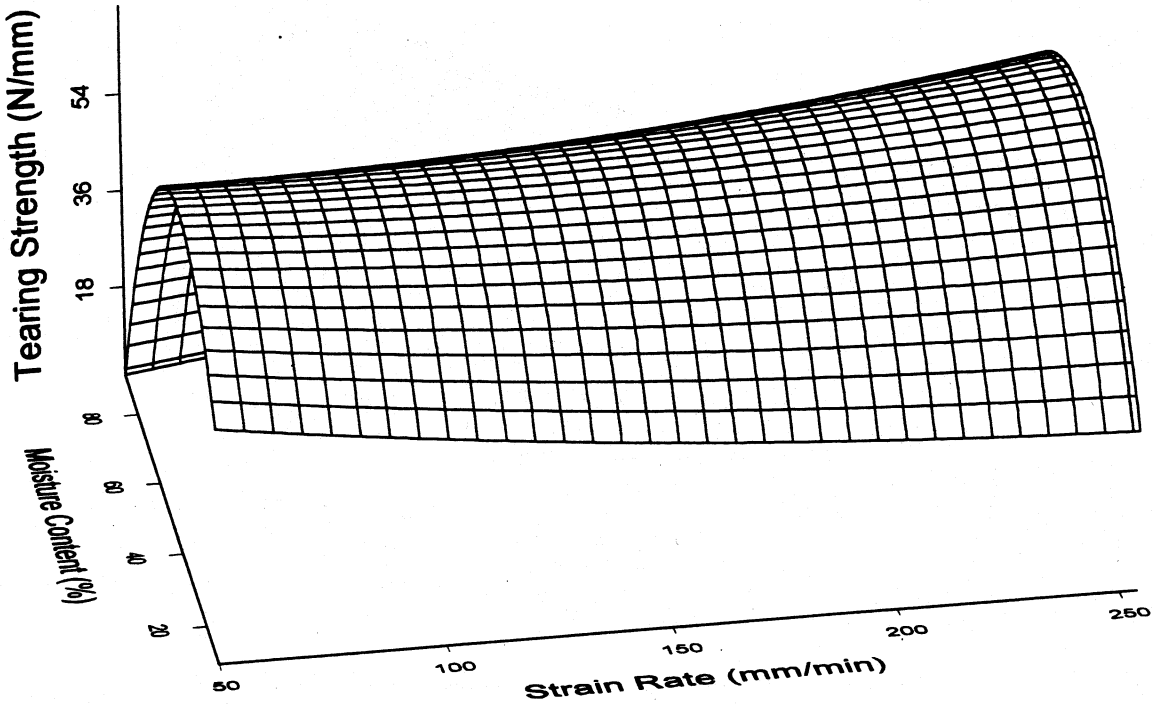

FIGURE 8. — Effect of strain rate and moisture content on tearing strength for sampling angle at 90°.

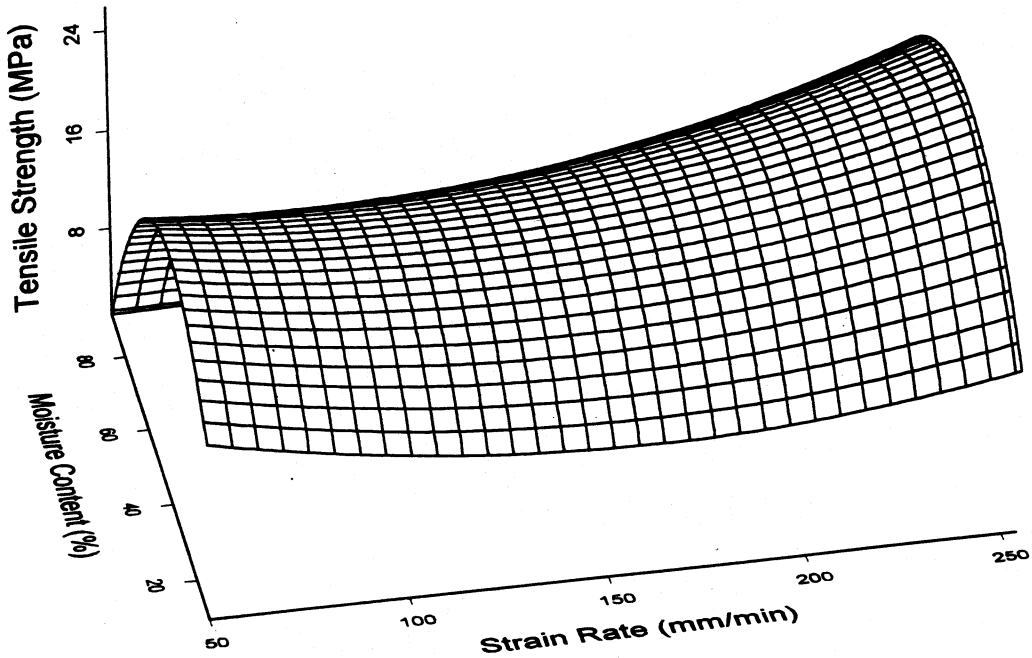

FIGURE 9. — Effect of strain rate and moisture content on tensile strength for sampling angle at 0°.

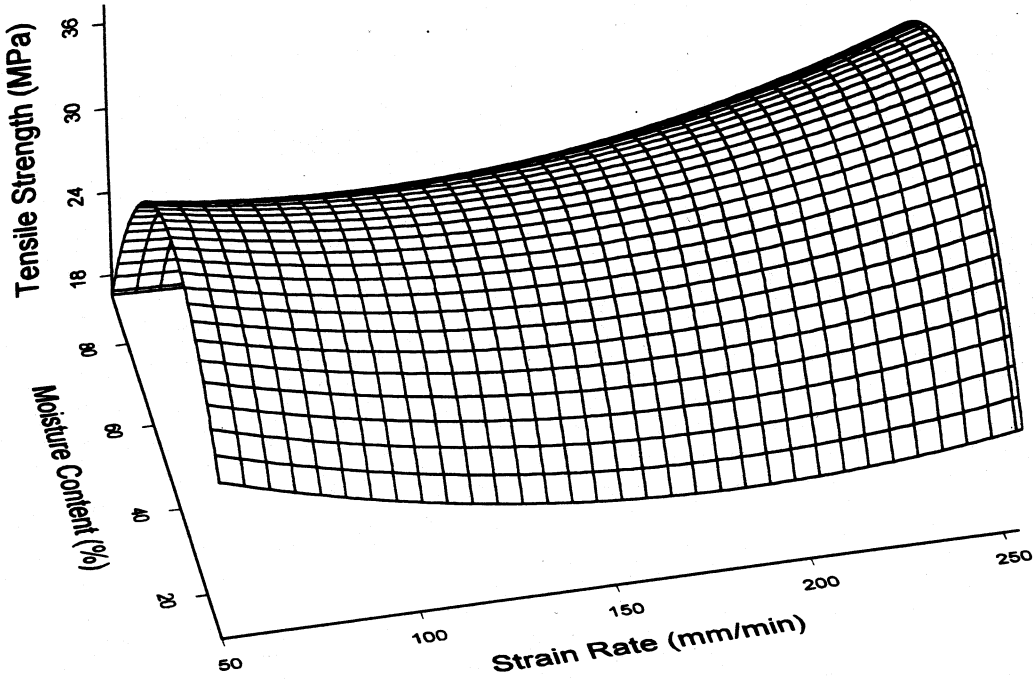

FIGURE 10. — Effect of strain rate and moisture content on tensile strength for sampling angle at 90°.

disrupts fiber adhesion, thereby reducing the sound emitted from tensile tests. These effects of weakening the adhesion between fiber fibers can further ease the movement of fiber bundles and allow them to more freely adjust their position for better load bearing, consequently improving both strengths. However, when leather contains much water, its integrity is undermined, therefore adversely affecting strength.

Sampling Angle

Figure 11 and Figure 12 illustrate the strength as a function of sampling angle and moisture content. The effect of moisture content has been discussed previously, whereas here, we only discuss the effect of sampling angle. As shown in Figure 11, the sampling angle has very little effect on tearing strength. This is rather contrary to tensile strength, which shows a high sampling angle dependence. Leather is known to be a highly anisotropic material. Various studies have shown[19] that the tensile strength depends on the sample angle. So does the tensile modulus, which has been known to be strongly associated with fiber orientation in leather. Our tests have also shown that tensile strength is greater the closer to the parallel direction (sample angle 90 or –90°) as illustrated in Figure 12.

The drastic difference between tensile strength and tear strength in response to sampling angle change is associated with their fracture mechanism. In tearing, the stress is concentrated at a local narrow area; shear force acts on the surface of fiber bundles and tearing resistance is mainly provided by the interlocks of fiber bundles. The orientation of fiber bundles does not pose a significant effect on the tearing resistance. Therefore, tearing strength depends very little on the sampling angles. In a tensile fracture, however, the stress covers a wide cross-sectional area of fiber bundles, which is a vector quantity. The tensile strength quantifies fracture stress in the one direction that it is being stretched. Therefore, the resistance is given only by the vector components parallel to the applied force direction. Obviously, the more fiber bundles that line up in this direction such as the samples taken from the parallel to back bone line, the higher the tensile strength. Therefore. tensile strength is greatly dependent upon sampling angle.

Correlation Between Tearing Strength and Fracture Energy

Statistical analysis showed that there is a rather poor correlation between tearing strength and tensile strength, with a correlation coefficient of 0.55. Further regression analysis as illustrated in Figure 13 shows a much better correlation between tearing strength and fracture energy. The correlation coefficient is 0.70. As mentioned before, the fracture energy is a measure of the integral of the force-elongation curve. There are two physical quantities that combine to produce energy, i.e. force and elongation. Fracture energy counts the summation of energy required for every fiber bundle movement until it fractures. Therefore, force and elongation (or stress and strain) are taken into account together from beginning to end. Figure 14 demonstrates an excellent correlation between fracture energy and the product of tensile strength and elongation. This is in contrast to tensile strength, which is only a measure of the stress required to fracture a material. Actually the term fracture energy has been used interchangeably with "toughness." It appears that good fracture energy reflects a superior balance of strength and flexibility. It has been known that leather strong in terms of tensile strength is not necessarily strong in terms of fracture energy. For example, a brittle leather may have excellent tensile strength, but it may have poor fracture energy because of its lack of adequate breaking elongation.

The picture emerging here is that tearing strength is governed greatly by the toughness of samples. Stress concentration has a significant adverse effect on tearing strength and good deformability can minimize its effects. This is the reason that a brittle leather produced from over-dried or insufficient removal of glue-like protein substances yields poor tearing strength. It is also clear that adequate bating, fatliquoring and drying processes that promote leather fiber bundle mobility are essential to better tearing strength.

Effects of Staking and Fatliquoring

In staking, leather is subjected to a very large number of rapidly oscillating, stretching and flexing cycles in every direction. It is an additional process in leathermaking to enhance the pliability of leather. This mechanical action is necessary to break weak adhesions within the fiber structure, thereby promoting the fibers' mobility.[20] The mechanical stresses that staking imposes on leather are very great, and if it is overdone it can adversely affect leather's integrity.[21] As shown in Figure 13, sample B, staking does not yield better tearing strength.

Fatliquoring is an oil-adding process by which the leather fibers are lubricated so that after drying they will be capable of slipping over one another. This process is practiced in leather-making to improve the flexibility and softness of leather. Its obvious effect on leather properties can be seen clearly in Figure 13, where A is the control sample, sample B has been staked and sample C has been staked and

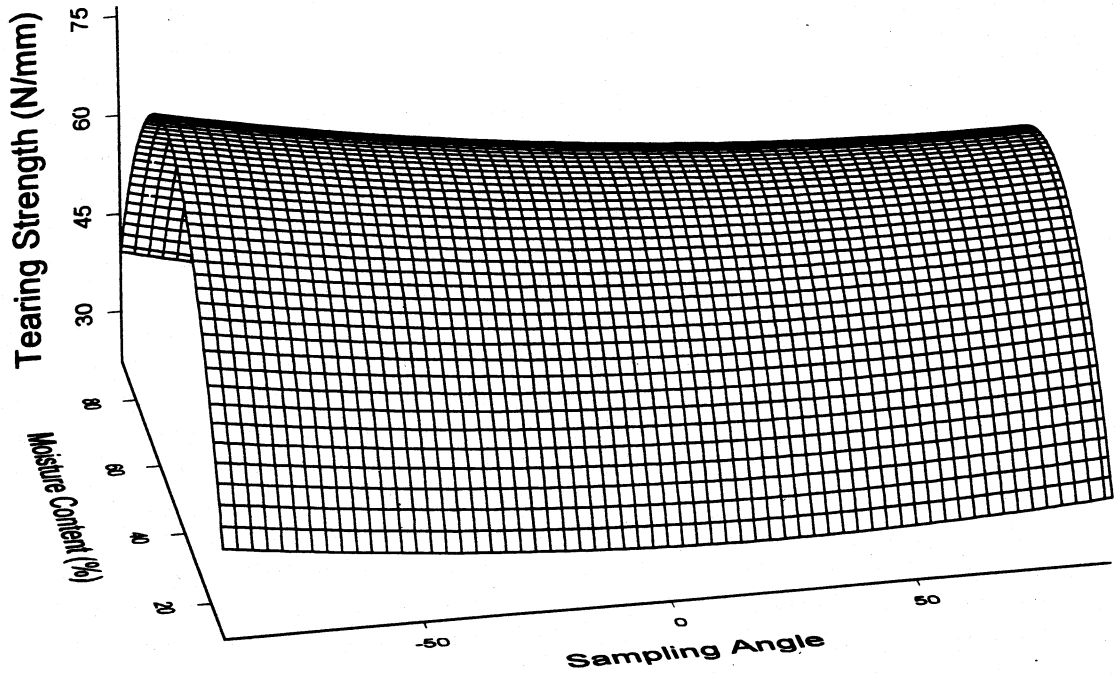

FIGURE 11. — Effect of sampling angle on tearing strength.

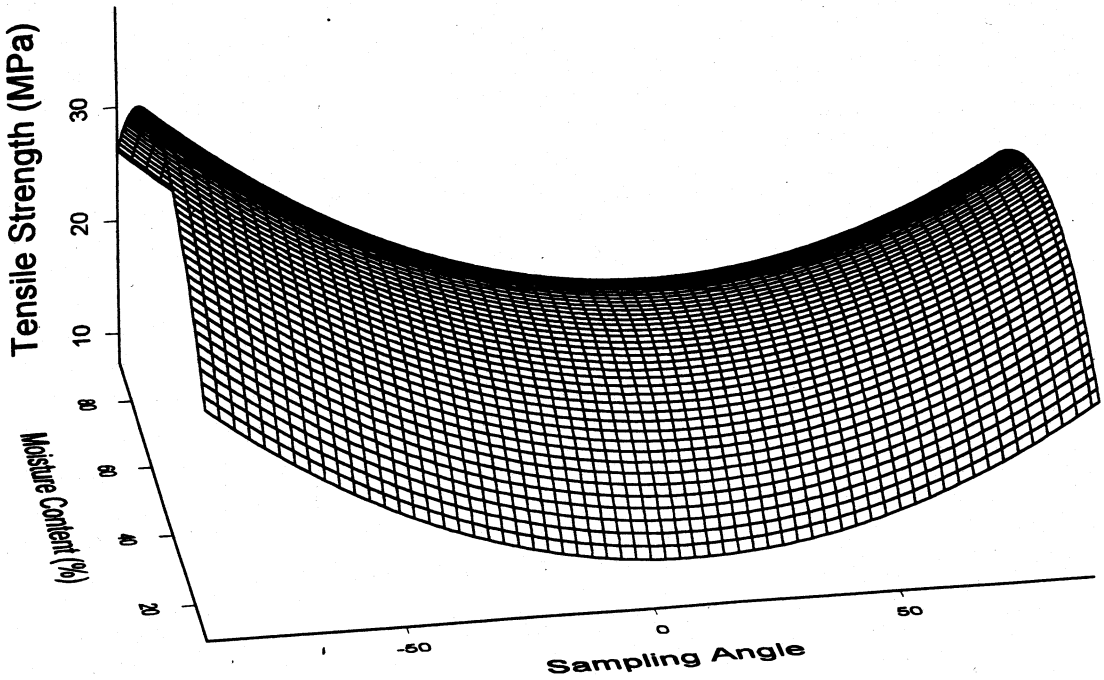

FIGURE 12. — Effect of sampling angle on tensile strength.

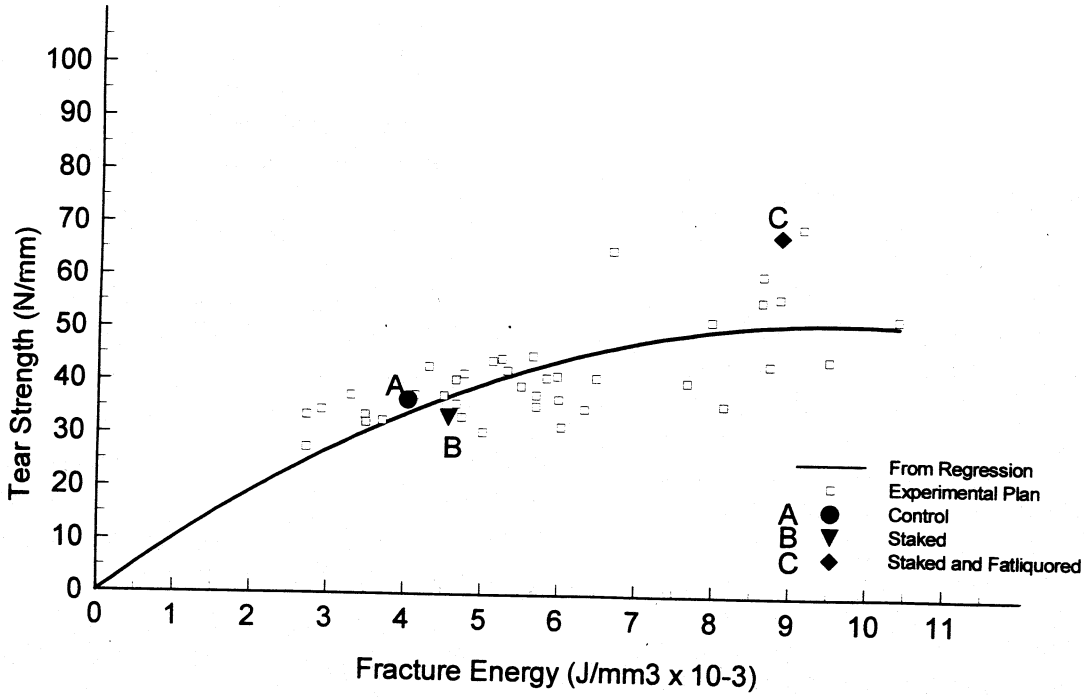

FIGURE 13. — Correlation between tearing strength and tensile fracture energy.

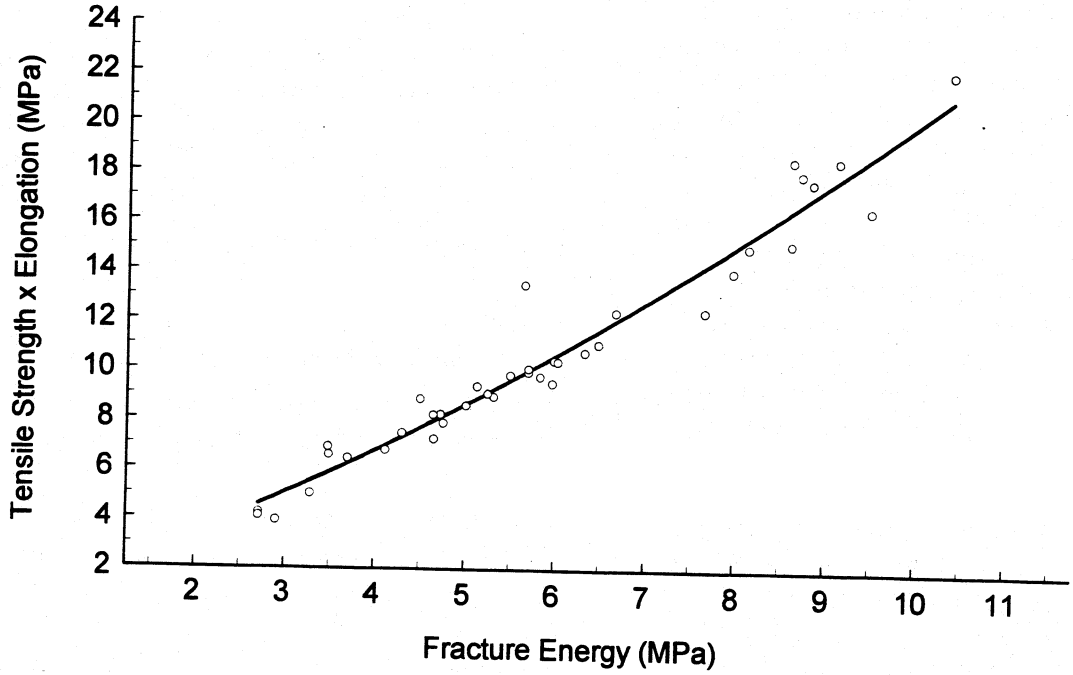

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

fatliquored as described in the experimental section. Sample B, which has been staked, does not show an improvement in tearing strength, whereas sample C, which has been fatliquored, shows much greater tearing strength and fracture energy than those of the control.

CONCLUSIONS

The relationship between tensile and tearing behavior has never been fully understood. Because of the lack of such knowledge, it is often difficult for the tanner to produce both good tensile strength and tear strength. Our essential objective for this investigation is to clarify the relationship between tensile strength and tear strength. Moreover, this study attempts to answer a frequent question in the tannery: why is leather that is strong in tensile strength not necessarily strong in tearing strength? We hope that the results of this investigation can lead to a more effective optimization of the leathermaking processes and yield a high quality leather strong in both tensile strength and tear strength. The tearing and tensile tests were performed on the same leather samples; therefore minimizing experimental error incurred by sample variation. Results showed that for the tearing tests a unique zigzag tearing pattern was observed due to the fluctuations in the tearing force, whereas the tensile tests demonstrated a uniform fracture pattern. Results also showed that strain rate does not significantly affect tearing strength, but does affect tensile strength. Moreover, both strengths increase with increasing moisture content up to certain levels, at which they start to decrease with increasing moisture content. A drastic difference between these two strengths is demonstrated in response to sampling angle change. Tearing strength showed little variation with a change of sampling angle, whereas tensile strength showed a maximum at close to parallel to the backbone direction, then steadily decreased when sampling angle deviated from the backbone line. Most importantly, we have demonstrated the importance of fracture energy to tearing strength. Good fracture energy reflects a superior balance of strength and flexibility. On the other hand, a brittle leather produced by over-drying or insufficient removal of glue-like protein substances yields poor tearing strength. Proper fatliquoring and moisture content are crucial factors for a good tear strength. Good deformability can minimize the stress concentration and yield a better tearing strength.

ACKNOWLEDGMENTS

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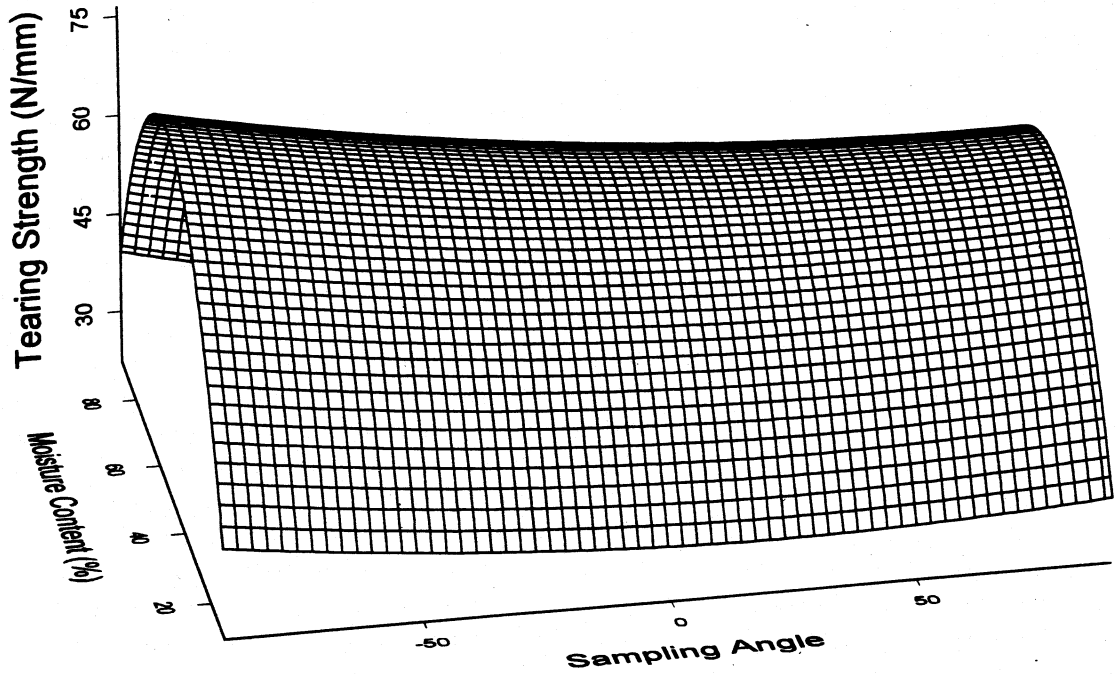

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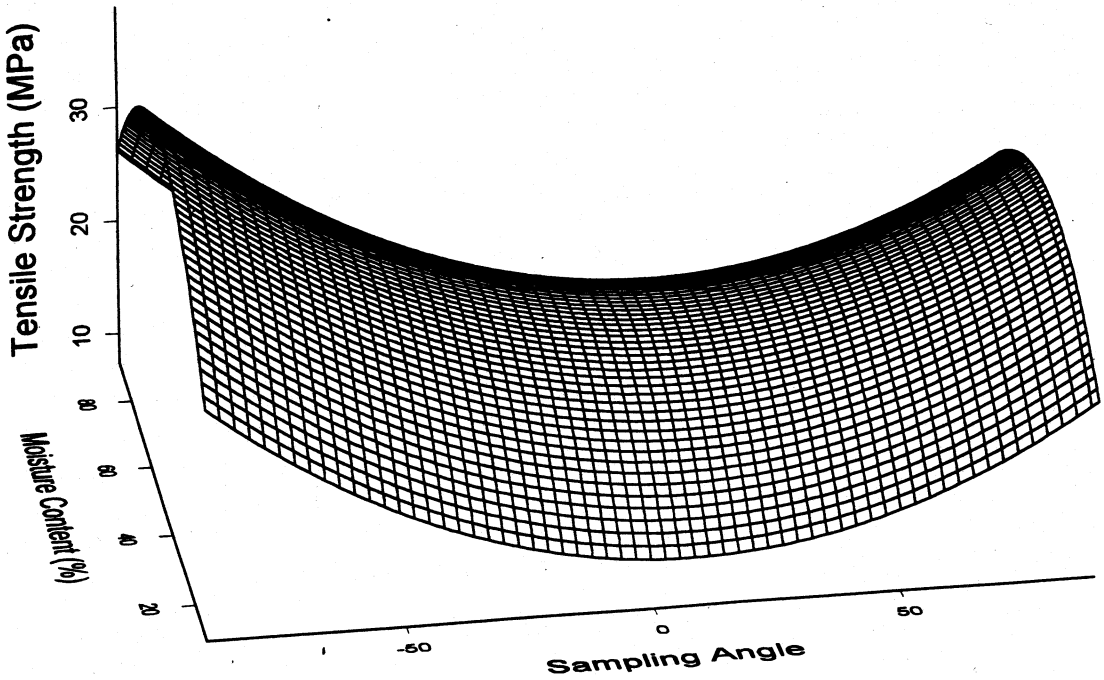
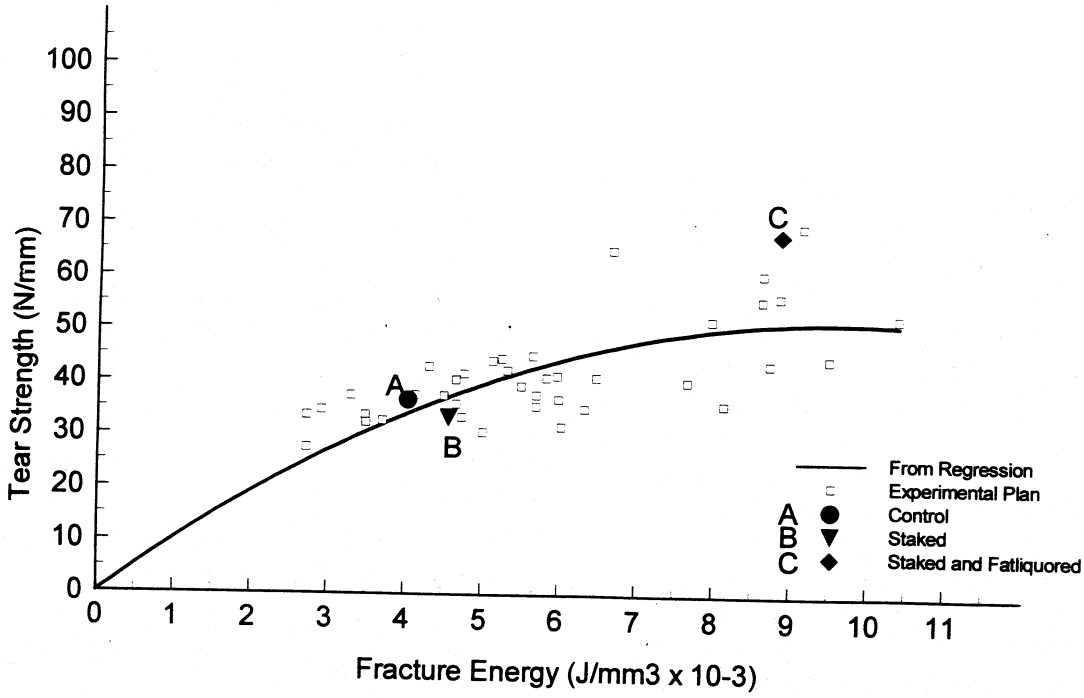


FIGURE 12. — Effect of sampling angle on tensile strength.



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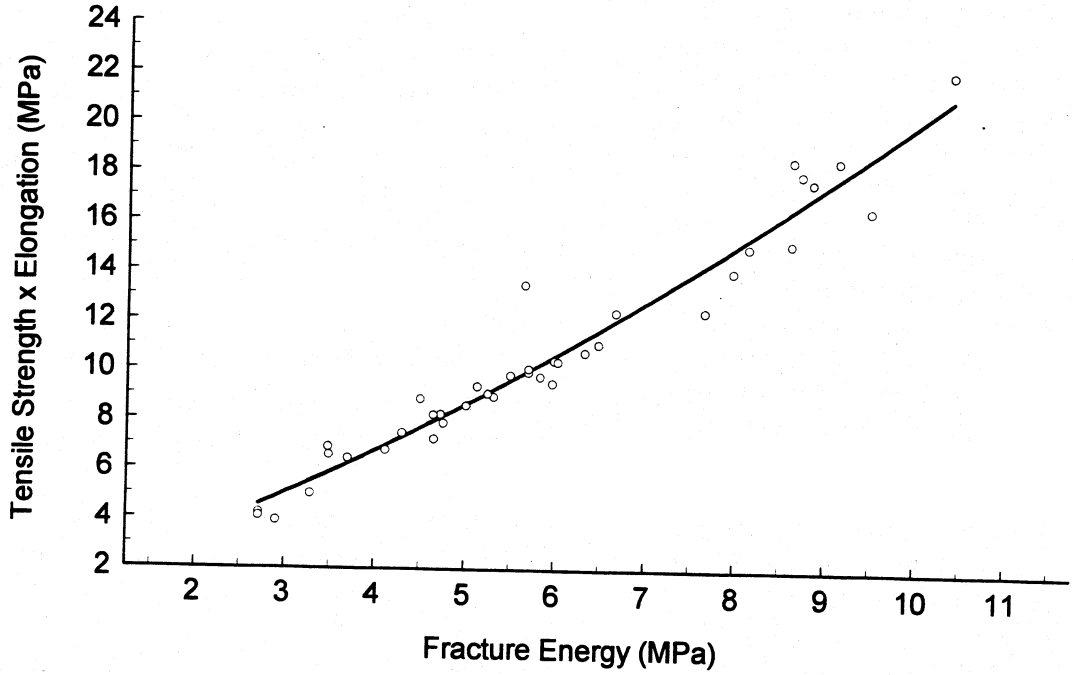

FIGURE 14. — Correlation between fracture energy and the product of tensile strength and breaking elongation.

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