THE FLEXIBILITY OF LEATHER* 2060

ABSTRACT

Three test methods, namely tensile, flexure, and torsion, were employed for quantitative measurement of the degree of flexibility (stiffness) of leather, rubber, and plastics. The torsion method was selected for studying the stiffness of leather specimens because of the speed and ease of testing, simplicity in treatment of data, reproducibility, and its suitability for temperature-dependence measurements. Stiffness values of light leathers at room temperature ranged from 300 psi to 10,000 psi. The lower values were similar to rubber and plasticized polyvinyl chloride, while the higher values approached those of the low-density polyethylenes. Sole leathers at room temperature ranged in stiffness from 8,000 psi to 40,000 psi. Synthetic sole compositions were much lower (700 to 2,000 psi) except Neolite‡ (10,000–18,000). The stiffness values for sole leather depended upon the previous mechanical conditioning given the specimen after manufacturing, making it rather difficult to specify its stiffness characteristic. The effect of temperature on the stiffness of leather was investigated and shown to be relatively small compared to various synthetic plastic and rubber compositions.

INTRODUCTION

One of the most important properties of leather or any other substance is its ability to be pulled, compressed, bent, twisted, etc. A popular term, and one that is widely employed to describe this ability, is flexibility. Flexibility is simply a means of describing the amount of resistance that a material offers to deformation when an outside force acts upon it. However, an examination of the literature including all types of handbooks containing data on mechanical properties of materials would fail to produce any quantitative information listed under the terminology flexibility. To explain this, a

*Presented at the Fifty-ninth Annual Meeting of the ALCA, Niagara Falls, Ontario, Canada, June 16–19, 1963.

†Eastern Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture.

‡Mention of commercial firms and products does not constitute an endorsement by the Department over others of similar nature not named.

study of the response that a material undergoes when subjected to an outside force must be made. This response is reflected in either a change in shape or volume of the body, or both. The extent of such change will depend, in a large part, on the make-up of the material and the amount of force applied. Thus, a measurement of flexibility must involve a relationship between stress (force) and strain (deformation). In mechanics the ratio of a stress to the corresponding strain is called a modulus. In other words, the modulus of a material is some measure of flexibility

The engineering literature contains a large amount of quantitative data on the moduli of metals, plastics, and rubbers. Essentially nothing is available in a general way on leather materials. Yet it is this kind of information that engineers use in determining the potentiality of a material for a particular application. Even in the case of metals, plastics, and rubber the reported values are often difficult to understand, since different moduli are reported for the same material depending upon the type of stress that was employed in the measurement. Listed in Table I are the main types of simple stresses, namely, tension, shear, and compression. An added difficulty in making comparisons of flexibility of materials is that the moduli obtained in a particular test method are referred to under a number of different names and symbols. For example, listed in Table I are five different names for the modulus obtained from a tensile test measurement.

TABLE I

STRESSES AND MODULI

Type of Stress (Force)	Name of Modulus	Symbols
Tension	Young's Modulus Modulus of elasticity Stretch modulus Elastic modulus Modulus of stiffness in tension	E, Y, E_T
Shear	Shear modulus Modulus of rigidity Coefficient of rigidity Modulus of elasticity in shear	G, μ, E_G
Compression (force on all surfaces)	Bulk modulus Modulus of elasticity in compression	B, K, E_B

For the sake of simplicity, the term that will be used throughout this paper will be "stiffness." If measurements are made in tension, then the term "stiffness in tension" will be employed or inferred, etc. The term *stiffness* was selected in preference to *flexibility* in reporting the data, since the numerical value of the stress-strain ratio increases with increased stiffness. If flexibility were used, a large numerical value would indicate small flexibility, adding to the confusion for understanding the data.

The three main types of stresses give rise to three kinds of stiffness. However, it is possible to obtain the same numerical value for all three if the material is homogeneous and exhibits an ideal elastic response. For many substances each test gives a different stiffness value. This is not unexpected, since measurements carried out in tension, shear, and compression are time-dependent and, in many instances, temperature-dependent, thus giving rise to variable stress-strain characteristics. The existence of a true elastic component in any material is debatable. Therefore, most researchers preface moduli terms with the word "apparent." However, an apparent value is still quite useful so long as its arbitrary nature and dependence on time, etc., are realized.

EXPERIMENTAL

Test methods.—Table II lists the three test methods, tensile, flexure, and torsion, that were investigated in the present study. It should be noted that flexure and torsion involve complex stresses. All of these methods are ASTM Standard Methods (1–4) and are used for plastics or rubber. The tensile method (1) involves the measurement of the initial slope and essentially linear portion of a load-elongation curve obtained with a tensile testing machine. The apparent stiffness in tension of the material is simply calculated as shown:

$$E_T = \frac{L_O}{Wt}\left(\frac{P}{\Delta L}\right)$$

where E_T = apparent stiffness in tension, psi.; L_O = original length, in.; W = width, in.: t = thickness, in.; P = load, lb.; and ΔL = length increase, in.

TABLE II

EXPERIMENTAL METHODS FOR MEASUREMENT OF "FLEXIBILITY"

Method	Type of Stress	Apparent Flexibility Designation and Symbol
Tensile	Tension	Stiffness in tension, E_T
Flexure (bending)	Tension and compression	Stiffness in flexure, E_F
Torsion	Shear (complex)	Stiffness in torsion, E_G

In the present work the slopes were measured in the initial portion of the curve only. For the leathers investigated, this varied from a minimum of 0.3% to a maximum of 2.5% elongation. Cyclic loading at 2.5% elongation showed essentially complete reversibility, indicating that the response of these leathers approximated an elastic system. Sample dimensions were: 4″ long, 0.5″ wide, and natural thickness. An Instron* tensile tester was used at three test speeds: 0.05, 1, and 10 in/min.

The second method is a flexure, or bending, test. This method, called stiffness, is also an official method of ALCA (5). It involves the measurement of the force required to bend a specimen through a given angle using a Tinius-Olsen* stiffness tester. The apparent stiffness is calculated as shown:

$$E_F = \frac{4 \times 10^{-2} \, S \, M}{W t^3} \left(\frac{R}{\phi} \right)$$

where E_F = apparent stiffness in flexure, psi; S = span length, in.; M = calibrated weight applied to pendulum system, in.-lb.; W = width, in.; t = thickness, in.; R = load scale reading, percent of maximum bending moment, M; and ϕ = reading on angular deflection scale converted into radians. An angle of 50° has generally been used in evaluations of leathers. The same general test method is used as a standard in testing plastics (2). However, instead of using a fixed angle the slope of load-scale reading versus angular deflection curve is used, which generally has an initial straight-line portion, provided the proper sample dimensions and loads are applied. It was observed with light leathers that if great care was not used in selecting the applied load the load–angular deflection plot showed essentially no linear portion. Using a single load reading at a fixed angle often gave different and erroneous results. Therefore, the results to be reported were taken according to the plastics standard test method (2) using a 0.5 in.-lb. Tinius-Olsen flexure tester.

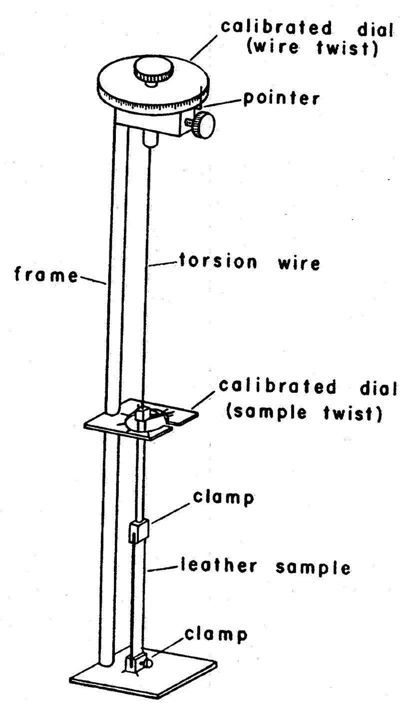
The third test is a torsion test in which a complex shearing force is applied to a specimen. It is a standard method of test for plastics (3) and rubbers (4) and is particularly suited for measuring the changes produced in a specimen by temperature. The method of measurement is a relatively simple one. It involves the measurement of the force required to twist a sample about its long axis an arbitrarily selected number of degrees. Any angle of twist up to about 180° gave reproducible results for light leathers. Apparently the strains involved are relatively small. An angle of twist of 90° was used in this study. With this technique one measurement, which requires less than one minute, is all that is needed for the calculation of the apparent stiffness of a material. No curves are drawn, as no slopes are employed. In addition, the method is particularly suited for making temperature-dependence studies.

*Mention of commercial firms and products does not constitute an endorsement by the Department over others of a similar nature not named.

The torsion instrument (6) that was used in the present work is illustrated in Fig. 1. The main component is a torsion wire which is mechanically linked to a long narrow specimen whose one end is fixed to the frame. A force is applied to the whole system (that is, wire and sample) by manually turning the upper dial. This dial is turned until the angle of twist of the specimen is 90°. The reading on the upper dial is then taken, and the stiffness is calculated. The relative stiffnesses of two specimens of the same dimensions are apparent from the upper dial readings. To convert dial reading into apparent stiffness in psi units, a wire constant must be determined (4, 6). The general formula that is used for the calculation is:

$$E_G = \frac{2.39\, L\, P}{W t^3 \mu} \frac{\theta w}{\theta_s}$$

where E_G = apparent stiffness in torison, psi; L = length, in.; P = wire constant, g-cm/degree; 2.39 = conversion constant; W = width, in.; t = thickness, in.; μ = constant (values depend on ratio of width to thickness); θ_w = twist of wire, degrees; and θ_s = twist of specimen, degrees (90° generally selected).



The specimen size selected for the torsion measurement was 4″ x ¼″. Each specimen was mechanically conditioned by twisting 90° once, unless otherwise indicated. In carrying out the torsion measurements as a function of temperature a silicone fluid was used as the heat transfer medium. The medium was cooled to −70°C. using dry ice and then slowly raised to +80°C. at approximately 2°C. per minute. Measurements were taken every 5° or 10°C. Silicone fluid exerted little or no effect on the temperature dependence of the leathers studied, as similar results were obtained using air as the heat transfer medium.

For studying the effect of compression on the stiffness of light leathers, specimens were placed between the platens of a hydraulic press. Pressures varying from 500 to 45,000 psi were applied for one minute. Thickness of the compressed specimens was measured five minutes upon removal from the press, and their stiffness was determined.

The light leather and sole leather specimens studied were taken from the same general area of regular production runs of commercially tanned sides. The amount of fatliquor in the various leathers investigated was not known. The synthetic compositions used for comparison with the light leathers were commercial materials, as were the synthetic sole materials. All materials were conditioned at 23°C. and 50% relative humidity for at least 24 hours before testing at the same conditions.

RESULTS AND DISCUSSION

Comparison of test methods.—Table III shows the results obtained on three types of materials, a light leather, a plastic, and a rubber, by the three test methods that were discussed. The effect of the rate of application of the load on the apparent stiffness in tension values is shown to be quite pronounced for all three materials, the lower testing rates giving the smaller values, although little difference between 1 and 0.05 in./min. was observed for the leather samples investigated. The speed of testing had little or no effect in the torsion and flexure methods. The exact rate is not easily determined in these methods but is relatively low. A comparison of the apparent stiffness values obtained by the three methods shows that the torsion and low rate tensile values are in fairly good agreement for all three materials. The values for the flexure test are much lower, approximately one-half of those obtained by the other two. Comparison of flexure and torsion test values for a large number (approximately 20) of light leathers showed that this large difference held true for about 50% of the specimens. Relatively good agreement between the two methods was obtained for the other 50% of the specimens. The reason for this was not apparent.

Because of the speed and ease of measurement, simplicity of stiffness determination, good reproducibility (which was about ± 7% for adjacent cuts), and suitability for temperature investigations, the torsion method was selected for studying the apparent stiffness of leather. All remaining data reported were obtained with this method.

TABLE III

COMPARISON OF TEST METHODS

Material	Stiffness, psi				
	Tension Test Speed			Torsion	Flexure
	10 in/min.	1 in/min.	0.05 in/min.		
Chrome-tanned–vegetable-retanned light leather	6100	4500	4300	4400	2300
Polyvinyl chloride + 35% di-2-ethyl hexyl phthalate	6000	5300	3000	2100	1200
Rubber-filled	—	5000	3900	3600	1800

TABLE IV

STIFFNESS IN TORSION OF LIGHT LEATHERS

Material	Stiffness, psi
LEATHER	
Side — chrome tan — glutaraldehyde retan — finished	1000
Side — chrome tan — resorcinol — formaldehyde retan — unfinished	800
Side — enzyme-unhaired — chrome tan — vegetable retan — finished	5400
Side — double chrome — vegetable retan — mechanical	1500
Calf — zirconium tan — syntan — unfinished	2300
Hide — vegetable tan — chrome retan — unfinished — upholstery	300
Hide — vegetable tan — chrome retan — finished — upholstery	700
Kip — chrome tan — vegetable retan — unfinished	2800
Calf — chrome tan — finished	7100
Calf — vegetable tan — unfinished	9500
SYNTHETIC COMPOSITIONS	
Polyvinyl chloride — 35% di-2-ethyl hexyl phthalate	2100
Rubber-filled	3600
Polyethylene, low-density	12,000

Stiffness of various leathers.—Shown in Table IV are the data that were obtained from a number of commercial light leathers at room temperature. Stiffness values ranged from 300 psi to almost 10,000 psi. No significance should be attached to the specific values for a particular tannage, since any one tanning process could give rise to values in this general range, depending on the raw stock, processing, and kind of leather being manufactured. Plasticized polyvinyl chloride sheets and filled rubbers have apparent stiffnesses in the lower end of this range. The larger values for the light leather approach the approximate stiffness of a low-density polyethylene.

Shown in Table V are the data obtained from some representative commercial sole materials. The stiffness values obtained for sole leathers ranged from about 8,000 psi to 40,000 psi. Synthetic sole materials ranged in stiffness from about 700 to 20,000 psi. Only one synthetic, Neolite, had a stiffness comparable to that of a leather sole. The most flexible sole leather corresponded to the stiffest light leather. It should be pointed out, however, that the value obtained on sole leathers could be changed substantially by mild mechanical working of the sample before the measurements. This was expected, since leather is subjected to large compressive forces during the manufacturing of soles. The values reported in the table are for samples that were mechanically twisted 90° a few times before the measurements were

TABLE V

STIFFNESS IN TORSION OF SOLE MATERIALS

Material	Stiffness, psi
LEATHER	
Vegetable-tanned (lime-dehaired)	39,000
Vegetable-tanned (lime-dehaired)	30,000
Vegetable-tanned (lime-dehaired) (flexible)	20,000
Vegetable-tanned (enzyme-dehaired)	20,000
D.A.S.*-tanned — vegetable retan	15,000
Vegetable-tanned (impregnated)	15,000
Vegetable-tanned (impregnated)	8,000
SYNTHETICS	
Neolite I	18,000
Neolite II	9,800
Neoprene nylon cord	2,000
Vulcanized cork	1,700
Plasticized vinyl	1,100
Paracril-ozo-rubber	700

taken. Once conditioned, the values were quite reproducible. Mechanical conditioning using a 180° twist and subsequent measurement of stiffness in the usual way also gave reproducible stiffness values; however, they were often less than one-half those obtained with the 90° mechanical working. Additional mechanical working at a twist larger than 180° produced apparent stiffness values that were further reduced. The stiffness value of one vegetable sole leather material was reduced from an initial value of about 30,000 to 5,000 psi. Neolite soles showed essentially no change in stiffness when mechanically worked under similar conditions. Leather soles appear unique in their behavior, but this makes it rather difficult to specify their stiffness.

On the other hand, for the light leathers investigated, the stiffness values obtained were generally little changed by mechanical conditioning as described for sole leather. A natural apparent stiffness is built into the hide system during processing and conditioning. This natural stiffness of light leathers of course can be changed by compressing.

Effect of compression on stiffness.—Shown in Fig. 2 is the effect of compression on stiffness, plotted as the log of stiffness versus percent decrease in thickness (compression set) or percent increase in apparent density. The leather specimen from which the data were obtained was a double chrome–heavy vegetable retan–finished mechanical leather. Other light leathers exhibited similar behavior. The compressed thickness was used to calculate the stiffness. Examination of the curve shows that up to 10% decrease in

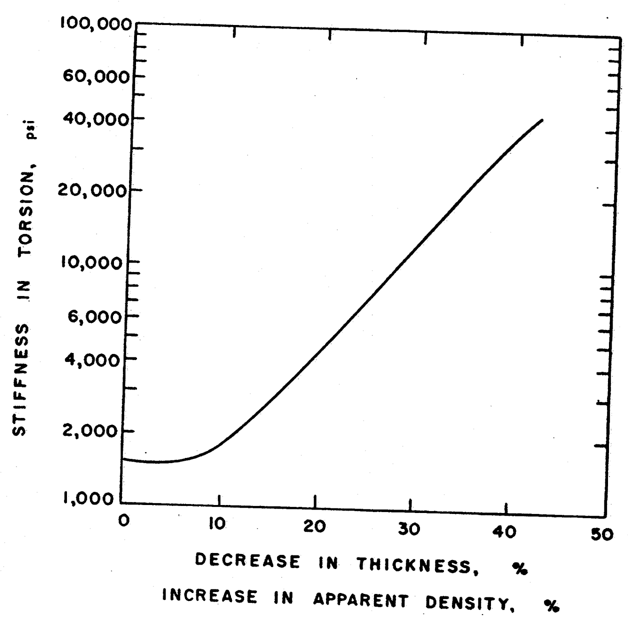


FIGURE 2.—Effect of compression on the stiffness of leather.

in the system, and the matrix as a whole is stiffened. Since the restraints were produced under relatively mild conditions and are, therefore, not permanent in nature, they should be relatively easy to remove. This was observed to be so. After a light-leather specimen which had a compression set of 35% was rolled and unrolled (like a rug) three times, its stiffness value was identical to that of its original stiffness.

Leather is a rather remarkable material in its physical behavior; certainly no homogeneous synthetic material exhibits a similar behavior. It appears that leather has a built-in mechanism which automatically increases its resistance to deformation to large external compressive forces, while it behaves as a relatively soft flexible material when subjected to small external compressive forces.

Effect of temperature on stiffness.—Plotted in Fig. 3 is the log of the stiffness versus temperature in a range of −60° to 80°C. for three randomly selected light leathers and a plasticized polyvinyl chloride. The stiffness of straight leather decreases very gradually and regularly with increasing temperature, while the vinyl plastic shows a sharp decrease in stiffness. The extremely small effect of temperature on stiffness of leather is well known qualitatively by anyone in the leather industry. In agreement with these results are those of Grassmann and Zeschitz (7), who reported that load extension curves of various leathers were essentially the same throughout the temperature range, −70° to 70°C.

Shown in Fig. 4 is the variation in stiffness with temperature for two straight and one impregnated sole leather. The straight sole leather curves

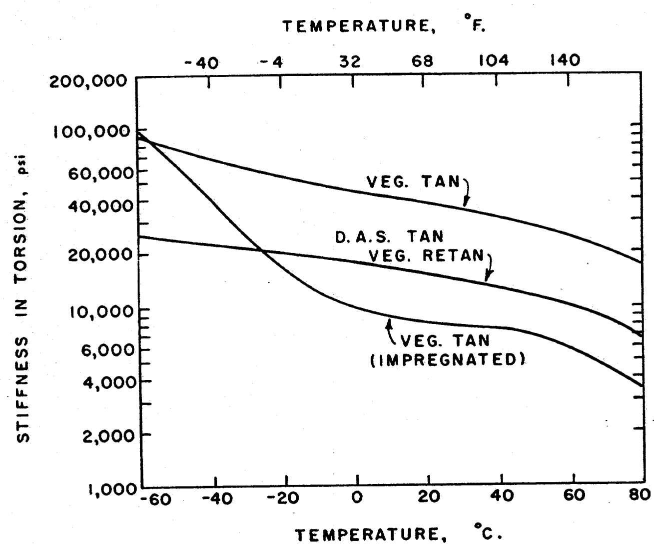


FIGURE 4.—Effect of temperature on the stiffness of sole leathers.

are similar to the light leathers. The stiffness of impregnated sole leathers has a much greater dependence on temperature particularly below 0°C. Other impregnated leathers studied gave similar curves. For comparison purposes Fig. 5 shows the temperature dependence exhibited by synthetic sole compositions.

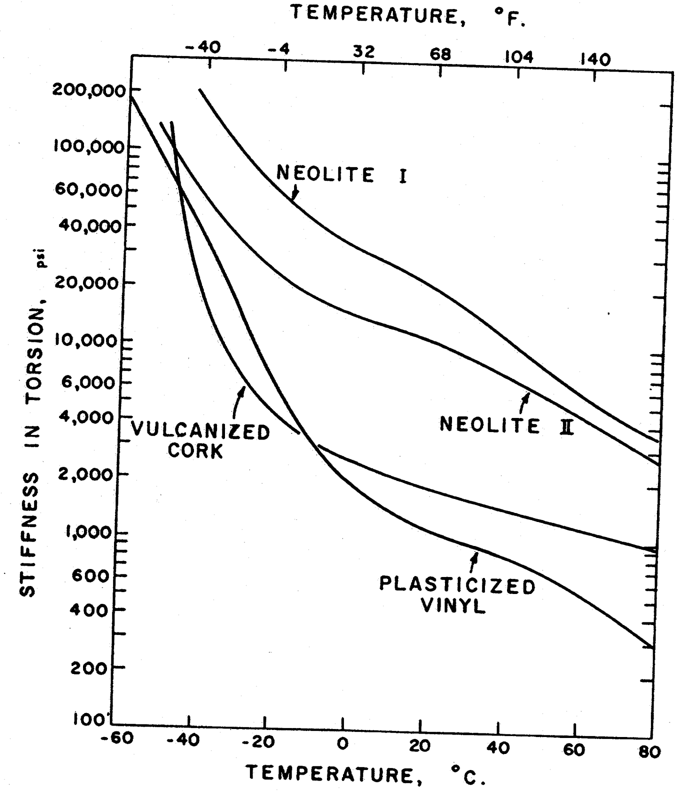


FIGURE 5.—Effect of temperature on the stiffness of synthetic sole compositions.

Two Neolite compositions investigated gave stiffness-temperature curves that were similar in shape; however, they differed in stiffness at any one temperature. Their stiffness decreases relatively rapidly and continuously with increasing temperature over the entire range studied. Below 0°C. the synthetic soles are similar in behavior to impregnated leather. However, above 0°C. the stiffness of the synthetic soles continues to decrease relatively rapidly with increasing temperature, while the stiffness of impregnated leather decreases only slightly.

A Neoprene nylon cord composition and a vulcanized cork composition gave similar stiffness-temperature curves. Only the curve for vulcanized cork is shown. At very low temperatures the decrease in stiffness with increasing temperature is very rapid. Above 0°C. the rate of change in stiffness decreases and becomes similar to that of impregnated leather. However, the stiffness values of these composition soles are less than ¼ those of impregnated leather soles over the entire temperature range studied. These compositions could qualitatively be described as soft rubbery materials at room temperature and above.

One plasticized vinyl sole composition and one carbon black–filled rubber composition sole were also studied. Both gave similar stiffness-temperature curves. Only the plasticized vinyl curve is shown in Fig. 5. Below 0°C. these compositions decrease in stiffness with increasing temperature at a rate between that of the Neolites and vulcanized cork. The rate of decrease is also greater than that of impregnated leather. Above 0°C. the stiffness-temperature curve flattens out to some extent and is similar to that of the Neolites. The stiffness values of these soles at room temperature and above are the lowest of all those tested. These compositions could qualitatively be described as becoming soft and flabby at the higher temperatures.

Since stiffness of the sole of a shoe undoubtedly contributes toward comfort, the leather soles certainly have the more desirable characteristics when temperature variations are encountered. This property is a very desirable one for many other end uses of leather.

REFERENCES

1. Book of ASTM Standards, 1961, Part 9, 448–459 (Method D 638-61T).
2. *Ibid.*, 420–425 (Method D 747-61T).
3. *Ibid.*, 415–419; Part 11, 423–427 (Method D 1043-61T).
4. *Ibid.*, Part 11, 453–461 (Method D 1053–61).
5. ALCA Method E-43.
6. Williamson, I. *British Plastics*, **23**, 87–90, 102 (1950).
7. Grassmann, W., and Zeschitz, E. *Das Leder*, **5**, 145–150 (1954)