

Introduction

Knit fabrics blended of wool and cotton provide warmth, resiliency, comfort, and unique aesthetic appeal that can be diminished by pilling. In normal wear and care, pill formation resulting from the contacts among projecting fiber ends at fabric surfaces can render a garment unwearable without causing garment failure. Ultimately, however, pill formation can cause strength losses in yarns and fabric. Through wear, abrasion loosens and releases surface fibers that entangle, yet are anchored to fibers embedded within the fabric construction. The relative tenacities and elongations of surface and anchor fibers determine the pilling phenomenon. In fact, the increased use of higher strength synthetic fibers in wool-blended fabrics since the 1950's has led to increased pilling.¹ Heightened awareness of pilling has developed with the demand for fabricating lighter fabrics with more fluid drape and comfort to target the casual, professional, and gala-evening apparel markets. Thus fashion and consumer-demand dictate the manufacture of textiles with finer yarn counts, lower twist factors, lighter fabric weights, and more pliable fabric constructions that may be comfortable and resilient but can be less resistant to abrasion.

Extensive study of pill formation, its growth and removal through wear, have led to an understanding of the various stages that develop in pilling. These stages include *initiation* where fibers entangle on the surface, *growth* as fibers pull out and become entangled further, and *wearing away* where the pills break from the anchoring fibers.² In studies of pill density it was shown that rapid pill formation led to high pill density with little pill removal when a strong synthetic fiber comprised the fabric blend of woolen knitwear. Generally in testing to evaluate pilling, laboratory-simulated wear tests are carried out over five to 40 minutes according to standard test methods. In the case of woolen knitwear pretreated for shrink-resistance through oxidative degradation of cystine residues in the proteins of wool with permanganate, it was shown that the pill density after five minutes was most indicative for measuring pill density. Testing for longer periods resulted in pills wearing away, thereby confounding the evaluation.³

There is a rich textile tradition of applying finishes to improve the aesthetic and functional aspects of wool and wool blended fabrics for enhanced end-use performance. The action on wool of acrylic, epoxy, polyamide, polyurethane, polyester, polyurea, and silicone-based resins that adhere mechanically or chemically by graft polymerization through the reactive free amino, thiol, or hydroxyl groups on wool have been the subjects of many studies.^{4,5,6,7,8,9}

The objective of this study was to examine the resistance to pilling of a commercial wool/cotton/nylon blended knit fabric by (a) removing the nylon, (b) by substituting nonchlorinated wool for chlorinated (shrinkproofed), and (c) by applying (to the dyed fabrics) functional finishes that would not impact negatively on fabric handle. Measurements for pilling were performed according to

the standard ASTM visual test method. These results were correlated with a new objective method based on digital image analysis that proved to correlate directly with the standard visual test.

Experimental

Fabric Preparation

Three two-layer jersey fabrics were used in this study. Each of the fabric layers, one layer blended of wool/ cotton/ nylon or wool/ cotton, and the other layer of 100% cotton, was constructed of single jersey knit and the layers were joined in knitting with stitches spaced 0.5 inches apart. The three fabrics are described as follows:

- 50% cotton/ 40% *shrink-treated* wool/ 10% nylon joined to 100% cotton
 - 60% cotton/ 40% *shrink-treated* wool joined to 100% cotton
 - 60% cotton/ 40% *untreated* wool joined to 100% cotton
- **Fabric 1-T**
 - **Fabric 2-T**
 - **Fabric 2-U**

A thirty yard lot (15-20 pounds) of each fabric type was knitted, dyed, padded with softener, dried, and finished by J.E. Morgan Knitting Mills, Inc., Tamaqua, PA.

The intimate blended yarns for each fabric were ring spun to size, 20/1, with 18 twists per inch, by Meritas Yarns, Columbus, GA, from 60s grade wool. The combed cotton yarns were open-end spun to size 20/1.

Dyeing was carried out in a THIES jet dyeing apparatus by a two-bath, two-step sequential process with reactive dye, Levafix Red E2RN, and acid dye, Telon Fast Red ERNA, LR 5:1, for the run time of 8 hours, following conventional reactive and acid dyeing procedures. After dyeing, the fabric was rinsed two times at 100F (37.8C) and a third time at 120F (48.9C) with 0.5% by weight of fiber (owf) Hipochem SS-400, anionic product (Highpoint Chemical Corporation, High Point, NC) to remove surface dye before a final fourth rinse. The thoroughly rinsed fabric was removed and passed through a padder to extract water before drying in a Santex calendaring, finishing bypass oven set to 335 (169C) – input temperature – through which it was passed at a rate of 12 yards / minute for drying at 275 (135C). The calendered fabric was dried in the relaxed state under warehouse climatic conditions. All fabrics were stabilized by this compressive shrinkage process. Garments made from these fabrics carry the label, “machine-wash, gentle – tumble dry, low.

Fabric Finishing

Finishes were applied in triplicate from fabric pieces cut from two-yard lengths of each of **Fabric 1-T**, **Fabric 2-T**, and **Fabric 2-U**. The following finishes were selected:

- Dicrylan WSR, 5% by weight of bath (owb), (Ciba Specialty Chemicals, Greensboro, NC), adurable finish, blend of a nonionic polyurethane (PU) emulsion, anionic polysiloxane and polyisocyanate PU was applied at Ciba Specialty Chemicals by pad/dry/cure with and without Ultrarsof HDP (Ciba Specialty Chemicals), an anionic high density polyethylene, 2% owb, with 0.3% owb sodium bicarbonate. The finished fabrics were cured at 325F (163C) for 4 minutes.
- Synthappret BAP (Bayer Corporation, Pittsburgh, PA), an anionic water soluble bisulfite adduct of isocyanate-polyisocyanate-polyurethane was applied at Scholler, Inc., Philadelphia, in concentrations of 0.5% by weight of fiber (owf), 1.0% owf, 2.0% owf, and 3.0% owf from solutions buffered to pH 7.1 - 7.3. After padding the fabric was dried at 250F (121C) for 5 minutes and cured at 330F (166C) for one minute.
- Glutaraldehyde (Union Carbide) was obtained as a mixture of 50% glutaraldehyde, 50% water and 0.5% methanol and was applied at Schuylkill Haven Bleach & Dye Works, Inc., Schuylkill Haven, PA, as 2.5% owb, pH 4.0-4.5, by padding, then dried and cured on a Santex conveyor dryer (Santamatic 2000-Model #CH-9555) at approximately 270-300F (132-149C).
- Creamoyl WF-1, WF-2, WF-3, and WF-4 (Scholler Inc.) are fatty amide blends with synthetic waxes. Each formulation was applied at Scholler Inc. in concentrations of 6% owf and 10% owf from solutions buffered pH 7.1 - 7.3. After padding the fabric was dried at 250F (121C) for 5 minutes and cured at 330F (166C) for 1 minute. Creamoyl WF-1 is a blend containing a medium molecular weight acrylic polymer and a dimethyl silicone fluid as the primary active components. Creamoyl WF-2 is a blend containing a medium molecular weight acrylic polymer and synthetic waxes as the primary active components. Creamoyl WF-3 is a blend containing a low molecular weight acrylic polymer and a dimethyl silicone fluid as the primary active components. Creamoyl WF-4 is a blend containing a low molecular weight acrylic polymer and synthetic waxes as the primary active components.
- Rhoplex ST 954 (Rohm & Haas Co., Philadelphia, PA), an anionic selfcrosslinking acrylic emulsion (glass transition temperature, $T_g = -23C$) was applied at Rohm & Haas, Spring House Laboratories using two different methods. For fabric pretreatment, 7-8% polymer solids on the weight of the fabric (fabric weight 0.55-0.69 oz/yd²) were applied by padding using 5% bath solids. The impregnated fabrics were simultaneously dried and cured for five minutes at 302F (150C). In the second application, the same polymer add-on was applied with a collapsible foam coating on each side of the fabric. The diluted Rhoplex ST-954 (10% solids formulation) was mechanically foamed to a density of 80-90 gram/liter and coated on the fabric with a 5 mils opening gap. The samples were simultaneously dried and cured for 5 minutes at 302F (150C).
- Freerez 805 MX/ Rhoplex K-3/ Aerotex 3030 (BF Goodrich, Pittsburgh, PA) was applied to the fabrics at Schuylkill Haven Bleach & Dye Works, Inc., as a mixture of Freerez 805 MX, 8% owb, a modified glyoxal resin with <0.1% free formaldehyde, Rhoplex K-3, (a nonionic selfcrosslinking acrylic emulsion, glass transition temperature, $T_g = -27C$, from Rohm & Haas) 2% owb, and Aerotex 3030, 3-5% owb, a hexamethoxymethylmelamine crosslinking agent, Freecat MX Accelerator (BF Goodrich), a buffered magnesium chloride catalyst, lactic acid, 1% owb and Freetex WLM, 1 - 2% owb (BF Goodrich) surfactant as compatibilizer for solubility. The solution was diluted with 100F

(38C) water to volume for the pad solution. The treated fabric was extracted through rubber rolls to moisture content of 130F (54C), dried in a conveyor dryer at 300F (149C) for three minutes, and cured at 310F (149C) for 2 minutes.

Pilling Evaluation

Prior to testing for pilling the dyed fabrics were laundered and dried one time following AATCC Test Method 135, "Dimensional Changes in Automatic Home Laundering of Woven and Knit Fabrics." The laundering procedure was as follows: machine wash normal agitation (AATCC detergent 1993), 120F (49C) wash temperature, tumble dry, delicate. The laundered fabric samples were conditioned at 70F (21C), 65% relative humidity for 24 hours. Pill testing was performed according to ASTM D3512, 1997, "Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics." The Random Tumble Pilling Tester was selected for this study. The standard visual test, based upon photographic standards, was used to evaluate pilling on a scale of five (no pilling) through one (most severe pilling). Three evaluators were used for visual assessment of three fabric replicates for each of **Fabric 1-T**, **Fabric 2-T**, and **Fabric 2-U** and the pilling ratings were averaged as shown in Tables 1 and 2.

The visual results were compared to those obtained by image analysis. The configuration of the image analysis components was as follows: an angular adjustable ring light consisting of eight lights arranged in a circular manner was set at a low lighting angle and positioned 12.7 mm from the fabric samples. All fabrics were positioned with the wool blend side facing the camera and all were at the same viewing angle. Three measurements were made for each of the three fabric replicates (one at the center, and one on each of two corners of an imaginary diagonal line across the fabric). The area of interest (AOI) was a 30 mm diameter circle (7.068 cm² area). A power regulator was utilized to maintain constant light intensity. The numbers of pills were recorded automatically as light objects in an 8-bit gray scale image that fell within the limits of the derived macro. Comparisons with the standard visual method are shown in Table 3.

Results

In preliminary investigations to screen finishes applied to a similar two-layer jersey knit fabric, 65% cotton/ 25% wool/ 10% nylon joined to 100% cotton jersey manufactured by J.E. Morgan Knitting Mills, Inc. for the purpose of improving pilling resistance, a five minute random pill test was established as the testing condition. Pills formed within five minutes of starting the test. After five minutes, with further prolonged tumbling to 30 minutes, pills increased and the fabric surface became severely degraded. The finishes shown in Table 1 below were selected from this screening test, applied to **Fabric 1-T**, and evaluated after a five-minute pilling test.

Table 1. Average Pilling Ratings for Wool/ Cotton/ Nylon Finished Fabrics 1-T

Sample Finishes	Ratings for RandomPilling Standard Visual Test	
Control, (dyed, unfinished)		1.5
Dicrylan WRS, 50% with 20% Ultrasof HDP		2.5
Dicrylan WRS, 50% without 20% Ultrasof HDP		2.5
Synthrapret BAP, 0.5%		1.5
Synthrapret BAP, 1.0%		1.5
Synthrapret BAP, 2.0%		1.5
Synthrapret BAP, 3.0%		2.5
Glutaraldehyde 2.5%		1.0
Creamoyl WF-1 6%		2.5
Creamoyl WF-1, 10%		2.5
Creamoyl WF-2, 6%		2.5
Creamoyl WF-2, 10%		3.5*
Creamoyl WF-3, 6%		3.0
Creamoyl WF-3, 10%		3.5*
Creamoyl WF-4, 6%		2.0
Creamoyl WF-4, 10%		3.0
Rhoplex ST 954, 5% pad/dry/cure		3.0
Rhoplex ST 954, 10% collapsible foam		2.0
Freerez 805 MX, 10%		3.0
Freerez 805 MX/ Rhoplex K-3/ Aerotex 3030		4.0*

* Finishes resulting in these ratings were applied to **Fabrics 2-T**, and **Fabrics 2-U** having no nylon. The results of applying the best performance finishes for pill resistance, Creamoyl WF-2, 10%, Creamoyl WF-3, 10%, and Freerez 805 MX/ Rhoplex K-3/ Aerotex 3030 are found in Table 2.

Table 2. Average Pilling Ratings for Nylon-Free Finished Fabrics 2-T, and Fabrics 2-U

Fabric Samples	Ratings for RandomPilling Standard Visual Test	
	Fabric 2-T	Fabric 2-U
	60% Cotton/ 40% Treated Wool	60% Cotton/ 40% Untreated Wool
Control (unfinished)	2.5	1.5
Creamoyl WF-2, 10%	4.0 *	2.0
Creamoyl WF-3, 10%	3.5	1.5
Freerez 805 MX/ Rhoplex K-3/ Aerotex 3030	5.0 *	4.0 *

*Fabric blends without nylon (Fabrics 2-T and 2-U) can exhibit higher ratings than those containing nylon (Fabrics 1-T).

Digital Image Analysis for Pilling Evaluation

A new image analysis system consisting of a charged-coupled-device camera, computer, frame grabber, and supporting imaging software also was used to evaluate pilling.¹⁰ The method, developed for this study, had a correlation coefficient of 0.993 when pill ratings derived from it were compared to those obtained by the visual ASTM D 3512 Photographic Standards for Pilling.¹¹ However, the three dimensional effects of the fabrics were thought to affect uniform illumination. To overcome this diffi-

culty, a mathematical macro was written that included area and length-to-breadth ratios of the shapes of individual pills as shown in Figure 1.

A regression analysis was performed comparing the pilling of the fabrics in Table 3 by the image analyzer to the pilling determined by the standard visual method. The resulting graph is shown in Figure 2 and is of the form:

$$y = 1.2525732 + 301.31708 * x^{-3.3204688} \quad (1)$$

where “x” refers to the number of pills determined by the image analyzer and “y” refers to the rating determined visually. The correlation coefficient of 0.984 shows an excellent correlation. The visual pilling rating, the pilling predicted using image analyzer data and equation 1, and the percent difference in the results obtained when using these two methods is shown in Table 3. Note that the average root mean square difference of the predicted pilling rating from image analysis and the visual pilling rating is only 4.48% or very good.

Table 3. Pilling Ratings by Visual Assessment and Digital Image Analysis

Sample Identification	Average Visual Pilling Rating (y)	Image Analysis Pilling Rating (x)	Difference, % [(x-y) / y] x 100
Control	1.50	1.44	-4.00
Synthrapret BAP, 1.0%	1.40	1.45	3.57
Glutaraldehyde, 2.5%	2.00	2.13	6.50
Dicrylan WRS, 5% with Ultrasof HDP	2.50	2.37	-5.20
Creamoyl WF-2, 10%	3.56	3.45	-3.09
Creamoyl WF-3, 10%	3.33	3.45	3.60
Average Root Mean Square Difference			4.48

Scanning Electron Microscopy

Random tumble pilling specimens were examined using a Scanning Electron Microscope in an effort to determine if the presence of nylon fibers caused greater pilling. A difference in fabric appearance was noted between **Fabric 1-T** (Figure 3a) and **Fabric 2-T** (Figure 3b), both laundered once and subjected to the pilling test. In Figure 3a there appears to be more surface roughness indicating a greater tendency for pill formation when nylon fibers are present in the fabric construction whereas in Figure 3b, the fabric construction is more clearly defined. Close examination in Figure 4 indicated that few nylon fibers appeared on the outside of pills. They were located within the pills where nylon appears to be both anchored to the fabric with cotton (note characteristic twists in cotton fibers) and wool (note characteristic scales) entangled about it and moving upward through the pill.

Discussion and Conclusion

The data show that in blends of wool treated by chlorination for shrink-proofing, **Fabrics 1-T and 2-T**, there is less tendency to form pills. Supposedly, shrinkproofing processes attack and soften the scale tips so that the wool scales lie flat on the fiber surface during washing with alkali.¹² In addition, the use of polymers to render wool unshrinkable has been described as “scale-masking” because with a uniform film-like deposit, wool becomes unshrinkable and its directional friction effect is decreased so that interfiber adhesion is prevented.¹³ Indeed this study shows that treated **Fabrics 1-T and 2-T** were more pill resistant than untreated **Fabric 2-U**.

A cost comparison of the blended yarns fabricated with treated and untreated wool, with or without nylon fibers is presented in Table 4. The analysis assumes that the only cost variable will be in that fabric layer containing the wool-blended yarn.

Table 4. Yarn Cost Comparisons for Fabrics 1-T, 2-T, and 2-U

Fabric Description	Base Cost of Yarn / Pound	Cost Difference/Pound versus Fabric 1-T
Fabric 1-T 50% Cotton/ 40% Treated Wool / 10% Nylon	\$3.15	
Fabric 2-T 60% Cotton/ 40% Treated Wool	\$3.09	\$0.06
Fabric 2-U 60% Cotton/ 40% Untreated Wool	\$2.99	\$0.16

By removing nylon there is almost a \$0.06 saving in the treated wool blend and a \$0.16 saving in the untreated wool blend. For a typical end-use, a men's button-front shirt weighing 13.5 pounds per dozen, this represents a savings of \$0.76 per dozen or a savings of \$0.06 per shirt. In the case of the untreated wool blend, removing nylon represents a savings of \$2.12 per dozen or \$0.18 per shirt. Removing nylon therefore can offer the customer a product with good pilling resistance and cost savings to the manufacturer.

When polymer finishes were applied to the blends containing treated wool with nylon fibers, in **Fabrics 1-T**, the glyoxal, acrylic, polyurethane, and polysiloxane-based resins were not as effective as the soft acrylic (low T_g) resins combined with dimethylsiloxane, synthetic waxes, glyoxal, and melamine. The latter provided adequate pilling resistance in the nylon-free blends containing untreated wool, **Fabrics 2-U**, and excellent resistance in the blends without nylon combining cotton with treated wool, **Fabrics 2-T**. This work also showed that wool blended fabrics exhibit less tendency to form pills when nylon is omitted from the wool/ cotton blend. This was established by visual assessment of pill formation using photographic standards and by a new image analysis method based upon the measurement of pill shape in terms of its length and breadth.

Pilling can conceivably be controlled by many variables that include the following: choice of staple fiber by fineness and length; choice of yarn type by the amount of twists per inch; and choice of fabric construction by yarn configuration. However, fashion dictates may preclude appropriate selections that prevent pilling. The results of this study indicate that untreated wool/cotton textiles blended with nylon can be made resistant to pilling provided the appropriate finish is applied. By removing nylon from blends of untreated and treated wool with cotton, the appropriate finish can impart high pilling resistance. Yet there is still a pressing need for an alternative to fabric finishing for alleviating pilling in untreated wool blends with cotton.

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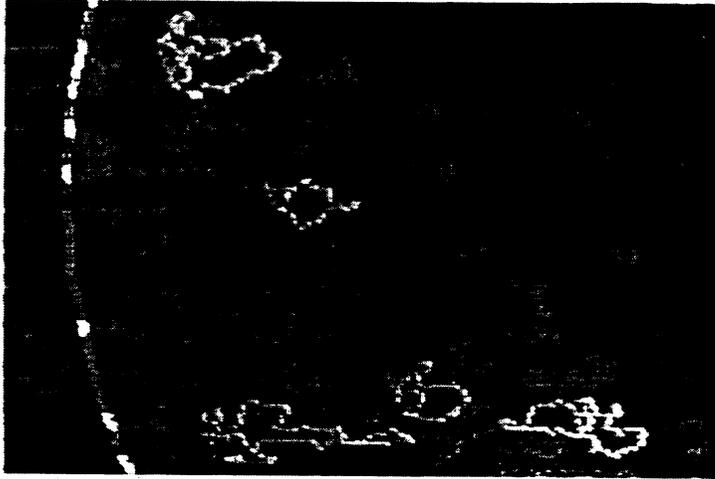


Figure 1. Area and length-to-breadth ratios of the shapes of individual pills as recorded by image analysis

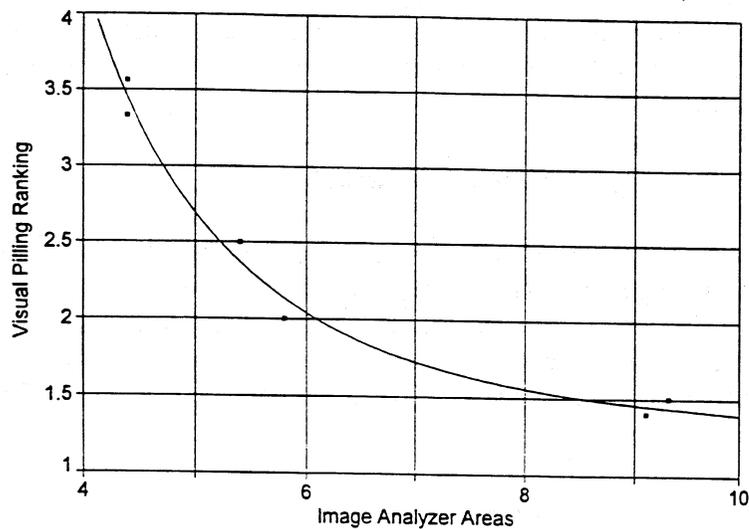


Figure 2. Graph illustrating the comparison of pilling areas automatically selected using an image analyzer and the visual ranking of pilling established by a panel of judges using the ASTM D3512 photograph standards.

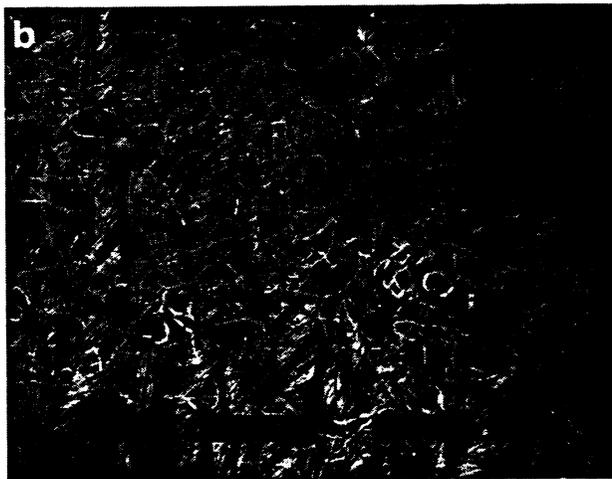
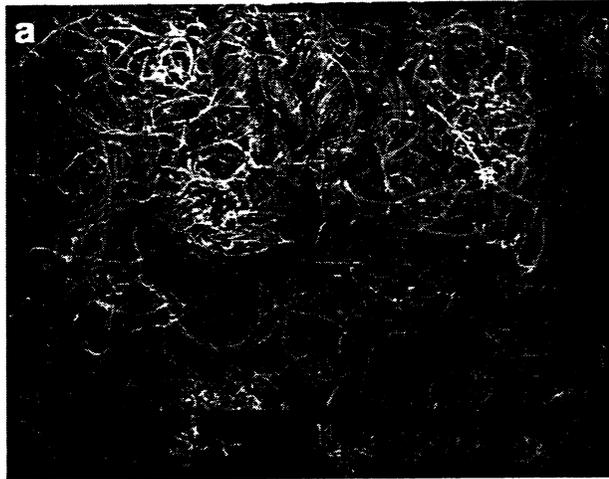


Figure 3. Scanning electron photomicrographs showing pilling: (a) – **Fabric 1-T** containing nylon and (b) – **Fabric 2-T** without nylon.



Figure 4. Scanning electron photomicrograph showing nylon fiber at the interface of pill and fabric surface in **Fabric 1-T**.