Gauge Length Effect on the Tensile Properties of Leather

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ABSTRACT: Tensile properties are important basic characteristics of materials and influence their end-use and performance. More importantly, in the case of leather due to end-use applications such as shoe uppers, automotive and furniture upholstery, mechanical properties such as tenacity are of extreme importance. Therefore, fundamental studies on the tensile properties of leather are needed. In this study, an attempt has been made to examine the effect of gauge length (GL) on the tensile properties of shoe upper leather. Two different specimens in the form of rectangular and dumbbell shapes have been cut from parallel and perpendicular directions to the body axis of the leather and have been tested. Results showed that the maximum breaking load and the percentage extension at break decreased with the increase in GL. Rectangular specimens showed a 30% decrease in maximum breaking load and a 13% decrease in percentage extension at break, while dumbbell specimens showed reductions in the order of 28 and 6%, respectively, as the GL increased from 9.53 cm to 23.5 cm. Highly varying supramolecular architecture of the collagen matrix and the frictional slippage caused by the free ends present in the collagen fibrils, which induce a weak-link effect similar to the one found in cotton fibers and yarns, are considered to be the probable reasons for this behavior. A limited scanning electron microscopic study has been undertaken to pictorially represent the breakage of leather at different GLs. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 1202–1209, 2006

Key words: fibers; viscoelastic properties; electron microscopy; strength; failure; structure

INTRODUCTION

Tensile strength of a material is the maximum amount of tensile load it can be subjected to before it leads to failure. Tensile characteristic is an important property as it relates to structural integrity, strength, and performance of the material. The theoretical strength of any material is estimated on the basis of the rupture strength of chemical bonds, which is never realized in practice. This is due to the presence of flaws that lead to localization of stress in excess of the theoretical stress and initiate the rupture process.[1] Therefore, it is logical to expect a decrease in breaking load with an increase in gauge length (GL) due to the presence of weak links.[2] The probability of increase in weak spots or links increases with the increase in GL. Peirce[3] proposed the "chain weak link" theory based on the data of the breaking strength of 10 and 30 in. of cotton yarns of a single yarn count. Duckett et al.[4] used this theory and resulting empirical relations to determine the true zero GL of single cotton fibers. Smith worked out an improvement on Peirce's theory and applied it to yarns.[5] Knox and Whitwell[6] used hazard function as a sensitive test for Peirce's data on cotton yarns and those of Morceton[7] on carbon filaments including their own data on viscose rayon filaments. They concluded that these materials cannot be represented as systems of simple links connected in series. As is evident from aforementioned brief discussions, to the best of our knowledge, there is no published information on the influence of GL on the tensile characteristics of leather.

Leather is a material derived from the permanent stabilization of a biopolymer, collagen.[8] The viscoelasticity nature of leather provides desirable mechanical properties such as strength and softness. Leather can be prepared to have maximum strength with less softness as used in shoe upper or sole. On the other hand, it is also possible to make it very soft with relatively low strength as used in apparels and gloves. Leather processing plays a vital role in determining its strength and softness.[9] Studies have been conducted relating the collagen fiber length with its mechanical properties.[10,11] Mitton and Morgan showed that an increase in collagen fiber length gives a decrease in strength and breaking extension.[10] Rajaram et al.[11] reported that there is a marked difference in the mechanical properties between collagen fibers of short lengths and those of longer ones. They explained this behavior on the basis of the internal friction and probable length of fibrils. As is evident from the aforemen-

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tioned discussions, the arrangement of the basic unit, structure, and the viscoelastic nature influence the mechanical properties of leather.

In this study, an attempt has been made to examine the effect of GL on the tensile properties of shoe upper leather. Results from the tensile tests, such as maximum load at break and percentage extension at break on dumbbell shaped specimens and rectangular shape specimens of varying GLs have been compared and analyzed. Dumbbell is the standard shape that is normally used in the standardized tensile testing of leather. The rectangular shape has been chosen to undertake a comparative study. Leather being a natural material, its strength varies along and across the backbone directions. Average of these values is generally regarded as the strength of leather. In this study, results from parallel and perpendicular directions to the backbone of the leather have been compared with that of their average values. Detailed analysis of the results is presented in this paper. Scanning electron microscopic (SEM) analysis of a few select broken samples has been carried out to have a quick understanding of the mechanism of fracture.

EXPERIMENTAL

Materials used

Full-grain resin-finished shoe upper leathers were procured from S.B. Foot Tanning Co., Minnesota. Thickness of the leather samples was 2.1 ± 0.1 mm per the ASTM D-1813 standard.[12] Apparent density of the leather samples was 0.79 ± 0.03 g/cm^3 per the ASTM D-2346 standard.[12]

Methods and measurements

A standard tensile testing procedure (ASTM D-2209) was used for all the measurements except the length of the leather specimen, which varied from 9.53 to 23.5 cm.[12] The standard GL for tensile testing of leather as recommended by the ASTM is 12.07 cm.[12] Hence, GLs were chosen such that the values were both lower as well as higher than that of standard GL. In this study, the various GLs used were 9.53, 10.80, 12.07, 14.61, 18.42, and 23.50 cm. Because of large sample size requirements, samples were cut from the butt portion of the leathers. Care was taken to cut the samples in and around the standard sampling[13] position. Dumbbell and rectangular shaped specimens were cut from two separate shoe upper leathers. The width of the rectangular specimens was 12.7 mm, as per the ASTM standard.[12] In this study, the GL is taken as the length of the specimen between the two grips, to be precise, the distance between the top edge of the bottom grip and the bottom edge of the top grip. This procedure was convenient for sample cutting and testing. For each GL, duplicate specimens were cut from parallel and perpendicular directions to the backbone of the leather. Dumbbell-shaped specimens were cut using steel dies and rectangle-shaped specimens were cut using cardboard patterns and knife. All specimens were conditioned at 23.0 ± 2.2°C and 52 ± 2% relative humidity over a period of 48 h. Universal testing machine (Instron, Model 5569) was used for breaking the leather samples. The rate of extension of crosshead was maintained at 275 mm/min.[12] Maximum load at break and the percentage extension at break (extension at break/GL × 100) were obtained from the tensile studies and were used for further analysis.

Scanning electron microscopic analysis

The broken rectangular and dumbbell leather specimens cut perpendicular to the backbone direction at GLs 9.53, 12.07, and 23.5 cm were collected after tensile testing. For comparison, an unbroken sample was cut from the sampling position[13] of the shoe upper leather. The specimens with the broken edge were cut into small samples and coated with gold–palladium to a thickness of 200 Å using Technics Hummer V sputter coater. The samples were analyzed using a Hitachi *S*-570 scanning electron microscope at an accelerating voltage of 6 KV and 8 KV and at a magnification of ×4000.

RESULTS AND DISCUSSION

Tensile properties of rectangular specimens at different GLs

As briefed in the introduction, the primary aim of this work was to examine the effect of GL on the tensile properties of leather. Rectangular specimens are simple shapes and easy to prepare when compared with the standard dumbbell shape required for tensile testing of leather. Also in the past, rectangular specimens were used in testing light leathers; including shoe upper leather.[14] Dumbbell shape has wide ends and a narrow middle portion. The grips of the tensile tester hold the specimen firmly at the wide ends. The connection between the wide ends and the narrow middle is through the reducing contours from the wide ends to the narrow middle portion. This helps in concentrating the applied load towards the narrow test area or the center of the specimen.[14] On the other hand, the stress concentration mechanism is not available in the rectangular specimens and hence the fracture can occur any point between the grips holding the specimen. This method of breaking will be able to better reflect the effect of GL on the tenacity of leather.

Maximum breaking load and percentage extension at break values of the shoe upper leather in parallel, perpendicular to the backbone directions of the leather

TABLE I
Maximum Breaking Load and Percentage Extension at Break Values of Upper Leather Tested Using Rectangular Specimens at Various Gauge Lengths[a]

Gauge length (cm)	Maximum breaking load (kgf)	Extension at break (mm)	Percentage extension at break
Parallel to the backbone			
9.53	52.6 ± 3.2	55 ± 0.8	58
10.80	48.1 ± 0.6	59 ± 0.4	55
12.07	50.0 ± 0.3	71 ± 2.8	59
14.61	45.8 ± 3.6	77 ± 1.9	53
18.42	45.3 ± 0.2	103 ± 2.4	56
23.50	37.4 ± 2.2	123 ± 2.7	52
Perpendicular to the backbone			
9.53	66.8 ± 1.0	39 ± 0.1	41
10.80	60.4 ± 1.6	42 ± 0.4	39
12.07	62.4 ± 0.3	52 ± 1.3	43
14.61	60.2 ± 1.4	62 ± 2.5	42
18.42	53.3 ± 1.6	75 ± 4.0	41
23.50	46.2 ± 2.4	80 ± 6.0	34
Average of parallel and perpendicular directions			
9.53	60.1 ± 7.1	—	49.5±8.5
10.80	54.2 ± 6.1	—	47±8.0
12.07	56.2 ± 6.2	—	51±8.0
14.61	53.0 ± 7.2	—	47.5±5.5
18.42	49.4 ± 4.0	—	48.5±7.5
23.50	41.8 ± 4.4	—	43±9.0

[a] Maximum breaking load and extension at break values are given as the average of duplicate measurements along with standard error values.

for rectangular specimens at different GLs are given in Table I. As is evident from the results, the breaking load decreases with the increase in GL. This trend is evident when the leather is tested both along and across the backbone directions. Results show that tenacity values of leather are higher when the leather was broken across the backbone direction. This may be due to the anisotropic arrangement of collagen fibers in the leather matrix. However, this trend is not seen in dumbbell specimens. Plots of maximum breaking load versus GL are shown in Figure 1(a, b) for parallel and perpendicular directions, respectively. It is seen that the decreasing trend of maximum load seems to fit linearly for both directions and have negative slopes. Negative slopes confirm that the maximum load at break is decreasing with the increase in GL in both directions. This is in accordance with the earlier observations in cotton yarns.[2]

The percentage extension at break also seems to follow a similar trend to that of the maximum load at break as shown in Table I. However, the extent of decrease is low compared with the maximum load. The decrease in percentage extension at break for GL increasing from 9.53 cm to 23.5 cm is 58 to 52% in parallel direction and 41 to 34% in perpendicular direction. Figure 2(a, b) shows the plot of percentage extension at break versus GL for parallel and perpendicular directions. Again, it is seen that the percentage extension at break is decreasing with the increase in GL with a negative slope when fitted linearly.

The average values of the maximum breaking load and percentage extension at break in parallel and perpendicular directions are also provided in Table I. The average load at break is decreasing almost uniformly from 60.1 kgf to 41.8 kgf with the increase in GL from 9.53 cm to 23.5 cm. The percentage extension at break also decreases from 49.5% to 43% with the increase in GL. Hence, on average, there is a 30% decrease in the maximum load and a 13% decrease in percentage extension at break with the increase in GL from 9.53 cm to 23.5 cm. Figure 3(a, b) shows the plot of average breaking load versus GL and average percentage extension at break versus GL. As is evident, the relationship can be represented linearly with a negative gradient. It is evident that the average values of the breaking load and percentage extension at break have negative slopes when related with GLs. This result concurs with the earlier results obtained in parallel and perpendicular directions and shows that GL influences the tensile values of leather.

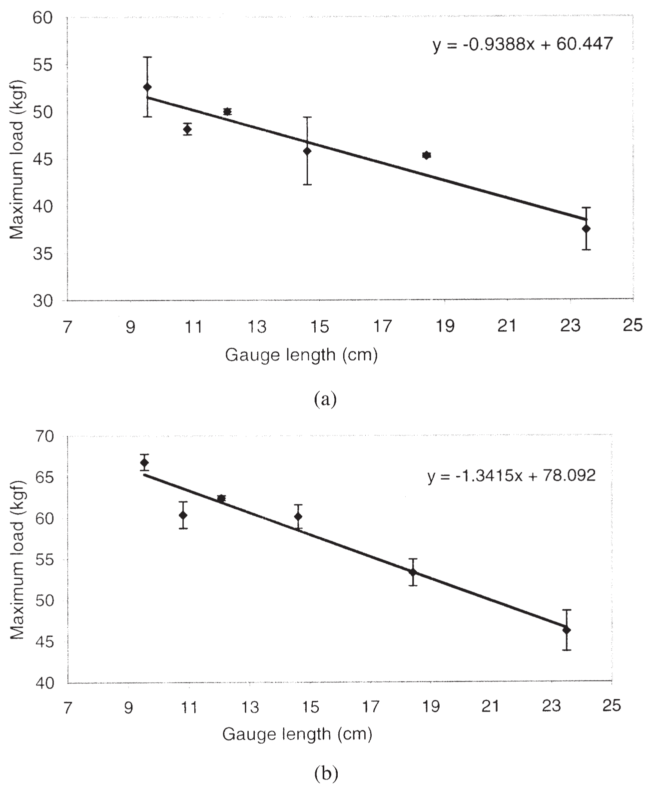

Figure 1 Maximum breaking load versus GL (a) along the backbone direction of rectangular specimen; (b) across the backbone direction of rectangular specimen.

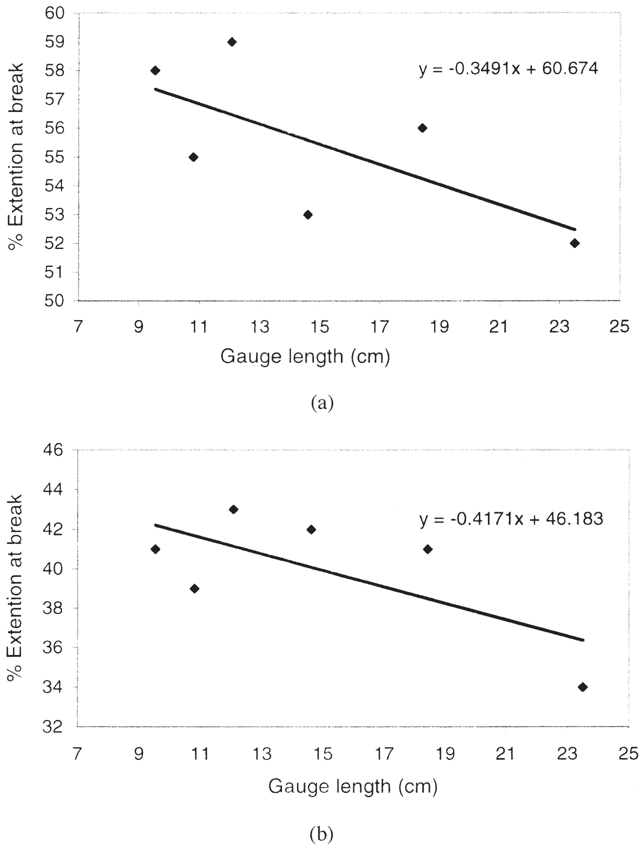

Figure 2 Percentage extension at break versus GL (a) along the backbone direction of rectangular specimen; (b) across the backbone direction of rectangular specimen.

Tensile properties of dumbbell specimens at different GLs

Maximum breaking load and percentage extension at break values of the shoe upper leather tested at various GLs for the dumbbell specimens in both parallel and perpendicular directions to the backbone and their average values are given in Table II. In general, the values of maximum breaking load and percentage extension at break derived from rectangular and dumbbell specimens are not comparable. This could be due to the difference in the stress concentration effect in rectangular and dumbbell specimens. It is seen that the maximum load decreases from 90.2 kgf to 51.3 kgf with the increase in GL from 9.53 cm to 23.5 cm for the dumbbell specimens cut parallel to backbone. The huge standard error values for the specimens having GL of 9.53 and 10.80 cm demonstrate the variations in the fiber structure or the fiber weave pattern within a hide and especially within a particular area,[15] in this case the butt portion of the leather. In the case of dumbbell specimens cut perpendicular to the backbone direction, the decrease is from 59.6 kgf to 57.1 kgf. The plot of maximum breaking load at break versus GL for the dumbbell specimens cut parallel and perpendicular directions to backbone is shown in Figure 4(a, b). It is seen that the relationships are fairly linear with negative slopes. Results indicate that there is a decreasing trend in breaking load values with the increase in GLs.

The percentage extension at break in both parallel and perpendicular directions does not follow a particular pattern with the increase in GL. However, in general, a decreasing trend is seen as shown in Figure 5(a, b) as evidenced by negative gradient. Average values of the maximum breaking load and percentage extension at break for parallel and perpendicular directions are given in Table II. As is evident, the maximum load at break decreases from 74.9 kgf to 54.2 kgf as the GL increases from 9.53 cm to 23.5 cm. On the other hand, the percentage extension at break increases and then decreases without following a particular pattern. However, a decreasing trend is evident for both properties as shown in Figure 6(a, b) as indicated by negative slopes. On average, there is a 28% decrease in the breaking load and 6% decrease in percentage extension at break as the GL increases from 9.53 cm to 23.5 cm for dumbbell specimens.

An interesting observation made from Figures 3(a) and 6(a) is that the effect of GL on decreasing breaking

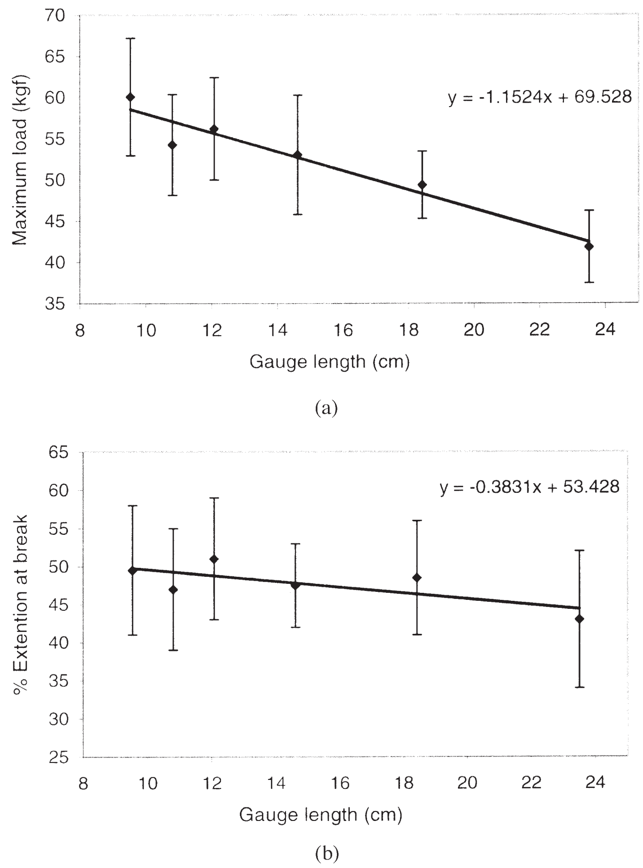

Figure 3 (a) Maximum breaking load versus GL (average of along and across the backbone direction of rectangular specimen). (b) Percentage extension at break versus GL (average of along and across the backbone direction of rectangular specimen).

TABLE II
Maximum Breaking Load and Percentage Extension at Break Values of Upper Leather Tested Using Dumbbell Specimens at Various Gauge Lengths[a]

Gauge length (cm)	Maximum breaking load (kgf)	Extension at break (mm)	Percentage extension at break
Parallel to the backbone			
9.53	90.2 ± 12.7	43 ± 3.7	45
10.80	85.3 ± 23.4	51 ± 3.5	47
12.07	65.6 ± 1.1	64 ± 1.9	53
14.61	72.2 ± 2.7	79 ± 2.4	54
18.42	64.6 ± 9.4	92 ± 6.7	50
23.50	51.3 ± 2.3	96 ± 13.7	41
Perpendicular to the backbone			
9.53	59.6 ± 0.1	42 ± 5.8	44
10.80	63.3 ± 1.7	48 ± 4.4	44
12.07	56.6 ± 4.4	53 ± 7.7	44
14.61	61.8 ± 5.0	65 ± 4.6	45
18.42	57.1 ± 1.5	83 ± 6.8	45
23.50	57.1 ± 0.5	101 ± 7.1	43
Average of parallel and perpendicular directions			
9.53	74.9 ± 15.4	—	44.5±0.5
10.80	74.3 ± 11.0	—	45.5±1.5
12.07	61.1 ± 4.5	—	48.5±4.5
14.61	67.0 ± 5.2	—	49.5±4.5
18.42	60.9 ± 3.8	—	47.5±2.5
23.50	54.2 ± 3.0	—	42±1.0

[a] Maximum breaking load and extension at break values are given as the average of duplicate measurements along with standard error values.

load is small in the 9–15 cm range, while its effect is predominant at higher GL range. This may be due to the presence of more number of weak links or free fiber ends at higher GLs. The sampling constraints as well as the nonavailability of leather in higher length and width pose difficulty in carrying out studies beyond 25 cm GL.

Scanning electron microscopic study

Select broken leather specimens after the tensile study have been subjected to SEM analysis. Scanning electron micrographs of broken leather specimens show that the fiber bundles are split into fibers. This phenomenon seems to be similar to that observed when polyester fibers were subjected to tensile fatigue.[16] Scanning electron micrographs of rectangular and dumbbell leather specimens broken at select GLs, at a higher magnification (×4000) are shown in Figure 7(a–g) along with an unbroken leather cross-sectional image. The micrographs show that, on average, the diameter of the fiber is 4.5 ± 1.5 μm. All the broken leather specimens show fibers with striations or kink bands. These striations or kink bands were observed in polyester fibers, viscose rayon fibers and wool carpet yarns, when they were subjected to tensile fatigue or flex fatigue testing.[17] Hence, the fracture may be initiated by the formation of striations due to the concentration of stress in the free ends of fibrils, fibers, and fiber bundles resulting in slippage and hence breakage. In addition, the striations lead to the fracture of fiber bundles at the weakest point and also the splitting of fiber bundles into fibers. This brief study as shown in Figure 7(a–g) showed the process of leather breakage at various GLs. Immediate understanding is that predominantly the breakage is due to the slippage of individual fibers. Catastrophic failure of individual fibers also took place although not predominant. This preliminary study warrants further elaborate SEM study.

Plausible reasons for the decrease in tensile properties of shoe upper leather with increase in GL

Results from the present study show a decreasing trend for the tensile properties such as the maximum breaking load and percentage extension at break with the increase in GL for the shoe upper leather. This result is evident for both rectangular and dumbbell

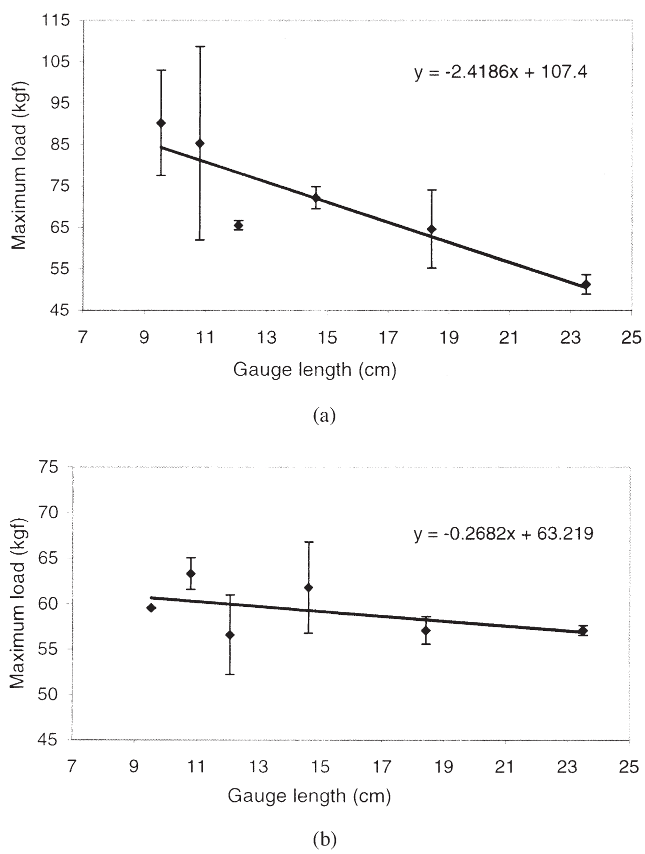

Figure 4 Maximum breaking load versus GL (a) along the backbone direction of dumbbell specimen; (b) across the backbone direction of dumbbell specimen.

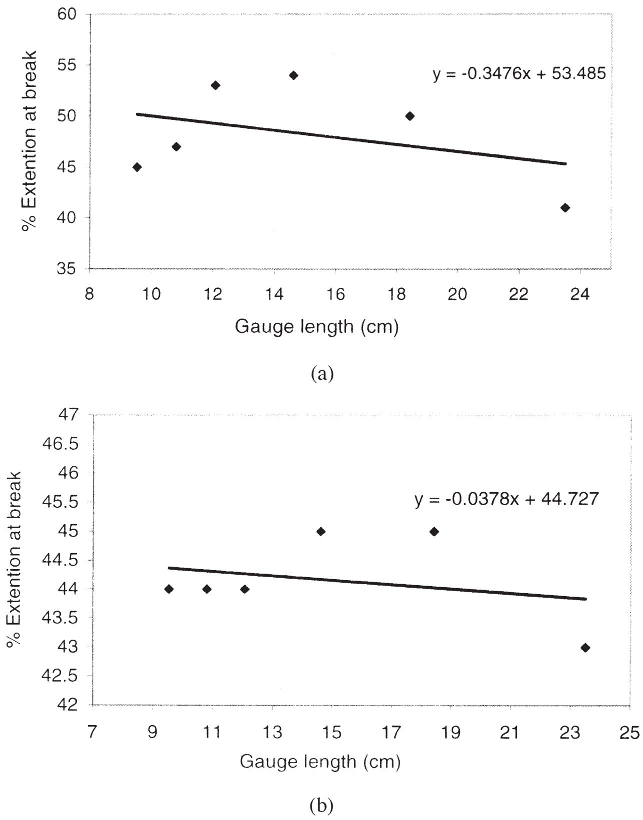

Figure 5 Percentage extension at break versus GL (a) along the backbone direction of dumbbell specimen; (b) across the backbone direction of dumbbell specimen.

specimens in both directions of testing. This is in accordance with the earlier studies with cotton yarns and related fibers.[2] Previous studies presented a "weak link" theory as the probable mechanism for the decrease in tensile strength of cotton yarns and fibers with increase in the GL.[2–7] It was based on the presence of flaws on a system of chemical bonds. However, leather is a highly complicated system to apply such a chemical bonding-based theory alone. To illustrate this point, let us consider two systems, namely dry collagen fibers and tanned collagen fibers. Following the method used by Meyer and Mark[18] for collagen fibers, it may be calculated that the theoretical strength of a dry collagen fiber would be about 290 kg/mm^2, if the mechanism of rupture consisted of breaking the covalent bonds (the C—N bond of 1.4 Å in length with energy of 48.6 kg cal/mole). However, this is almost 30 times higher than the observed tensile strength of collagen fibers.[11,19] If the mechanism of rupture of a collagen fiber under stress is similar to that discussed above, it is clear that the introduction of any new linkages between neighboring polypeptide chains will tend to resist the slippage of the chains over each other, and therefore, lead to an increase in tensile strength. Tanned collagen fibers, in principle, possess such additional linkages introduced during the tanning process, also known as crosslinking.[9] However, the tanning process does not increase, but decrease the tensile strength of raw or untanned collagen fibers. It has been shown that the formaldehyde tanned collagen fibers, which have additional methylene bridges between the polypeptide chains, show greatest decrease in mean breaking length among all the tannages investigated, which includes vegetable tannins that do not introduce any appreciable crosslinking.[19] This shows that the leather is a highly complicated system to apply a chemical bonding-based theory alone. Therefore, it is logical to justify the presence of weak links or spots at extended specimen lengths to be one of the reasons for the decreasing breaking load values.

The tensile strength of leather and its resistance to stretching vary greatly over the entire area of a skin. These properties vary also according to the kind and age of the animal, degree of the tannage, the chemical composition, and the degree of splitting.[15] Rajaram et al.[11] proposed the internal frictional slippage and the variations in the length of collagen fibrils as probable reasons for tenacity variations at molecular level. Since the collagen fiber bundle is composed of individual fibrils, which may have varying length, there is

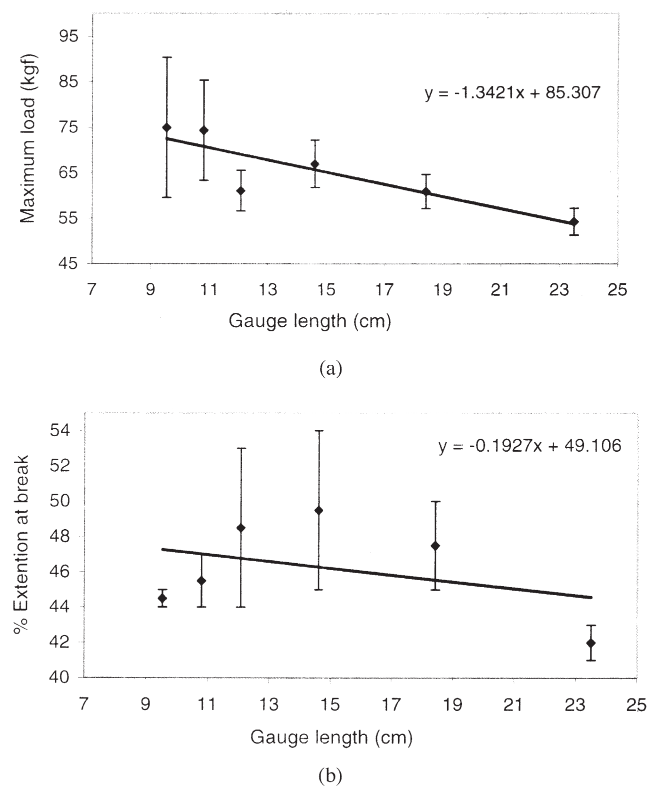

Figure 6 (a) Maximum breaking load versus GL (average of along and across the backbone direction of dumbbell specimen). (b) Percentage extension at break versus GL (average of along and across the backbone direction of dumbbell specimen).

a definite probability of a number of free ends of the fibrils within the tested length. These free ends are weak points in the collagen fiber structure. The fibrils having free ends do not contribute to the tensile strength of the bundle to the same extent as those which have no free ends. The contribution made by the fibrils having free ends is through the friction they experience when they try to slide past other fibrils. As the length of the fiber tested increases, the occurrence of fibrillar free ends increases; consequently the stress taken up will be less and hence the breaking stress is less for longer lengths.[11] In addition, more free ends will induce more frictional slippage resulting in less load bearing ability and hence decrease in the tensile strength.

Analogous to the studies by Rajaram et al.,[11] it is possible to consider leather as a matrix made up of collagen fiber bundles of varying length along with chemicals added during processing for improving the bulk properties. The fiber bundles are formed by parallel joining of single fibers. Each fiber is composed of the elemental fibers. At unit structural level, elemental fibers are composed of fibrils, which are grouped as elemental fibrils. The construction of the matrix is characterized by branching and interlocking. It is assumed that the elemental fibers divide into two parts and each of these join with another to form another elemental fiber strand. A fiber separates into two parts and both of these join with another, changing also in spatial direction from the original fiber as reported by Heidemann.[9] It is this branching of the collagen structure that provides a woven structure to leather and its characteristic mechanical properties and viscoelasticity. Collagen fiber bundles present in the leather matrix are discontinuous and randomly arranged. Hence, it is highly likely to find more number of free ends among fiber bundles as the GL increases. Fiber bundles having free ends will experience frictional slippage when they glide over other fiber bundles and other chemical constituents in the leather such as tanning agents, aromatic polymeric compounds (synthetic tanning agents), etc. The energy associated with friction initiates fracture of fibers and fiber bundles in the leather matrix even in the relatively lower load. Hence, the irregular arrangement at the supramolecular level and frictional slippage at higher sample length are probable causes for the

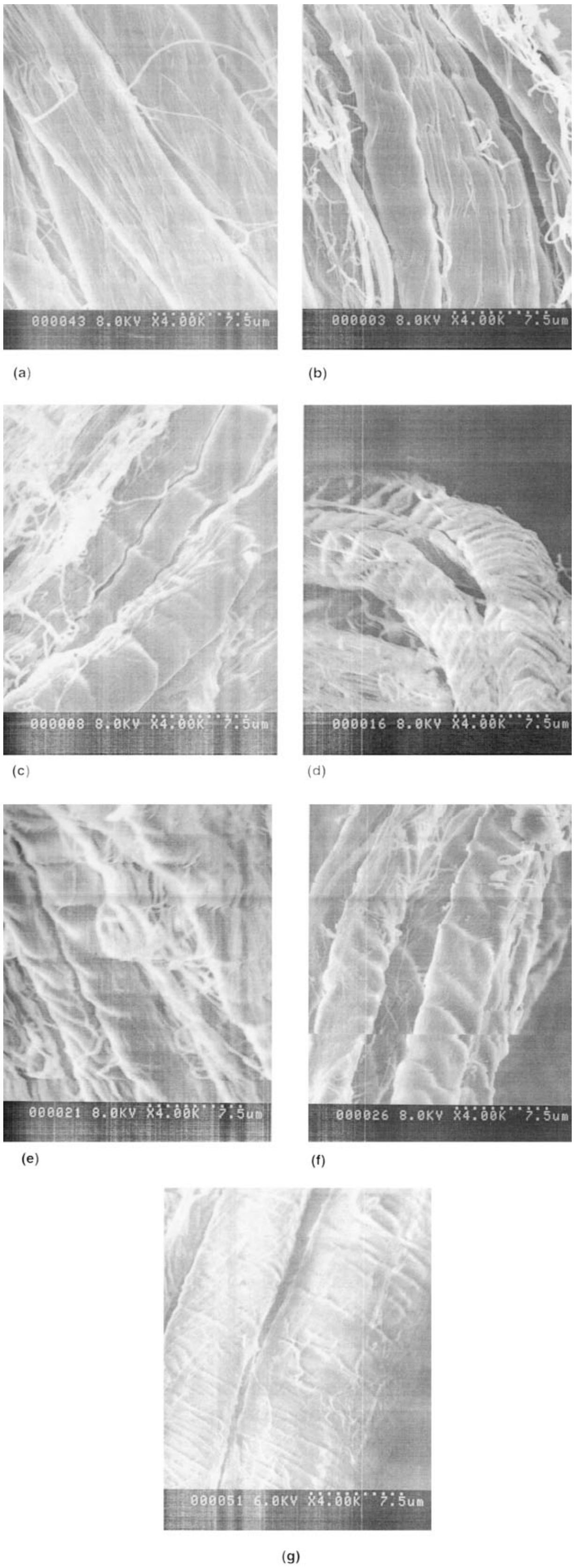

Figure 7 Scanning electron micrographs of broken leather specimens showing the fibers at a magnification of ×4000. (a) leather cut section before breaking; broken rectangular specimens cut perpendicular to the backbone direction of GLs (b) 9.53 cm, (c) 12.07 cm, and (d) 23.5 cm; broken dumbbell specimens cut perpendicular to the backbone direction of GLs (e) 9.53 cm, (f) 12.07 cm, and (g) 23.5 cm.

reduction in load bearing capacity of leather. The experimental results obtained in this study support this reasoning. The results of this study will be useful in understanding the tensile property requirements of leather meant for shoe uppers, automotive and furniture upholstery, etc, where the leather is subjected to force on a relatively larger area in comparison to the standard testing dimensions, both during product manufacture as well as usage.

CONCLUSIONS

The effect of increase in the GL on the tensile properties of shoe upper leather has been studied using rectangular and dumbbell specimens in two different directions of the leather. Results show that the maximum load at break as well as percentage extension at break values decrease with the increase in the GL. This study hypothesizes the structural arrangements in leather and related mechanical properties such as the frictional slippage and viscoelasticity are probable reasons for the decrease in tensile properties at higher GL. In addition, the variations that are associated with the characteristics of collagen fiber bundles and their structural architecture could also contribute to the decrease in tensile properties with increase in GL.

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