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Viscoelastic Characteristics of Typical Shoe Outsole Materials and Their Effects on Walkway Friction Models*

ABSTRACT: The physical laws governing the forces encountered when two materials in contact move, or tend to move, relative to another, have been developed over the last three hundred years. The assumptions used in these theories considered materials to be elastic in nature. A number of problems arise in applying these theories to footwear outsole materials. For example, the materials can be viscoelastic, which can alter their response to applied loads. Friction in elastomers has been shown to be made up of two different terms: adhesion and deformation. Waves of detachment have been observed in sliding elastomers that are the result of viscoelastic instability at the contact surface. Although this has been established in various laboratory tests, it has not been shown that typical conditions encountered during gait (forces, walking/sliding speed, temperatures, pressures) fit the adhesion/deformation model of elastomers. Available methods to measure/simulate friction during gait are controversial. Viscoelastic materials properties can vary with rate of loading, including friction and mechanical. Tensile tests at various strain rates were performed on typical commercially available shoe outsole materials-leather, and Neolite®. The results did not show any significant trend with respect to strain rate and measured mechanical properties.

KEYWORDS: forensic science, engineering, viscoelastic, polymers, friction, leather, Neolite®

The historic basis for the physical laws governing the frictional behavior of two solids while in contact, (whether moving or stationary) were developed beginning in the sixteenth century. These laws have become known as the Amontons-Coulomb model (1,2). The relevant sections of Amontons-Coulomb can be summarized as follows:

• Frictional force is independent of contact area and velocity.
• The force acts in a direction opposite the actual or intended motion.
• The frictional force is equal to a "constant" (coefficient of friction) multiplied by the normal force.

Morin (1835) proposed a separate *static* as well as *dynamic* coefficient of friction (3). Sampson et al. (4) described the transition between static and dynamic friction.

These *frictional laws* were assumed independent of the mechanical characteristics of the material involved. All materials—both elastic and viscoelastic—were characterized by the same relationships. Viscoelastic materials are those whose load/deformation (or stress/strain) relationships are time dependent. The deformation characteristics of elastic solids, (metals and ceramics) can be described as being generally time independent, i.e., the rate of loading under typical conditions, has no effect on the materials' deformation response.

Elastomer Material Properties

Elastomers is a generic term used to describe specific polymeric materials, both with carbon chain and heterochain structures. These materials generally exhibit "rubber-like" mechanical properties. The term polymer denotes a molecule formed by the repetition of a smaller unit (mer). Polymers typically are long chain molecules made of hundreds or thousands of these repeating units. Viscoelasticity is a concept used to describe the combination of elastic solid and viscous fluid behavior exhibited by real polymers when subjected to mechanical forces (5). Hookean solid behavior is characterized by a linear stress versus strain relationship up to the elastic limit.

$$\sigma = E\epsilon \quad \text{(the spring)}$$

where

σ = normal stress,
E = spring constant, and
ϵ = normal strain.

These terms are mathematically combined (in series) with a linear Newtonian fluid viscosity/shear stress/rate of shear strain relationship

$$\tau = \eta\gamma \quad \text{(the dashpot)}$$

where

τ = shear stress,
η = viscosity, and
γ = rate of shear strain.

This provides a theoretical framework for the observed mechanical behavior of polymers under load. This combination, of the

spring and the *dashpot* in series, is known as the Maxwell element (Fig. 1).

This model can qualitatively characterize the mechanical behavior of polymers under certain loading regimes. More complex models composed of springs and dashpots in series with other springs and dashpots in parallel, or multiple springs/dashpots in parallel, (each with different E's and ηs) can be developed to reflect more accurately the behavior of real materials (5).

The internal "structure" of these amorphous polymers (long chain molecules) is composed of strongly bonded covalent chains, containing *linear* regions with the balance of the chain not having any regularity in structure. There are relatively weak van der Waals bonds between these chains. If there are no primary bonds between these molecules, the material is thermoplastic, or "meltable," e.g., natural rubber. If strong covalent bonds have been formed between these chains, as in vulcanized rubber, the material is thermosetting, and cannot be remelted.

An important parameter that can be used to characterize the mechanical properties of polymers is the glass transition temperature, T_g. It has been defined as "the temperature below which free rotations cease because of intramolecular barriers" (5). Essentially this means that no long-range molecular rearrangement is possible below the glass transition temperature. Below this temperature, a polymer behaves mechanically as an elastic, *semi-brittle* solid, and above this temperature, the same polymer exhibits *plastic flow* and other creep characteristics. The practical effect on thermal and mechanical properties of having the polymer either above or below this temperature is significant. The value of this temperature can be modified by the addition of fillers, and plasticizers. The experimental determination of the glass transition temperature for a given polymer formulation can be performed using mechanical testing e.g., the torsion pendulum used in the ASTM Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics (ASTM D 4065), in which the variation of dynamic elastic modulus with temperature is measured. At the glass transition temperature, a significant change in this mechanical property is easily seen.

The effect of material structure and properties on their frictional response was studied by Schallamach (6). He moved loaded rubber hemispheres along transparent plates and found that the contact diameter was dependent on applied load (as per classical theory of elasticity). It was also found that the coefficient of friction increased with sliding speed and surface smoothness. Grosch (7) described the relation between friction and viscoelastic characteristics of rubber as being composed of two factors:

- Adhesion of rubber to the contacting surface, and
- Deformation of the rubber as it slides on a rough surface.

His experiments involved sliding rubber samples at different velocities and different temperatures on either smooth or rough surfaces. The maximum sliding velocity was below the value that would result in a significant rise in interface temperature, so this factor could be neglected. The results show that the variation of coefficient of friction, μ, with testing temperature and sliding speed can be represented on a single *master curve* typical of the Williams-Landel-Ferry shift (WLF) (8). The WLF shift mathematically relates the variation in polymer material properties to testing temperature and testing speed. This allows the superposition of these mechanical property data on the same set of coordinates. Ludema and Tabor (9) also describe the relationship between the frictional and viscoelastic properties of polymers. They characterized adhesion and deformation as the two mechanisms that describe sliding friction between solids.

- *Adhesion*—shearing of the junctions formed at the contact surfaces.
- *Deformation*—dragging/penetrating of the asperities of the harder material through the surface of the softer one.

In metals, the adhesion term is the shearing of metallic bridges at the interface, although the deformation term is represented as plastic grooving of the surfaces. This is contrasted to the situation in polymers in which the adhesion arises from molecular forces between the two surfaces that may be of the same magnitude as the molecular forces within the bodies. Because the interface may be as strong as the bulk polymer, this can result in the polymer interface being torn during sliding. Their study attempted to determine the affect of varying sliding speed and test temperature on the measured coefficient of friction. All testing was done using a hemispherically tipped hard (e.g., steel) surface sliding on a polymeric flat surface. Their experimental procedure effectively eliminated the deformation term, thereby allowing only the adhesion effect to be measured. The results show that the coefficient of friction (μ) is correlated to the viscoelastic properties of rubber when tested above its glass transition temperature. The variation of μ followed the form of the tensile strength variation of rubber with temperature and rate of loading, as plotted using the Williams-Landel-Ferry shift. The results for other polymers, e.g., nylon and polyethylene, tested below their glass transition temperature, show a variation of μ with testing speed and temperature. However, this variation did not correlate with the viscoelastic properties of these polymers.

Schallamach (10) postulated a molecular model of polymers during frictional processes that describe rubber molecules attaching themselves to the interface during sliding, and then detaching at a later time. This process has been given the name Schallamach waves. Schallamach (11) directly observed the contact area made between a hemispherically shaped rubber material against a hard, smooth surface. It was seen that "waves" of detachment separate from the rubber material and propagate along the surface. Gross displacement was associated with these waves. Between these waves, adhesion occurred between the surfaces. When these waves are present, frictional stress appears independent of sliding speed and testing temperature.

Johnson et al. (12) showed the contact area between a rigid sphere and a flat rubber surface was greater than that predicted by the classical theory of elasticity, as a result of the addition of
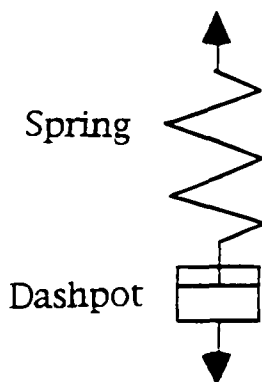

FIG. 1—*Series combination of spring and dashpot (Maxwell model).*

intramolecular forces and van der Waals bonds. Roberts and Jackson (13) described the sliding frictional characteristics of rubber hemispheres (with different compounding formulas) in contact with a smooth glass surface. The Schallamach waves observed were believed to originate in either elastic or viscoelastic instability caused by tangential stresses at the contact surfaces. The rubber surface must unpeel, and then buckle. The energy required to unpeel these waves is affected by the viscoelastic properties of rubber; i.e., this energy is rate dependent. Their experimental procedure was to vary the sliding speed between the rubber hemisphere(s) and the glass contact surface, while simultaneously observing microscopically the formation of Schallamach waves at the interface. The velocity and distance between the waves was measured. It was found that the surface energy of the peeling rubber materials likely has a central role in frictional behavior of rubber. This peeling process is viscoelastic in nature.

Roberts and Thomas (14) describe the adhesion and friction of smooth rubber in contact with rigid surfaces. It was found that the adhesion between these materials is dependent on surface energy when the contact area increases, and is rate dependent. Roberts (15) summarizes the theories of rubber friction into:

• *Molecular*—Bonds formed at the interface are strained and later broken. Frictional forces should maximize at a specific speed, and conversely decay to zero at very low speeds. However, the presence of the static coefficient of friction of rubber shows that adhesive bonds between the rubber and contacting surface exist, which are in contradiction to the molecular theory.

• *Macroscopic*—A number of theories have been postulated, e.g., small areas within the rubber interface (domains) are able to sustain a small, finite force indefinitely, which can account for static friction. Another mechanism has tearing occurring in a rubber layer approximately 10 nm from the surface.

Barquins (16) describes a new mechanism of rubber friction. He applied forces to a large rigid sphere in contact with a rubber plate, (with a low normal load), and caused it to slide. He found at the rear of the sphere/rubber interface, a crack tip moved towards the center of the sphere during this sliding. Schallamach waves moved across the contact area. Sudden slip occurred at this rear area, with the frictional force decreasing. This slip resulted in the formation of a viscoelastic bulge in this area that caused instantaneous sticking. A healing then occurred, resulting in the formation of two cracks (in a closing mode) that reduces the size of the reattachment fold. Subsequent to this, peeling occurred, and the frictional force increased. This reattachment fold looks like a Schallamach wave (also formed by the sticking of a viscoelastic bulge to a rigid slider surface), but is fundamentally different, originating at the rear edge, and does not provide relative motion between the surfaces in contact.

Barquins (17) described an experiment in which a rigid sphere was forced into a viscoelastic solid. The contact time was varied, and a sudden tensile force required to separate the materials was applied. It was found that the time required for this separation increased, reflecting an improvement in adherence of these materials. Barquins (18) introduced the concepts of fracture mechanics in the study of the effect of testing machine stiffness on adherence of elastomers. The growth of cracks has been standardized as Mode I, Mode II, and Mode III. Mode I is the crack opening mode, referring to a tensile stress applied normal to the faces of the crack. The edge of contact was visualized as a crack propagating in fracture Mode I in the rubber/glass interface. Equations are

developed that predict the dependence of the adherence force on the stiffness of the testing machine used. Ellis (19) describes a "run-in" effect on rubber friction. Test results show that when an indentor traverses a rubber track, a lubricating film is formed more rapidly than when a rubber indentor moves along a glass track. Barquins and Roberts (20) describe the measured friction of rubber sliders moving along a glass track (flat and wavy) and abrasive paper. Parameters varied included the sliding speed, temperature, normal load, and contact geometry. For smooth surfaces, it was seen that friction varied slightly with velocity (as per the WLF parameter). For smooth surfaces, rubber viscoelastic properties were of secondary importance, except near the glass transition temperature. Contact geometry appears to be an important factor in affecting the value of friction. Fritzon (21) described a test procedure using elastomeric composites sliding on a cast iron surface. The parameters varied were contact pressure, sliding speed, and temperature.

Barquins (22) in a review of the theories of adherence, friction, and wear of rubber-like materials, pointed out that the regime in which the previously noted detachment folds are formed has not yet been identified. However, these detachment folds appear at a critical sliding speed that depends on adhesive properties of the surface, contact geometry, elastic properties of the rubber, the load, and the temperature of contacting surfaces. It was found that the surface of the elastomeric sample has a significant effect on the friction coefficient. As temperature, pressure, and sliding speed increased, friction coefficient decreased. Fisher et al. (23) described tests performed on ultra-high molecular weight polyethylene using a tri-pin-on disc frictional/wear testing machine. These tests were conducted using bovine serum as a lubricant. It was found that the measured coefficient of friction did not significantly vary with sliding velocity.

Polymers used as footwear outsoles typically contain fillers. Bahadur and Gong (24) described the effect of fillers on the tribological properties of polymers. These properties include wear resistance and strength. The types of fillers in their study were solid lubricants, metal powders, and oxides. The solid lubricants (graphite, MoS_2, and PTFE) were found to reduce the coefficient of friction. Metal powders and inorganic compounds both increased the coefficient of friction. The wear rate of soft polymers can be reduced with the introduction of fillers. However, they ultimately conclude that the tribological behavior of filled polymers is "still clouded with mysteries" and very few conclusions can be drawn.

A unique factor in sliding of rubber-like materials is the stick-slip phenomenon. This has been studied by many researchers, and has been found to exist above a critical sliding velocity. Historically, this phenomenon has been theorized to be the result of a negative slope in the friction-velocity curve of the polymer. Rorrer et al. (25) describe a hemispherical elastomer sliding on a rigid surface. Four separate stick-slip (harmonic oscillations) regimes were identified. Their results show that stick-slip did not require a negative slope in the friction-velocity curve. They postulate that testing techniques using a rigid sphere on an elastomer surface provide different results than an elastomeric sphere on a flat rigid surface.

Leather Material Properties

Leather, a naturally occurring material, is made from the skin or hides of various animals. Processing includes soaking the hides in tanning material after the animal's hair has been removed. The various tanning solutions used provide pliability in the leather as

well as improving mechanical properties. As a result of its use in a variety of applications: harnesses, clothes, shoes, belts etc., numerous government/industry standards were developed to provide a means of comparing commercial leather products.

Among the mechanical property tests and specifications widely used for leather is the tensile test. Hobbs (26) discusses an experimental protocol in which he varied the testing speed of the jaws in a conventional tensile testing machine to determine the effect on the tensile strength and elongation of the leather specimens. The variable factors with respect to the leather used were hide location and the different hides. A typical flat 'dumbbell'-type specimen shape was used. He found the greatest change in tensile strength at the lowest jaw speeds: from 0.5 to 1.0 in./min, with a minimal change when the jaw speed was varied between 6 and 12 in./min. There was a statistically significant change in tensile strength as the jaw speed varied from 12 to 20 in./min. The elongation data were erratic over the range of jaw speeds chosen, and it was felt that jaw speed does not have a statistically significant effect on elongation. Lollar (27), describing the significance of the tensile test as applied to leather, lists the known factors affecting the mechanical behavior of leather in service as being temperature, humidity, grain, thickness, orientation on hide, and tanning process. The wide variety of available hides, and the significant effect of leather treatment properties on mechanical properties have resulted in industry groups and public sector organizations promulgating standards in an attempt to quantify important leather properties. The breaking load of the test specimen was not necessarily proportional to the cross-sectional area that was in agreement with previous work.

Komanowsky, et al. (28) describe the stress relaxation behavior of leather. Stress relaxation is a process polymers can undergo when they are deformed to a constant length, and held at that length, e.g., a gasket. In time, the initially developed stresses within the polymer decay. They describe the structure of leather as being a network of interwoven fiber bundles separated from each other as a result of internal twisting. Spaces also exist among these bundles and the molecules. Leather exhibits a nonlinear viscoelastic behavior similar to other biomaterials (skin, ligaments) but different from continuous polymers. Their explanation of these mechanical properties of leather is based on the macrostructural properties, and not on the viscoelastic nature of the collagen fibers. The creep and stress relaxation aspects of leather were modeled using three Maxwell elements in parallel. The mathematical representation of this model was (Fig. 2)

$$E(t) = E_1 e^{(-t/T_1)} + E_2 e^{(-t/T_2)} + E_3 e^{(-t/T_3)}$$

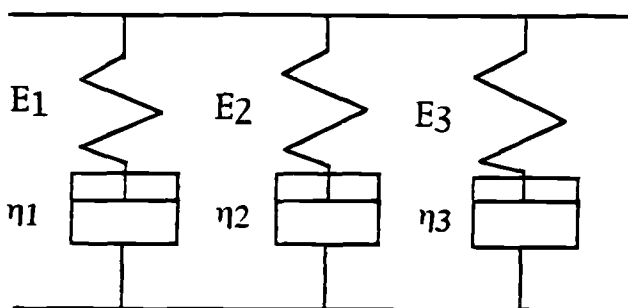where $E(t)$ is the modulus of elasticity of the entire model at any

FIG. 2—Rheological model of leather during stress-relaxation.

time t_1, E_1, E_2, and E_3 are the respective spring constants of each of the Maxwell elements; and T_1 is the relaxation time of element one, equal to η_1/E_1 where η_1 is the viscosity of "fluid" in dashpot of first Maxwell element, etc. The test procedure involved simultaneous stretching of six samples and continuous monitoring of the resulting stress. The effects of moisture content, fatliquor content, and temperature on stress relaxation behavior of leather were observed. As moisture content, fatliquor content, and temperature increased, relaxation moduli and relaxation time both decreased.

Viscoelastic materials, such as typical footwear outsoles, e.g. Neolite® and leather, can be described in terms of their time dependent response to applied forces. Braun and Brungraber (29) describe the assumptions used in "classical" frictional behavior of materials, static coefficient greater than dynamic coefficient and Amontons/Coulomb relationships as not being applicable to polymers. James (30) postulated a continuous change of frictional coefficients, with velocity for rubber and plastic materials, in contradiction to the theorized separate and distinct static and dynamic coefficients. His experimental results show an increase of friction (kinetic) as sliding velocity increases.

Materials and Methods

A study was undertaken on the effect of rate of loading on tensile properties of typical shoe outsole materials. The materials used were leather shoe outsoles manufactured by the Daniel Forbes company, Westfield, PA, and Neolite® outsoles manufactured by the Goodyear Tire Company. The leather soles were selected based on similarity in appearance, and were of prime grade, thought to be Level 2 on a scale of 1 to 4.

The Neolite® had the following compounding formulation:

68.7 parts SBR
50 parts polybutadiene
20 parts high styrene resin
50 parts silica
5 parts resin
5 parts processing oil
3 parts sulfur
2 parts carbowax
1 part each antioxidants, DPT, and MBTS

Durometer readings were taken on the outsoles. Die cut, dumbbell-shaped test specimens were removed from the test outsoles. Their overall shape was similar to that specified in the ASTM Test Method for Tensile Strength of Leather (ASTM D 2209), and Footwear Industries of America Test Method for Tensile Strength and Elongation of Solings (FIA 328) and Test Method for Tensile Strength and Elongation of Man-Made Solings (FIA 329). Overall test specimen length was 7.625 in., with a 3.75-in. length between test machine jaws. A 2.5 in. long by 0.5 in. wide and 0.22 in. thick gage length was used. The specimens were then inserted into a Tinius Olsen 1000 lb LoCap table top testing machine.

Results

Leather

The rate of loading used was 0.02, 0.2, 2.0, and 20.0 in./min. The test results for the tensile testing showed an erratic relationship between failure stress and rate of loading (see Fig. 3), and a similar relationship between elongation and rate of loading (see Fig. 4). A number of the leather specimens did not fail within the test
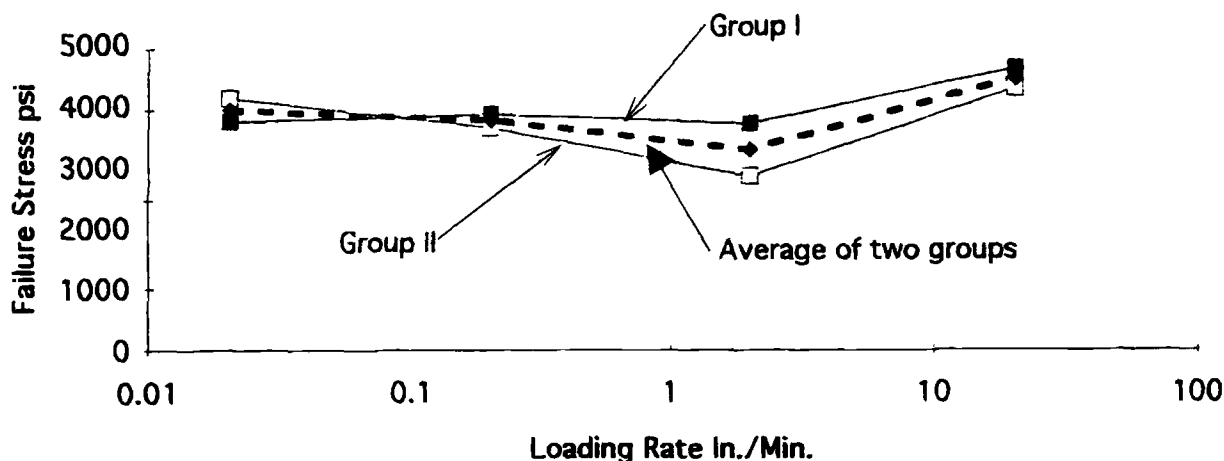
Failure Stress v. Load rate - Leather

FIG. 3—*Failure stress of leather at different loading rates.*
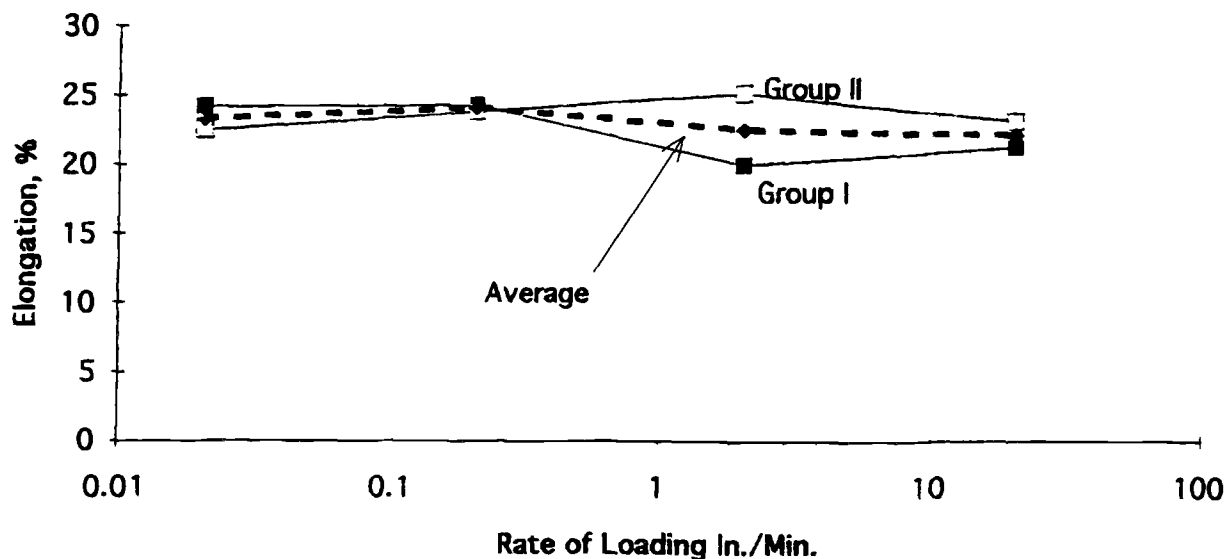
Elongation v. Load Rate - Leather

FIG. 4—*Elongation of leather at different loading rates.*

section, but at the intersection between the straight section and the curved radius (Fig. 5). Test results were averaged as follows:

Specimens that failed within the gage length (Group I) (see Fig. 6).
Specimens that failed at intersection between gage length end and curved end (Group II).
All specimens (Group III).
Durometer readings (Shore A) were 87.

Neolite®

When the rate of loading was either 10 or 20 in./min., the specimens elongated almost 400% before fracture. With lower rates of loading, (2 to 0.2 in./min), the specimens did not fracture, but slipped out of the testing machine jaws. The slope of the load

versus elongation curves were taken at 100% elongation for various rates of loading. The slope was 133 lb/in. for jaw speeds of 2 and 20 in./min. The slope was 100 lb/in. when the jaw speed was 0.2 in./min. The thinning of the material resulted in slippage in the testing machine jaws at speeds lower than 10 in./min, and consequently no failure occurred with these specimens.

The average fracture load was 211 lb (1918 psi). Average elongation to fracture was 373%. Durometer readings (Shore A) were 85.

Conclusion

Tribology has been defined as "the science of rubbing." The historical record of research in tribology has focused primarily on friction between machine components, from a basic physical understanding point of view, as well as the drive to reduce this
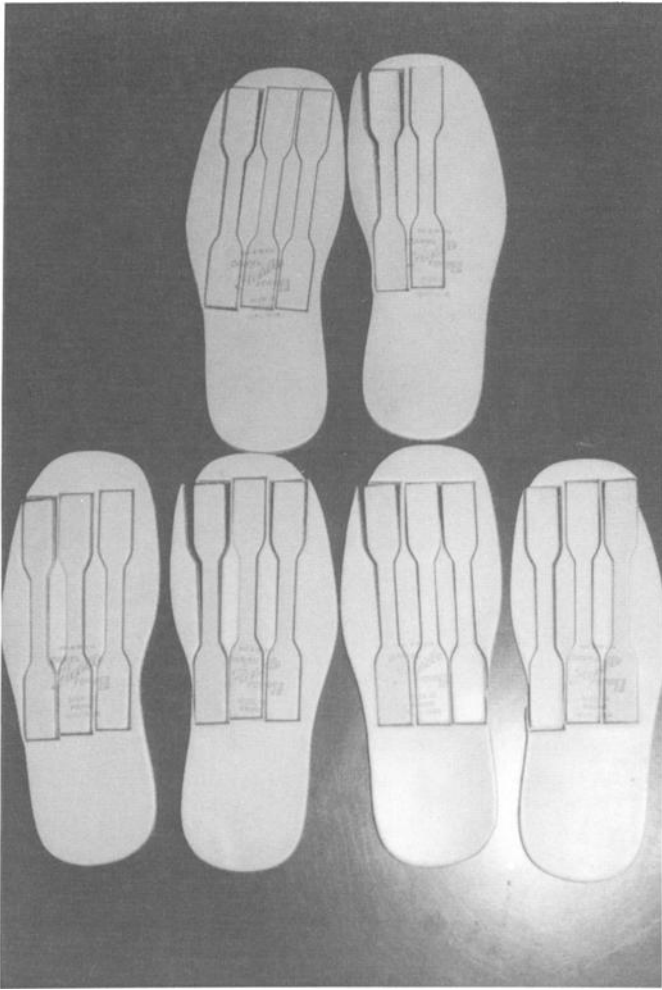
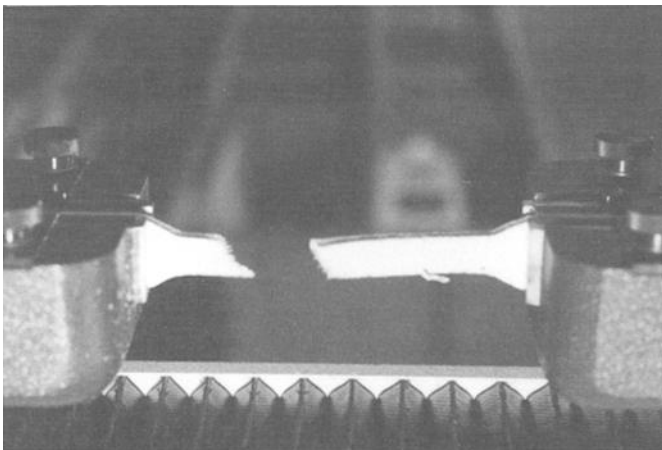FIG. 5—*Location of die cut test specimens in leather outsole.*

FIG. 6—*Leather specimen failure within gage length (Group I).*

friction. Many efforts have been made, and are ongoing, to theoretically define, and experimentally verify the factors that enter into the tribological behavior of materials in real-life situations. The frictional problems involved in walkway friction models are a relatively recent area of study, and bring with it new concepts with respect to tribology. It is not yet clear how the unique material characteristics of elastomers should be taken into account in walkway models of friction. The classical theory of friction, based on the assumption of a "block on an inclined plane," may or may not provide a sound foundation for theories and experimental verification. Determination of the factors involved, and their relative importance, in characterizing a footwear outsole/walkway combination from the point of view of pedestrian slip resistance is a controversial subject with very few uniformly accepted concepts. The type of friction to be measured—static, dynamic, continuous—the methodology used, and the test conditions are among the parameters that are in question. Further research is required to quantify the parameters involved in walkway friction in conjunction with the material properties of the footwear outsole/walkway combination. It is hoped that appropriate mathematical models taking into account the viscoelastic character of these materials (both outsoles and walkways) can be developed, along with testing protocols that can experimentally verify the theories.

The inconsistency of the reported test results could reflect the sampling procedure used in choosing the outsoles, and or the normal variation in properties of leather. Further testing will be undertaken to attempt to quantify any relationship between testing speed and tensile properties of outsole materials. Combining these tests with tribological testing, focusing on varying contact speed, may yield a relationship between tensile properties and frictional ones. Given the well-defined relationships that have been found for polymer mechanical properties and speed of testing, it seems reasonable that a similar relationship (of tribological characteristics and speed) may be found on a macroscopic level. Exploring the effect of sliding speed (kinetic friction) on measured friction values may yield results that can be applied to frictional models of outsole materials.

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