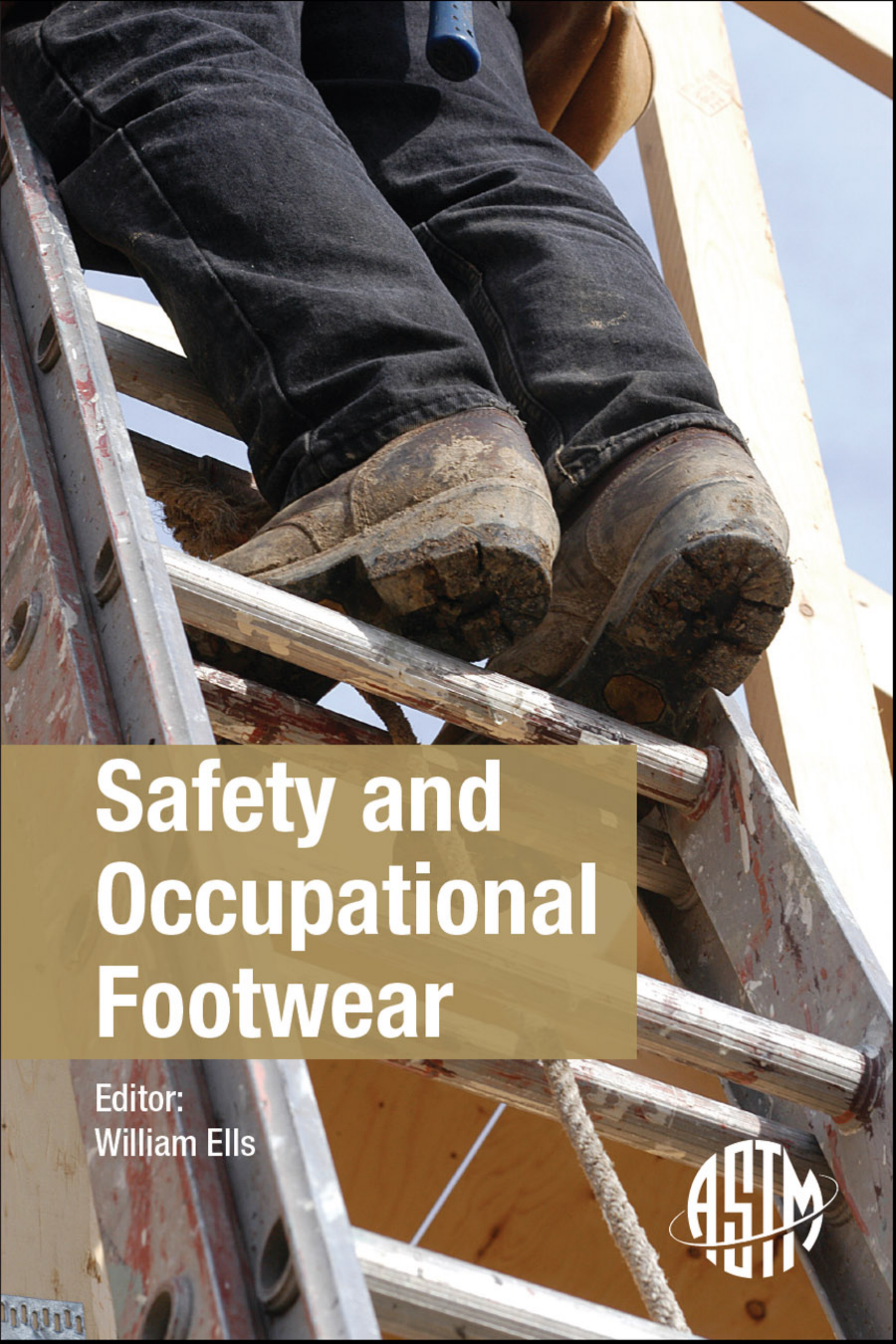

Safety and Occupational Footwear

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Dedication

This publication, Manual 71 on *Safety and Occupational Footwear,* is dedicated to the friendship and memory of Daniel A. Schultz. Dan joined ASTM International in 1998. He was director of developmental operations at ASTM International and passed away in June 2012. Dan had responsibility for several ASTM committees, including F13 on Pedestrian/Walkway Safety and Footwear. His wisdom, courage, and passion for life should be an inspiration for all of us.

Farewell, our cherished friend.

Foreword

THIS PUBLICATION, *Safety and Occupational Footwear*, was sponsored by Committee F13 on Pedestrian/Walkway Safety and Footwear. This is Manual 71 in ASTM International's manual series.

Acknowledgments

This manual was brought to fruition by the efforts of many dedicated individuals from ASTM committee F13 and in particular those of the Footwear subcommittee F13.30, especially Mark Blanchette, Semper Scientific; Richard Bourque, Precision Testing Labs; Ty Fernsler, Meramec Industries; James Flynn, J2 Engineering, Inc.; Robert Hall, U.S. Army; Lori Hyllengren, SB Foot Tanning, Red Wing Shoe Company; Paul Matonich, Honeywell Safety Products; Thomas Rork, consultant; and Bert Spiller, Timberland Boot Company.

In addition, I wish to convey accolades to those committee members who are all veterans in their field and who brought a broad spectrum of interests and technical expertise to this manual. They have devoted considerable time, energy, and resources to support this endeavor. I am also grateful to the reviewers of the various chapters, who through their perusal of the chapters and their suggestions permitted good manuscripts to be made better.

Finally, I would like to thank the publication staff of ASTM International, especially Kathy Dernoga and Monica Siperko who have given us guidance and assistance from the outset of the venture.

Contents

Chapter 1 | Safety and Occupational Footwear Design and Style Characteristics, Fit and Sizing

To assist the safety professional in developing a working understanding of footwear and its role in foot protection, this book will present an overview of various aspects of safety and occupational footwear. It is not intended to be a comprehensive explanation of all the complexities and interlocking factors in footwear design, manufacturing, and selection. The intent of this book is to provide an understandable and user friendly overview of safety and occupational footwear and the applicable ASTM test methods and standards.

GENERAL FOOTWEAR DESIGN AND STYLE CONSIDERATIONS

As part of this guide to safety and occupational footwear selection and care, this segment is focused on fundamentals and is condensed. Suffice it to say that choice of the last, insole, and construction is primarily driven by the performance characteristics needed in the footwear. Of course, design also has aesthetic and cosmetic considerations, but the chief concern should always be performance.

Footwear is one small part of any workplace hazard assessment program. Ultimate selection and footwear choice must reside with the company safety professional who monitors, updates, and manages the respective program. Choice of footwear should be appropriate to the wearer, the environment in which it will be worn, and to the activities to be performed. For example, construction and components suitable for a 250-pound man working in an industrial environment, such as a machine shop or heavy machinery assembly, may not be appropriate for a woman with a slight build working in a distribution center or as a plumber. Common sense should be your guide, augmented by footwear professionals serving specific industries. Advice can be sought from manufacturers, qualified distributors, and other providers of protective footwear. These professionals would be more aware of available safety and occupational footwear alternatives for specific working environments. Some factors to be considered:

- Physique and fitness of wearer
- Intended working position—sitting, standing, or walking

- Physical environment in which footwear will be worn—hot or cold, wet or dry, coarse or smooth ground, firm or soft ground, and so on; also the existence or potential existence of contaminants such as oil, water, chemicals, and so forth
- Hazard assessment to determine level of protection needed such as safety toes, metatarsal protection, puncture resistance, as well as slip resistance and traction requirements
- Electrical protection, which may include electrical hazard (EH) protection, or static dissipative (SD) or conductive requirements

The sections that follow will address these and other questions in greater detail.

FIT AND SIZING

Fit is an individual preference. The wearer is the final arbiter of what fits and what does not. Footwear should be tried on wearing socks that will be used in the work environment. If possible, temperature should be the same as, or at least similar to, the work environment.

Any intended aftermarket footbeds, arch supports, or orthotics, whether prescription or over-the-counter, must be worn when trying on footwear because anything inserted into the footwear will affect the fit. Note that if an aftermarket insert extends under the toe cap, it will reduce impact and compression clearance, increasing the danger and risk of injury. Independently certified ASTM safety footwear has been engineered, manufactured, and tested using the original footbed/insole that comes with the product. The use of any other aftermarket footbed, arch support, or orthotic that is different from the original footbed/insole that came with the footwear may negatively affect the protection offered and shifts risk of injury to the user.

When considering footwear, measure both feet and fit to the larger one. But remember footwear sizing and width as marked is not an absolute. In other words, not all footwear of a specific size and width will fit exactly the same. Subtle differences in shape, style, aesthetics, materials, and construction will most likely result in size variations. Be sure the wearer tries shoes on both feet because there are slight size differences in everyone's left and right foot. They should walk in the footwear and be sure that the footwear is neither too tight and pinching, nor too loose and slipping.

Footwear should be snug enough to ensure stability and minimize movement of the foot within the footwear, especially in the heel area, to avoid creating friction, which will generate heat, and, in some instances, cause blisters.

The ball, or widest area of the forefoot, the protrusion just behind the big toe, should match the widest part of the footwear. A fit professional can determine the ball to heel measurement critical to correct fit. But if the ball of your foot and the widest part of the footwear do not match, then another size is called for, regardless of suitability in overall length.

> Compare the arch length to the heel-to-toe length. Generally you'll use the larger of the two measurements as the correct shoe size. If the arch length and

heel-to-toe length are the same, this will be the shoe size. If the heel-to-toe length is larger than the arch length, then fit to the heel-to-toe size. If arch length is larger than heel-to-toe, then fit to arch length [1].

Feet will swell during the course of a normal workday, so it is best not to try on footwear early in the morning or later in the evening.

FOOTWEAR COMPONENTS AND CONSTRUCTION

Bear in mind that the goal of this book is to provide a working understanding of footwear and its role in foot protection. Footwear construction itself will be addressed from the point of view of performance and selection.

Any discussion of footwear construction should start with two critical components—the last and insole, although only the insole actually remains in the footwear after manufacturing.

The Last

- Definition: A foot-shaped form, made today of machined hard plastic or cast aluminum, over which all footwear is made.
- The last is the single most important determinate of size and width of the footwear.
- A unique last is used to make each size and width (Fig. 1.1).
- Two-dimensional materials such as leather or synthetic woven textiles are assembled or stitched together making the footwear upper. The assembled upper is “lasted” or shaped and formed over the last, taking on its three-dimensional size and character.
- The last and insole are the foundation or “guts” of the boot. Correct last and insole selection are critical to comfort, fit, and performance.

FIG. 1.1 Footwear last.

The Insole

- Definition: Traditionally, a relatively thin, firm moisture-resistant material most often produced in the form of a sheet (could be cellulose or synthetic nonwoven or leather), ranging in thickness from 0.04 to 0.12 in. (1 to 3 mm), which is cut to correct dimensions for each size and width and around which the shoe is built by either stitching, cementing, or otherwise attaching the upper and midsole to the insole.
- Integrity of the insole is critical to performance and fit. If the insole fails, the boot could literally fall apart.
- The insole, in combination with the shank, also adds torsional rigidity to the boot, providing firm support to the foot.
- Protective insole materials may be used or added to provide puncture resistant performance.

Ankle/Leg Height

Industrial and occupational footwear can be divided into four main groups by height (Fig. 1.2):

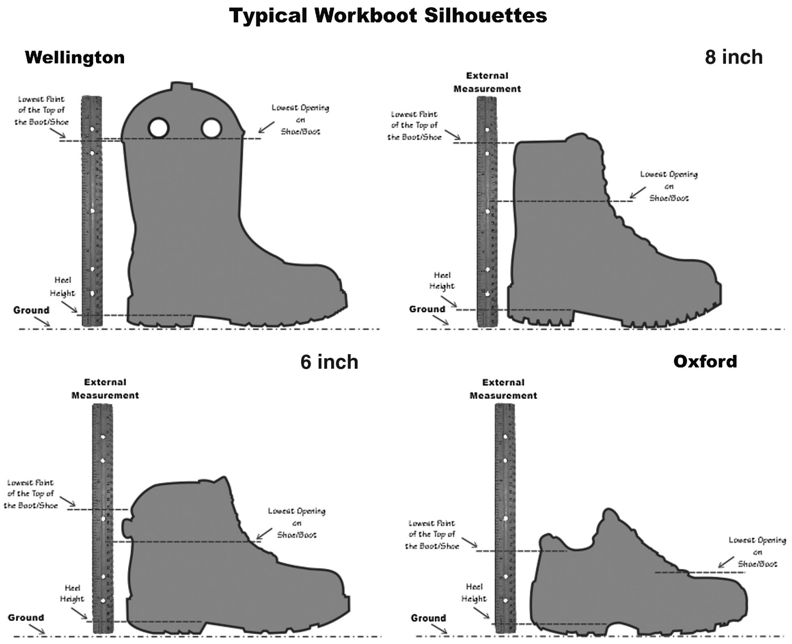
- Oxford: A low cut, offering no ankle support.
- Six-Inch: Commonly referred to as a chukka. Sits just below ankle height, providing minimal ankle support.
- Eight-Inch: Over the ankle. This height is best when ankle support is required.
- Wellington (ten-inch and up): Generally, boots of this height are pull-on styles without laces that will allow movement of the ankle, providing less support.

Currently, there is no widely accepted method of exactly measuring shaft height. It should be noted that height may vary by individual styles and sizes and may not exactly conform to a six-inch, eight-inch, or ten-inch description. Footwear may offer a degree of protection from outside elements and foreign materials. The height needed should be determined by assessing the height of the potential hazard. A simple external measurement from the floor or walking surface to the lowest point of entry or top of boot may be used to determine if footwear height is adequate.

CONSTRUCTION

Footwear construction is the manner or method used to attach the upper to the midsole and outsole. This may be done by stitching, cementing, or some other means. As with design, choice of construction is dependent upon the desired performance parameters and other considerations. The goal of this discussion is to provide the safety professional with a basic understanding of common footwear constructions, as well as the strengths and shortcomings of each. A number of

FIG. 1.2 Typical industrial and safety footwear silhouettes.



constructions commonly used in protective and occupational footwear are shown in Fig. 1.3. They are:

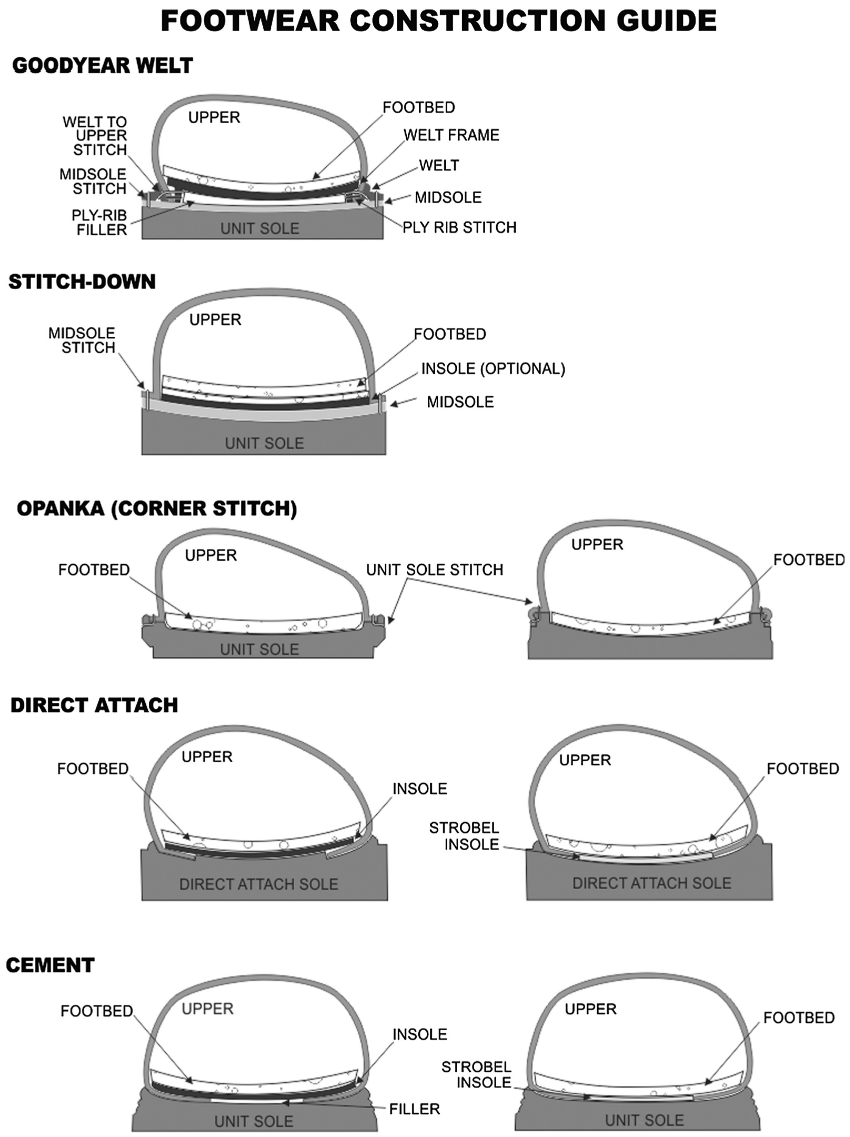
- Goodyear welt
- Stitch-down
- Opanka (corner stitch)
- Direct attach
- Cement

Other methods of construction are described further within this chapter.

Goodyear Welt

The defining feature of Goodyear welt construction is that the upper is attached to the midsole/outsole by two separate stitches (Fig. 1.4). The first stitch is the "Goodyear" stitch that goes through the welt, upper, and ply-rib that is attached to the insole. The second stitch goes through the welt and midsole, and possibly the outsole. This construction results in relatively firm but nevertheless pliable footwear that will eventually mold to the wearer's foot. Goodyear welt construction provides a very stable platform, one often used in work and heavy duty outdoor boots.

FIG. 1.3 Types of footwear construction.



Although the upper and midsole are attached by stitching, the outsole is most commonly attached to the midsole by adhesive; it can, however, also be attached by stitching.

A more modern assembly technique is to mechanically direct attach the sole to the welt instead of stitching a midsole and cementing or stitching the outsole. This

FIG. 1.4 Stitched welted edge. (With permission from the Timberland Boot Company, available at www.timberlandpro.com.)

results in a construction that combines lightweight flexibility with a high degree of torsional stability.

Stitch-Down

In stitch-down construction (**Fig. 1.5**), the footwear upper is lasted outward (in constructions such as cement or strobe, the upper is lasted under the foot) creating an approximately 90° flanged leather "lip" around the perimeter of the upper. In stitch-down construction, the flanged upper is then either stitched to a solid midsole or insole and then cemented to a traditional midsole/outsole unit sole resulting in a flexible durable construction. This construction provides a very

FIG. 1.5 Stitch-down construction. (With permission from the Danner Boot Company, available at www. danner.com.)

stable platform—one that is also often found used in work and heavy duty outdoor boots.

Although the upper and midsole are attached by stitching, the outsole is most often attached to the midsole using an adhesive. As with welt construction, this makes the outsole replaceable by a competent shoe repairer.

For both Goodyear welted and stitch-down constructions, it should be noted that resoling with a sole design or material different from the original may negatively affect the level of protection (such as the functionality of EH, SD, and other protective properties designed into the original footwear).

Further benefit of these two constructions is the ability to use high oil content leathers or synthetic fiber upper materials that cannot be attached to the soling system using adhesive or direct injection construction techniques. High oil content and/or barnyard resistant leathers can offer increased durability when subjected to harsh work environments compared to split, split suede, or nubuck leather upper materials.

Goodyear welted and stitch-down constructions will eventually shape and conform to the unique characteristics of each individual's feet. Because there can be a period of what is often referred to as "breaking in," it is wise to plan on wearing a new pair of boots for several hours or a half day until the wearer is sure they fit properly and are not causing discomfort.

Opanka (Corner Stitch)

In Opanka (named after the machinery used to stitch the upper to the soling) or corner stitch construction, the flanged upper is stitched by machine or is hand-sewn to a midsole/outsole unit sole that is molded with a top edge and perimeter sidewall groove. The thread connects upper to sole without the use of an innersole or secondary midsole, often resulting in a very flexible, lightweight, footwear construction.

Cement

In cement construction, the upper and midsole are attached to the insole using adhesives, usually a hot-melt or heat-activated cement. Great advances in the science of adhesives have made this construction a popular choice, offering greater flexibility and lighter weight than stitched constructions such as Goodyear welt, stitch-down, and so on. In recent years, cement construction has become a popular option for work and safety footwear (Figs. 1.3 and 1.6).

Flat Lasted

The upper is mechanically stretched over the last, and the under flap (edge) of the upper is then cemented to the bottom of the insole. The midsole and/or outsole is then attached using specialized adhesive.

Strobel

The upper is stitched closed to a flexible fabric-type material using a Strobel stitch to join the upper and the sock, then is "force lasted" to shape, that is, the last is

FIG.1.6 Cement constructed footwear. (With permission from the Timberland Boot Company, available at www.timberlandpro.com.)

literally pushed into the shoe. Typically, there is no insole board used because it is often replaced by the Stroble sock. Because this method provides lighter weight and very flexible footwear, most athletic shoes use this construction. This construction is also commonly used on footwear found in use within the food service industry.

String Lasted

String lasted is a very simplistic method of lasting that results in the least amount of shape control. A “string” or cord is loosely stitched to the edge of the upper using a circular marrow stitch ending in two loose ends about five to six inches long sticking out at the heel. The upper is then positioned on the last and the cord ends are firmly pulled to draw the upper over the last. The upper is cemented in place and the loose, extending cord ends are trimmed off. The mid- and/or outsole is then attached to the shoe, which is then finished as necessary.

Close Edge

Close edge construction means that the outsole is trimmed almost flush with the upper. This is common on athletic-inspired, light weight footwear.

Bond Welt

For bond welt styles, cement construction mimics the appearance but not the performance of Goodyear welted footwear. This is accomplished by cementing a decorative stitched welt to the top of the midsole before trimming.

Net Fit

In this case, the outsole is made “net-fit” (in its final shape and size) and is not trimmed. This provides a visual appeal that cannot be achieved with trimmed edges.

DIRECT ATTACH

In the direct attach shoe-making process, the upper is assembled (as described in the various types of constructions noted earlier) and then is pulled over a last that is mounted onto a direct attach soling machine. The process of direct attaching the midsole and/or outsole is most often done either by injection or open pour. These processes often result in more flexible, lightweight footwear. See Figs. 1.3, 1.7, and 1.8 for direct attach soling material options.

Soling options used in the direct attach process include polyurethane (PU), polyvinylchloride (PVC), thermal plastic urethane (TPU), and vulcanized rubber. In direct attach construction, the lasted upper is held in a fixed position on an injection machine—usually a rotary table or carousel setup (Fig. 1.7). The soling mold clamps tightly around the upper material in preparation for bonding and forming a sole directly to the footwear upper. As in cement construction, the lasted upper can be manufactured using flat, Strobel, or string lasted methods as previously described. Midsole design options are unlimited, ranging from a traditional simulated welt to a unique athletic/hiker inspired sport sidewall treatment. Tread pattern options will depend on soling system material choices as well as the intended end use. Many direct attach machines have multiple injection heads allowing for the use of multiple materials. Differences in the soling materials used, and their densities, will determine the specific end use benefits.

Polymeric Footwear

Polymeric footwear is also known as vulcanized footwear. Natural rubber is a material made from the viscous extract of the rubber plant. Rubber used for industrial soling applications usually is a synthetic derived from crude oil.

FIG. 1.7 Direct attach process. (With permission from the Desma Shoe Machine Company, available at www.desma.de.)

FIG. 1.8 Direct attach footwear. (With permission from Wolverine World Wide, available at www.wolverine.com.)

Vulcanized footwear is manufactured to provide a completely waterproof product that may also resist oils and chemicals. Over-the-foot shoes and overshoes can be produced in this manner. As with many other footwear constructions, protection offered in an over-the-foot product may include safety toes, puncture resistant midsoles, metatarsal protection, and electrical hazard and conductive properties.

Vulcanized footwear is produced by pulling a fabric lining material over a metal last or foot/leg form. Various precut reinforcement pieces of fabric-backed rubber and uncured rubber are then applied in layers to create the desired footwear. Outsoles are then added to complete the boot assembly process.

The finished boots are left on the lasts and placed within a vulcanization chamber for approximately one hour at 350°F (177°C). This process chemically bonds and cures the footwear. After this process is completed, the boots are removed from the lasts and tested for waterproofness. Insoles are then placed within the boots and they are then readied for shipment (Fig. 1.9).

Materials and Methods Commonly Used in the Production of Direct Attach Footwear

Polyurethane

Two component reactive urethane systems offer lightweight comfort as well as solid durability. Typical systems are polyether, polyester, or special polyether/polyester hybrids. Traditionally, polyester was used in applications where strength and abrasion resistance were required, and polyether-based systems were used in lightweight comfort and traction end uses. Today's technology has blended the boundaries to the point where footwear manufacturers and urethane suppliers work in tandem to create optimum performance regardless of system choice. Biobased systems are also being introduced providing environmental options for the end user. Reactive urethane system

FIG. 1.9 Polymeric (vulcanized) footwear. (With permission from Muck Boots, available at **www.muckbootsandshoes.com**.)

soling may have low to moderate resistance to hot contact and can be compounded to have oil/fuel resistance.

The polyurethane (PU) material is either injected or poured into molds; through various chemical reactions in the molds and through controlled time and temperature, the process is completed and a finished boot is produced. Safety toes and puncture resistant midsoles can also be added to the boots and can be uniformly and permanently molded into place.

As described earlier, polyurethane (PU) is a synthetic, foamed material that is made up of chemical components that can often withstand organic fats, hydrocarbons, mild chemicals, animal fats, oils, and industrial grease. The components are mixed at a temperature of approximately 122°F (50°C) to form a polymer that contains tiny air bubbles. The combination of soft and hard components forms the basis for flexibility and durability that is found in PU footwear. PU boots are known for being lightweight and durable because of the materials used. Other benefits of this construction type include its inherent impermeable (waterproof) material characteristics and its ability to be cleaned quickly and easily, including the option of sterilization in a high temperature/pressure autoclave apparatus (for use in a healthcare related industry).

Single Density

A combined midsole/outsole is the most economical soling alternative providing basic comfort and durability characteristics. Because the material must function as the cushioning as well as be abrasion resistant, blown soling provides moderate weight relief applicable for basic indoor or outdoor environments.

Dual Density

Using various midsole and outsole material combinations, this process allows the footwear manufacturer to optimize weight, cushioning, durability, and traction performance properties. Outsole material options include solid elastomers, blown urethanes, rubber, or thermal plastics. This allows the footwear manufacturer to create deep outdoor inspired lugs or intricate patterned tread designs while utilizing multiple material options.

Thermal Plastic

A nonreactive-based system that uses heat to transform a premanufactured pellet into a liquid form so it can be remolded into a given shape. These materials are often used in the manufacture of footwear soling systems such as PVC, TPU, or thermal plastic rubber (TPR). PVC and TPU materials can also be compounded to be oil resistant and are available in solid and blown structures. TPR is primarily used in the occupational footwear category. TPR is a thermal-based soling that by nature will have limited resistance to hot contact but that can also be engineered to have oil and fuel resistance properties.

As described earlier, thermal plastics are solid materials. Traditionally, PVC has been the material of choice and provides resistance to water, alcohols, and concentrated acids and alkalis. For the footwear-making process, the thermal plastic is formed into small pellets that are injected into high pressure, clamshell molds that produce a one-piece construction for over-the-foot and overshoe products. Safety toes and puncture resistant midsoles can also be added to the boots and can be uniformly molded securely into place.

Compression Molded Rubber

An alternative way to manufacture waterproof rubber footwear is to use a compression molding technique tailoring temperature and time to match predefined cure rates. These parameters are designed to provide the desired performance requirements of the finished footwear. Compounded uncured rubber preforms are weighed and cut to fit specific mold cavities. Safety components such as puncture resistant devises and/or protective toe caps can be inserted into the mold in order to become an integral part of the footwear. At the end of the molding cycle, the footwear is removed from the mold, allowed to cool, trimmed, and readied for packaging. Based upon their formulation, rubber compounds can offer a broad performance range of shoe soles designed to meet various requirements such as abrasion, oil/fuel, and fire resistance, and so on. Rubber is sometimes also used in the direct attach process. During the direct attach rubber process the rubber is vulcanized directly to the upper.

When considering any construction of footwear, keep the workplace environment in mind. High heat applications may require flame retardant or nonthermal plastic material such as leather. Thermal plastic materials may be better suited to wet and/or chemical laden environments. Cold conditions may require specially formulated materials that retain flexibility and strength at sub-freezing conditions.

Reference

[1] The Brannock Device Co., "Find the Correct Shoe Size," available at **http://brannock.com/cgi-bin/start.cgi/brannock/instructions**, 2012.

Chapter 2 | Footwear Upper Materials

UPPER MATERIALS

Materials used in footwear construction can be broken into two primary uses: internal (lining and footbed covers) and external (upper materials or components). Each use has a different performance requirement depending on the functional or aesthetic purpose. Key material attributes to consider when selecting safety footwear are

- Environment
    - Will footwear be used in a dry, relatively clean atmosphere (for instance warehousing) or will it be worn in a wet or contaminated (dirt, chemicals, etc.) arena?
    - Does the footwear need to insulate and protect against cold and/or inclement weather?
    - Will the footwear be used in hot, external (for example, roofing) or internal (for example, manufacturing processes that generate heat) climates?
- Hazard Assessment
    - Are certain portions or all of the footwear subjected to the potential for increased wear and tear? For instance, electricians or plumbers may require extra abrasion protection on the toe if they are crawling routinely.
    - Is the footwear going to be subjected to high heat or particles that may be molten or hot to the touch?
    - Will the footwear be worn primarily at night and require visibility enhancements?
    - Are there closure system requirements for immediate release or for quick entry?
    - Is the shoe used in conjunction with security systems (metallic versus non-metallic components)?

EXTERNAL

Leather or Synthetic

The upper (above the sole) portion of the shoe may be constructed from either leather or synthetic materials, or a combination of both. The upper provides the foot with protection from the elements similar to that of an animal skin. Leather is a general term for hide or skin that has been chemically and mechanically treated (a process commonly referred to as tanning) to prevent putrefaction while retaining most of its original fiber structure. This dense fiber structure gives leather high tensile, puncture, and tear strength, while offering the comfort of flexibility and breathability. Leather can be retanned or finished with materials to impart characteristics such as water, chemical, fungal, flame, and abrasion resistance. The thickness, appearance, and feel of leather vary by design and end use.

Generally, most shoes and boots meant for work or rugged everyday use are made from leather, although there are synthetic upper materials that provide adequate durability and protection. Synthetics may be lighter in weight and more breathable, depending on the shoe construction.

Wet or Dry

Many shoes can be worn for different environments; however, keeping the feet dry requires careful construction and material selection. There are two types of waterproof construction: Seam seal, as the name describes, upper materials must be waterproof and stitched seams are sealed with a flexible waterproofing sealant; and membrane, a full lining material that forms a barrier to the elements. Both constructions require materials that will not wick water over the top of the footwear. Ideally, materials in both constructions are waterproof and are tested and evaluated often in accordance with a variety test method, such as SATRA TM230 [**1**], which simulates the mechanical flexing action of footwear when one is walking.

Seam sealed products require the sealant be directly applied to the primary substrate. This eliminates all multilayer synthetics and generally restricts this construction technique to all leather or leather/polymer hybrids. Waterproof performance is tied to the waterproofness of the upper material. Historically, leather seam sealed footwear requires 15,000 to 25,000 Maeser flexes (ASTM **D2099** [**2**]); 15,000 flexes equates to approximately seven miles walking at a normal pace or three hours in water. Leather tops (shafts) attached with or without waterproofed seams to polymer upper bottoms may have substantially higher waterproof properties because the polymer upper bottom waterproof characteristics are not affected by flexing the way leather fibers are.

Waterproof membrane, often referred to as bootie construction, consists of a water barrier between the footwear lining and the external upper material. The barrier allows for the use of nonwicking materials. Synthetic materials may be used in conjunction with or without leather because the stitched seams are not required to be sealed. Some synthetic materials are coated with barrier films to prevent water penetration while others are designed to promote air circulation for improved comfort.

One of the primary benefits of seam seal and membrane constructed footwear uppers (versus solid impermeable footwear, polymeric/vulcanized—most often made of 100 % rubber, thermal plastics, or urethanes)—is their inherent breathable comfort and support. Breathability can be measured using tests such as SATRA TM376 [**3**], which simulates the hot, damp atmosphere inside the shoe during wear. Stitched patterns with lacing systems conform to the foot and allow the wearer to customize the fit based on how tightly tied or secured are the hook and loop, strap, or buckle. Most leather and many synthetic textiles or microfiber nonwovens provide varying degrees of protection from the elements yet allow perspiration to escape, helping to keep the foot dry.

Hazard/Protection Assessment

Most nonleather footwear upper materials, unless manufactured with aramid (a specific class of synthetic fibers engineered to not melt when exposed to high heat or flame) or chemically treated natural fibers (cotton, rayon, wool), should be avoided when working around molten metal or the potential for sparks or flame.

Nylon-based synthetic uppers are inherently more abrasion resistant than polyester materials often found in athletic footwear, making them good alternatives for use in environments that may break down or dry out leather, as well as in areas with high ambient temperatures excluding molten particles or flame.

Hybrid constructions combining leather and synthetic upper materials can bridge the gap between environments where strategic protection is required. One example would be the use of a rubber- or urethane-based toe overlay to increase abrasion resistance (the toe being an area on the work shoe or boot that is subjected to perhaps the most wear and tear). Rubber- and/or urethane-coated or molded substrates come closest to providing abrasion-resistant properties similar to soling.

Another example is the use of textile panels in a work boot shaft, or in the tongue gusset, that would be better at allowing perspiration to escape while helping to keep dirt and debris out. Woven textiles are defined by the amount of fiber used to manufacture them as well as by the weave pattern. Typical work appropriate deniers are 600, 1000, or 1500. The larger the number, the stronger and (generally speaking) the more durable the textile will be. Synthetic microfiber upper material durability is based on thickness similar to leather. The heavier the weight, generally the more durable, although fiber entanglement and surface finish also play an important role in material durability.

Closure Systems

There are many different ways to secure a shoe or boot to the foot. Traditionally, work footwear used stamped metal eyelets to reinforce punched holes in the front of the upper; a lace was threaded in and out of the eyelets. When the lace was pulled tight, the upper would close over the tongue, and when the lace was tied, the work boot/shoe would be securely attached to the foot. Key attributes to consider are that the eyelets do not corrode and that the lace will withstand daily use and will not abrade. Today there are many choices for eyelet materials and finishes. Non-metallic materials such as nylon allow hardware to be mechanically fastened (stitched) to the upper, while polycarbonate eyelets can be mechanically crimped to the upper similar to metallic hardware. In addition to traditional eyelets, there are hooks for ease of lacing taller boots, speed lace loops for quick cinching, and locking hardware (when lacing taller boots, so that the lower half of the boot will stay secure while the top half of the boot is being laced). The more prominent a piece of hardware, the stronger it must be to prevent bending, tearing, breaking, or separating from the upper. Lace materials and aesthetics vary widely. As with upper textiles, nylon-based materials provide the abrasion resistance needed for daily wear and the friction for staying tied. Leather laces offer the best molten protection but because they are cut from the leather hide, they do not have uniform strength. Flame-resistant treatments provide synthetic fiber laces with moderate protection for use in high heat and/or spark environments. Natural lace materials such as cotton will not melt but do not provide the same strength and abrasion resistance as synthetic fiber laces. Hook and loop and buckle strap closure systems are also finding their way into work footwear—primarily in environments where simple, quick on and off footwear is required (for example, in emergency first responder footwear).

Thread

Much like upper textiles and synthetic lace fibers, threads used to stitch together footwear appropriate for work or rugged conditions require strength, resistance to breaking, and abrasion resistance. For most applications, nylon-based threads have the essential properties to keep footwear parts stitched together. There are two components to the primary upper stitching in footwear—the upper thread and the bobbin thread. Although not usually touted in product features and benefits, the proper sizing of both components will ensure long-lasting seam integrity. Specialty applications such as molten materials, high heat, or spark environments may require similar aramid fiber-based threads to maintain seam integrity without melting or stretching apart.

INTERNAL

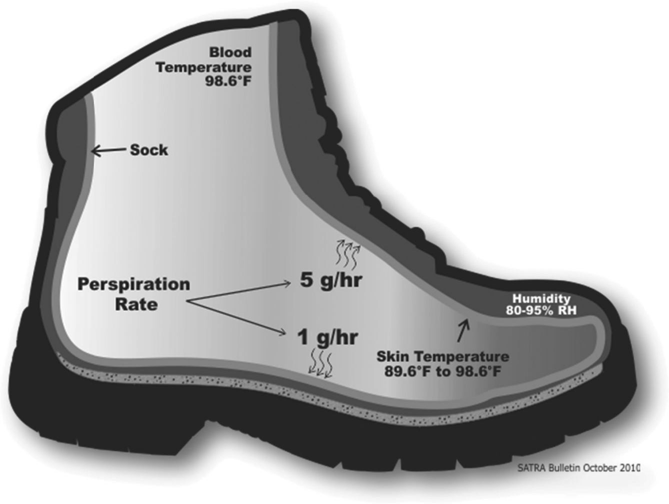
Linings

Lining materials serve several functions including moisture management, comfort/cushioning, and durability. One of the most important functions of a lining is to help manage the internal environment of the shoe. The foot is one of the primary areas of the body that produces perspiration in an effort to cool the skin. There are two types of perspiration: insensible and sensible. Evaporation of moisture from the skin takes place continually even when no liquid sweat is present on the surface. This is known as insensible perspiration, and it clearly has a cooling affect due to the high latent heat of evaporation of water [4]. Typical rates of insensible perspiration for the foot are between 1 and 5 mg/cm [5]. Sensible perspiration is linked to the skin temperature—the higher the skin temperature, the higher the rate at which perspiration is produced [5]. Foot temperatures are controlled by the rate of blood flow to the feet and by the evaporation of perspiration [6]. Core body temperature has a significant influence over extremity (hands and feet) temperatures. However, studies have shown activity rate (coinciding with increased blood flow) is a primary contributor to foot skin temperature change and to an increase in the sensible perspiration rate on the dorsal surface of the foot (Fig. 2.1) [7].

The lining of the work shoe/boot must be designed and engineered to capture the perspiration and to help move the moisture to the outer surface of the shoe upper away from the foot. The lining, in addition to the outer materials, can also help with ventilation. Because the foot shape changes throughout the day, upper and lining packages must promote flexibility for maximum comfort. Given the high humidity of the internal shoe microclimate coupled with the constant motion of the foot associated with daily work functions, footwear lining materials must resist pilling and abrading even though they are under constant motion.

Many times, specialized materials such as leather or heavy duty nonwovens are used in the heel area to provide that extra protection. This additional heel material (counter pocket) helps to hold the foot securely in place, limiting movement and

FIG. 2.1 Typical moisture and temperature variations found within footwear. (With permission from SATRA Technology Centre, Kettering, Northants, United Kingdom, available at www.satratechnology.com.)



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friction that can result in heat and moisture buildup and, ultimately, can provide the opportunity for blistering.

Special treatments for linings and footbeds to minimize bacterial buildup caused by perspiration are now available and are routinely featured and promoted to assist in overall foot health and odor protection.

Cold or Hot

Footwear constructed with leather or synthetic materials can be made to insulate against cold by keeping the warmth inside the footwear or to ventilate by promoting air circulation to cool inside the footwear. Synthetic fibers that create pockets of trapped air insulate against the cold. This insulation is typically defined in grams; the actual measurement refers to the amount of material in a specific circular area. Thermal insulation of footwear, however, is best assessed using whole shoe test methods such as SATRA TM436 [8].

Safety or cccupational footwear used daily on the job may not require the same level of insulation to keep the foot warm as do footwear for stationary uses such as hunting, fishing, and spectator sports. Overinsulating for a job that involves even moderate activity could have the reverse effect. Overheating causes perspiration. Perspiration can collect faster than when the lining, insulation, membrane, or upper materials can transport water vapor out of the boot. Moisture vapor testing quantifies the rate at which a given material allows water vapor to pass through it. Water saturated materials conduct cold or heat more quickly than dry materials. Typical insulation levels for work-related footwear are 200-g, 400-g, and 600-g levels. These levels refer to the weight of the insulation packages used in the production of the footwear. Leading footwear and apparel insulation suppliers have insulation performance guidelines to help a consumer select the right insulation level for the job.

Key features to look for in cold weather work footwear are the appropriate insulation level for the work activity and climate (as mentioned earlier), underfoot materials intended to minimize the potential for conducting cold from ground contact into the boot/shoe, insulation positioned to protect the dorsal surface of the foot where the primary arteries are located, and lining/membrane/upper materials that allow water vapor (perspiration) to escape while helping to retain as much of the foot core temperature as possible.

Stiffeners and Protective Components

Footwear uses molded forms in the heel and toe to maintain shape and fit. Work footwear will typically use heavier gauge, stronger materials than fashion, sport, or casual footwear. Properly shaped heels help secure the foot in the work shoe/boot. Protective components built into the footwear may include toe cap, metatarsal guard, and/or puncture resistant plate/device. Protective toe caps are not removable and provide protection from impact and compression in accordance with ASTM **F2413** [9] standards. Protective toe caps are manufactured in metallic and non-metallic materials.

Performance must meet the same standard across all materials. Benefits such as lighter weight and/or the ability to go through metal detection security stations would be some of the factors to consider when selecting a protective toe material type. Toe shapes are also variable. As long as the performance criteria are satisfied, personal preference and fit should be the guide to use when selecting the right footwear for the job. In combination with toe protection, some work footwear uses polymer-based materials to create metatarsal guards designed to protect the top surface of the foot against damage from impact. Whether external or internal, metatarsal protection must also be a permanent part of the footwear and must meet applicable ASTM F2413 performance standards. Puncture-resistant devises can be used in protective (ASTM F2413) or nonprotective (ASTM F2982) [10] safety footwear. They are primarily made from metallic sheets or textile composite laminates and are a permanent part of the footwear, located between the foot and the outsole. Both provide high degrees of protection from underfoot puncture while at the same time maintaining flexibility of the shoe/boot. Again, a typical consideration for choosing between the two material types are environments requiring non-metallic footwear such as for going in and out of metal detection security areas. With regard to weight, non-metallic devices weigh slightly less than similarly sized metallic plates, and they also may be more flexible. When climate is a concern, metallic plates conduct temperature fluctuations much faster than non-metallic puncture-resistant devices, which may be more appropriate for extreme temperature environments. As for the degree of protection, although both materials must meet ASTM F2413 or ASTM F2982 puncture-resistance performance standards, non-metallic textile woven laminates can be sewn into footwear, whereas metallic plates are truly solid devices.

Insoles and Footbeds

The purpose of removable insoles, often referred to as footbeds, is to support the unique structure of the human foot while providing cushioning and comfort between the foot and the inside of the shoe. When moderated by a suitable insole, the pressure and trauma the foot experiences are reduced. Preferred properties include lightweight, flexible, shock absorbing, compression resistant, breathable, antimicrobial, and, in some cases, static dissipative properties.

Footbeds and insoles should provide cushioning, pressure distribution, longevity, and comfort. It is important to note that footwear that meets ASTM protective footwear standards has been tested and certified with the original insoles and footbeds (Fig. 2.2). Important note: The use of aftermarket products may limit the function of the footwear and as such voids any certification of the footwear. Common materials used in the production of insoles and footbeds include ethylene vinyl acetate (EVA), open cell foam, and microcellular polyurethane.

Performance criteria often include cushioning (shock attenuation), pressure distribution (F-Scan®), and longevity (compression set). Test methods include SATRA TM159 [2002] [11], which assess the cushioning performance properties of insole

FIG. 2.2 Various type of footbeds used in safety footwear. (With permission from Remington Products, available at **www.remprod.com**.)

materials when new and after repeated dynamic compression. Test pieces are compressed 10,800 times, and, after reconditioning, the percent change in thickness is measured and reported as compression set and compression spread. SATRA TM142 [1992] [**12**] is a falling mass shock absorption test. This evaluates materials for maximum deceleration, maximum penetration, and energy return. F-Scan is used to measure and retrieve pressure profile information between the foot and insole.

In summary, removable footbeds and insoles should provide:

- Cushioning
- Pressure distribution
- Longevity
- Comfort

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[4] Bunten, J., M.A., "Insensible Perspiration," *Foot Comfort*, SATRA SR44, 3.1.5.3, 1983, p. 26.

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[6] Bunten, J., M.A., "Temperature," *Foot Comfort*, SATRA SR44, 2.4, 1983, p. 9.

[7] Bunten, J., M.A., "Perspiration," *Foot Comfort*, SATRA SR44, 3.15; "Blood Flow and Skin Temperature," SATRA SR44 3.16, 1983, pp. 25–36.

[8] SATRA TM436, "Determination of Whole Shoe Thermal Insulation Value and Cold Rating," SATRA Technology Centre, Kettering Northants, United Kingdom, 2010.

[9] ASTM Standard F2413–11: "Standard Specification for Performance Requirements for Protective (Safety) Toe Cap Footwear," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2011.

[10] ASTM Standard F2982–12: "Standard Specification for Polyester Composition Floor Tile," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2012.

[11] SATRA TM159, "Cushioning Properties," SATRA Technology Centre, Kettering Northants, United Kingdom, 2002.

[12] SATRA TM142, "Falling Mass Shock Absorption Test," SATRA Technology Centre, Kettering Northants, United Kingdom, 1992.

Chapter 3 | Soling Materials

The outsole that can be used alone—or in conjunction with a midsole and possibly other components—forms the foundation of all footwear. The outsole is the protective layer of material between the foot and the ground. Outsoles provide and contribute to a wide variety of functions including durability, flexibility, traction, slip resistance, insulation, and comfort. Many of today's footwear styles use a "unit sole," which means the sole and heel are combined into one unit. The unit sole is applied to the shoe in a single operation and helps to simplify production of the footwear. Other styles of footwear may utilize separate soles, heels, and midsoles that when combined become a soling system. It is possible that within the soling system the shoe manufacturer can also incorporate such items as devices to protect against puncture, to provide improved stability, and to dissipate energy current as well as other benefits. There is no one type of outsole that is regarded as the "best" for all footwear. Depending on style, design, manufacturing processes, and the intended use of the footwear, the outsole system will vary (**Figs. 3.1** and **3.2**).

For use as a reference, following is a brief description of the most widely used types of outsoles today. Each of these soling materials may be offered alone or in conjunction with others. Each one may come in a variety of formulations and/or styles intended to work best with the style of footwear and the material specifications required and the features and benefits the footwear is intended to be provide. Various styles of soles, heels, unit soles, midsoles, and other devices can be combined into the soling system. Other devices may include products designed to protect against puncture (**Fig. 3.3**) as well as heel inserts intended to provide added support and stability (**Fig. 3.4**).

POLYURETHANE

Polyurethane (PU) can be used in most common footwear constructions including welt, cement, stitch-down, little-way (a footwear construction method common among casual footwear such as boat shoes and moccasins), and direct attach methods. Polyurethane has a cell structure consisting of numerous tiny air bubbles on the interior with an outer solid polyurethane skin that provides greater durability, oil

FIG. 3.1 Polyurethane unit sole. (With permission from Meramec, Inc., available at **www.meramec.com**.)

FIG. 3.2 Rubber sole with separately attached heel. (With permission from Vibram USA, available at **www.vibram.com**.)

FIG. 3.3 Non-metallic and steel puncture-resistant devices. (With permission from Meramec, Inc., available at **www.meramec.com**.)

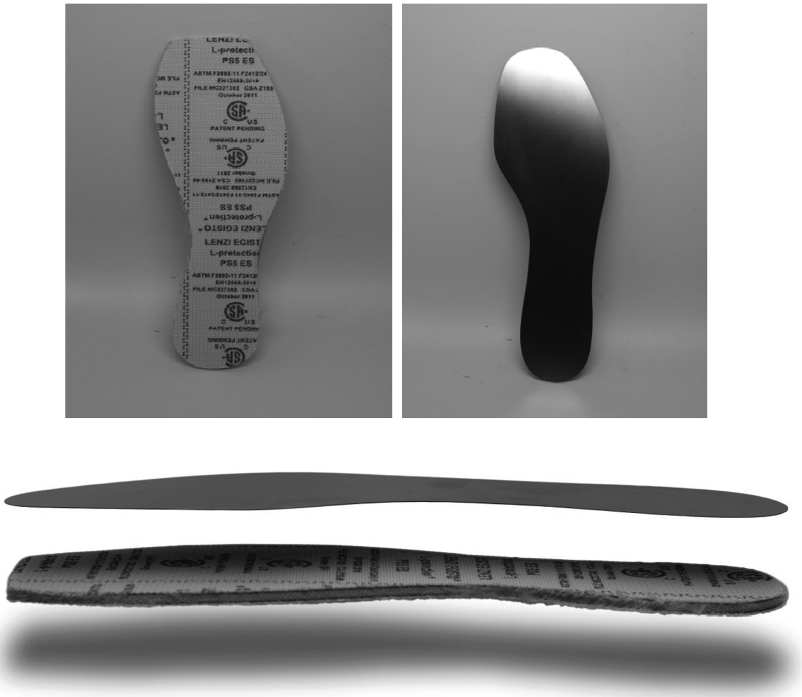


FIG. 3.4 Thermal plastic urethane (TPU) heel inserts. (With permission from Timberland Boot Company, available at **www.timberlandpro.com**.)

and chemical resistance, and slip resistance. In addition, polyurethane soles provide excellent shock-absorbing properties even though taking very little compression set. Polyurethane outsoles are often designed with textured surfaces and finished in a variety of colors and textures. An additional option to single-density polyurethane soles is dual-density polyurethane, which combines a low-density polyurethane midsole with a stronger type of polyurethane on the wear surface. This increases the shock absorption and durability of the outsole. Polyurethane is a good choice for casual, dress, sandals, industrial, and work service footwear.

When used for a midsole, in conjunction with other outsole materials, polyurethane provides additional shock absorption and comfort.

Polyurethanes are formed by combining two reactive chemicals to produce the finished product. Urethanes are available in polyether and polyester formulations. Although great advances have been made in the world of urethanes, in general terms, polyesters are most commonly used for their resistance to chemicals, while polyether provides protection against the effects of moisture (a condition referred to as hydrolysis).

THERMOPLASTIC POLYURETHANE

High-performance thermoplastic polyurethane (TPU) is most commonly used for injection molding. When used for outsoles, TPU has excellent physical properties in addition to good slip, oil, fuel, and grease resistance. Being thermoplastic, TPU has its limitations in areas where high surface temperatures are present. TPU materials can provide excellent surface definition and can be molded clear, as well as in translucent colors.

RUBBER

Most rubber compounds used in safety footwear are synthetic rubbers. Numerous synthetic rubber base polymers are used independently and/or blended with other synthetic and/or natural rubber bases to provide the desired performance specifications. As with the countless uses of rubber in our daily lives, rubber used in footwear can be formulated to provide the desired results when taking into consideration the needs for oil and chemical resistance; energy conductivity; insulation from cold, heat, and/or electrical shock; traction and slip; and flame resistance. Rubber is thermal set, making it less susceptible to the effects of heat and cold. Rubber soles and thin midsoles (used in welt construction) are most often produced as solid materials, but also in expanded materials, making them lighter. It is important to note that given the wide range of rubber base polymers used in today's footwear, the performance characteristics can vary widely.

ETHYLENE VINYL ACETATE

Ethylene vinyl acetate (EVA) is a lightweight, expanded material that has been used extensively for outsoles due to its cushioning properties and comfort. When used as a midsole, and combined with another soling material for the outsole, EVA helps to reduce the weight of the overall outsole system while providing additional shock absorption and comfort. EVA is often used for sandals, orthopedic shoes, slippers, athletic shoes, and men's and women's casual footwear. Recent developments in injected EVA materials have created a new category of net fit outsoles and molded footwear.

LEATHER

Although seldom used as an outsole on safety footwear, leather offers a traditional, fashionable, natural appearance. Leather is found most often in welt construction dress footwear. Resistance to oil, solvents, and moisture is generally poor, leading to reduced durability.

THERMAL PLASTIC RUBBER

Thermal plastic rubber (TPR) is a dominant type of soling material used in today's casual footwear. TPR soles are lightweight, flexible, durable, and slip resistant. TPR soles come in many designs and can be made to look like rubber and leather. TPR soles are used on sandals, athletic and casual shoes for men and women, and on children's shoes. Depending on the blend of TPR, it can also have applications in lightweight work and duty footwear.

POLYVINYL CHLORIDE

Polyvinyl chloride (PVC) is a low-cost soling alternative to rubber, TPR, PU, and most other soling materials. Used primarily on low-cost footwear, PVC is often found on cement, string lasted, and direct attach constructed footwear. Generally, PVC has poor oil and solvent resistance.

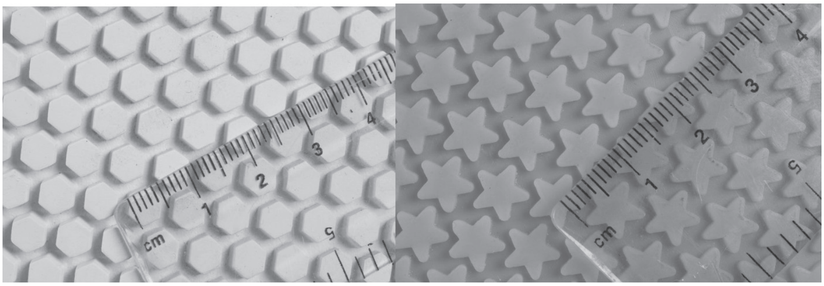
CREPE

Crepe is part of the rubber family and the closest footwear soling material directly sourced from the rubber tree. It is often referred to as "natural rubber" soling. Used primarily in its natural state, crepe is denser, prone to color loss, and is not recommended for hot weather applications. Crepe is mainly used in casual footwear, slippers, and moccasins.

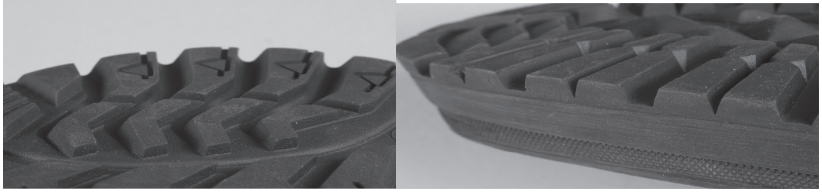
SOLING DESIGNS

As with soling materials, soling designs differ widely. Although certain design characteristics' lug shapes, grooves, and spacing, as well as overall gauges are intended to aid in the performance of the footwear. There is also a desire for style, as well as function. If all footwear soling designs were to look the same, footwear style options would be very limited. As is the case with materials, no one design can be optimal for all applications. Safety footwear, with its array of uses, environmental applications, and the performance specifications often mandated for its use, can present challenges in design. **Figure 3.5** is intended to provide some insight into common design criteria often considered when designing safety footwear. It is important to note that the soling

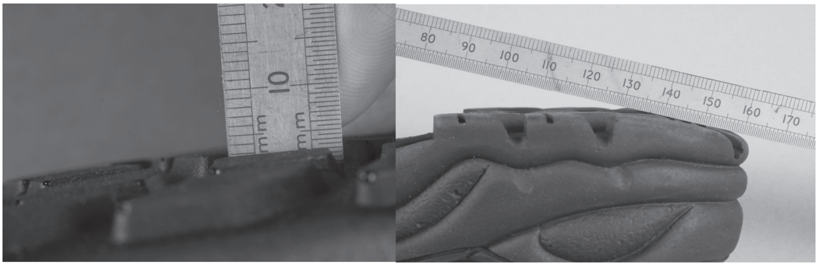
FIG. 3.5 Typical design characteristics common to footwear soling design and engineering. (With permission from SATRA Technology Centre, Kettering, Northants, United Kingdom, available at **www.satratechnology.com**.)



(a) Examples of slip-resisting tread designs consisting of smaller patterns with sharp leading edges intended to optimize grip.



(b) Examples of sole tread designs with deeper and wider lug patterns for enhanced traction.



(c) Examples of design depth and angular characteristics commonly used in the design and engineering of footwear outsoles.

design and the materials used in the soling system together provide the intended characteristics. Not all materials can be molded in all designs nor can all designs be molded in all materials.

Often the major concerns safety professionals wish to address are those centered on the area of slip resistance. In order to better understand slip-resistance needs, we must also understand the differences in slip resistance versus traction. For example, during a typical day, a construction worker may traverse from the rough terrain of a job site's exterior, with its rock and building debris, to the interior of the building, which has a lobby of polished marble. The needs of the worker differ in each case. In the exterior environment, a worker's footwear may need to bridge over larger, uneven surfaces, some of which may be pointed and/or unstable. For this type of environment, a wider profile design may be best; thus, there is a need for traction. When walking through or working in the interior of the building, where water and other contaminants may be present, a less aggressive design with a greater amount of surface contact may be a better option—thus the increased need for slip resistance. Similarly, the needs of a worker in a meatpacking plant can differ widely from those who work in mining. Likewise, although a nurse and a maintenance worker may both work in a hospital, when considering their major roles and work environments, they each have differing needs with regard to slip resistance and traction.

Figure 3.5 illustrates a number of design details, some of which include size and depth variation of design as well as angles of particular design characteristics. These examples are intended to provide a general overview of a number of design characteristics that aid in the performance of occupational footwear. Such characteristics are most often intended to enhance the traction, slip resistance, and durability of the footwear. This illustration does not cover all aspects of designs as production processes and materials may have limitations.

Chapter 4 | Specifications and Test Methods for Safety Toe Protective Footwear

In general, protective footwear is designed to provide an enhanced level of hazard protection to the wearer that would not be present in nonprotective footwear. It should be noted that protective footwear cannot be expected to provide absolute protection against every hazard or every level of hazard. A detailed description of the specifications and the corresponding test methods may be found in ASTM F2412 Standard Test Methods for Foot Protection [1] and ASTM F2413 Standard Specification for Performance Requirements for Protective (Safety) Toe Cap Footwear [2] and ASTM F2892 Standard Performance Requirements for Soft Toe Protective Footwear Non-Safety/Non-Protective Toe [3].

For chain saw protective footwear and leg apparel, please reference ASTM F1818 [4] and ASTM F1897 [5].

For structural firefighting footwear, please reference the most recent edition of NFPA 1971 [6]. For wildland firefighting footwear, please see NFPA 1977 [7].

The following are brief descriptions and illustrations of various types of protective safety toe footwear, along with an overview of the performance specifications and the methods used to test the footwear.

PROTECTIVE TOE IMPACT RESISTANCE

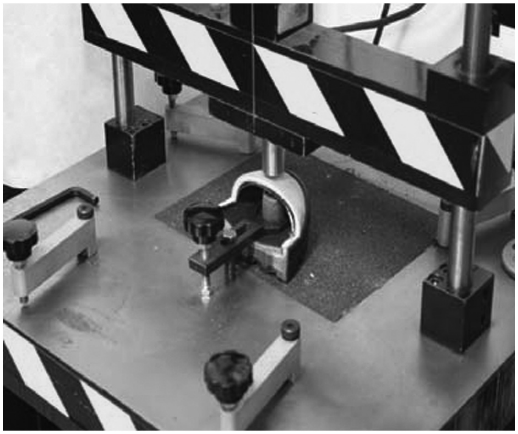
Safety toe footwear must contain, as a permanent component of the footwear, a reinforced toe section (as specified in ASTM F2412 and ASTM F2413) that would be capable of withstanding an impact force of 101.7 joules (75 foot pounds) of energy without deforming the toe area downward to less than 12.7 millimeters (0.5 inches) above the footbed for men's shoes and 11.9 millimeters (0.468 inches) for women's shoes.

The impact test is conducted by dropping a 50-pound weight, shaped as described in ASTM F2412, Section 5, at a speed of 2995 $\pm$ 61 millimeters per second (117.9 $\pm$ 2.4 inches per second) as shown in Fig. 4.1.

PROTECTIVE TOE COMPRESSION RESISTANCE

Safety toe footwear must also be capable of withstanding a compressive (slowly applied) force of 11,121 newtons (2,500 pounds) without deforming the toe area downward to

FIG. 4.1 Impact testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)



less than 12.7 millimeters (0.5 inches) above the footbed for men's shoes and 11.9 millimeters (0.468 inches) for women's shoes.

The compressive test is conducted by slowly applying a force as described in ASTM **F2412**, Section 6, at a speed of 222.4 newtons per second (50 pounds per second) until it reaches 11,121 newtons (2,500 pounds). (See **Fig. 4.2**.)

FIG. 4.2 Compression testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)

Care, Use, and Disposal of Impact- and Compression-Resistant Footwear

If there is evidence of physical damage to the toe and/or evidence of physical damage to the toe area, replace the footwear at once. Warning: If an aftermarket insert or insole is added to this footwear, that device may reduce the impact and compression clearance.

METATARSAL IMPACT RESISTANCE

In addition to meeting the requirements of protective toe impact and compression resistance described earlier, metatarsal protective footwear must also include a reinforced layer of protection for the foot's metatarsal area. The metatarsal bones are behind the toes and forward of the ankles on the top part of the foot.

Metatarsal protection should be recommended anytime potential hazards exist that may result in blunt trauma injury to the metatarsal portion of the foot from falling, moving, or rolling objects or equipment.

Metatarsal protective footwear must be capable of withstanding an impact force of 101.7 joules (75 foot pounds) of energy without deforming the inside metatarsal area downward to less than 25.4 mm (1.0 inch) for men's footwear and 23.8 mm (0.937 inches) for women's footwear when tested as described in ASTM **F2412**, Section 7 (**Fig. 4.3**).

Care, Use, and Disposal of Metatarsal Impact-Resistant Footwear

Be certain to keep any external metatarsal guards properly laced into the footwear. Dispose of the footwear after an impact to the metatarsal guard has occurred or after the exterior covering becomes torn exposing the metatarsal guard. Note: A metatarsal guard could also be an integral part of the footwear, such as in fire boots.

FIG. 4.3 Metatarsal impact testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)

CONDUCTIVE PROTECTIVE FOOTWEAR

Conductive protective footwear is designed to prevent the possibility of static electricity buildup in the wearer. This type of footwear is designed for use where a possibility of explosion may exist.

Conductive protective footwear must demonstrate a resistance of 0.0 to 500,000 ohms when tested as described in ASTM **F2412**, Section 8.

Care, Use, and Disposal of Conductive Protective Footwear

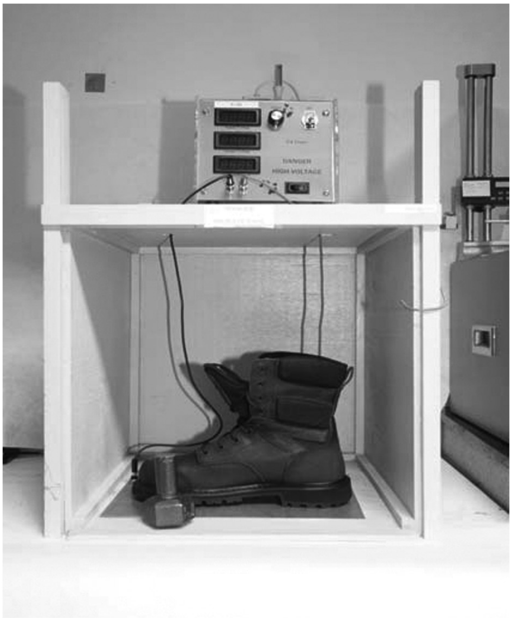
Keep the outsoles clean. Do not add aftermarket insoles, as doing so may affect conductivity. Dispose of the footwear if it becomes contaminated and/or no longer test conductive (**Fig. 4.4**).

Warning: Conductive footwear should not be worn near open electrical circuits or highly charged objects of any kind that require electrical hazard (nonconductive) footwear. Check with your footwear supplier if you have any questions regarding the proper choice.

ELECTRIC HAZARD RESISTANT FOOTWEAR

Electric hazard (EH) resistant footwear is designed as a secondary layer of protection against electric shock to the wearer, in the event of an accidental contact

FIG. 4.4 Conductive footwear testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)



by stepping on an electrical circuit. Electric hazard resistant footwear should never be worn when the wearer will intentionally come into contact with a live electrical circuit. Dielectric overshoes are specifically designed for that type of environment.

Electric hazard resistant footwear must withstand the application of 18,000 volts rms with current leakage or flow no greater than 1.0 mA when tested as described in ASTM F2412, Section 9 (Fig. 4.5).

Electrical hazard resistant footwear can be found in compliance with or without protective toe, impact, and compression resistance. These standards are detailed within ASTM F2412 and F2892.

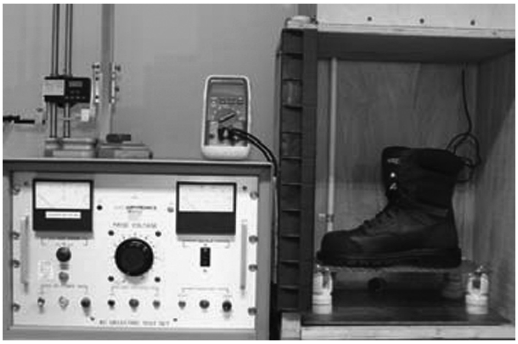
Care, Use, and Disposal of Electric Hazard Resistant Footwear

Avoid moisture and keep the shoes and outsoles free of conductive materials such as screws, nails, and metal shavings. Dry the footwear thoroughly after use. Clean outer rubber with a mild soap and warm water. Store all rubber footwear away from electric motors or electric fields to avoid cracking. Inspect footwear for any visible damage prior to use, such as punctures, tears, snags, and cracking.

Dispose of the footwear if the uppers are punctured, cut, or if they show signs of cracking, are imbedded with conductive materials, or if wear causes the outsole thickness to diminish noticably. These conditions will result in significant reduction or elimination of the footwear's protection if the wearer steps on an electrical circuit.

Warning: Electric hazard nonconductive footwear should not be worn near explosives or in other environments that require conductive footwear. Check with your footwear supplier if you have any questions regarding the proper choice.

FIG. 4.5 Electrical hazard testing. (With permission from Precision Testing Laboratories, available at www.precisiontesting.com.)



Footwear with electrical hazard protective soles and heels is recommended for general use to reduce the risk of injury from accidentally stepping on live electrical conductors of less than 600 volts ac. It will be particularly advantageous to use such footwear where potential electrical hazards exist. Because of the possibility that the shock-resistance property may be degraded when worn, the footwear must never be used in place of conventional dielectric footwear, insulating rubber mats, and so on. The shock-resistance properties can be maintained if the footwear is used in dry conditions and if the outer sole remains free from chemical contaminants such as road salt and embedded conductive materials (metal particles, thumbtacks, nails, etc.). The sole and heel of the footwear should be inspected regularly. Absolutely no modifications should be made to the footwear that may negate its electrical insulating properties.

DIELECTRIC FOOTWEAR

Dielectric footwear consists of three types of overshoe footwear as designated in ASTM standards **F1116** [8] and **F1117** [9]. These types are rubbers (low cut), boots, and galoshes.

Dielectric footwear is designed as an additional layer of protection against electric shock in the event the wearer accidentally comes into contact with electrical conductors, apparatus, or circuits.

Dielectric footwear is tested in accordance with ASTM **F1116** (Standard Test Method for Determining Dielectric Strength of Dielectric Footwear). Per ASTM **F1116**, 100 % of the footwear produced is tested to this standard. This footwear is also tested in full wet conditions, with water covering the exterior of the boot as well as the majority of the interior to a level that does not produce flashover (**Fig. 4.6**).

FIG. 4.6 Dielectric testing. From ASTM **F1117-03**(2008), Standard Specification for Dielectric Footwear.

Care, Use, and Disposal of Dielectric Footwear

Avoid moisture and keep the shoes and outsoles free of conductive materials such as screws, nails, and metal shavings. Dry the footwear thoroughly after use. Clean outer rubber with a mild soap and warm water. Store all rubber footwear away from electric motors or electric fields to avoid cracking. Inspect footwear for any visible damage prior to use, such as punctures, tears, snags, and cracking. Dispose of the footwear if the outsoles and/or uppers are punctured, cut, or show signs of cracking, if they are imbedded with conductive materials, or if significant wear causes the outsole thickness to diminish significantly. Any such evidence should result in immediate replacement of the footwear because this will result in significantly reduced or no protection against electrical contact.

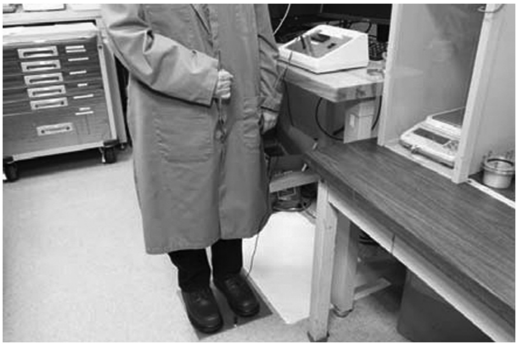
STATIC DISSIPATIVE FOOTWEAR

Static dissipative (SD) footwear can be found in compliance with and without protective toe impact resistance and protective toe compression resistance. These standards are detailed in ASTM **F2413** and **F2892**. Static dissipative footwear is meant for use in environments such as electrical assembly areas and it must prevent the buildup of excess static electricity while at the same time providing the wearer limited protection against electric shock. It must also demonstrate a lower level of resistance of 10^6 ohms (1 megohm) and an upper level of resistance of 10^8 (100 megohms) when tested as described in ASTM **F2412**, Section 10 (**Fig. 4.7**).

Care, Use, and Disposal of Static Dissipative Footwear

For maximum SD performance and longevity, SD footwear should be worn indoors with care taken to keep the outsole clean. Do not add aftermarket comfort insoles because that will adversely affect the static dissipative properties. It is recommended to

FIG. 4.7 Static dissipative (SD) testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)



test for required resistance levels on a regular basis to ensure compliance. Disposal of the footwear is recommended when it no longer tests to the required workplace standard.

PUNCTURE-RESISTANT FOOTWEAR

There are numerous product designs and materials used in the production of puncture-resistant devices. Regardless of these variations, all products must meet the performance requirements of the applicable standard.

Puncture-resistant footwear contains a puncture resistant-device placed between the foot and the outsole. Per ASTM **F2413** and **F2892**, the puncture-resistant device must be an integral, permanently attached part of the footwear (**Fig. 4.8**). These ASTM standards are not to be used for the certification of aftermarket puncture-resistant devices or for those devices that are not an integral part of the footwear as originally produced.

Puncture-resistant footwear must resist a force of 1,200 newtons (270 pounds) without the puncture-resistant device being visibly penetrated when tested in accordance with ASTM **F2412**, Section 11.

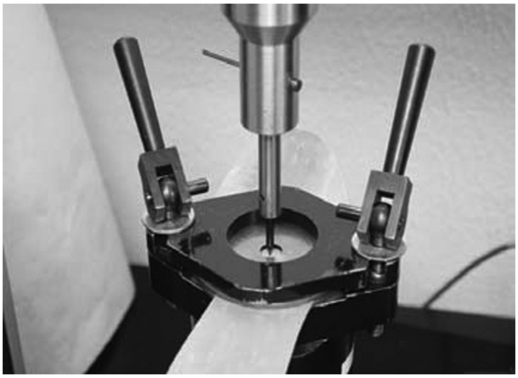
Puncture-resistant footwear must show no sign of corrosion, delamination, or deterioration after being exposed to a 5 % salt solution for 24 hours in accordance with ASTM **B117** [**10**].

Puncture-resistant footwear must show no sign of delamination of layers or cracking after 1.5 million flexes when tested in accordance with ASTM **F2412**, Section 11.

Note: In order to ensure optimum protection, the testing of puncture-resistant devices is performed on the devices themselves (outside and independent of the actual footwear; see **Fig. 4.9**).

FIG. 4.8 Integrated puncture-resistant device. Boot for testing courtesy of STC Footwear (**www.stcfootwear.com**). (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)

FIG. 4.9 Puncture-resistant device testing. (With permission from Precision Testing Laboratories, available at **www.precisiontesting.com**.)



Care, Use, and Disposal of Puncture-Resistant Footwear

No special care is needed to maintain the puncture-resistant device. Dispose of the footwear after an object becomes imbedded in the puncture-resistant device.

References

[1] ASTM Standard F2412–11: "Standard Test Methods for Foot Protection," *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2011.

[2] ASTM Standard F2413–11: "Standard Specification for Performance Requirements for Protective (Safety) Toe Cap Footwear," *Annual Book of ASTM Standards.* ASTM International, West Conshohocken, PA, 2011.

[3] ASTM Standard F2892–11: "Standard Specification for Performance Requirements for Soft Toe Protective Footwear (Non-Safety/Non-Protective Toe)," *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2011.

[4] ASTM Standard F1818–13: "Standard Specification for Foot Protection for Chain Saw Users," *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2013.

[5] ASTM Standard F1897–08: "Standard Specification for Leg Protection for Chain Saw Users," *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2008.

[6] NFPA 1971: "Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting," National Fire Protection Association, Quincy, MA, 2011.

[7] NFPA 1977: "Standard on Protective Clothing and Equipment for Wildland Fire Fighting," National Fire Protection Association, Quincy, MA, 2013.

[8] ASTM Standard F1116–03. “Standard Test Method for Determining Dielectric Strength of Dielectric Footwear,” *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2008.

[9] ASTM Standard F1117–03: “Standard Specification for Dielectric Footwear,” *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2008.

[10] ASTM Standard B117–11: “Standard Practice for Operating Salt Spray (Fog) Apparatus,” *Annual Book of ASTM Standards,* ASTM International, West Conshohocken, PA, 2011.

Chapter 5 | Slip Resistance

INTRODUCTION

Slip resistance is the most often discussed topic involving safety footwear. To best understand how slip resistance relates to safety, one needs to consider the range of factors that can collectively affect slip resistance. The ongoing scientific research on slip resistance aims to identify these factors, with the ultimate purpose of establishing safety through understanding. Although much information has been studied, written, and reviewed, given the range of variables that affect slip, further research is still necessary. Using the information available and a well-intended plan of review, this guide will assist in making informed recommendations for footwear that best fits the specific needs of the intended user. Given the number of contributing factors to slip events and the inherent elements of randomness and unpredictability with which they occur, it is important to establish that no testing, either human subject or mechanical, can accurately predict with 100 % certainty the required level of safety so that slips will not occur.

The shoe–floor interface is the driving factor in providing secure footing. Contaminants at the shoe–floor interface can affect shoe–floor contact and therefore prevent optimum shoe–floor interaction. Additional factors that contribute to slip resistance include walkway condition and maintenance, area lighting, biomechanics of the ambulator, age and functional status of the ambulator, footwear type and condition, and others. Within this chapter, the definitions of the terms "slip resistance," "slip resistant," and "walkway tribometer" are from ASTM **F1646** [1].

- Slip resistance (noun)—the relative force that resists the tendency of the shoe or foot to slide along the walkway surface. Slip resistance is related to a combination of factors including the walkway surface, the footwear bottom, and the presence of foreign materials between them.
- Slip resistant (adjective)—the provision of adequate slip resistance to reduce the likelihood of slip for pedestrians using reasonable care on the walking surface under expected use conditions.

- Walkway tribometer (noun)—any apparatus used to measure the friction forces acting at an interface between a walkway surface and a shoe material. This is the definition of walkway tribometer within ASTM **F2508** [**2**].

This chapter will provide insight into the physical science of friction, how friction relates to slip, references to peer-reviewed scientific research, as well as information pertaining to the various methods of testing for slip resistance. Those methods include testing related to walkways and footwear.

THE QUESTIONS MOST OFTEN ASKED

What is a safe coefficient of friction (COF)? What is the best method of testing slip resistance? How do I compare one test method's results to another? The information throughout this chapter serves as a guide to answering these questions and to why there are no exact answers.

Tribometers are mechanical instruments that purport to measure the COF between a test foot and floor in order to assess a pedestrian's risk of slipping while walking. Many different types of walkway tribometers exist, and empirical research has shown that not all tribometers measure the same COF on the same surface [**3**]. For example, a COF of 0.3 obtained on a particular tribometer will not correlate to 0.3 on another tribometer. The "classic" laws of friction formulated in the 17th century stated that COF was independent of contact area and velocity; however, these laws are not obeyed by viscoelastic materials such as the synthetic polymers used in most shoe outsoles, tribometer test feet, and certain flooring materials. In the presence of these polymers, the parameters of peak force, loading rate, pressure, and time of contact between the tribometer test foot or shoe and test surface influence tribometer COF values. Because these parameters diverge widely among tribometer types, no single safe threshold COF value can be defined that encompasses all tribometer results. To be meaningful, a safe threshold COF value would have to be associated with a specific calibrated tribometer, test foot material, and test method. To date, no study has been performed that defines the safe threshold COF for a specific tribometer for all combinations of footwear, contaminant, and floor type.

AVAILABLE FRICTON AND UTILIZED FRICTION

This purpose of this section is to provide a basic education as to why slips occur. As the chapter progresses, the topics of slip-resistance testing and applicable standards will be covered. The information provided is an introduction into the complex and multivariate event that is slipping.

Background

The function of footwear is to provide protection, safety, comfort, and enhanced performance during dynamic and static activities. With respect to safety and performance, it is essential that footwear deter slipping. Slipping has been reported as being responsible for 62 % of underfoot accidents in the workplace [**4**]. Additionally, slips are considered to be the primary cause of falls [5]. In 2008, slips and trips were responsible for 6.9 % of occupational sprain and strain injuries [6] and accounted for 3 % of all occupational injuries and illnesses [7]. The U.S. Bureau of Labor Statistics reports that falls on the same level and falls to a lower level have incidence rates per 10,000 full-time workers of 18.0 and 7.3, respectively [8]. By the year 2020, it has been estimated that slip-and fall-related injuries will approach 17 million annually with associated health care costs in the billions [9]. To prevent slips and slip-related injuries, it is necessary to understand the conditions that increase slip risk and the terminology.

Available Friction

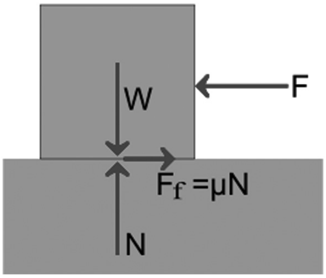
Why do slips occur? To discuss why slips occur, the role of friction first must be introduced. Friction can be defined as a force that opposes motion. For example, if you drag the sole of your shoe along a dry tile floor, you will likely feel a resistance to that motion; your shoe may even squeak. The resistance you feel is actually friction (see Fig. 5.1).

In Fig. 5.1, the weight (W) of the block is equal to the vertical force (N) acting upward. This represents Newton's third law of motion, which states that for every action there is an equal and opposite reaction. If a force (F) is applied to the block, motion of the block is resisted by the friction force (Ff). The friction force (Ff) is proportional to the vertical force (N), where Ff = μN. The coefficient of friction, mu (μ), is commonly referred to as available friction. With respect to slip- and fall-related literature, available friction or the coefficient of friction is abbreviated COF.

$$\text{Available friction} = \text{COF}$$

A larger COF represents a larger friction force and a greater resistance to motion. Conversely, a lower COF represents a smaller friction force and a lower resistance to motion. Available friction is the friction provided by the environment, more specifically, the shoe–floor interface. The floor and the shoe can each influence available friction for a variety of reasons. The friction measured at the

FIG 5.1 Forces involved that contribute to slips and slip prevention.



shoe–floor interface can be represented by either static or dynamic coefficients. The static coefficient of friction represents the friction requirement to deter slip onset, whereas the dynamic coefficient represents the friction requirement to deter slip continuation and uncontrollable foot slide (i.e., slipping) [10]. The dynamic coefficient of friction is most often associated with descriptions of available friction. Often, the term available friction is used interchangeably with slip resistance. For example, assessing the slip resistance of a shoe sole means determining the amount of available friction it provides, or its COF.

Utilized Friction

Human walking, or gait, has two distinct phases: stance and swing. The stance phase refers to when a reference foot is in contact with the ground, while the swing phase refers to when that same reference foot is off the ground [11]. During walking, slips that result in falls typically occur in early stance (when the foot first hits the floor) as body weight is transferred onto the lead limb. The ground reaction forces (GRFs) during this period of weight acceptance are critical in determining if the available friction provided by the shoe–floor interface will be sufficient to prevent slips. Ground reaction forces are the equal and opposite reactions (Newton's third law) to a person's body weight. These are the forces that act from the floor back up into the body. It is important to note that GRFs are measured in a laboratory setting by having a person walk over a device called a force plate (**Fig. 5.2**).

Ground reaction forces occur in three directions: vertical, anterior–posterior, and medial–lateral. The vertical GRF acts directly upward from the floor. The anterior–posterior GRF acts forward and backward. The medial–lateral GRF acts left and right. Measuring GRFs in a lab setting is a useful tool for determining the conditions that elicit slips. Ground reaction force data are used to calculate the second type of friction in the context of slips and falls, utilized friction. Utilized friction (abbreviated uCOF) is defined as the friction force required to maintain motion without slipping [12]. It is calculated as a ratio of resultant shear force to the vertical ground reaction force (**Equation 5.1**) [13–20]. The resultant shear force is the sum of the anterior–posterior and medial–lateral GRFs.

$$\text{uCOF} = \frac{\text{Resultant Shear GRF}}{\text{Vertical GRF}} = \frac{\sqrt{(F_{\text{Anterior–Posterior}})^2 + (F_{\text{Medial–Lateral}})^2}}{F_{\text{vertical}}} \qquad \textbf{Eq. 5.1}$$

Why Slips Occur

Unperturbed ambulation (walking, turning, running, etc.) requires that the available friction at the shoe–floor interface exceed the peak utilized friction of the person walking. Therefore, slips occur when an individual's peak uCOF exceeds the available friction provided by the shoe–floor interface [15–18,21]. The greater a person's uCOF is compared to the available friction provided by the shoe–floor interface, the greater the likelihood of a slip occurring. Conversely, the greater the available friction compared

FIG. 5.2 Interface between a human foot and a force plate.

to a person's peak uCOF, the lesser the likelihood of a slip occurring. This applies for any shoe–floor–contaminant scenario. Previous research has shown that numerous factors can affect uCOF including walking velocity, activity, age, sex, shoe sole hardness, and shoe type [13,15,17–20]. Some scenarios that increase utilized friction are walking fast versus walking slowly, walking in high heel shoes versus low heel shoes, walking in soft sole shoes versus hard sole shoes, running versus walking, and running versus cutting.

To deter a slip event from occurring, the available friction at the shoe–floor interface must exceed the person's uCOF. During walking, the peak uCOF has been reported to range from 0.15 to 0.31 for normal speeds [13,15,19,22,23]. However, more dynamic activities such as running and cutting utilize more friction to perform without slipping, ranging from 0.48 to 0.83 [24]. A general rule of thumb is that the more dynamic an activity, the more friction is required to perform it without slipping.

THE USE OF TRIBOMETERS TO MEASURE WALKWAY FRICTION

Walkway tribometers (slip testers) are mechanical instruments that are used to measure the slip resistance of walkway surfaces. These instruments are used in many industries to test product safety. These include the insurance, risk management, forensic, flooring, floor-coating, and shoe industries.

The coefficient of friction between the shoe and the floor surface has been found to be a significant factor in controlling slips and falls [25]. In an effort to reduce the probability of a slip, it is essential that there be some means of monitoring walkway slip resistance. To that end, various types of tribometers have been developed and marketed to those responsible for monitoring flooring.

Tribometers can broadly be classified into two groups—those that are fixed in place and are normally utilized in a laboratory setting and those that are portable and can be transported to the site of interest. Portable tribometers will be addressed here, and laboratory-based whole shoe testers will be discussed later. Portable tribometers can be placed into three classes based on their design and method of measurement. The three classes include drag sleds, pendulums, and articulated struts.

The drag sled class consists of a mechanism with a sled of a known weight that is dragged across the floor at a constant velocity. The coefficient of friction is calculated by dividing the horizontal force generated during the movement of the sled by the vertical force due to the weight of the sled [26].

The Horizontal Pull Slipmeter (HPS) is a type of drag sled tribometer that was invented by Charles Irvine at the Liberty Mutual Research Safety Institute in Hopkinton, Massachusetts (Fig. 5.3). The HPS consists of an approximately six-pound weight that is pulled across the tested surface by a motorized power source at a speed of approximately 3.5 inches per minute. The sled of the HPS is supported on three 0.5-inch diameter standard Neolite® test feet (Fig. 5.3). Measurements of slip resistance are read from a Chatillon force gauge that is incorporated into the sled of the HPS. The measurements are provided as a "slip index" that is ten times the coefficient of friction. A slip index of 4.0 would indicate a COF of 0.4. ASTM International Standard F609 (Standard Test Method for Using a Horizontal Pull Slipmeter) outlines the use of the HPS. In the standard, it is noted that the HPS is to be used to measure the slip resistance of dry surfaces only [27].

The Model 80 slip tester is a type of drag sled tester that is similar in principle to the HPS. With the Model 80, a "fish scale" type dynamometer is used by the operator to pull the tester rather than connecting the unit to a motor drive (Fig. 5.4) [28]. The Model 80 may be used for testing wet and dry surfaces.

The Horizontal Dynamometer Pull Meter is another type of drag sled tribometer. It utilizes a heel assembly consisting of an eight-inch, square wooden block fitted with

FIG. 5.3 (a) Horizontal Pull Slipmeter and (b) test feet on the Horizontal Pull Slipmeter.

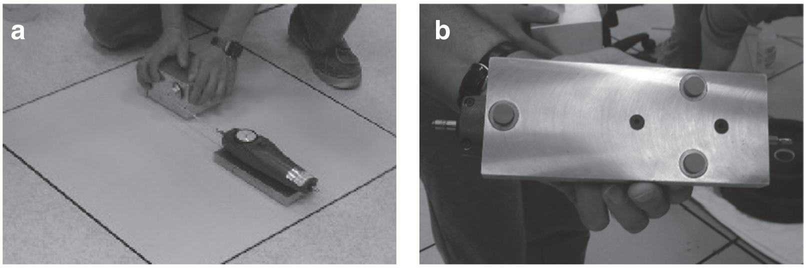
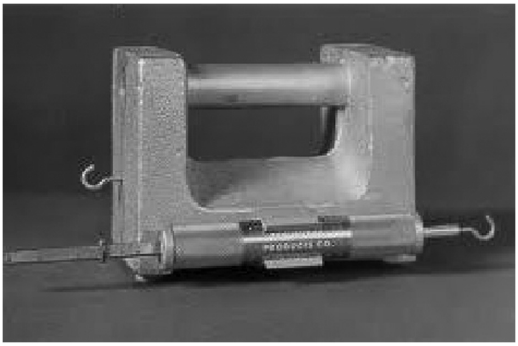


FIG. 5.4. Model 80.



a three-inch by three-inch Neolite test foot. A 50-pound weight is placed on top of the block (Fig. 5.5). Measurement of the force (in pounds) required to move the block laterally is recorded by a force gauge attached to the block (Fig. 5.5). The coefficient of friction is calculated by dividing the lateral force by the weight of the tribometer. ASTM International Standard C1028-07e1 (Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull Meter Method) outlines the use of the Horizontal Dynamometer Pull Meter. The standard states that this method may be used for testing wet and dry surfaces [29].

The Tortus II, Tortus III, and the BOT 3000 are motorized drag sleds (Figs. 5.6, 5.7, and 5.8). The Tortus III is a newer model of the Tortus II. Both models of the Tortus measure dynamic coefficient of friction, and the BOT 3000 measures static and dynamic coefficients of friction. All three drag sleds have a slider pad that is located inside the body of the tribometer. To operate the drag sleds, a downward force

FIG. 5.5 (a) Horizontal Dynamometer Pull Meter and (b) force gauge.

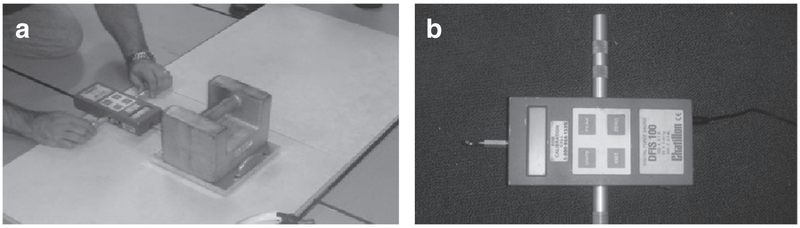


FIG. 5.6 Tortus II.

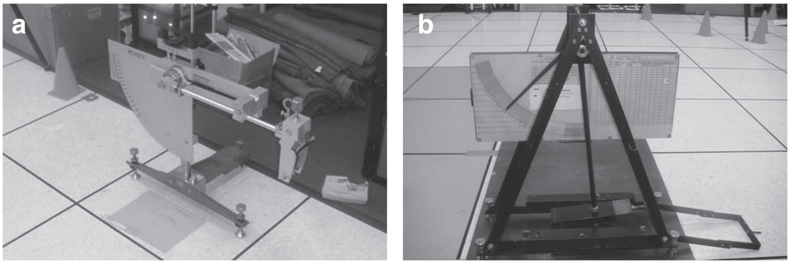
FIG. 5.7 Tortus III.

sufficient to hold the slider pad against the floor is applied. The body is mounted on wheels that are powered by an electric motor located inside the tribometer body. When activated, the tribometer is designed to travel across the floor at a constant velocity. During movement, the friction between the floor and the slider pad is sufficient to deflect the pad. This deflection produces a reading of lateral force. The coefficient of friction is continuously calculated by dividing the lateral force by the downward force. The results are provided via a digital display and a print out. All three devices can be used on wet and dry surfaces [**30–33**].

Another type of tribometer consists of a pendulum to which a test foot material is attached. Two pendulum testers are the Wessex and the Sigler (**Fig. 5.9**).

FIG. 5.8 BOT 3000.

FIG. 5.9 (a) Wessex pendulum and (b) Sigler pendulum.

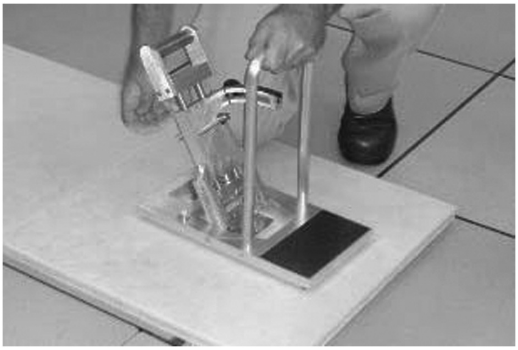


The pendulum is released from an initial horizontal position and then falls and sweeps across the tested surface. Kinetic energy is lost as the test foot contacts and passes across the surface. The reduction in kinetic energy results in the pendulum failing to return to its initial height. The difference between the initial and final heights of the pendulum is directly related to the coefficient of friction between the tested surface and the test foot. The moving pendulum measures dynamic friction. Pendulums can be used to test wet and dry surfaces [**25,28,34**].

The articulated strut class of tribometers includes the Brungraber MK II and MK III as well as the English XL VIT (**Figs. 5.10**, **5.11**, and **5.12**). These tribometers are equipped with an inclinable articulated strut. A test foot, mounted to the bottom of the strut, is raised above the floor surface and a trigger mechanism is activated causing the test foot to move toward the floor. The articulated strut allows the simultaneous application of the vertical and horizontal forces as the test foot strikes the floor surface.

FIG. 5.10 Brungraber MK II.

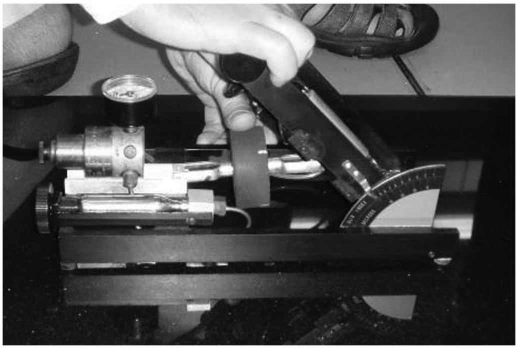
FIG. 5.11 Brungraber MK III.



If no slip is detected, the test foot is again raised and the angle of inclination is incrementally increased from vertical. The process is repeated until the test foot slips upon contact with the test surface. The measurement of the coefficient of friction is read directly off a scale located on the side of the tribometer. The scale provides a measurement of the tangent of the strut's angle of inclination from vertical at the time of slip. All articulated strut tribometers can be used to test wet and dry surfaces [**28,35**].

The Brungraber MK II and MK III are equipped with three-inch, square, Neolite test feet. The striking force for the MK II is provided by a ten-pound weight, but the MK III is spring driven. The English XL VIT is equipped with a 1.25-inch diameter Neolite test foot. The striking force for the English XL VIT is provided by compressed CO_2 that is regulated to a gauge pressure of 25 pounds per square inch [**35–37**].

FIG. 5.12 English XL VIT.



The use of different walkway tribometers is problematic. When measuring the slip resistance of the same area of a single walkway surface, the measurements generated have been found to vary among tribometer classes, types, and among specific tribometers of the same type. This is not unexpected because the measurements are a function of the material being tested, the test foot material, the operator of the tribometer, and the specific tribometer [**3,36,38–41**]. The problem then becomes one of creating a method to provide meaning to the varying measurements generated during testing.

In 2010, Powers et al. investigated the validity of walkway tribometer measurements based on two criteria: the abilities of walkway tribometers to correctly rank and statistically differentiate the COF of four floor surfaces. The four types of flooring tiles were polished black granite, porcelain, vinyl composition tile (VCT), and ceramic. To rank the tiles in order of slip resistance, 80 subjects were recruited to walk across the tiles, and the subjects were monitored using an eight-camera motion analysis system. The tiles were wetted prior to each trial. All slips were recorded, and the tiles were ranked in order of slip resistance using the number of slips per tile. The polished black granite was the most slippery, and it was followed in decreasing order of slipperiness by porcelain, VCT, and ceramic. It was reported that several drag sled tribometers (C1028, Tortus II and III, and HPS) failed both validation criteria [**3**]. This study was sponsored in part by ASTM International and was performed at the Musculoskeletal Biomechanics Research Laboratory of the University of Southern California (USC).

The same types of tiles that were used in the testing for the USC study are available for purchase through the Web site of ASTM International [**42**]. The flooring tiles utilized in that study are called reference surfaces because they can also be used to reference the slip resistance values generated during testing back to the slip performance of humans walking over the same type of tiles. With the availability of the reference surfaces, ASTM International Committee F13, Pedestrian/Walkway Safety and Footwear, created ASTM International Standard **F2508** (Standard Practice for Validation and Calibration of Walkway Tribometers Using Reference Surfaces). The standard involves using the reference tiles to validate tribometer performance. In order for the performance of a tribometer to be considered valid, the tribometer must satisfy two criteria: first, the tribometer must be able to rank the COF values of the reference tiles in the proper order, and, second, the COF values must be statistically differentiated from one another [**2**]. As was observed in the case of the drag sleds in the Powers et al. study, until tribometers can pass both **F2508** validation criteria, ASTM International Committee F13 Pedestrian/Walkway Safety and Footwear cannot recommend their use to assess slip resistance.

That a specific tribometer can differentiate among the reference tiles and rank the surfaces in the correct order provides confidence in the validity of measurements generated by that specific tribometer when it is used to test other surfaces. To give meaning to the measurements from other surfaces, they must be compared to the measurements that were obtained by that same tribometer during testing of the reference tiles. The values for slip resistance acquired during testing of the reference surfaces can be used as benchmarks. If a slip resistance value of 0.3 is obtained from testing a walkway surface, the meaning of the 0.3 value is unknown until it is compared to the values obtained from testing the reference tiles. If, when testing the reference tiles, the slippery polished granite produced a value of 0.3, a value of 0.3 would indicate that the walkway has a slippery surface. If, however, a value of 0.3 was obtained during testing of the slip-resistant ceramic tile, a value of 0.3 would indicate that the walkway was slip resistant. Using the reference tiles provides meaning for measurements of other surfaces, and the basis of that meaning can be traced back to the human subject testing at USC [**3,40**].

WHOLE SHOE TESTERS

Previous pages within this chapter focused on the various portable tribometers (slip testers) originally designed for the testing of walkways. Walkway tribometers provide useful information, primarily as it relates to the friction attributes of the walkway when utilizing a pre-prescribed test foot sized for a particular tribometer (for example: the three-inch-square test foot of the Mark II) [**43**]. In the past, due to the absence of alternative test methods (and presently to some degree), safety professionals along with footwear material providers and footwear manufacturers relied on walkway tribometers to test the COF of footwear soling materials. Utilizing such testers and test methods may be helpful as a means of ranking materials. However, attempting to relate the results from tribometer testing to testing of an actual footwear bottom has been called into question. Concern has also been raised that results based on methods intended for walkway testing often do not take into consideration the design attributes of the footwear bottom. For example, the footwear design found at the rear area of the heel, the area of the shoe that first comes in contact with the walkway surface during walking, is most often not the same tread pattern found in the forefoot of the footwear. Furthermore, to accommodate some tribometer designs, it is often necessary to extract the test foot sample from the forefoot area of the footwear outsole (typically a three-inch-square or circular test foot).

In the 1970s, SATRA Technology Centre of the United Kingdom, which at the time received funding from the British government, researched developing a means of testing actual footwear against numerous walkway materials under dry and contaminated conditions. Years later, SATRA developed a new class of slip tester, the mechanical whole shoe tester (SATRA STM 603, see **Fig. 5.13**) [**44**] and published the applicable test method, SATRA TM144 Friction (Slip Resistance) of Footwear and Floorings [**45**].

The fundamental principles of a whole shoe tester include the application of a defined vertical load placed upon the actual footwear, along with a defined horizontal movement of the walkway surface, with the footwear and the walkway surface having been secured to the test machine. Once the resulting forces are achieved, and, at a specific point in the testing sequence, the COF is measured and then graphically reported [**45**].

In the early 2000s, the European Union's European Committee for Standardization personal protective equipment (PPE) footwear committee evaluated the SATRA TM144 test method, which later formed the basis of the European Standard (EN) 13287:2004 (Personal Protective Equipment; Footwear; Test Method for Slip Resistance). This standard was subsequently adopted by the International Organization for Standardization (ISO) as EN ISO 13287:2007 [**46**], later revised, and

FIG. 5.13 SATRA STM 603 whole shoe tester. (With permission from SATRA Technology Centre, Kettering, Northants, United Kingdom, available at **www.satratechnology.com**.)

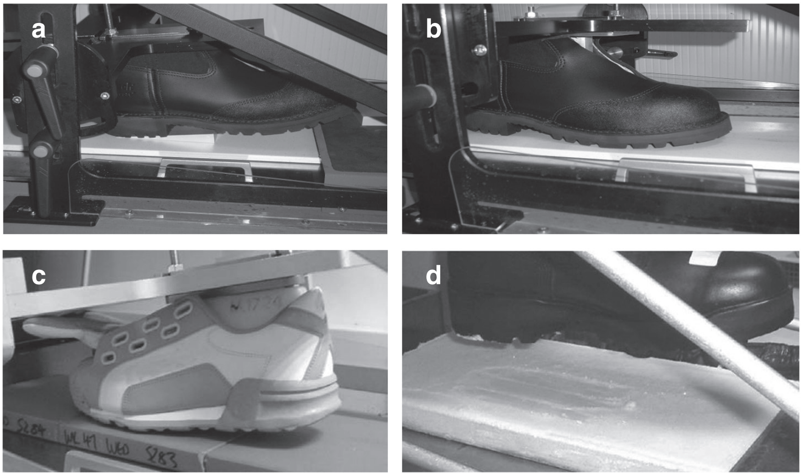
is currently published as EN ISO 13287:2012. This EN ISO standard is the required test method for measuring the slip resistance of all safety and protective footwear worn mainly by industrial workers for specific hazard protection that carries the European Conformity (CE) mark. A CE mark indicates that a product has been approved by the applicable European standard.

In 2009, ASTM International and SATRA signed an agreement that in 2011 brought about the balloting, approval, and publication of ASTM **F2913** (Standard Test Method for Measuring the Coefficient of Friction for Evaluation of Slip Performance of Footwear and Test Surfaces/Flooring Using a Whole Shoe Tester) [**47**]. ASTM **F2913** allows for the testing of footwear in three different test modes: heel contact, shoe flat contact, and toe contact. The test method also allows for the introduction of various walkway surfaces, traditional and nontraditional, as well as the controlled introduction of contaminants. **Figure 5.14** illustrates the three test modes, one of which depicts testing on an icy surface.

In 2009, the Canadian Standards Association (CSA) adapted the basis of EN ISO 13287:2007 for the testing of footwear as mandated within the CSA Z195 Protective Footwear standard [**48**]. Using the fundamental principles of the test methodologies on which these standards were built was an important step in attempting to bring a reasonable level of global harmonization to the testing of footwear slip resistance.

As with any mechanical testing, the data collected is best used as a tool when considering the choice of footwear. Consider using mechanical testing as part of a

FIG. 5.14 (a) **F2913** Heel contact testing, (b) **F2913** Flat contact testing, (c) **F2913** Forepart contact testing, and (d) **F2913** Flat testing on ice. (With permission from SATRA Technology Centre, Kettering, Northants, United Kingdom.)



selection process, and, where possible, introduce an additional human wear trial. Such considerations may be helpful in cases where extreme conditions may be realized or where a given contaminate is often present in a defined work environment. As previously discussed, COF will vary among classes of tribometers, types of tribometers, and tribometers of the same type. In much the same way, COF measurements will vary among different types of whole shoe testers and among specific whole shoe testers of the same type. Importantly, although all slip testers (whole shoe testers and tribometers) measure the coefficient of friction, testing performed using one class and type of slip tester should not be directly compared to the data collected from a slip tester of a different class and type. For example, the COF data collected using a whole shoe tester (ASTM **F2913**) should not be directly compared to the COF data collected when footwear materials have been tested using a Mark II, James machine [**49**], or other slip tester. Additionally, comparing data among slip testers of the same class and type should be done with caution.

SAFE THRESHOLD LEVELS

Within industry and academia there is much discussion and debate centered on the "safe threshold COF number." Given the number of factors that influence COF and slip risk, there is not a singular COF value that can be referenced as a "safe threshold." Within the slip resistance community, minimum COF values have been suggested based on what some consider safe levels of slip resistance. For example, SATRA suggests a minimum COF value of 0.3 when using its TM144 test method on dry and wet quarry tile for general or everyday footwear but would look for higher COF levels in more demanding applications or where risk of injury is greater (e.g., safety and sports applications). Additionally, standard setting bodies may reference a given test method and suggest minimum COF requirements. Such minimum COF values most often utilize a given test method/tribometer and require testing a specific combination of flooring, shoe, or shoe materials along with the introduction of a given contaminate into the test regime. EN ISO 13287 requires testing of safety footwear on ceramic tile contaminated with a solution of soapy water and stainless steel contaminated with glycerin.

In the case of test method EN ISO 13287 and other standards in which it is referenced, minimum COF values are specified. The minimum requirements for a steel surface are intended to be a conservative performance measure in order to mitigate the risk of slipping. It is important to note that these specific combinations of materials and minimum COF values were developed using a consensus process and were considered to be among the most challenging conditions a worker might encounter. Thus, the requirement on the steel surface represents relatively high performance for footwear on this surface but does not indicate a "safe" level.

The CSA, as part of Footwear Standard Z195:09, requires the use of test methodology EN ISO 13287. Through amendments to the EN ISO standard, CSA Z195:09 prescribes which flooring and contaminates are to be used when testing. Although

CSA Z195:09 does not set a minimum COF value, it does require product labeling that details the COF values achieved during testing of the footwear being offered.

At this time, the ASTM International Committee F13 Pedestrian/Walkway Safety and Footwear is in discussions as how to best provide guidance with respect to the selection of walkways, contaminates, footwear, and minimum COF safety values that when combined with a given method will offer a reasonable level of safety. It is the position of those who helped develop this book that when using an ASTM-approved test method, it is best to consider the data collected for that specific method on its own merits and use that data as part of the criteria for selecting safety footwear. Contact footwear providers for copies of such data.

CONSIDERATIONS FOR PURCHASING SAFETY FOOTWEAR

If you are the safety director responsible for buying footwear for the workplace, there are two things to consider: (1) what relevant workplace information do you need to know and (2) what questions do you need to ask a potential supplier. First, you should have a comprehensive understanding of the environment in which the footwear will be used, including the types of floor surfaces, exposure to potential contaminants, and activities to be performed. Providing the supplier with this information will allow for a more appropriate recommendation for slip-deterrent footwear. Second, you should be able to ask a supplier questions about their footwear recommendations. Inquire about "what if" scenarios such as: What if a person steps in oil (or another contaminant)? For what activities are these shoes recommended? Has the slip resistance of these shoes been tested, and, if so, what testing protocol was used for testing, how did the shoes rate compared to other styles, and do they have a written report of the results? Is the outsole designed for durability while maintaining its functional attributes? Are there any limitations of these shoes? Knowledge of the workplace environment in which footwear will be worn in addition to coordinating with a supplier regarding the safety and application of workplace footwear will greatly decrease the likelihood of slips and slip-related injuries occurring.

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