Coefficient of Friction
An Overview of:
Floor Surfaces, Polishes and Maintenance Interaction

The importance of slip resistance and floor safety is of primary concern to the floor polish industry and its affiliate organizations. The Consumer Specialties Products Association continues to actively research slip resistance and continues these efforts today, through the Polishes and Floor Maintenance Division’s Scientific Committee. To better understand the complexity of slip resistance, it is important to review the science involved in the various aspects of the majority of interactions that play a role in creating a walking surface that is firm, stable and slip resistant. Among the topics to be discussed are an overview of the complexity of walking, the importance of friction and its measurement through the use of the James Machine, as well as other tribometers.

The Complexity of Walking

Walking is an enormously complex activity involving interactions between multiple musculoskeletal groups, kinesthetic sensory input, as well as nerve and balance feedback. All of this information is automatically and unconsciously assimilated and coordinated by the brain to allow mobility to occur. If we had to be aware of all the complexities involved in walking, we would probably choose to be stationary, sensate plants. As we evolved from the stability of four legs to bipedal ambulation, efficient locomotion assumes an adequate frictional interface where the foot (or shoe sole material) meets the floor.  

More specifically, it is generally accepted from repeated biomechanical studies of walking, that human locomotion is possible only when the foot/floor-walking interface provides a sufficient frictional force. The frictional force available must be adequate enough so that the foot remains stationary, relative to the floor surface when horizontal forces are applied by the leg to either push forward or stop the walking body. If the frictional force is insufficient, the horizontal force will cause the foot to move, relative to the floor, and this is known (by its technical name) as a slip. Since the center of gravity of the walking body is unsupported during a slip, unless it is caught or brought under control, a slip can result in a fall. However, if the center of gravity is successfully brought under control after either a slip or a trip, the incident is called a 'stumble'.

The frictional force exerted at the walking interface to oppose the horizontal forces of walking is a property of the two surfaces, which meet at the walking interface. It is a function of the chemical compositions and physical structures (particularly roughness and planarity) of both of the surfaces that make the interface. Since a polish-coated floor is very often one of these surfaces, the frictional properties of a polish film have been of great importance to the floor polish industry.

1 For walking on level (horizontal surfaces), a gait cycle occurs between the heel strike of one foot, and the subsequent heel strike of the same foot. The process of walking includes the intermediate steps that occur during the gait cycle, – the toe-off, swing phase, heel strike, and stance phase. Temple, J. The Staircase Studies of Hazards, falls, and safer design. Cambridge, (MA): MIT Press, 1992
FRICTION

Friction is one of the first topics (after optics) to be subjected to systematic scientific study. Though both Galileo and da Vinci addressed it, and thousands of scientists since, it is still not fully understood and there is no generally accepted scientific theory for the molecular causes of the frictional force. However, there are a number of general, pertinent facts about friction as it relates to human locomotion, which are universally accepted. Scientists have studied the force of friction by closely examining those instances where its effect has been reduced to zero. That is, they examine and vary the forces that are acting on an interface at the instant when slipping just begins to occur. In this instant the frictional force keeping the two surfaces of the interface from moving relative to each other is exactly balanced by the tangential force, which is trying to move them.

The frictional force available at the walking interface is directly proportional to the vertical force holding the interface together. This is called the 'normal' (or vertical) force and is provided by the mass or weight of the pedestrian. If an increasing horizontal (or tangential) force were applied to the interface, at some point it would become greater than the restraining frictional force and the two surfaces of the walking interface would move relative to each other. At some point, by increasing the horizontal force, it would overcome the frictional force and the foot would accelerate away (slip) from the point of contact. Higher horizontal forces arise when a pedestrian is accelerating, or running, or sharply changing direction of travel. The same slip result would occur if, instead of increasing the horizontal force, we would keep it constant and now decrease the vertical force. Since there is now less force holding the interface together, less horizontal force will be required to cause the surfaces to slip.

If both the tangential force and the normal force at an interface are allowed to vary independently, it was found that a greater normal force would require a greater tangential force for slip to occur. In fact, for a given interface, the ratio of the tangential force to the normal force is a constant, and this constant is called the static coefficient of friction. The prefix "static" is added to the name for the coefficient of friction because the surfaces of the interface are not moving (or are static) relative to each other as the tangential force is applied. This also distinguishes it from another type of friction constant, the dynamic coefficient of friction. The dynamic COF pertains to the case when the two faces are moving relative to each other as the retarding frictional force is applied. Dynamic friction is also called sliding friction or braking friction.

If the two surfaces of a frictional interface are moving relative to each other, (one surface is sliding over the other), their motion will be slowed by the dynamic frictional force acting against the forces, which are trying to keep them in motion. When the dynamic frictional force is exactly balanced by the accelerating forces (so that no net tangential force is acting on the moving interface) the surfaces will continue to move relative to each other at a constant velocity. There will be no acceleration or deceleration.

As with the static frictional force, the dynamic frictional force is increased as the normal force pressing the surfaces together is increased. Like static friction, dynamic friction is a function of the chemical compositions and physical structures (particularly roughness and planarity) of both of the surfaces that make the interface. For a given interface, the ratio of the retarding dynamic frictional force to the normal force is a constant, called the dynamic coefficient of friction.
Despite these similarities, dynamic and static coefficients of friction are not related to each other, though it is generally the case that the static coefficient of friction is greater than the dynamic coefficient of friction for a given interface. That is, a greater tangential force is needed to start the surfaces of an interface in motion than is required to keep them in motion. The dynamic coefficient of friction is much easier to measure than static coefficient of friction, but unfortunately the dynamic frictional force has nothing to do with the prevention of slip incidents.

### The James Machine

Development of reliable test methods for evaluating the slip resistance of floor polishes has been a primary concern to the polish industry. In 1944, the Polishes and Floor Maintenance Division of CSPA initiated cooperative investigations in the measurement of the static coefficient of friction of commercially available floor finishes with Sydney V. James and Underwriters' Laboratory. By 1964 this work had expanded to the point that a permanent subcommittee for testing slip resistance was established by the Polishes and Floor Maintenance Division of CSPA.

This committee's work led to the refinement of the James Machine and significantly contributed to the development of ASTM standard test method D-2047 "for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine". The Polishes and Floor Maintenance Division of CSPA continues to investigate proposed methods for testing slip resistance today through the efforts of this committee.

The James Machine is a laboratory instrument, which measures static coefficient of friction by application of an 80-pound normal force through an articulated (i.e., has pivots at both ends) strut to a 3-inch square pivoting 'shoe'. The surface of this shoe is one of the surfaces of the friction interface. The dimensions of the test sensor and weight selected for the instrument were adopted to the design of the James Machine based upon research conducted by the National Bureau of Standards investigation of floor safety. ASTM D-2047 specifies that the shoe surface be made of a very specific leather sole material (US government specifications for cure and tanning of World War II

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2 This is why a skidding car takes longer to bring to a stop than does one, which is not skidding. The rolling tire surface is static relative to the road even though the car is moving. The tire/road interface is designed to have a high static coefficient of friction. When the tire is not skidding, retarding dynamic friction is provided by the brakes, which are designed to have a high dynamic coefficient of friction. If the wheel is stopped by locking the brakes, the inertial mass of the car provides a tangential force to the tire/road interface that is greater than the static frictional force, and the tire will slide or skid. Since the brakes are locked, the brake lining/brake drum (or disk) interface is static and the wheel will rotate again only after the pressure on the break (normal force on the interface) is reduced.

3 There is considerable conjecture (on the basis of various theoretical views of pedestrian locomotion) that dynamic friction is pertinent to recovery from a slip (making the incident a stumble). However it is generally held that this is true only for younger, agile pedestrians and therefore not pertinent for pedestrian safety in general. Even in the most liberal interpretations, dynamic frictional forces may change the proportion of slip incidents, which progress to become falls. Dynamic frictional forces do not influence the probability of slip incidents occurring in the first place.

military footwear). The leather for the shoe was chosen (at the time the machine and standard test method was being developed) as the least slip resistant sole material in common commercial use. The other surface of the friction interface is a floor finish film, applied and aged under very specific conditions to approximate polish on a worn, highly trafficked floor.
In the operation of the James Machine the friction interface is slowly moved away from the upper pivot point of the loaded articulated strut. Because the weight is now applied at an increasing angle (from the vertical), the normal force is decreased (cosine of the angle) and a horizontal force is introduced (sine of the angle). At some point the ratio of the horizontal and vertical forces will exceed the static coefficient of friction of the interface, and slip will occur. This point is automatically recorded on a calibrated paper chart. To minimize the influence of random errors and variables, ASTM D-2047 specifies that the reported static coefficient of friction of a polish be the average of at least twelve individual determinations, made on at least three different tiles.

During the development of criteria for determining whether a polish was acceptable for product liability insurance, James included specific performance parameters. His research correlated the results of laboratory tests and tests made on actual floors under service conditions, as well as field experience for several years culminated to recommending a minimum value as an acceptable coefficient of friction. This value recommended by S.V. James in 1945 to the Casualty Council of Underwriters Laboratories, Inc, was judged to provide a surface with a sufficiently high static coefficient of friction to provide walkway surfaces presenting a reasonable risk.

When CSPA member companies joined in the program for obtaining similar data, generated through their investigations or through contract labs, James was able to use this much larger database to draw a very important conclusion. He found that if the polish had a static coefficient of friction, as measured by the James Machine of 0.5 or greater, there were no complaints received by Underwriters' Labs concerning slip resistance. A static coefficient of friction of 0.5 or greater thus became the UL criteria for slip resistant polishes.

This performance criterion of 0.5 static coefficient of friction as measured by ASTM D-2047 and the James Machine was reinforced by the expanded database developed by CSPA Polishes and Floor Maintenance Division members. The data base continued to expand and had come to be based on hundreds of million of gallons of floor finish, which have been subjected to trillions and trillions of pedestrian passes.

5 The chart is marked in a non-linear calibration of the coefficient of friction, which is the tangent of the angle of deviation of the strut from true vertical. Because the strut is a fixed length, the angle of deviation is proportional to the distance the interface has moved from its initial position. The calibrated James Machine charts are available only from CSPA.

6 A paper given at the 1971 CSPA Mid-Year meeting gave a theoretical justification for the 0.5 static coefficient of friction criteria for a safe walkway surface, based on biomechanical studies of human walking. They found that a static coefficient of friction of 0.3 should be sufficient for normal walking over a clean surface with leather-shod shoes. Ekkebus, C. F., and Killey W., Validity of 0.5 Static Coefficient of Friction (James Machine) as a Measure of Safe Walkway Surfaces, Test Methods and General Information, January 1977 277-80 Chemical Specialties Manufacturers Association, Inc

While reassuring, this theoretical analysis is not as important as the strength of the statistical evidence gained from the industry's experience with millions of gallons of floor finishes.
The strength of the correlation was recognized by the Federal Trade Commission in 1953 when they required that a polish film must meet the 0.5 static coefficient of friction performance criteria to use the terms "slip resistant, slip retardant, or terms of similar import" on its label. By 1970 the weight of the statistical data was so great that the Scientific Committee of CSPA Polishes and Floor Maintenance Division adopted a system of self-certification for floor finish slip resistance in the industry. ASTM D 2047 remains, to date, the first and only voluntary consensus standard that specifies a compliance criterion, namely, 0.5 static coefficient of friction. 7

**Other Means of Measuring of Slip Resistance**

As mentioned previously, the development of reliable test methods for evaluating the slip resistance of floor polishes has been a primary concern to the polish industry. In 1964, the Polishes and Floor Maintenance Division of CSPA established a permanent scientific subcommittee to investigate alternative machines and procedures for slip resistance measurement. The criteria for acceptance as an alternative to the James Machine were established and included that the proposed candidates must accurately reproduce the slip resistance measurements of the James Machine, be robust, and if possible, be economically feasible to build or purchase.

This committee has subjected every viable commercially available machine or proposed design in the literature to extensive evaluations. The evaluated machines include (as the best known examples): The Liberty Mutual Horizontal-Pull Slip meter; Sigler machine; The Topaka tester; Tortus automated slip tester; Brungraber Mark I; Brungraber Mark II; English Variable Incidence Tribometer, model XL (VIT). With the sole exception of the Brungraber Mark I, all of these instruments are designed primarily to measure dynamic coefficient of friction.

The work of the Scientific Subcommittee and members of the Polishes and Floor Maintenance Division of CSPA continue their research of slip resistance and investigating technologies to evaluate and safeguard floors.

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