

Measurement of the Slipperiness of Walkway Surfaces

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The establishment of a safety code for walkway surfaces has been materially handicapped by the lack of an adequate method of measuring slipperiness. The mechanics of walking as related to slipping and the design of testing instruments are briefly discussed. In order to test floors in actual service a portable slipperiness tester of the pendulum-impact type was designed and constructed. The design is based on the premise that, in the process of ordinary walking, slipping is most likely to occur when the walkway surface is first contacted by the edge of the heel. The instrument and test procedure are described. The effects of varying some of the constants of the instrument, such as the angle of contact between the test heel and the walkway surface, and the pressure between the heel and the walkway, are discussed. Typical results obtained with both rubber and leather test heels and under both dry and wet conditions are given for various flooring and finishing materials.

In general, the traction furnished by dry rubber heels is much better than that obtained with dry leather heels. Many walkway surfaces are hazardous when wet. Good antislip properties under wet conditions are usually associated with rough particles that project through the film of water and thus prevent its action as a lubricant.

I. Introduction

Slippery walkway surfaces are responsible for a large number of serious injuries and accidental deaths each year. Haste and carelessness on the part of the users are frequently contributing factors. A survey of accidents in a large Government building in Washington revealed that out of 492 "lost time" injuries reported during a 19-month period, 313, or 64 percent, were due to slips and falls on walkway surfaces. According to the safety engineer who compiled the statistics, a total of 809 slips and falls were reported during the period. Of these, 496 were recorded as "no lost time" injuries. In an endeavor to reduce the frequency of such accidents, a joint research has been undertaken by the National Safety Council and the National Bureau of Standards directed toward developing data that may be used by a representative sectional committee in the preparation of a code for safe walkway surfaces. The Council is conducting a statistical survey of accidents from falls, and the Bureau is engaged in an engineering study of both walkways and footwear materials, which are equally involved in slipping.

The establishment of a safety code for walkway surfaces has been materially handicapped by the lack of an adequate method of measuring slipperiness. The correlation between coefficients of friction as commonly measured, and slipperiness as actually experienced, is not good, especially where wet surfaces are involved. Therefore, one of the first requirements of the project was the development of a suitable instrument and method for measuring slipperiness.

A walkway surface is often thought of as having a single coefficient of friction. Such is not the case. Slipperiness is not a constant of the walkway or of the contact surface of the footwear but is a function of both surfaces and is materially affected by their condition. This would be quite evident to anyone who attempts to dance on a waxed floor with rubber-soled shoes in place of leather-soled shoes. Rubber soles snub, whereas leather soles slide readily. Whether the surfaces are clean or dirty, dry or wet, are also material factors.

II. Human Locomotion

A study of the mechanics of walking was made as an aid in the design of testing instruments.

Slow-motion pictures of people walking were taken with concealed cameras so that the subjects were unaware of being photographed and were thus likely to be walking naturally. These pictures reveal that the leg slows down at the termination of its swing and then appears to vault onto the walkway, the other leg being used as a pole. They also show that the foot is first placed upon the walkway at an angle so that only the rear edge of the heel contacts the walkway surface during the early stages of the retarding phase of a step. The other foot remains in contact with the walkway, thus bearing part of the vertical load, until the heel rocks forward and the foot is fully planted.

A survey of worn heels showed that maximum wear usually occurs at the outside border of the rear portion of a heel. The contour of this worn portion is generally in the form of a curve rather than a straight line.

Probable angles that heels of shoes make with a walkway surface at the first instant of contact were determined from the motion pictures and from the contour of worn heels. For 35 men's shoes, the angle of contact ranged from 11° to 32° , with an average value of 23° . For 16 women's shoes, including both high and low heels, the angle ranged from 12° to 32° , with an average value of 19° . For 38 worn heels, the maximum angle that tangents to the worn portion made with a horizontal plane ranged from 19° to 33° , with an average value of 26° .

According to the literature,^{1 2 3} the horizontal component of the force exerted by the leg on a walkway surface reaches a maximum in the forward direction shortly after the heel makes contact with the walkway, decreases rapidly at first and then slowly as the foot deploys, and rapidly reaches a maximum in the backward direction as the ball of the foot prepares to leave the walkway. These horizontal components are the forces that must be counteracted by friction in order to avoid slipping.

III. Slipperiness Tester

The location of a floor relative to exterior doors or manufacturing processes where floors are normally wet, oily, or coated with various types

of waste materials determines to a large extent the texture of its worn surface and thus its slipperiness. The surface of a marble or concrete floor may become scratched and roughened to an appreciable degree from wear when located close to a street entrance, whereas the surface of a similar floor may become smooth or even glazed when located some distance from a street entrance or other source of abrasive grit.

It is extremely difficult to reproduce such a variety of surfaces by artificial means. Therefore, it is desirable that a slipperiness tester be so designed that it can be used to test floors in actual service. Such an instrument has been designed and constructed at the National Bureau of Standards (see fig. 1). The design is based on the premise that, in the process of ordinary walking, slipping is most likely to occur when the rear edge of the heel contacts the walkway surface. The instrument is similar in many respects to one previously described.⁴

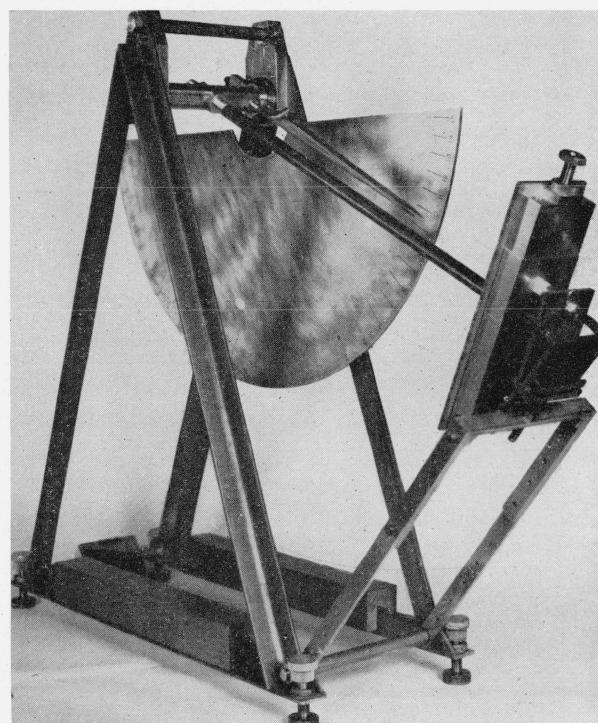


FIGURE 1. Portable slipperiness tester of the pendulum-impact type.

By means of a pendulum, a heel material is impacted onto and swept over the walkway surface to be tested. A mechanical heel (see fig. 2) forms

¹ Herbert Elftman, Anat. Record **59**, 481 (1934).

² Herbert Elftman and J. Manter, Science **88**, 152 (1938).

³ Herbert Elftman, Arbeitsphysiol. **10**, 485 (1939).

⁴ P. A. Sigler, NBS Building Materials and Structures Report BMS 100 (1943).

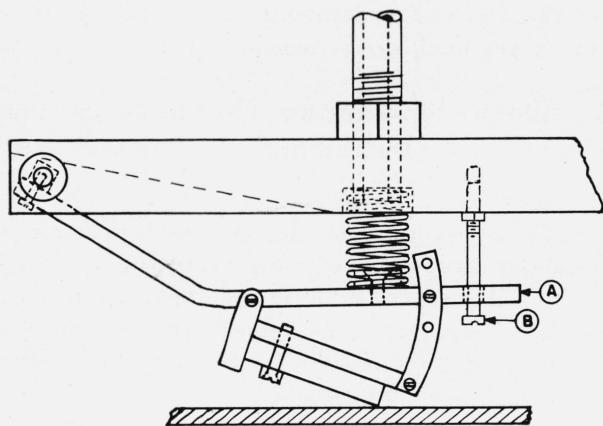


FIGURE 2. Details of mechanical heel.

the lower end of the pendulum and is so arranged that a 1½-in.-square test piece of rubber, leather, or other heel material can be attached to the underside at various angles so that only the rear edge of the test piece makes contact with the walkway. A helical spring is used to press the edge of the test piece against the walkway during contact. A pointer attached to the framework indicates on a scale (see fig. 1) the maximum height to which the center of gravity of the pendulum rises above its lowest (plumb) position.

Both the potential energy of the pendulum at the beginning of a swing and its residual energy at the end of a swing can be determined from the known weight and position of the center of gravity of the pendulum. The difference, or loss in energy, is equal to the work done in sliding the mechanical heel over the walkway surface, which is the average frictional force times the distance of contact. By definition the average frictional force is equal to the coefficient of friction times the average force normal to the plane of contact. From these relations an equation can be established for the coefficient of friction, or what we prefer to call the "antslip coefficient", in which all factors except the scale reading at the end of the swing are known constants of the instrument.

The values of these constants for the Bureau's instrument are the weight of the unbalanced portion of the pendulum, $W=3.17$ lb; the effective height of the center of gravity of the pendulum at the beginning of a swing, $H=9.8$ in; the distance of contact, $D=3.76$ in; the force pressing the edge of the heel against the walkway surface ranges from a minimum of 6.1 lb at the beginning and end of contact to a maximum of 7.4 lb at the midpoint

of contact, giving an average force, $P=6.75$ lb.

For theoretical considerations, the average force as an arithmetical mean introduces a slight error because the variation in the force is dependent upon an arc rather than upon its subtended chord. The error has been calculated to be approximately 2 percent and does not effect the relative order of the results.

From the above relations and constants, the equation for the antislip coefficient, U , is found to be

$$U = \frac{W(H-h)}{DP} = 1.244 - 0.125h,$$

where h is the scale reading or height of the center of gravity of the pendulum at the end of the swing when the usual contact between the mechanical heel and walkway surface is made.

In this equation, the assumption is made that during the entire distance of contact between the heel and walkway surface the variation in pressure follows a straight-line relationship. This is not strictly correct as some vibration is set up in the mechanical heel as a result of the impact on the walkway. The vibrations occur mainly during the first portion of the contact and appear to follow a similar pattern for smooth-faced materials. In view of the probable effect on the results of large differences in the amount of vibration, it is felt that the present instrument is not suited for testing very rough or embossed surfaces.

The maximum linear velocity attained by the edge of the heel from a release height of 10 in. is approximately 150 ft/min. The total weight of the instrument, including the two brass weights to keep the instrument from being displaced by the impact of the mechanical heel on the walkway, is approximately 27 lb.

IV. Test Procedure

The test procedure consists in leveling the instrument, by means of screws and a spirit level, in the direction of the swing of the pendulum and so that the edge of the heel is parallel to the walkway surface in the direction perpendicular to the swing. At the same time the edge of the heel must be adjusted to a definite height in relation to the walkway surface. The instrument itself is used to maintain this latter adjustment

constant. With a $\frac{1}{8}$ -in. spacer, placed between the hinged metal strap, *A*, and the stop, *B* (see fig. 2), the height of the heel is adjusted so that the scale reading at the end of a swing of the pendulum, released from a scale reading of 10, is lowered by 0.1 in., that is, from 9.8 to 9.7. The normal frictional loss of the instrument, including that of the pointer, is 0.2 in. The $\frac{1}{8}$ -in. thickness was selected as a suitable control of the distance of contact. A small mirror clamped on the brace at the front of the instrument and a flashlight are used to facilitate the adjusting of the instrument when conducting tests on floors in actual service.

After the required adjustments are made, the edge of the heel material is lightly ground with No. 3/0 abrasive paper and thoroughly brushed so as to maintain it in a uniform condition. With the spacer removed, the pendulum is then released from a definite height, 10 in., and the edge of the heel permitted to sweep over the walkway surface. The height to which the center of gravity of the pendulum swings beyond a plumb position, *h* value, is used to compute the antislip coefficient. The apparatus is then moved to another location and the procedure repeated.

Tests have shown that the surface of a walkway is usually changed by repeated sweeps of the mechanical heel over the same location. In order to be able to duplicate test conditions, separate test pieces or heels are used for testing under wet conditions. The edges are lightly ground, and the test pieces immersed in water for at least $\frac{1}{2}$ hr. prior to making the tests. This is particularly important for absorbent materials such as leather, as the results are influenced by the degree of wetting, being lower with increase in wetting. When testing under wet conditions, a puddle of water is maintained on the floor surface.

It is recognized that the edge of a heel may become coated with wax, dirt, oil, or other foreign material during the process of walking. Likewise, particles of grit may become embedded in the heel and the edge appreciably roughened when walking over rough surfaces. Repeated tests on a waxed asphalt tile corridor without buffing the edge of a leather test heel between sweeps of the mechanical heel showed that the results changed for the first three tests and then became relatively constant. The antislip coefficients for the latter tests were approximately 20 percent lower than

for the first test and were approximately 10 percent lower than for the second test.

V. Effects of Varying Constants of the Instrument

Statistical analyses of data obtained with the instrument show that the standard deviations from the means usually range between 0.01 and 0.03. Where fairly uniform walkway surfaces are involved, representative values can be obtained by averaging the results of from three to five individual measurements for each test condition.

The effect of varying the angle of contact between the heel and the walkway surface was investigated. Angles of contact used were 10° , 20° , and 30° . In general, the antislip coefficients were found to decrease slightly with increase in the angle of contact. However, the differences in the results were too small to be considered significant, and an angle of 20° was adopted for general use.

The effect of varying the force and thus the pressure between the heel and the walkway surface was also investigated. The force normal to the walkway surface was varied by installing helical springs of different strength on the mechanical heel. The three springs used exerted an average force of 3.7, 6.7, and 11.2 lb, respectively. Although these forces may seem small, because of the small area of contact, they represent an approximate variation in pressure of from 40 to 120 lb/in². Significant differences in the results were observed, especially under dry conditions (see table 1). In general, lower antislip coefficients were obtained with increase in the pressure. For any given pressure, however, the antislip characteristics of the different walkway surfaces tested maintained a similar relative order. A similar tendency for the antislip coefficients to decrease with increasing pressure was also noted from a comparison of results obtained with test heels having appreciably worn and rounded edges and results obtained with test heels having unworn and square edges. Therefore, the antislip coefficients obtained by this method should be considered as relative rather than absolute values, and the establishment of a minimum antislip coefficient for walkway surfaces as a specification or code requirement would have to be based on a definite method of test.

TABLE 1. Effect of varying the pressure between the mechanical heel and the walkway surface

Walkway surface and test heel	Antislip coefficient with spring exerting average force of—		
	3.7 lb	6.7 lb	11.2 lb
Tennessee marble:			
Rubber heel, dry	0.81	0.75	(^a)
Leather heel, dry	.46	.40	0.35
Asphalt tile:			
Rubber heel, dry	.99	.93	(^a)
Leather heel, dry	.64	.56	.54
Rubber tile:			
Rubber heel, dry	.94	.81	.69
Leather heel, dry	.45	.40	.35
Rubber tile containing alundum grit:			
Rubber heel, dry	.88	.81	.69
Leather heel, dry	.52	.44	.38
Linoleum:			
Rubber heel, dry	.95	.84	.69
Leather heel, dry	.49	.39	.30
Felt-backed tile, cellulose nitrate composition:			
Rubber heel, dry	.86	.74	.60
Leather heel, dry	.41	.32	.24

^a Pendulum stalled.

VI. Results and Discussion

Typical results obtained with both rubber and leather test heels and under both dry and wet conditions are given in table 2. The standard abrasion compound specified in Federal Specification ZZ-R-601a, Rubber Goods; General Specifications, was used as rubber test heels. The leather test heels conformed to Federal Specification KK-L-261b, Leather; Sole, Vegetable-Tanned, Factory.

All the walkway surfaces gave relatively high antislip coefficients with dry rubber heels, and thus good traction should be experienced with such footwear. In general, much lower coefficients were obtained with dry leather heels, the values ranging from one indicating poor traction, 0.30, to one indicating good traction, 0.50. When wet, many of the surfaces would be classed as potentially hazardous for both rubber and leather footwear. Outstanding exceptions are tests 1, 7, 8, 21, and 22 (see table 2). Good antislip properties under wet conditions are usually associated with asperities that project through the film of water and thus prevent its action as a lubricant. The asperities may represent either the roughened surfaces of the walkway or footwear materials themselves or particles of embedded sand or grit. A smooth terrazzo floor

showed poor antislip properties when wet, whereas a soapstone stair tread and a rubber and cotton matting having rough surfaces showed fair antislip properties when wet (see figs. 3, 4, and 5 and tests 4, 7, and 21 in table 2).

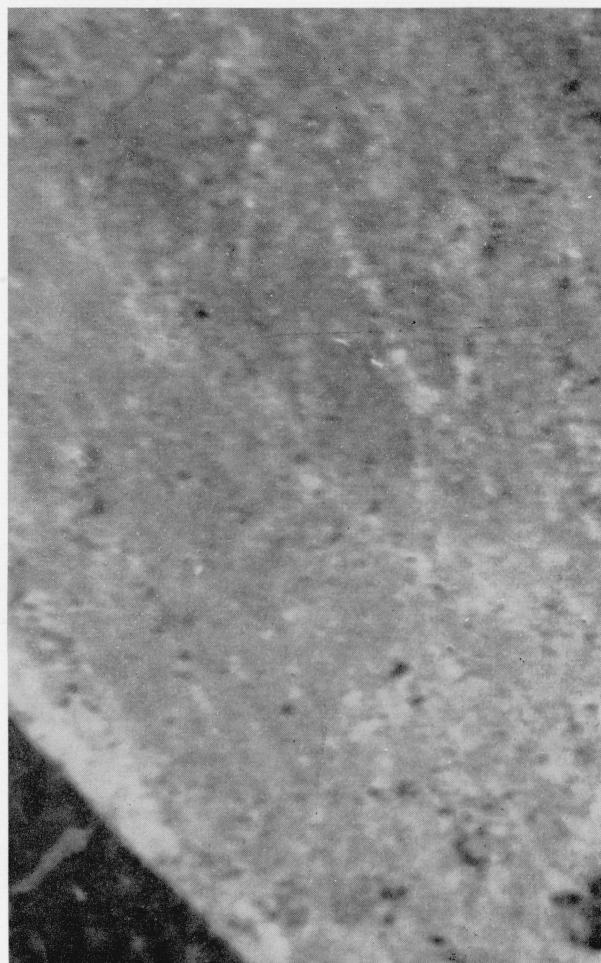


FIGURE 3. Photomicrograph of terrazzo floor, test 4 in table 2.

Magnification, $\times 30$.

The results shown for the two concrete floors (tests 1 and 2) and the two vinyl resin floorings (tests 22 and 23) demonstrate the importance of surface condition and the inadvisability of assigning a single coefficient or even a single range of coefficients to one type of flooring.

The antislip properties of terrazzo were improved by the addition of an aggregate containing an abrasive (tests 4 and 5).

A waxed pressed fiberboard was considered to be exceptionally slippery by employees of the

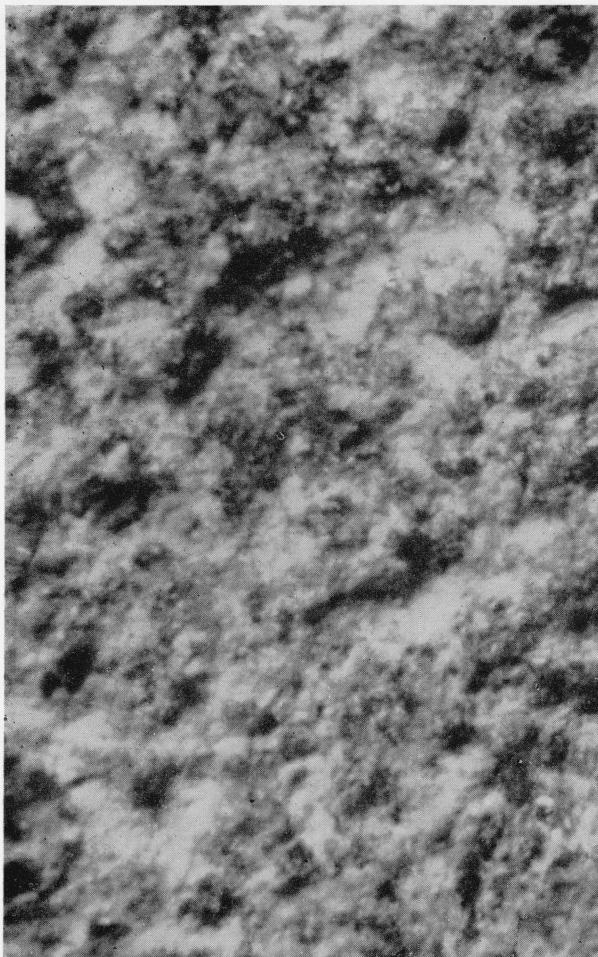


FIGURE 4. Photomicrograph of soapstone stair tread, test 7 in table 2.

Magnification, $\times 30$.

establishment where the floor was located. Measurements (test 11) substantiate their experience.

Tests 12 to 15 are representative of a series of tests on panels of brown battleship linoleum treated with different types and brands of floor waxes. Although the tests were made on an actual installation of linoleum, the area was used primarily for test purposes and had been subjected to very little traffic. Thus, the linoleum still retained most of its factory-applied coatings of sealer and wax. The antislip characteristics of the various test panels were found to be quite similar. The lowest antislip coefficient under dry conditions was obtained with a leather heel on the panel treated with a solvent-type wax (test 13). Machine polishing the panels treated with a water-emulsion wax caused a slight increase

in the coefficients (tests 14 and 15). A similar tendency was found for other brands tested. The small differences found between one-coat and three-coat applications of the water-emulsion waxes were not consistent for the different brands tested.

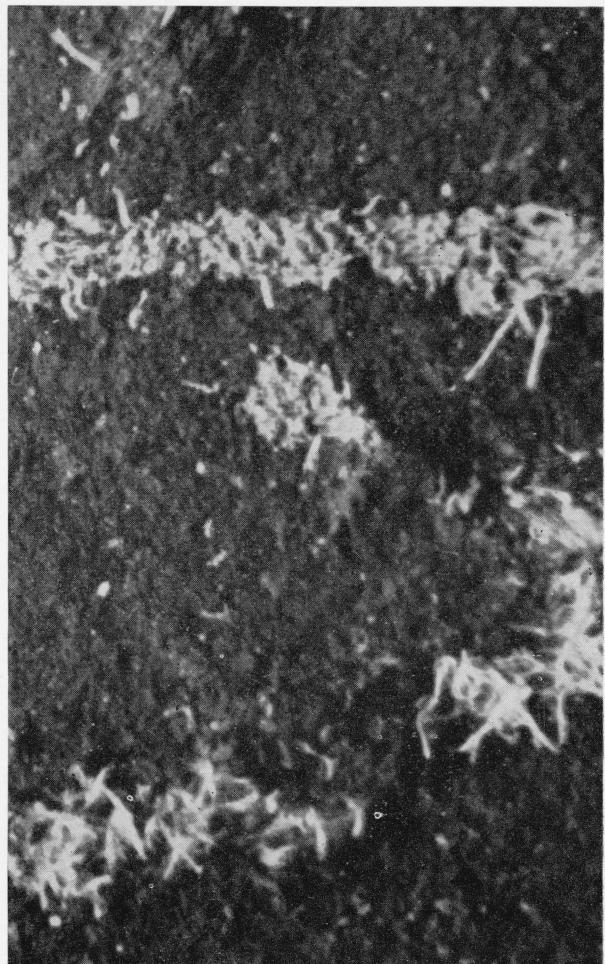


FIGURE 5. Photomicrograph of rubber and cotton matting, test 21 in table 2.

Magnification, $\times 30$.

Tests 16, 18, and 19 were made on floors being maintained by a particular method and floor polish, which, according to representatives of the hospital where the tests were conducted, has resulted in a material reduction in accidents due to slippery floors. Although these floors would be considered unsafe when wet, the antislip coefficients obtained with a dry leather heel were higher than frequently found for the types of floors involved.

TABLE 2. Relative slipperiness of a variety of walkway surfaces

Test number	Walkway surface	'Antislip coefficient			
		Rubber heel		Leather heel	
		Dry	Wet	Dry	Wet
1	Concrete slab, ground with silicon carbide ^a	0.65	0.60	0.37	0.43
2	Cement-mortar topping, worn smooth ^b	.64	.28	.37	.19
3	Paving brick, worn smooth ^b	.68	.38	.27	.27
4	Terrazzo, worn smooth ^b	.53	.25	.35	.16
5	Terrazzo, containing alundum grit, worn smooth ^b	.74	.33	.44	.18
6	Quarry tile, worn smooth ^b	.69	.28	.31	.20
7	Soapstone stair tread, sand rubbed finish ^a	.69	.59	.42	.45
8	Metal plate coated with phenolic resin and No. 46 alundum ^a	.69	.45	.64	.47
9	Yellow pine; sanded (abrasives No. 3, 1½, and 0), sealed (penetrating seal), burnished (steel wool), waxed (water-emulsion type), and polished ^b	.52	.16	.19	.16
10	White-oak, maintained with solvent-type wax (<i>E</i>), polished ^b	.49	.19	.24	.17
11	Pressed fiberboard, maintained with solvent-type wax (<i>E</i>), polished ^b	.47	.15	.26	.14
12	Linoleum (<i>M</i>), scrubbed and cleaned ^a	.68	.19	.32	.10
13	Linoleum (<i>M</i>), solvent-type wax (<i>F</i>), polished ^a	.62	.19	.25	.13
14	Linoleum (<i>M</i>), water-emulsion wax (<i>G</i>), one coat ^a				
	Not polished	.66	.19	.28	.09
	Polished	.68	.16	.34	.11
15	Linoleum (<i>M</i>), water-emulsion wax (<i>G</i>), three coats ^a				
	Not polished	.70	.14	.31	.07
	Polished	.71	.16	.34	.10
16	Linoleum (<i>N</i>), maintained with water-emulsion wax (<i>H</i>), polished ^b	.67	.21	.40	.20
17	Rubber tile (<i>O</i>), maintained with solvent-type wax (<i>E</i>), polished ^b	.61	.17	.29	.16
18	Rubber tile (<i>P</i>), maintained with water-emulsion wax (<i>H</i>), polished ^b	.80	.32	.42	.20
19	Asphalt tile (<i>R</i>), maintained with water-emulsion wax (<i>H</i>), polished ^b	.82	.29	.48	.24
20	Asphalt tile (<i>S</i>), maintained with water-emulsion wax (<i>I</i>), polished ^b	.76	.22	.37	.15
21	Rubber-and-cotton matting, corrugated, worn rough ^b	.61	.38	.48	.32
22	Vinyl resin flooring (<i>T</i>), worn rough ^b	.59	.35	.48	.30
23	Vinyl resin flooring (<i>U</i>), smooth molded surface ^a	.47	.22	.25	.21

^a Laboratory specimens in an unworn condition.

^b Floor areas in actual service.

^c Tested parallel to corrugations.

A summary of the results of a rather extensive investigation of untreated and waxed asphalt-tile corridors in a large Government building in Washington is presented graphically in figure 6. Approximately 800 measurements were involved, with the standard deviations⁵ from the means averaging about 0.02. The tests were made on four different corridors. The floor area of each corridor was

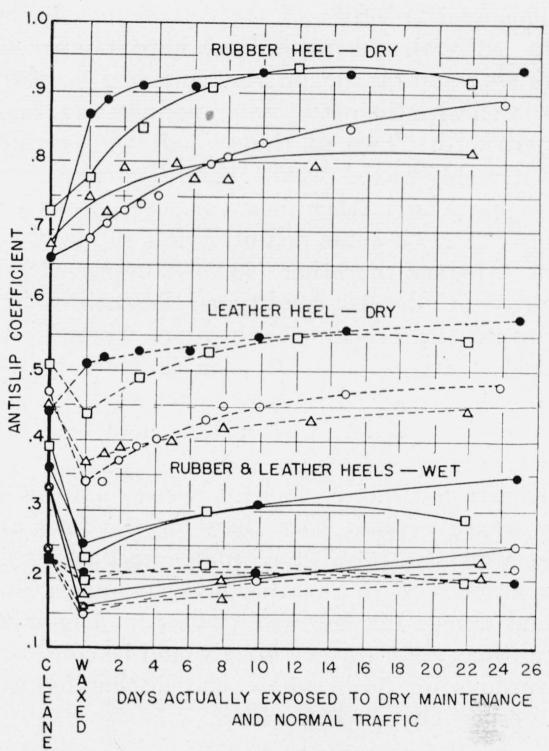


FIGURE 6. Relative slipperiness of untreated and variously waxed asphalt tile corridors.

—, Rubber heel; - - -, leather heel; ○, wax A; △, wax B; ●, wax C; □, wax D.

approximately 5,200 ft², and thus, measurements could be made at widely spaced, random locations. Each corridor was thoroughly scrubbed and cleaned at night by the building maintenance crew so as to remove surface coatings. Slipperiness tests were made the following day on each of the cleaned corridors with both rubber and leather test heels and under both dry and wet conditions.

Each corridor was then given a specific waxing treatment at night and again tested the following day. All of the waxes were of the water-emulsion type. Two coats of waxes *A*, *B*, and *C* were applied and the floors machine polished after each coat. Three coats of wax *D* were applied and the floor machine polished only after the last coat.

Measurements were repeated on each of the corridors at various time intervals in order to determine what changes occurred in the slipperiness of the waxed floors when exposed to normal maintenance and traffic. The maintenance consisted in dry bushing and machine polishing the floors at the end of each work day. In figure 6, only work days were counted as days of exposure.

⁵ Statistical measure of scattering.

Slipperiness of Walkway Surfaces

The relative order of the antislip coefficients obtained with the pendulum, impact-type slipperiness tester for the different corridors correlated very well with their relative slipperiness as actually experienced. Two of the asphalt tile corridors when freshly waxed (waxes *A* and *B*) were decidedly slippery to leather footwear, even when dry. One (wax *A*) became definitely less slippery with time, whereas the other (wax *B*) improved only slightly. Under dry conditions, the antislip properties of the other two corridors when freshly waxed (waxes *C* and *D*) were satisfactory with leather footwear. All the corridors when dry gave very good traction with rubber footwear both before and after waxing.

Higher antislip coefficients were obtained for the waxed asphalt tiles than for the untreated tiles when tested with a rubber heel under dry conditions. With a leather heel the opposite was found except for one wax (wax *C*). Under wet conditions all of the corridors would be considered hazardous for both rubber and leather footwear and especially so when waxed.

In general, the antislip properties of the waxed asphalt tile corridors improved with continued exposure to dry maintenance and normal traffic. Measurements made on the corridors after they were scrubbed with plain water and machine polished were too varied to warrant any generalized conclusions.

The results of these tests, considered in relation to slipperiness as actually experienced, indicate that a slippery condition does or does not exist, according to whether the measured coefficient is less or greater than 0.4.

Slipperiness measurements, although significant, may not in themselves afford an adequate basis for selecting the most satisfactory commercial floor treatment. Other factors, such as durability, appearance, ease, and cost of maintenance, and the requirements of existing specifications, would also need to be considered in determining the suitability of any floor finish.

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