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Floor slipperiness measurement: friction coefficient, roughness of floors, and subjective perception under spillage conditions

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Abstract

Measurement of the coefficient of friction (COF) between the shoe/sole and the floor is essential in understanding the risk of slipping accidents. In this research, the COF of five floor materials commonly used on a university campus, under five surface conditions including dry and four liquid spillage conditions, were measured. The COF measurements were conducted using a Brungraber Mark II slip tester with four footwear materials: leather, neolite, ethylene vinyl acetate, and blown rubber. The results of the COF measurements showed that floor tile, footwear material, and surface conditions were all significant factors affecting the COF. Interactions between these factors were also significant. Four surface roughness parameters (R_a, R_{tm}, R_{pm}, R_q) of the five tiles selected in the friction measurement were measured using a profilometer. The roughness of the two ceramic tiles was significantly higher than the three non-ceramic tiles. The correlation between the four roughness parameters and the measured COF was very high ($r = 0.932$ to 0.99) under both wet and water–detergent conditions. The tile and surface conditions in the friction measurements were presented to 24 subjects and the subjective evaluation of floor slipperiness was determined. The differences of the scores from the five surface conditions were statistically significant. The difference under floor tile conditions with the same spillage condition was, however, not significant. Spearman's rank correlation coefficients between subjective score and measured COF using neolite footwear were in the range of 0.8–0.975 for the five floors under all the surface conditions. This implies that

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subjective scores may reasonably reflect floor slipperiness measured with the Brungraber Mark II slip tester using neolite footwear pad.

Keywords: Coefficient of friction (COF); Brungraber Mark II slip tester; Spills on floor; Perceived floor slipperiness

1. Introduction

Accidents caused by slips and falls on slippery surfaces present a significant safety problem (Leamon, 1992; Swensen et al., 1992; Grönqvist, 1995; Leclercq et al., 1995). Foot slips on floors are due to insufficient friction between the sole and the floor. The control of slipping events requires the establishment of a friction standard for the shoe/floor combination and the use of materials that meet this standard. Friction between the shoe and the floor may be determined statically or dynamically, the former is the static coefficient of friction (SCOF) and the later is the dynamic coefficient of friction (DCOF). The DCOF is expected to be a determining factor affecting slipperiness, as the foot is in motion when the shoe comes in contact with the floor (Andres and Chaffin, 1985; Tisserand, 1985). In practice, during normal walking conditions, the contact time between the sole and the floor is so short that SCOF may not be relevant (Perkins, 1978). Brungraber (1967), on the other hand, claimed that SCOF was the most significant parameter affecting slip resistance of floors. Perkins and Wilson (1983) also suggested that SCOF is a better indicator of slipperiness since it determines whether a slip will be initiated. The measurement of SCOF is usually easier than that of DCOF, since the later involves complicated control of the motion between the two contact surfaces. A measured SCOF of 0.5 has been adopted as a safety standard in the USA (Miller, 1983).

It is generally accepted that smooth surfaces are more slippery than rough surfaces. The COF between the shoe sole and the floor has been shown to be highly dependant on the roughness of the floor surface (Chang et al., 2001a). The roughness of a surface may be determined by using various surface roughness parameters. The arithmetical average of surface heights (R_a) is a commonly used one. Stevenson et al. (1989) indicated that DCOF under contaminated conditions, measured with a dynamic setup to simulate human slips, increases almost linearly with R_a, and increases only somewhat beyond certain R_a values. Grönqvist et al. (1990) reported that Pearson's product-moment correlation coefficient between the DCOF for glycerol contaminated floors and R_a was 0.87, with $p < 0.001$. They suggested that an adequate R_a value for a proper slip resistance should be about 7–9 μm.

In addition to R_a, other roughness parameters have also been discussed. Harris and Shaw (1988) reported strong correlation ($\rho = 0.83$) between the average maximum peak to valley distance in each cut-off length (R_{tm}) and users' opinions of floor safety. Manning et al. (1990) and Manning and Jones (1994) reported that the rank correlation coefficients between the measured friction and R_{tm} of shoe surfaces were 0.64 and 0.757 for wet and oily surfaces, respectively. Chang (1998) reported that the

DCOF and the average of the maximum height above the mean line in each cut-off length (R_{pm}) was as high as 0.97. Chang (2001) expanded his study to include three different footwear materials on porcelain tiles with four different contaminants. The results showed that the R_{pm} had a strong correlation ($r = 0.77$ to 0.86) with DCOF measured on tiles contaminated by an 85% glycerol solution.

Spillage is common in many public and working areas. Water and detergent solutions are common due to leakage and/or floor maintenance. On the university campus where the first author served, the floors of the kitchens of the 15 restaurants are almost always covered with liquids during most meal serving periods. Spillage is the primary source of these contaminants. Spillage may occur when cooking oils are poured into and/or removed from the vat or the pan. The oil on the floor immediately after the leakage may be very thick. It may then be spread to the adjacent area and mixed with water by the workers' shoes after repeatedly walking over the area. Spillage also happens in the serving areas of the campus restaurants, and even walkways in other buildings, when people take their meals to certain locations to eat. Spillage not only occurred in the restaurants and food serving areas but also in the machine shops, laboratories, garages, and certain equipment storage areas. Liquid leakage from a container, a machine or a vehicle is the primary source of these contaminations. A pool of contaminant may accumulate on the floor if the leakage is not removed immediately. The friction of a floor surface is altered when covered with liquids. Liquids of varying viscosities produce varying lubricating effects between the shoe and the floor. The effect is to separate the shoe sole and the floor, thus reducing the friction available (Grönqvist, 1995; Leclercq et al., 1995). Manning and Jones (2001) pointed out that oil contamination is the most dangerous because the DCOF values on such floors are invariably lower with oil contamination than with water.

In addition to tribological effects, a subject's perception of floor slipperiness is also essential in slip prevention as the subject may then manipulate gait patterns when walking on a slippery surface to reduce the probability of a slip. The floor slipperiness is initially judged by the subject's visual perception. Myung et al. (1993) compared the subjective ranking of slipperiness and the DCOF of ceramic, steel, vinyl, plywood, and sandpaper. Their results indicated that humans have a promising ability to subjectively differentiate floor slipperiness with a reliable confidence rating for the tested surfaces, even though the slipperiness difference might not be large. They concluded that humans were reliable, but risky, discriminators of floor slipperiness. Cohen and Cohen (1994a) asked their subjects to visually compare 23 tested tiles to a standard tile with a SCOF of 0.5 and judge whether the tile was more slippery. They found a significant number of disagreements between subjective responses and the SCOF values of the tiles, in contrast to the findings of Myung et al. (1993). In a follow-up study, Cohen and Cohen (1994b) exposed 8 subjects to 10 outdoor walking surfaces under both dry and wet conditions. The subjects observed and then walked over each surface under each condition before rating their perception of floor slipperiness on a one-to-seven scale. Pearson's correlation coefficients between the DCOF of the surfaces and the subjective ratings were calculated. The authors found that the correlation was weak for the dry condition ($r = 0.045$

and 0.241 for 'observed' and 'experienced' ratings, respectively) and moderate for the wet condition ($r = 0.407$ and 0.677 for the two ratings, respectively). The results from both of the studies (Cohen and Cohen, 1994a,b) indicated that humans' perceptions of floor slipperiness might be quite different from the actual traction of the floor as measured by COF. A false perception of floor slipperiness may result in an inappropriate gait pattern and result in slippage of the foot on the floor.

Friction has been commonly adopted as an indicator of slipperiness. Measurement of the COF between footwear material and floor has been the subject of much research (Stevenson et al., 1989; Manning et al., 1990; Grönqvist, 1995; Leclercq et al., 1995; Chang and Matz, 2001). Extensions of friction measurement to roughness measurement have also been reported (Grönqvist et al., 1990; Manning and Jones, 2001; Chang, 1998, 1999, 2001, 2002a; Chang et al., 2001a). In addition to friction and roughness measurements, subjective measurement has also been discussed (Swensen et al., 1992; Myung et al., 1993; Cohen and Cohen, 1994a,b; Grönqvist et al., 2001). However, most of the studies involving tribology, surface geometry, and subjective measurements addressed at most two factors at a time. Field studies that combine friction, roughness measurement and subjective scoring are rare. In addition, spillage of oil has not been addressed in friction measurements in the previous studies. The objectives of this study were:

- to measure the COF of five commonly used floor tiles on a university campus under one dry and four liquid-spillage conditions using four footwear materials;
- to measure the roughness of the selected floor tiles;
- to investigate the perceived floor slipperiness by human subjects for the floor-spillage conditions; and
- to discuss the correlations between the measured COF and perceived floor slipperiness.

2. Method

To accomplish the objectives of the study, factors and/or conditions related to the floor friction measurement, including the measurement device, footwear samples, floor tiles, surface conditions, and measurement procedures, are discussed in Sections 2.1–2.4. The field measurements of floor roughness and of subjective perception of floor slipperiness are described in Sections 2.5 and 2.6, respectively.

2.1. Measurement device

The Brungraber Mark II, used in this study, is a portable, inclinable, articulated strut slip tester (PIAST) as shown in Fig. 1. The operating principle of this tester is to simultaneously apply forces parallel and normal to a floor surface by impacting a footwear sample on the floor. A weight of 4.54 kg drives an inclined-strut to impact the floor surface at an inclined angle to the vertical. The footwear sample is approximately 7.62 by 7.62 cm and is within a height of 3.175–6.35 mm from the floor

Fig. 1. The Brungraber Mark II used in field measurements.

surface. The angle of the strut is increased until a slip occurs on impact. The starting angle should be smaller than the angle at which a slip is anticipated and the angle is increased until a slip occurs. The tangent of the angle is the COF marked on the tester.

The COF values measured with the Brungraber Mark II tester were compared with the horizontal–vertical force ratio (F_H/F_V) obtained from a force platform (Grönqvist et al., 1999; Powers et al., 1999). The results indicated that the COF obtained directly from the Brungraber Mark II and from the force plate measurements showed good agreement over a range of floor surfaces and contaminants for both non-slip and barely slip conditions. The Mark II was also shown to have a good correlation ($r > 0.954$) with the DCOF measured with a dynamic apparatus designed to simulate a slip (Grönqvist et al., 1999).

The standard test method for the Brungraber Mark II was proposed by the ASTM (2001). According to the ASTM standard, it might be necessary to average the maximum COF that a non-slip occurs and the minimum COF that a slip occurs. Repeated measurements at one location are also recommended to obtain a better representation of floor conditions. The operation manual from the manufacturer recommends six repeated measurements should be made at the same location and averaged as the final result. The slip criterion in determining whether a slip or a non-slip occurred followed the one recommended by Chang (2002b).

2.2. Testing materials

Five floors commonly encountered on a university campus were selected for the study. They were vinyl composition, granite, terrazzo, ceramic A, and ceramic B. The vinyl and terrazzo are widely used in the classrooms, library, and dormitories on campus, the granite is used in the major entrances of several buildings, and ceramic A and B are widely used in the lavatories. All the floor tiles were larger than the footwear pad used in the slip tester. One area for each floor material was selected for the measurements. Since the selection of the location of the friction measurement has not been established in the standard, the very first tile, in the middle of the walkway, at the entrance of a building/floor or lavatory was measured.

Four footwear samples were used: leather, neolite, ethylene vinyl acetate (EVA), and blown rubber (BR) with the densities of 0.96, 1.29, 0.21, and 0.56 g/cm^3, respectively. The leather and the neolite footwear samples were supplied by the manufacturer of the tester. The EVA and the BR samples, both commonly used shoe sole materials, were supplied by a shoe manufacturer. The shore-A hardnesses of EVA and BR were in the range of 50–60. The shore-A hardnesses of leather and neolite were in the range of 93–96. All the footwear materials used were flat; in other words, there was not any tread or groove on the testing samples of the footwear materials. Tread design of the sole of footwear is common for people on campus. Measurement of COF using a flat footwear material may underestimate the actual friction that people experience on those floors. This is a limitation of the investigation.

2.3. Surface condition

The floors were measured under five surface conditions including dry, wet, water–detergent mixture, vegetable oil, and engine oil (Mobil 20W-50). Wet and water–detergent floors are very common in all the buildings, especially after daily floor maintenance. Vegetable oil may be found on the floors of the kitchen and dining areas of the dormitories. Spills of engine oil sometimes occur on the floors of the machine shops, garages, and laboratories.

Water sufficient to flood the test area was applied to cover the floor tile surface in the wet condition. The water was replenished throughout the repeated impacts during the measurement so that the thickness of water was controlled by the surface tension. For the water–detergent condition, a 5% (by volume) detergent solution was applied to the floor as in the wet condition. For the vegetable and engine oil conditions, the oils were poured onto the floor to duplicate oil spillage conditions. The oil-covered area was as big as the footwear sample of the Mark II tester. The thicknesses of the oils on the floor were controlled by the surface tensions. All the contaminants were removed using absorbent papers after the measurements of each surface condition. For the oily conditions, the floor was further cleaned using a detergent solution to remove the oil and then wiped with a mop and absorbent papers. The floor was blown dry using a hair drier after all the cleaning processes.

2.4. Friction measurement

The measurements were in the direction of the walking path of the selected tiles. Six measurements were taken with each footwear sample/floor/contamination condition. A total of 600 ($6\times4\times5\times5$) measurements were made. Before the measurements, all the footwear samples and tiles were wiped with a 50% ethanol solution and were blown dry using a hair drier. For wet, water–detergent, and the two oily conditions, the liquids were applied after this cleaning process. Sanding of the test footwear sample using 400 grit silicon carbide abrasive paper was done before the measurement of each footwear sample/floor/surface condition. The sanding was repeated nine times (approximately 15 cm in length) in the friction measurement direction of the sample. The sanding process was repeated at a 90° rotation of the sample. After the sanding, a brush was used to remove the debris on the footwear sample. New abrasive paper was used for each sanding process. The purpose of sanding was to standardize the surface condition of the footwear sample before each measurement. After the measurement of each floor/surface condition, the footwear sample was wiped using absorbent papers to remove excessive contaminants and then cleaned using the 5% detergent solution. The surface was rinsed thoroughly with tap water and dried with a hair drier.

The COF range of the Brungraber Mark II tester is 0–1.1. The maximum COF value was adopted if the measurement exceeded the range of the tester. The difference between the readings of two adjacent markers on the tester is 0.01. Interpolation was required when the reading fell between the markers. A value of one-quarter, one half, or three quarters was assigned as a reading between the markers if the pointer was less than half, equal to half, or more than half between the markers, respectively.

2.5. Floor surface roughness measurement

Floor surface texture is shown to affect COF (Chang et al., 2001a; Kim et al., 2001). Surface roughness determines the primary texture of the surface, and is normally used for quantification of floor topography. A rougher floor surface generally leads to a higher COF (Chang, 1998). Surface parameter R_a, root mean square of surface heights (R_q), the average peak to valley height in each cut-off length (R_{tm}), and the arithmetic mean of the maximum height of the profile above the mean line in each cut-off length (R_{pm}) were measured using a Mitutoyo Surftest 301 profilometer for the five floor tiles. The measurements for each tile were taken at the four corners at the same location tested by the Brungraber Mark II (see Fig. 2). The roughness measurements were taken in the same direction as the COF measurements. The travel distance of the profilometer was 12.5 mm with a cut-off length of 2.5 mm. Eight measurements (2 replications$\times$4 corners) were taken for each tile. The means and standard deviations were calculated for the tiles.

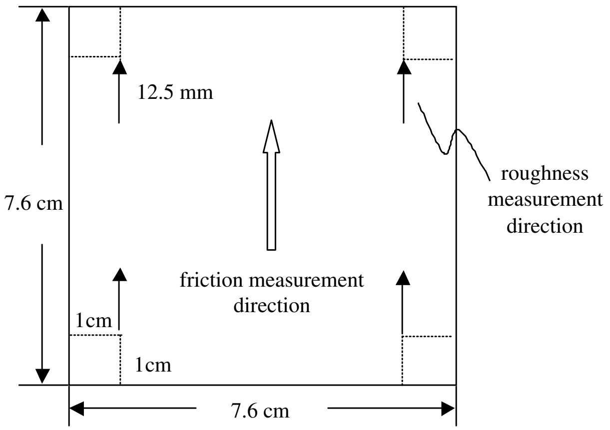

Fig. 2. Locations and direction of friction and roughness measurements.

2.6. Visual perception of slipperiness

To investigate the perceived slipperiness of floor/surface conditions, a subjective visual evaluation of slipperiness was conducted using the same floor tiles used in the friction measurements. Twenty-four subjects, including 12 males and 12 females, were recruited for the survey. The average age of the subjects was 22.83 (±8.11) years. The five surface conditions for measuring COF were reproduced following the procedure in Section 2.3 on the tiles where the friction data were taken. Each subject was brought to the location of each tile and was asked to inspect visually and determine the slipperiness on a 1–5 scale. The scale from 1 to 5 corresponds to EXTREMELY SLIPPERY, VERY SLIPPERY, SLIPPERY, SOMEWHAT SLIPPERY, and NOT SLIPPERY, respectively. The order of floor-surface conditions presented to each subject was randomly arranged. At least one day later, each subject repeated the same evaluation for the same floor-surface conditions. This allows the calculation of test–retest reliability of the perception of floor slipperiness. A total of 48 surveys were collected and used for the statistical analysis.

3. Results

3.1. COF measurement

Table 1 shows the measured COF under all the experimental conditions. Friction was generally high on the dry condition. However, there were exceptions: EVA seemed to have a smaller COF on dry floors as compared with the other footwear materials. The mean COF values of EVA on the terrazzo, vinyl, and ceramic A were less than 0.5, which is a commonly accepted safety standard. The COF of leather on ceramic B also failed to reach 0.5. None of the COF values of the liquid-contaminated

Table 1
Mean and standard deviation of COF under experimental conditions

		Dry	Wet	Water–detergent	Vegetable oil	Engine oil
Terrazzo	Leather	0.615 (0.036)	0.004 (0.003)	0.005 (0.002)	0.003 (0.000)	0.005 (0.003)
	Neolite	0.631 (0.019)	0.016 (0.003)	0.026 (0.012)	0.004 (0.001)	0.006 (0.003)
	EVA	0.247 (0.017)	0.010 (0.005)	0.007 (0.002)	0.007 (0.002)	0.009 (0.002)
	BR	1.07 (0.000)	0.006 (0.002)	0.007 (0.002)	0.004 (0.002)	0.011 (0.002)
Vinyl	Leather	0.654 (0.075)	0.012 (0.011)	0.004 (0.002)	0.016 (0.005)	0.009 (0.006)
	Neolite	0.634 (0.117)	0.031 (0.021)	0.016 (0.004)	0.006 (0.003)	0.007 (0.004)
	EVA	0.368 (0.029)	0.012 (0.002)	0.007 (0.002)	0.006 (0.003)	0.014 (0.002)
	BR	1.07 (0.000)	0.008 (0.003)	0.006 (0.002)	0.003 (0.001)	0.017 (0.002)
Granite	Leather	0.519 (0.037)	0.010 (0.007)	0.007 (0.002)	0.004 (0.003)	0.006 (0.005)
	Neolite	0.562 (0.084)	0.012 (0.006)	0.016 (0.003)	0.004 (0.002)	0.013 (0.004)
	EVA	1.070 (0.000)	0.006 (0.002)	0.007 (0.002)	0.007 (0.002)	0.006 (0.002)
	BR	1.070 (0.000)	0.006 (0.002)	0.006 (0.002)	0.008 (0.001)	0.020 (0.003)
Ceramic A	Leather	0.617 (0.029)	0.021 (0.003)	0.021 (0.007)	0.018 (0.004)	0.008 (0.003)
	Neolite	0.841 (0.020)	0.347 (0.033)	0.426 (0.018)	0.007 (0.004)	0.006 (0.003)
	EVA	0.487 (0.035)	–	–	–	–
	BR	1.07 (0.000)	–	–	–	–
Ceramic B	Leather	0.314 (0.022)	0.022 (0.007)	0.020 (0.008)	0.006 (0.003)	0.006 (0.003)
	Neolite	0.747 (0.027)	0.193 (0.025)	0.163 (0.014)	0.008 (0.000)	0.008 (0.000)
	EVA	1.070 (0.000)	0.019 (0.004)	–	–	–
	BR	1.070 (0.000)	0.043 (0.004)	–	–	–

(–) COF less than 0.0025.

conditions reached the 0.5 standard. An analysis of variance (ANOVA) was performed to determine the effects of the floor, shoe, and surface factors on the measured COF. The results showed that the effects of the three factors on the COF were statistically significant ($p < 0.0001$). The two-way and three-way interaction effects were also all significant ($p < 0.0001$). Tables 2–4 show the results of Duncan's multiple range tests for floors, footwear materials, and surfaces, respectively. In Table 2, the COF values for all the floors were significantly different from one another. The order, from high to low, was ceramic A, ceramic B, granite, vinyl, and terrazzo. The COF values of all footwear materials were also significantly different

Table 2
Duncan's multiple range test results for floor

Floor	Mean COF	Group*
Terrazzo	0.135	A
Vinyl	0.145	B
Granite	0.168	C
Ceramic B	0.184	D
Ceramic A	0.193	E

* Different letters in group indicate they were significantly different under $\alpha = 0.05$.

Table 3
Duncan's multiple range test results for footwear

Footwear	Mean COF	Group*
EVA	0.117	A
Leather	0.134	B
Neolite	0.189	C
BR	0.220	D

* Different letters in group indicate they were significantly different under $\alpha = 0.05$.

Table 4
Duncan's multiple range test results for surface conditions

Surface condition	Mean COF	Group*
Vegetable oil	0.005	A
Engine oil	0.007	A
Water–detergent	0.037	B
Wet	0.039	B
Dry	0.736	C

* Different letters in group indicate they were significantly different under $\alpha = 0.05$.

from one another (see Table 3). BR showed the highest COF, next neolite, then leather, and finally EVA. For the different surface conditions, dry floors showed the highest COF, wet and water–detergent floors were the next, and the two oily floors were the lowest (see Table 4). The difference between the wet and water–detergent conditions was not statistically significant. Neither was the difference between the vegetable oil and engine oil significant.

Figs. 3–5 show the two-way interaction of the three factors. In Fig. 3, the COF values reduced sharply when the floor tiles were covered by liquid of any kind as compared to the dry condition. The COF approached zero for terrazzo, vinyl, and granite tiles with liquids on them and also the two ceramic tiles with either oil on them. For the wet and water–detergent conditions, ceramic A and B showed higher COF values, compared to the other three tiles. In Fig. 4, the COF of BR was very consistent (at 0.22 level) over various floors. For the other three footwear materials, variations were obvious among floor tiles. Neolite showed a higher COF on ceramic tiles, especially on ceramic A, as compared to the other three tiles. The mean COFs of neolite on terrazzo, vinyl, and granite, under all surface conditions, were in the range of 0.12–0.14. The EVA showed higher COF values on granite and ceramic B (both at 0.22) as compared to the other three tiles. The COF values of EVA on terrazzo, vinyl, and ceramic A were all less than 0.1. The COF values of leather on granite and ceramic B (both less than 0.1) were low as compared with the other tiles. The COF values of leather on terrazzo, vinyl, and ceramic A were in the range of 0.13–0.14. Fig. 5 shows the interaction between footwear materials and contaminated conditions. The BR showed a very high COF as compared with the other three footwear materials on dry floors. Under all liquid covered conditions, all footwear materials showed a relatively low COF. On wet and water–detergent floors, neolite

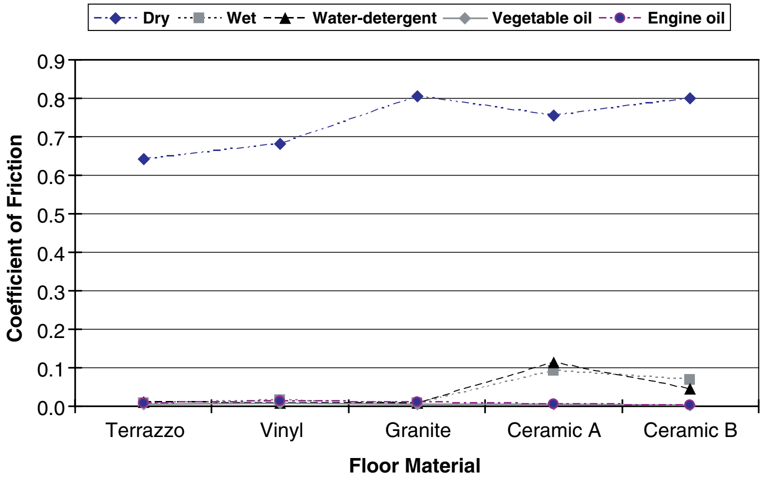

Fig. 3. Interaction between floors and contaminants, the COF values were averaged for footwear materials.

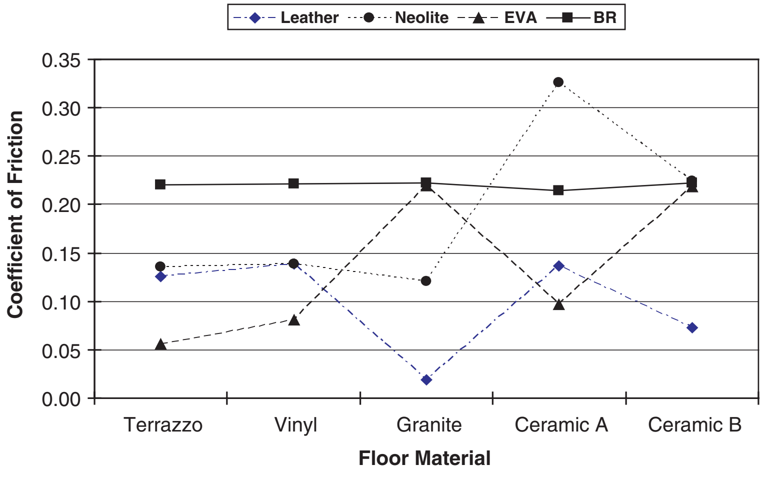

Fig. 4. Interaction between floors and footwear materials, the COF values were averaged for contaminated conditions.

showed higher COF values (about 0.12) than the other three footwear materials (less than 0.01).

To compare the COF of the four contaminated conditions to the dry condition, a term—*friction loss* of a contaminated condition can be calculated as

$$\text{Friction loss} = (\text{COF}_{\text{contaminant}} - \text{COF}_{\text{dry}})/\text{COF}_{\text{dry}} \times 100\%$$

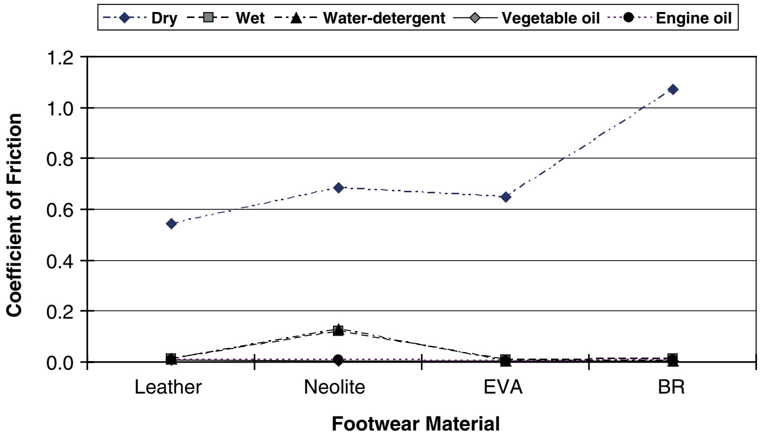

Fig. 5. Interaction between footwear materials and contaminated conditions, the COF values were averaged for floor tiles.

The friction losses were surprisingly high for the spillage conditions. In all the footwear–tile conditions, the friction loss was over 93% and even as high as 99.77%. There were a few exceptions: neolite on ceramic A lost only 58.74% and 49.35% on wet and water–detergent conditions, respectively. Neither was the friction loss of neolite on ceramic B as high as the other footwear materials under contaminated conditions (74.16% and 78.18% for wet and water–detergent conditions, respectively).

3.2. Roughness of floor tiles

Table 5 shows the means, standard deviations, and results of Duncan's multiple range tests of the roughness measurements of the five floors. For the four roughness parameters, the variations of means among the five floors were very consistent. The average R_a values of ceramic A, ceramic B, terrazzo, granite, and vinyl were 6.85, 5.08, 1.17, 0.79, and 0.59 μm, respectively. The R_a of ceramic A was significantly higher ($p < 0.05$) than all other tiles. Ceramic B was significantly higher ($p < 0.05$)

Table 5
Mean (standard deviation) roughness (μm) and comparison using Duncan's multiple range test of five floor tiles

Floor	R_a	R_{tm}	R_q	R_{pm}
Vinyl	0.59(0.24) A*	4.43(1.36) A*	0.81(0.36) A*	2.46(1.77) A*
Terrazzo	1.17(0.21) B	8.31(1.84) B	1.59(0.34) A, B	4.05(0.59) A
Granite	0.79(0.33) A, B	8.11(2.40) B	2.09(1.21) B	7.15(2.24) A
Ceramic B	5.08(0.53) C	21.59(2.62) C	6.09(0.67) C	15.00(3.01) B
Ceramic A	6.85(0.67) D	33.88(3.59) D	8.83(0.93) D	31.99(11.05) C

* Different letters indicate that they were significantly different at $\alpha = 0.05$.

Table 6
Pearson's correlation coefficients (r) between floor roughness and COF under different contamination conditions

	R_a	R_q	R_{tm}	R_{pm}
Dry	0.422	0.491	0.418	0.423
Wet	0.990**	0.977**	0.968**	0.932*
Water–detergent	0.946*	0.959**	0.977**	0.990**
Vegetable oil	−0.449	−0.419	−0.378	−0.226
Engine oil	−0.909*	−0.837	−0.862	−0.754
Overall	0.856	0.898*	0.861	0.862

*$p < 0.05$, **$p < 0.01$.

than the three non-ceramic tiles. The difference between terrazzo and granite was not statistically significant, nor was the difference between granite and vinyl. For R_{tm}, the rank of the tiles from high to low was the same as that of R_a. The difference between terrazzo and granite was not significant. For R_q, the rank of the tiles was: ceramic A, ceramic B, granite, terrazzo, and vinyl. The difference between granite and terrazzo was not significant, nor was the difference between terrazzo and vinyl. For R_{pm}, the rank for the tiles was the same as that of R_q. The differences among granite, terrazzo, and vinyl did not reach the statistical significance level. Pearson's correlation coefficients between the four roughness parameters and COF for different contamination conditions were calculated and shown in Table 6. For all the four roughness parameters, the correlation between COF and roughness parameters under wet and water–detergent conditions were very high ($r = 0.932$ to 0.99). The correlation coefficients were comparatively low (at 0.4 level) in the dry condition. For the vegetable oil and engine oil conditions, negative correlations were found for the COF and roughness parameters. The negative correlation for the engine oil condition was high as compared to the vegetable oil condition.

3.3. Perceived slipperiness of the floor/contamination conditions

The subjective scores of floor slipperiness among the subjects for the floor-surface conditions were tested using a Chi-square test. The result showed that the difference between the test and retest scorings was not statistically significant. All the subjective scores were used for the subsequent Kruskal–Wallis test for the floor tiles and surface conditions. The results of the Kruskal–Wallis test for the surface conditions due to contaminants were significant ($p < 0.001$). The mean scores for the dry, wet, water–detergent, vegetable oil, and engine oil contaminated conditions were 4.62, 3.70, 3.14, 1.91, and 1.79, respectively (see Fig. 6). The multiple comparison tests showed that differences between any combination of two among the floor conditions, dry and all contaminated, were significant ($p < 0.05$). The difference of the subjective scores for the floor tiles, however, did not reach the significance level under the Kruskal–Wallis test ($p = 0.092$). The mean scores for the granite, vinyl, ceramic A, ceramic B, and terrazzo were 2.89, 2.93, 3.05, 3.10, and 3.18, respectively, as shown in Fig. 7.

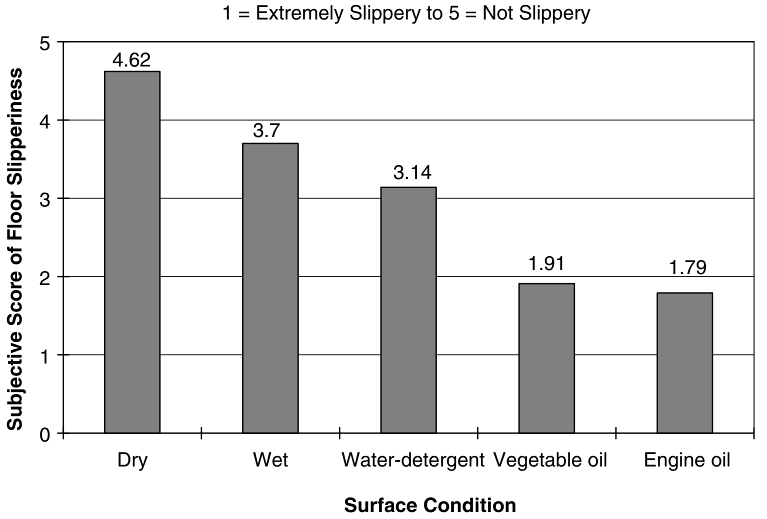

Fig. 6. Subjective score of floor slipperiness under different surface spillage conditions.

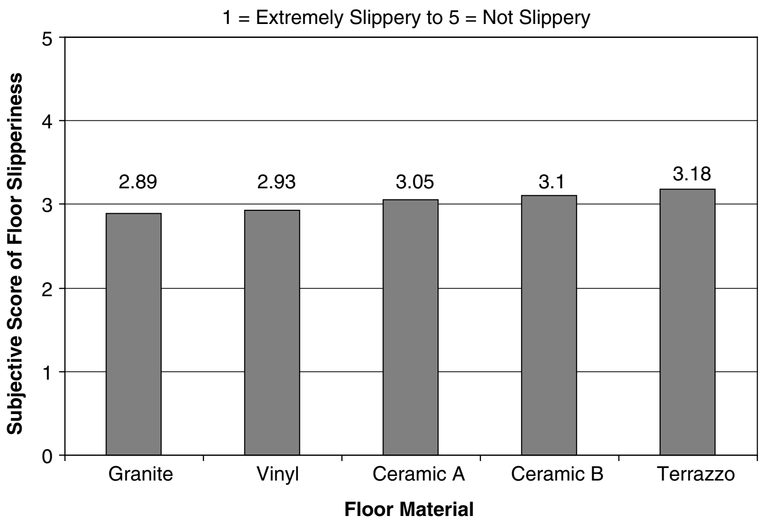

Fig. 7. The effect of floor material on the subjective score of floor slipperiness.

Spearman's rank correlation coefficients (ρ) between the subjective scores of floor slipperiness and the COF values measured with the Brungraber Mark II slip tester were calculated and shown in Table 7. Since six friction measurements were recorded for each experimental condition, the averaged COF value for each condition was used in the calculation of Spearman's correlation coefficients. For terrazzo, the COF

Table 7
Spearman's correlation coefficients (ρ) between subjective scores of floor slipperiness and COF for footwear samples and floor tiles

	Terrazzo	Granite	Vinyl	Ceramic A	Ceramic B
Leather	0.410	0.900*	0.500	0.975**	0.667
Neolite	0.800	0.800	0.900*	0.900*	0.975**
EVA	0.667	0.527	0.400	0.707	0.894*
BR	0.300	0.051	0.400	0.707	0.894*

$^{*}p < 0.05$, $^{**}p < 0.01$.

measured using neolite showed the highest correlation ($\rho = 0.8$). For granite, the correlation coefficient based on the leather sample was the highest ($\rho = 0.9$, $p < 0.05$) and neolite was the second ($\rho = 0.8$). The correlation coefficient based on the BR sample on granite was very low ($\rho = 0.051$). For the vinyl floor, the neolite sample again showed the highest correlation ($\rho = 0.9$, $p < 0.05$). For ceramic A, both leather and neolite samples showed high correlation ($\rho = 0.975$, $p < 0.01$; and $\rho = 0.9$, $p < 0.05$, respectively). Ceramic B, neolite, EVA, and BR all showed high correlation coefficients with the values of 0.975 ($p < 0.01$), 0.894 ($p < 0.05$), and 0.894 ($p < 0.05$), respectively. It may be concluded that neolite was the footwear material for which COF best correlated with subjective scores of floor slipperiness.

4. Discussion

4.1. Floor slipperiness

Selection of floor tiles with a proper COF is of great importance for slip prevention. It, however, appears that the COF depends not only on floor tiles but also on footwear materials and surface conditions. Variations of the COF of the four footwear samples were high on different floor tiles. This was consistent with the findings of Chang and Matz (2001). Neolite showed higher friction values on both the two ceramic tiles and also on wet and water–detergent floors. Neolite may be a better soling material for the footwear of janitors who are responsible for cleaning lavatories where ceramic A and B tiles are often found. BR, on the other hand, provided more consistent friction values for the five floors. It is, therefore, a better choice for people who need to walk around the campus on all these floors frequently.

The COF of wet and water–detergent floors were significantly higher than the values of the two oil-covered floors. The difference is attributed to the thickness of the film on the floor and the viscosity of the two types of liquids. Both the film thickness and the viscosity of the oils are higher than those of the wet and water–detergent conditions. The squeeze-film effect on COF was very significant for all the contaminated conditions, specially when the footwear material is flat and the floor surface is smooth. The extremely low COF values for terrazzo, vinyl, and granite under all liquid contaminated conditions could be, therefore, easily explained.

Ceramic A and ceramic B are used in lavatories as slip-resistant floor materials. The results of the measured COF indicated that the COF values of both tiles under wet and water–detergent conditions were very low.

Moore (1972) explained the squeeze-film effect using the following equation:

$$t = \frac{K\mu A^2}{F_N}\left[\frac{1}{h^2} - \frac{1}{h_0^2}\right] \tag{1}$$

where t is the time needed for the film thickness to decrease from the initial thickness h_0 to a thickness h, F_N the normal force, K a shape constant, μ the viscosity of the liquid, and A the contact area between the surface. On liquid-contaminated floors, the larger initial thickness (h_0), the longer the descending time (t), the more slippery the floor might be. In other words, the thicker the liquid on the floor, the lower the COF will be. A maximal h_0 occurs when the thickness is controlled by the surface tension in an unconfined situation, which results in the most slippery condition for a certain liquid on the floor.

The low COF values for the liquid-contaminated conditions may also be attributed to the slip tester being used. Chang (1999) found that the squeeze-film effect could be the main contributor to high COF variations and low COF values under water-contaminated conditions using the Brungraber Mark II. Assuming that the initial thickness is the same in Eq. (1), the time for the film thickness to decrease when using a slip measurement device is inversely proportional to F_N/A^2. Chang et al. (2001b) reported that the F_N/A^2 of Brungraber Mark II is the smallest (0.07 N/cm^2) among the four slip measurement devices compared. The squeeze-film effect is more pronounced when using the Mark II than three other slipmeters. In other words, the COF values using the Mark II under liquid-contaminated conditions might be lower than that using other similar devices.

4.2. Floor roughness versus COF

The friction of the floor surface is affected by surface roughness. The average R_a values for vinyl, terrazzo, granite, ceramic B, and ceramic A were 0.59, 1.17, 0.79, 5.08, and 6.85 μm, respectively. The average R_q values for the five tiles were 0.81, 1.59, 2.09, 6.09, and 8.83 μm, respectively. Grönqvist et al. (1990), based on a cut-off length of 0.8 mm in roughness measurement, pointed out that an adequate R_a value should be about 7–9 μm for a proper slip resistance. Chang et al. (2003) indicated that the values of these four surface parameters increased as the cut-off length was increased. Even when using a cut-off length of 2.5 mm, all the tiles in this study failed to meet such a roughness level. The ranks of both the R_a and the COF of the tiles were consistent. The only exception was that terrazzo, compared to the granite, had a higher R_a but a lower COF value. The rank of R_q was also consistent with COF values with the exception that terrazzo showed a higher R_q but a lower COF as compared to the vinyl. Chang (1999) indicated that the effect of surface roughness on slip resistance might well be detected using the Brungraber Mark II. This was confirmed by the consistency between the measured COF and the roughness parameters in the current study.

The negative correlation between surface roughness parameters and the measured COF for the vegetable oil and engine oil conditions shown in Table 6 may be attributed to the extremely low and concentrated COF values for the two conditions. Interpretation of correlation, under such a circumstance, may not be meaningful when the majority of the data were concentrated in a narrow band of the data range. Chang et al. (2001a) suggested that roughness measurement of floor surface might be adopted as an alternative to the COF for slip resistance assessment in the future. The correlation coefficients from the current study showed that COF might be well represented by floor roughness under the wet and water–detergent contaminated conditions. Floor roughness may not be an appropriate indicator of floor slipperiness under the oily conditions with extremely low friction values.

4.3. Subjective score of floor slipperiness versus COF

The perceived floor slipperiness scores were significant ($p < 0.001$) under different surface conditions. The engine oil condition was ranked as the most slippery one, followed by the vegetable oil condition, next with the water–detergent condition, then the wet condition, and finally the dry condition. This, however, did not totally agree with the friction results in Table 4, where both the COF values of the vegetable oil and engine oil conditions were extremely low, but the difference was not statistically significant. Moreover, the subjects felt that the wet–detergent condition was more slippery than the wet condition but the difference between the two conditions in Table 4 was not significant either. For floor tiles, the subjective scores of floor slipperiness were not significantly different from one another, but the differences among the floors were statistically significant for the COF measured using the Brungraber Mark II slip tester.

Human subjects seem incapable of differentiating the slipperiness of different floor materials. The mean subjective score of granite was the lowest among all tiles, which means that the subjects felt granite was most slippery among the five tiles (see Fig. 7). The measured COF of granite was, however, higher than the values of the vinyl and terrazzo. The subjects rated the terrazzo as the least slippery floor, but comparison of the COF among the tiles showed that terrazzo was the most slippery one based on the measured COF. The ranking of subjective scores for both the floor and contaminated conditions seemed to lack consistency with the COF measured by the slip tester. This was consistent with the findings of the two studies by Cohen and Cohen (1994a,b).

5. Conclusion

It was apparent that friction was significantly affected by footwear material, floor tile, and the presence of contaminants on the floor. The COF varied when different sole materials and floors were used. Selection of proper shoe/sole and tile materials was essential in the prevention of slipping. The importance of removing spillage from the floor was even more obvious due to the huge friction loss that could occur. When liquid spilled on the floor, the COF was reduced significantly due to the squeeze-film effect no matter what type of liquid used in this study was present.

The roughness measured on-site was consistent with the COF for the five floors with few exceptions. The correlations between COF and floor roughness of the five tiles were high for the wet and water–detergent conditions. The four surface roughness parameters may be used to rate floor slipperiness as an alternative to friction measurement using the Brungraber Mark II slip tester under the wet and water–detergent conditions. The subjective scoring of floor slipperiness showed that the subjects could well differentiate floor slipperiness under various spillage conditions, but performed poorly at rating floor tile materials for slipperiness. For the five floor tiles studied, subjective scores may reasonably reflect the COF measured with the Brungraber Mark II slip tester with a neolite footwear pad.

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