

Friction Between Footwear and Floor Covered With Solid Particles Under Dry and Wet Conditions

Kai Way Li

State Key Laboratory of Automotive Safety and Energy, China
Department of Industrial Engineering, Tsinghua University, Beijing, China
Department of Industrial Management, Chung Hua University, Hsin-Chu, Taiwan

Fanxing Meng
Wei Zhang

State Key Laboratory of Automotive Safety and Energy, China
Department of Industrial Engineering, Tsinghua University, Beijing, China

Solid particles on the floor, both dry and wet, are common but their effects on the friction on the floor were seldom discussed in the literature. In this study, friction measurements were conducted to test the effects of particle size of solid contaminants on the friction coefficient on the floor under footwear, floor, and surface conditions. The results supported the hypothesis that particle size of solids affected the friction coefficient and the effects depended on footwear, floor, and surface conditions. On dry surfaces, solid particles resulted in friction loss when the Neolite footwear pad was used. On the other hand, solid particles provided additional friction when measured with the ethylene vinyl acetate (EVA) footwear pad. On wet surfaces, introducing solid particles made the floors more slip-resistant and such effects depended on particle size. This study provides information for better understanding of the mechanism of slipping when solid contaminants are present.

slip & fall friction measurement solid contaminants Brungraber Mark II

1. INTRODUCTION

Slipping and falling are responsible for a great amount of injury expenditures in the workplace globally [1, 2, 3, 4, 5]. Slipping and falling are also major contributors to civilian casualties and injuries especially for older adults [6, 7, 8]. It is a common belief that the risk of slip and fall depends on floor slipperiness [9]. The coefficient of friction (COF) on the floor has been adopted as a major indicator of floor slipperiness [10, 11]. One of the most common methods of assessing slipperiness is to measure the COF between the shoe and floor surface [12]. A measured static COF of .50 has been adopted as a

safety guideline in the USA [13]. In Europe, various standards for assessing floor slipperiness have been established concerning the potential of slipping and falling. For example, Standard No. BS 7976:2002 recommends the use of a pendulum tester to assess floor slipperiness [14]. The slip potential of a floor is determined according to the reading (pendulum test value [PTV]) of the tester. The slip potential is low if $PTV = 36$ (or $COF = .37$) or more. Standard No. DIN 51130:2004 recommends the use of a ramp-type test to assess floor slipperiness [15]. Floor slipperiness is determined by ramp angle when the subject starts to slip. The COF values are obtained based on ramp angles.

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Correspondence should be sent to Kai Way Li, 707 Sec 2 WuFu Road, Hsin-Chu, Taiwan 300. E-mail: kai@chu.edu.tw.

Many factors affect the COF on the floor and floor contamination is probably one of the most commonly discussed issues in practice. Water contamination is not uncommon. It is a common belief that wet floors are more slippery than dry ones. This belief has been supported by both scientific theory and empirical studies. Moore's squeeze film theory is probably the most frequently mentioned scientific basis describing the effects of liquid on the friction on a floor [16]. Empirical evidence showing wet floors were more slippery than dry ones may be found in many friction measurement studies both in the laboratory [17, 18, 19] and in the field [11, 20, 21, 22].

According to Grönqvist and Roine [1] and Manning, Ayers, Jones, et al. [23], ~80% of slip and fall cases occurred where the floor or ground was soiled. This percentage was much higher than the 45% for liquid contaminated floors [23]. The Health and Safety Laboratory in the UK also observed significant risk of slipping to pedestrians due to the introduction of solid particulate contaminants [24]. However, there was only a limited amount of literature discussing the effects of solid contaminants on the friction at footwear–floor interface either theoretically or empirically.

Heshmat, Godet, and Berthier hypothesized that the friction mechanisms for dry particulates could include rolling, shearing, normal fracture, elasticity, and sliding [25]. Li, Hsu, Chang, et al. conducted friction measurements under dry, wet, and sand-covered conditions [26]. They found significant friction reductions (71% to 92%) when the floors were covered with sand particles as compared with those of dry floors, depending on the type of the footwear material and floor. They discussed the sliding and interlocking effects of solids on the friction between the footwear and floor and addressed the importance of the rigidity, strength, and geometric characteristics of solid particles. They concluded that the effects of sand particles on the COF were more prominent than water for most footwear material–floor conditions tested in their experiment.

Mills, Dwyer-Joyce, and Loo-Morrey conducted friction measurements on floors contaminated with solid particles with the British pendu-

lum tester [24]. They indicated that the sliding, shearing, and rolling mechanisms of solids were significant on the friction of a floor and floor roughness, particle size, and shape factor played a role in those mechanisms. As the particle size and the shape factor increase, a rolling or tumbling mechanism dominates. They concluded that introducing a small amount of a solid contaminant into the shoe–floor contact could result in a significant reduction in the friction. Particulate contaminants were found to have a comparable effect to fluid contaminants on smooth floors.

The COF at the footwear–floor interface has been shown to be highly dependent on the roughness of floor surface [12, 22, 27]. Grönqvist, Roine, Korhonen, et al. reported that the Pearson correlation coefficient between the dynamic friction for glycerol contaminated floors and arithmetic average of surface height (surface roughness, R_a) was .87 and suggested that an adequate R_a value for a proper slip resistance should be ~7–9 μm [28]. Floor roughness may also affect the COF on the floor when solid contaminants are present. Mills et al. found that surface roughness has a significant effect on the friction on a floor when covered with solid particles [24]. Their results showed that the effects of solid particles on the reduction in friction were more significant in smooth floors than in rough ones. In the smoothest tile they tested, the reduction in the COF was from over 1 to .25, while a COF reduction of .02 was observed for the roughest tile tested. They concluded that a rough surface coped much better than a smooth one in the presence of dry solid particles, with the COF being far more predictable.

Friction measurements under both wet [29, 30] and solid contaminated conditions [24, 26] were found in the literature. However, there is no report, so far, discussing the friction measurements with liquid and solid particles are present simultaneously on the floor even though such conditions are common in reality. This study was designed to investigate the effects of solid particle size on the measured COF under both dry and wet conditions. The main hypothesis of the study was that particle size of solids on the floor affects the COF and the effects depend on footwear,

floor, and surface. It discusses the effects of footwear, floor, and surface conditions on the friction on the floor with solid particles of different sizes.

2. METHODS

Friction measurements were conducted in the laboratory. The temperature and humidity during measurements were $\sim 22^{\circ}\text{C}$ and 76%, respectively.

2.1. Measurement Device

The Brungraber Mark II (BM II; Slip-Test, USA), also known as a portable inclinable articulated strut slip tester (PIAST), is a commonly used friction measurement device [11, 21, 22, 31]. On this slipmeter, there is an aluminum support on the lower end of the strut, which suspends a shoe holder for the attachment of a footwear pad. The footwear sample is $\sim 7.6 \times 7.6$ cm, 3.19–6.35 mm from the floor surface. A weight of 4.54 kg drives the inclined strut to impact the footwear pad upon striking on the floor for a possible slip movement. The starting COF for a measurement should be lower than the COF at which a slip is anticipated and the COF is increased until a slip occurs. A minimum COF of 0 may always be used as an initial value. The strut is perpendicular to the measured surface before it strikes the floor at this minimum initial value. The angle of the strut is increased until a slip occurs and the tangent of the angle is the COF marked on the tester. The difference between the readings of two adjacent markers on the tester is 0.01. The lower marker is assigned as the COF when the reading is between the markers. Operations of the BM II followed the recommendations in Standard No. ASTM F1677-05 [32].

2.2. Footwear and Floor Conditions

Two commonly used floors were selected in this study. They were smooth and rough ceramic tiles. The arithmetic averages of surface roughness (R_a) of these two tiles, measured with an SJ-301 profilometer (Mitutoyo America, USA), were 0.80 and 4.6 μm , respectively.

One Neolite and one ethylene vinyl acetate (EVA) footwear pad were adopted. Both footwear pads were flat without tread. The Shore-A hardness of these two footwear samples were 93 and 45, respectively. The density of the Neolite and EVA samples were 1.27 and 0.097 g/cm^3 , respectively. Before the measurements, all the footwear pads and floors were wiped with a 50% ethanol solution and were blown dry with a hair drier.

2.3. Surface Conditions

Friction measurements were conducted under two surface conditions: dry and wet. For the dry condition, dry clean floors were measured. For the wet condition, 10 ml of water were applied in the testing area to resemble actual wet floor surface conditions. The same amount of water was replenished throughout the repeated impacts during the measurement so that the thickness of water was controlled with surface tension [22].

2.4. Particle Sizes

For each footwear, floor, and surface condition, there were six solid contaminated conditions. The first one was the condition without solid (or with a size 0). For the other solid contaminated conditions, silica particles were tested in the friction measurements. Five sizes of particles were tested: 75, 120, 180, 270, and 500 μm . For measurements of each particle size, silica particles with a weight of 10 g were applied. Particles were positioned as evenly as possible on the testing area on the tile with a special comb. Li et al. [26] and Mills et al. [24] adopted a similar approach with applying solid particles. During the measurements for the dry conditions with particles, the operator did not replenish the particles during the repetitive strikes as in the wet measurements. It was likely that the distribution of the solid particles altered upon each footwear pad strike. However, it was believed that the surface condition did not change significantly between the repetitive strikes since most solid particles remained in the striking area after a strike.

For the wet conditions with particles, silica particles were prepared in the same way as for the dry conditions. For particles of 75 μm , a solution was prepared by mixing particles of 10 g into 10 ml of water. Before each test, the operator stirred the solution and poured it onto the test area. The operator replenished the same amount of the solution during repetitive strikes as in the wet measurements. For solids over 75 μm , solid particles of 10 g were evenly spread in the test area as in the dry surface with particles conditions. Then, 10 ml of water were applied on the particles to make a mixture of solids and water. The operator replenished the same amount of water during repetitive strikes as in the wet conditions but did not replenish solid particles as in the dry, solid contaminated conditions.

2.5. Experiment Design

The friction measurements were conducted with a four-factor (2 floor surfaces \times 2 footwear pads \times 2 surface conditions \times 6 particle sizes) experimental design with six replications. A total of 288 ($2 \times 2 \times 2 \times 6 \times 6$) measurements were conducted. Analysis of variance (ANOVA) of the COF was performed. Pair-wised t tests were conducted for comparison purposes. Data analyses were performed with SPSS 14.0.

3. RESULTS

The ANOVA results for all the data indicated that the main effects of all the four factors and their two-, three-, and four-way interactions were statistically significant ($p < .001$). Like Li et al. [26] and Manning and Jones [33] reported, footwear, floor, and surface conditions were all significant factors affecting the COF. More detailed analyses focused on particle size related effects.

Pair-wised t tests comparing the difference between the COF values measured on the smooth and rough floors under the surface, footwear, and particle size conditions were conducted. The COF values on both the smooth and rough surfaces measured with the EVA footwear pad under wet conditions without particles were all 0. For both the dry-Neolite-500-m and wet-EVA-75-m

conditions, the COF values on the smooth floor were significantly ($p < .05$ and $p < .001$, respectively) higher than those on the rough floor. For conditions other than these three, the COF values on the rough floor were significantly ($p < .001$) higher than those on the smooth floor.

Pair-wised t tests comparing the difference between the COF values measured with the Neolite and EVA footwear pads under the surface, floor, and particle size conditions were conducted. Table 1 shows the results. The difference between the COF values measured with the Neolite and EVA footwear pads for all surface, floor, and particle size conditions except three were statistically significant at $p < .001$. The exceptions were the 120- and 500-m conditions measured on smooth dry floor and the 0-m (or no-particle) condition measured on smooth wet floor. The difference between the Neolite and EVA pads was found to depend on particle size. For all the 0, 75, and 120 μm particle conditions except the dry-smooth-120- μm and the wet-smooth-0- μm conditions, the COF values measured with the Neolite footwear pad were significantly ($p < .001$) higher than those of the EVA. For all the 270 and 500 μm particle conditions, except the dry-smooth-500- μm particle condition, the COF values measured with the EVA footwear pad were significantly ($p < .001$) higher than those of the Neolite. The 180 μm seemed to be a “transitional” size for the two footwear pads. The COF values measured with the EVA pad were significantly ($p < .001$) higher than those of the Neolite when the 180 μm particles were on the dry surface. The COF values measured with the EVA pad were significantly ($p < .001$) lower than those of the Neolite when these particles were on the wet floor.

Both surface condition and particle size were significant ($p < .001$) factors affecting the COF. Figure 1 shows the averaged COF values for the dry and wet surfaces on the smooth floor measured with the Neolite footwear pad. Pair-wised t tests were conducted to compare the difference between the dry and wet surfaces. For particle sizes 0, 75, and 120 μm , the COF values on the dry surface were significantly ($p < .001$) higher than those on the wet surface. For particle sizes

TABLE 1. Coefficient of Friction (COF) Values Measured With Neolite and Ethylene Vinyl Acetate (EVA) Footwear Pads

Surface	Floor	Particle Size (µm)	Neolite	EVA		
Dry	smooth	0*	.548 (.015)	.170 (.013)		
		75*	.287 (.014)	.245 (.010)		
		120	.285 (.008)	.290 (.006)		
		180*	.213 (.005)	.280 (.000)		
		270*	.162 (.008)	.237 (.005)		
		500	.222 (.010)	.220 (.006)		
		0*	.752 (.008)	.232 (.004)		
	rough	75*	.477 (.015)	.345 (.005)		
		120*	.497 (.008)	.363 (.008)		
		180*	.302 (.010)	.442 (.008)		
		270*	.210 (.009)	.325 (.008)		
		500*	.208 (.008)	.315 (.005)		
		Wet	smooth	0	.000 (.000)	.000 (.000)
				75*	.077 (.005)	.023 (.005)
120*	.250 (.011)			.045 (.005)		
180*	.275 (.008)			.140 (.006)		
270*	.185 (.008)			.245 (.008)		
500*	.228 (.008)			.265 (.005)		
0*	.233 (.005)			.000 (.000)		
rough	75*		.250 (.009)	.005 (.005)		
	120*		.293 (.012)	.162 (.008)		
	180*		.288 (.010)	.180 (.009)		
	270*		.260 (.006)	.312 (.010)		
	500*		.298 (.010)	.323 (.008)		

Notes. * $p < .001$; values in parentheses are standard deviations.

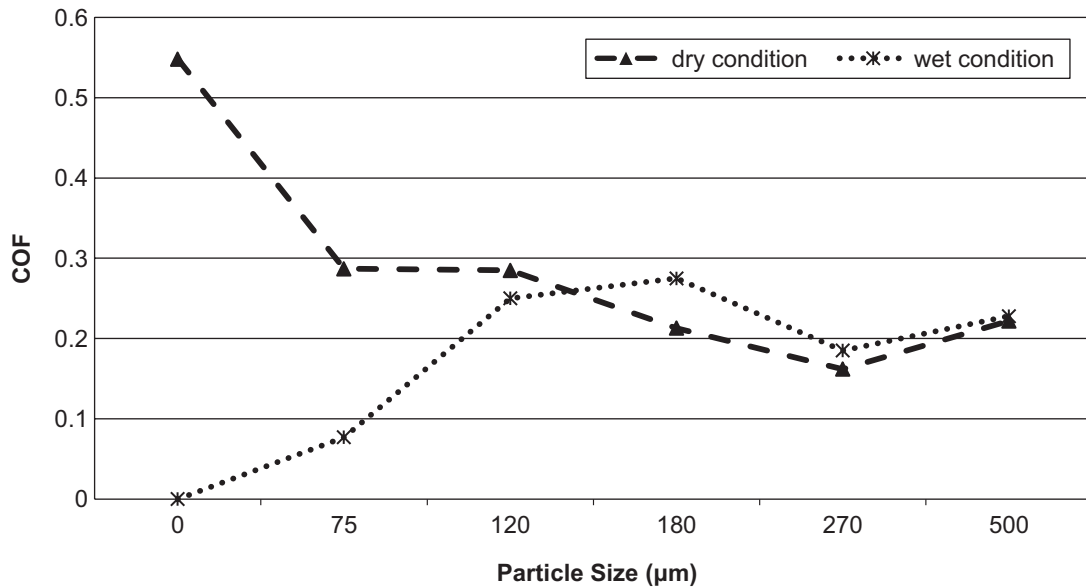


Figure 1. Coefficient of friction (COF) on smooth floor measured with Neolite footwear pad.

180 and 270 μm , the COF values on the dry surface were significantly ($p < .001$) lower than those on the wet surface. For the 500 μm particle conditions, the COF values on the dry and wet surfaces were not significantly different.

Figure 2 shows the averaged COF values on the dry and wet surfaces on the rough floor measured with the Neolite footwear pad. For particle sizes 0, 75, and 120 μm , the COF values on the dry surface were significantly ($p < .001$) higher than

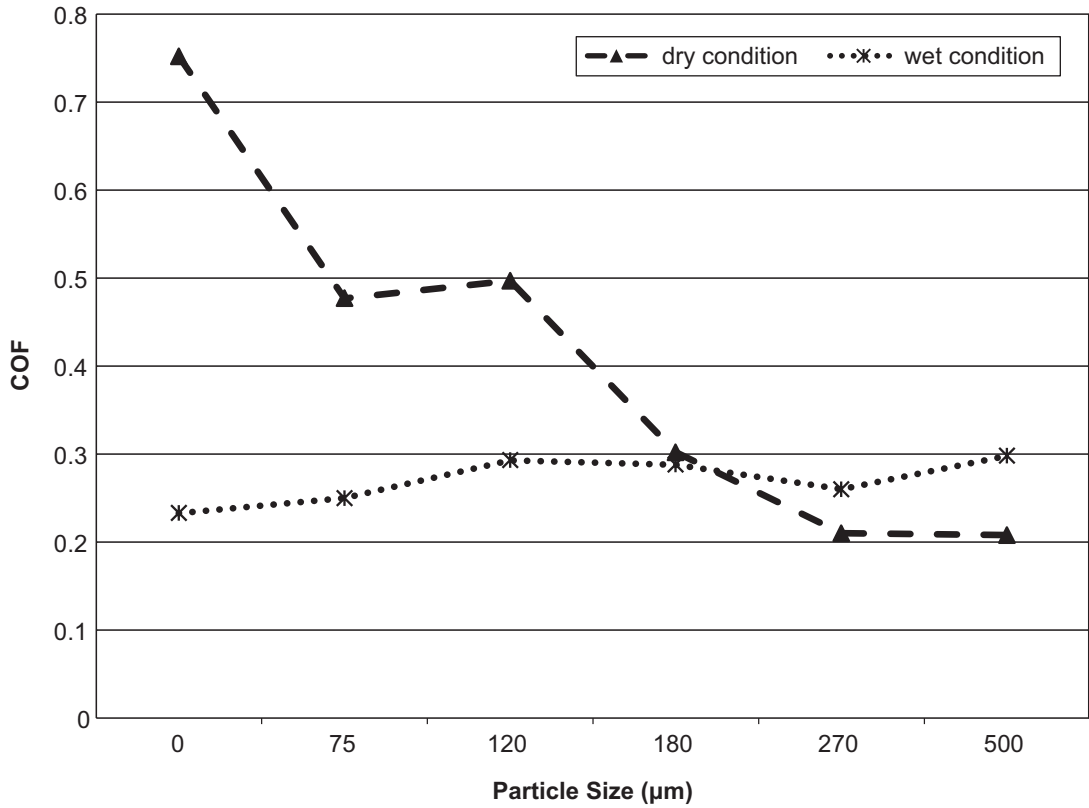


Figure 2. Coefficient of friction (COF) on rough floor measured with Neolite footwear pad.

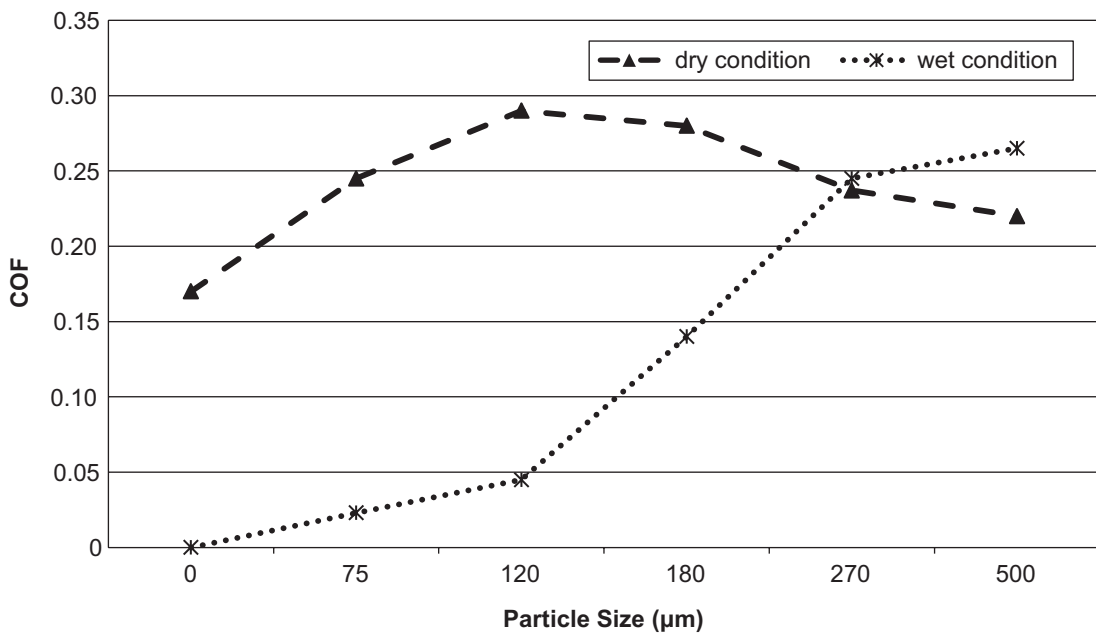


Figure 3. Coefficient of friction (COF) on smooth floor measured with ethylene vinyl acetate (EVA) footwear pad.

those on the wet surface. For the 180 μm particle condition, the COF on the dry surface was also significantly ($p < .05$) higher than that on the wet surface. For the 270 and 500 μm particle conditions, the wet surface had significantly ($p < .001$) higher COF values than the dry surface.

Figure 3 shows the averaged COF values on the dry and wet surfaces on the smooth floor measured with the EVA footwear pad. For particle sizes 0, 75, 120, and 180 μm, the COF values on the dry surface were significantly ($p < .001$) higher than those on the wet surface. For the 500 μm particle conditions, the wet surface had

significantly ($p < .001$) higher COF values than the dry surface. For the 270 μm particle conditions, the COF values on the dry and wet surfaces were not significantly different.

Figure 4 shows the averaged COF values on the dry and wet surfaces on the smooth floor measured with the EVA footwear pad. For particle sizes 0, 75, 120, 180, and 270 μm, the COF values on the dry surface were all significantly ($p < .001$) higher than those on the wet surface. For the 500 μm particle conditions, the COF values on the dry and wet surfaces were not significantly different.

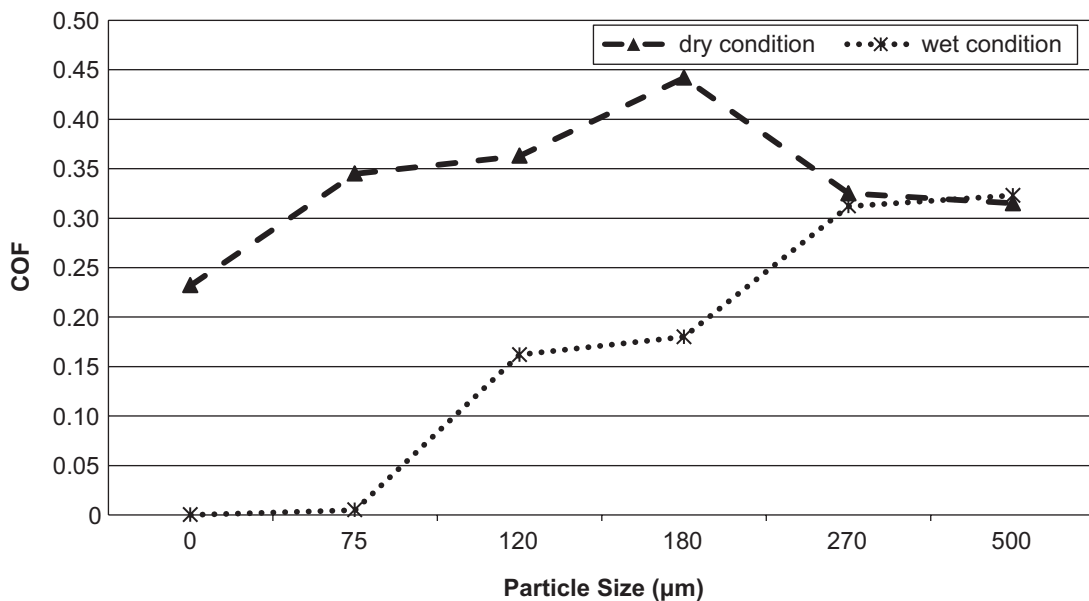


Figure 4. Coefficient of friction (COF) on rough floor measured with ethylene vinyl acetate (EVA) footwear pad.

4. DISCUSSION

Li, Chang, and Leamon [22] and Chang [34] discussed the effects of floor roughness under both dry and liquid contaminated conditions. The roughness on the floor surface also affects the friction on the floor when there are solid particles due to possible interlocking effects [24, 26]. The rough floor in the present study had significantly ($p < .001$) higher COF than the smooth floor under 21 (out of 24) footwear, surface, and particle size conditions. This was consistent with Mills et al. [24].

Friction measurements on wet floors were very common. The effects of water on the friction on a floor may be explained with the squeeze film the-

ory [16]. The effects of solid particles on the COF at the footwear–floor interface, on the other hand, are much more complicated than wet conditions. Liquids on the floor tend to decrease the surface friction, but solid particles on the floor may decrease or increase the friction on the floor, depending on factors such as characteristics of the particles, viscoelastic properties of the footwear, and roughness of the floor, etc.

Both adhesion and hysteresis contribute to the total friction between a sliding elastomer and a rigid surface. The adhesion component predominates and is due to a molecular-kinetic stick–slip phenomenon under most nonlubricant conditions. The adhesion term, however, assumes a very low

value on lubricated surfaces as the lubricant could interrupt or suppress the molecular bonding between the contacting surfaces [16]. When this happens, the hysteresis component becomes more important in providing friction. The Neolite pad is the standard test linen for friction measurements recommended by Standard No. ASTM F1677-05 [32]. It is an elastomer with high hardness. The EVA is a relatively soft elastomer and is a common shoe sole material. Without solid contaminants, the Neolite pad showed higher COF values than the EVA pad on the rough-dry, rough-wet, and smooth-dry surfaces. This was probably due to the better adhesion friction of the Neolite than the EVA. This persisted even when there were solid particles of 120 μm or less. The adhesion friction between the footwear pad and the floor diminished when there were large particles (180 μm or more on dry surface and 270 μm or more on wet surface) and the hysteresis became dominant. The hysteresis (or deformation) of the EVA was more prominent than the Neolite when impacting on large particles because of its softness and viscoelasticity. This was why the EVA pad had significant higher COF than the Neolite pad when there were particles of 270 μm or more.

The effects of particle size on friction were discussed in the literature. According to Mills et al., there is a critical diameter above which the particles behave in a more discrete fashion and are able to roll/tumble through the contact independently of other particles [24]. The critical diameter, or the cohesive limit, is $\sim 50\text{--}55$ μm . All the solid particles tested in the present study were larger than this limit indicating that the cohesive effects between particles might be neglected.

The effects of particle size on the COF depend on footwear and surface conditions. On the dry surfaces measured with the Neolite pad, the COF decreased when the particle size increased (see Figures 1–2). The particles on the floor acted as a lubricant which resisted the contact of the footwear pad and the floor and blocked the adhesion between the two surfaces. Large particles apparently had better lubricant effects than the small ones. The solid particles might slide, roll, or tumble on the floor upon impact of the footwear pad

with more or less interlocking on the floor. The friction associated with sliding, rolling, tumbling, and possible interlocking was probably lower than the loss of adhesion due to the blocking of the particles.

For the dry surfaces measured with the EVA pad (see Figures 3–4), however, all the COF values for conditions with particles were higher than those without particles. The particles, under this condition, acted not as a lubricant but a “resister” for the two contacting surfaces. The particles allowed early, indirect contact of the EVA pad on the floor and facilitated the joint effects of adhesion, deformation, and interlocking. Due to its softness, the EVA pad could touch the floor even though there were particles beneath. This could reduce the loss of adhesion because of the blocking of the particles. For the smooth and rough floors tested with the EVA pad, the highest COF values were observed for particle sizes of 120 and 180 μm , respectively. These sizes probably allowed the best, among the tested sizes, joint effects for adhesion, hysteresis, and interlocking friction.

On wet surfaces, all the COF values for the conditions with particles measured with the Neolite footwear pad were significantly ($p < .001$) higher than those without solid particles. These also existed when the EVA pad was used. An exception was on the rough surface where the COF of the 75 μm particle condition was the same as that without particles. In Figures 1–4, there seems to be a trend that the difference between COF values of the dry and wet surfaces converged with increasing particle size. This phenomenon supports the hypothesis that the effects of water on friction faded when there were particles large enough to eliminate the need to squeeze the film. The squeeze film theory was no longer applicable when this happened.

When both water and solid particles were on the floor, the viscosity of water might resist the movements of solid particles, either sliding, rolling, or tumbling. The resistance might become stronger when the particle size increased. The capillarity of water between the particles might also contribute to resist particle movement which might reduce the loss of friction at the

footwear–floor interface. Further studies are required to investigate such a phenomenon.

Mills et al. showed that both the size and shape of solids affected the friction between the footwear and floor [24]. As only one type of solid was tested, the shape factor was not considered in the present study. The silica particles tested in this study may represent solids of irregular shape. The friction on floors with solids of different shape and with liquids should be investigated in the future for a better understanding of the mechanism of friction related to pedestrian safety. In addition, according to Mills et al., solid particles under 50–55 μm may not move discretely due to strong cohesiveness [24]. This cohesiveness may become even stronger when water is present. The mixture of water and such small particles (or powder) could generate pasta- or mud-like contaminants. The friction pattern may be quite different in the presence of this type of contaminant. This may also be a topic of future research.

5. CONCLUSION

Slipping and falling are common. The risk of slipping and falling depends on floor slipperiness, or alternatively the COF, at the footwear–floor interface. A friction measurement experiment was conducted to test the effects of particle size of solids on the COF on the floor under two footwear pads, two floors, and two surface conditions. The results showed that the particle size, footwear, floor, and surface conditions and all their interactions affected the COF significantly ($p < .001$). Our data supported the main hypothesis of the study that particle size of solids on the floor affected the COF and the effects depended on footwear, floor, and surface conditions. On dry surfaces, solid particles played a role of a lubricant, which resulted in loss of friction when the Neolite footwear pad was used. The solid particles, on the other hand, provided additional friction when the EVA footwear pad was used. On wet surfaces, the floors were more slip-resistant, for both footwear pads, when there were solid particles.

Clean floors, without either solid particles or liquids, are always recommended for good house-

keeping. However, solid particles and/or liquids are sometimes inevitably present on the floor at certain workplaces. The implication of this study is that soft shoe sole materials are more desirable than hard ones when the floor is dry and covered with solid particles as the former are associated with a lower risk of slipping. On wet surfaces, solid particles diminish the squeeze film effects between the footwear pad and the floor and the hardness of the footwear pad has lesser impact on the COF.

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