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Relationship between Friction Coefficient and Surface Roughness of Stone and Ceramic Floors

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Abstract: Slips and falls are common occupational incidents worldwide. The friction on a floor surface is one of the critical environmental factors affecting the risk of a slip. In this research, we conducted friction measurements on stone and ceramic floor tiles under dry, wet, and water–detergent (WD) solution covered conditions using a horizontal pull slip meter (HPS). Our purposes were to quantify the slip resistance of commonly used stone and ceramic floors under different surface conditions and to validate the curvilinear relationship between the coefficient of friction (COF) and surface roughness of the floors proposed in the literature. The COF data were analyzed together with a surface profile parameter (R_a) of the floor samples. The results showed that the COFs of the stone floors were significantly ($p < 0.0001$) higher than those of the ceramic floors. All the floors under the dry conditions were slip resistant when adopting the ANSI 1264.2 criterion. Two and five ceramic floors were not slip resistant under the wet and WD solution covered conditions, respectively. Three polynomial regression equations were established to describe the relationship between the COF and R_a. The curvilinear functions of these models indicate that the three-zone (initial growth, steady-growth, and plateau) concept concerning the COF–R_a relationship in the literature was valid when static COF values measured using an HPS were adopted. In addition, the three-zone concept was valid not only on WD solution covered surfaces but also on dry and wet surfaces.

Keywords: slip; trip and fall; coefficient of friction; horizontal pull slipmeter; floor roughness

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1. Introduction

Slips and falls create significant safety and health problems for workers worldwide [1,2]. The official statistics in Taiwan indicate that there were 2,608 falls on the same level and 566 falls from height at the workplace in 2018, which accounted for 23% and 5% of all occupational incidents, respectively [3]. The national statistics in Singapore indicate that slips, trips, and falls have accounted for 34.3% and 28.2% of all major and minor injuries at the workplace, respectively [4]. The injuries statistics in Hong Kong indicated that same level falls have accounted for 29.6% of all injuries at workplaces [5]. Similar statistics may be found in other countries [6,7]. These statistics highlight the significance of slip and fall issues in the safety and health of workers and the need for efforts in understanding the mechanism and control of slips and falls.

A slip has been identified as the primary precedent event of a fall. Courtney et al. [8] indicated that slip contributed to 40% to 50% of all fall-related injuries in the USA. It is commonly accepted that people are more likely to slip when walking on slippery floor surfaces. Friction has been adopted as one of the measures of floor slipperiness [9]. Slip occurs because friction between the footwear and floor is inadequate to resist the movement of the shoe sole on the floor, especially at the moment of the heel landing on the floor. The friction between the footwear and floor may be quantified using the available coefficient of friction (COF) [10]. The friction required to resist the movement of the shoe sole on the floor, on the other hand, may be quantified using the required COF [11].

Measurements of both the required and available COF are complicated. The former requires the recruitment of human participants and the use of one or more force platforms so as to analyze the ground reaction force of the foot on the floor [12,13]. The latter, on the other hand, requires the use of a friction measurement device, also called a tribometer or a slipmeter, to measure the COF of the floor under certain footwear and floor conditions [9,14]. The required friction depends on the gait pattern of a walker and is dependent on human factors [11,15,16]. The available COF is influenced not only by the characteristics of the footwear and floor but also by the friction measurement device adopted [9,17,18].

Measurements of the available COF have been reported both in the field and in the laboratory. Field measurements were normally conducted to assess the risk of slip and fall in certain workplaces, such as restaurants and other jobs in public places [19–21]. Such assessments might be performed to compare the friction measurement results with the perceived floor slipperiness of human participants [22]. The friction measurements conducted in the laboratory were normally performed to explore the mechanisms of slipping of the shoe sole on the floor. Studies testing the effects of the floor, footwear, floor inclined angle, and floor surface contaminations on slipperiness have been reported [14,18,23–32]. There were also studies comparing the testing parameters, test methods, reliability, and validity of friction measurement devices [13,17,32–35].

There is a general awareness that rough floors are more slip resistant than the smooth ones. Floor roughness was found to be positively correlated with the COF of the floor [26,35,36]. The surface profile characteristics of the floor predominantly contribute to the friction at the footwear–floor interface in two aspects. The first one is that asperities on the floor surface could interlock with the tread on the shoe sole and, hence, impede the shoe sole from sliding on the floor. The second one is that floor roughness provides void space for drainage when the floor is covered by liquid, which allows faster contact of the shoe sole and the floor [26,36].

Many surface roughness parameters have been defined to depict the surface profiles of a floor surface. The correlations between more than 20 of these parameters and the slip resistance of floors have been discussed [37]. The parameter R_a, also known as the center line average of surface heights (CLA), is one of the most commonly used roughness parameters in discussing friction on the floor [38]. Li et al. [38] measured the R_a and subjective rating of floor slipperiness on their floor samples. They found these two measures were highly correlated ($\rho = 0.79$, $p < 0.0001$) with each other. They concluded that R_a may be adopted as one of the predictors of the perceived floor slipperiness of human participants. Grönqvist et al. [39] measured the dynamic COF of floor samples with varying floor roughness. The COF and R_a of their floor samples were highly correlated ($r = 0.87$, $p < 0.001$) with each other. They recommended R_a values of 7–9 μm and 16–22 μm for adequate (dynamic COF = 0.2) and very slip resistant (dynamic COF = 0.3) floors, respectively, on glycerol contaminated surfaces. Kim et al. [26] claimed that an R_a higher than 17 μm might be sufficient for proper slip resistance (dynamic COF = 0.4) on soapsuds contaminated floors. Chen et al. [36] reported that, when the floor was contaminated by viscous (38 mPa·s or higher) liquid, the frictions on all the floors they tested were extremely low (almost zero). When the viscosity of the liquid on the floor was low (2 mPa·s or less), the floor may still be slip resistant (static COF = 0.5) if the R_a of the floor surface was 40 μm or higher. The COF values in the above-mentioned studies were measured using different devices and protocols. The recommended floor roughness levels in those studies are, therefore, not comparable.

Kim et al. [26] introduced a concept of surface roughness zones in the mechanism of friction at the footwear–floor interface. They demonstrated that the slip resistance increases slowly with the increase of floor roughness when the surface roughness is low. In this "initial low-grow zone", multiple friction mechanisms are involved between the shoe sole and floor while interlocking effects are not present. In the "steady-growth zone," the interlocking of the floor asperities with the shoe sole dominating the friction and linear relationship between the floor roughness and COF is likely. In the "plateau zone," the interlocking mechanisms become exhausted and increasing the floor roughness made no further benefits in increasing the COF of the floor. Based on a dynamic COF of 0.4, they recommended using R_a values of 17 and 50 μm as the lower and upper bounds of the steady-growth zone. They indicated that finding the floor roughness range in such a zone is critical in establishing a slip resistant floor environment. The study of Kim et al. [26] was performed using a pendulum-type friction tester, and they used a dynamic COF of 0.4 as a criterion of slip resistance. It is well known that the theoretical bases of using static and dynamic friction in assessing the risk of slip and fall are different. It has also been shown that the COF readings on a floor sample may be dependent on the friction measurement device [9]. Whether the concept of surface roughness zones will be valid or not is not clear when using both a different friction measurements device and a static COF in the criterion of slip resistance.

The main objective of the current study was to validate the three-zone concept of Kim et al. [26] using a different friction measurement device and criterion of slip resistance. Establishing regression models to predict the COF on the tested floors using their R_a values was also one of the objectives of this study. These models provide quantitative evidence to show the relationship between the COF and R_a. In addition, both stone and ceramic floorings are commonly used both indoors and outdoors. Friction measurements for these floors are essential to quantify the risk of slipping on these floors. Our third objective was to quantify the slip resistance of the commonly used stone and ceramic floors under different surface conditions.

2. Method

A friction measurement experiment was performed in the laboratory.

2.1. Friction Measurement Device

A horizontal pull slip meter (HPS, S.C.S Forces, Agawam, MA, USA) was used (see Figure 1). This slip meter encompasses a power unit and a weight unit. There are three circular footwear pads (Neolite, Akron, OH, USA, Ø12.7 mm) on the bottom of the weight unit. The Neolite footwear pads had an averaged specific gravity of 1.27 ± 0.02 and a Shore A hardness of 94. The total contact area of the footwear pad on the floor is approximately 3.8 cm^2. The contact pressure between the footwear pads and floor surface is approximately 70.2 kPa. There is a motor inside the box of the power unit. This motor rotates to generate a horizontal pull force to drag the weight unit (2700 ± 34 g). The reading on the meter at the moment when the weight unit starts to move is the slip index [40]. This slip index is ten times the static COF at the footwear–floor interface. The rationale of the HPS is to determine the coefficient of friction by dividing the horizontal pull force by the gravity of the weight unit. This is similar to that of the sliding friction tester in the literature [41].

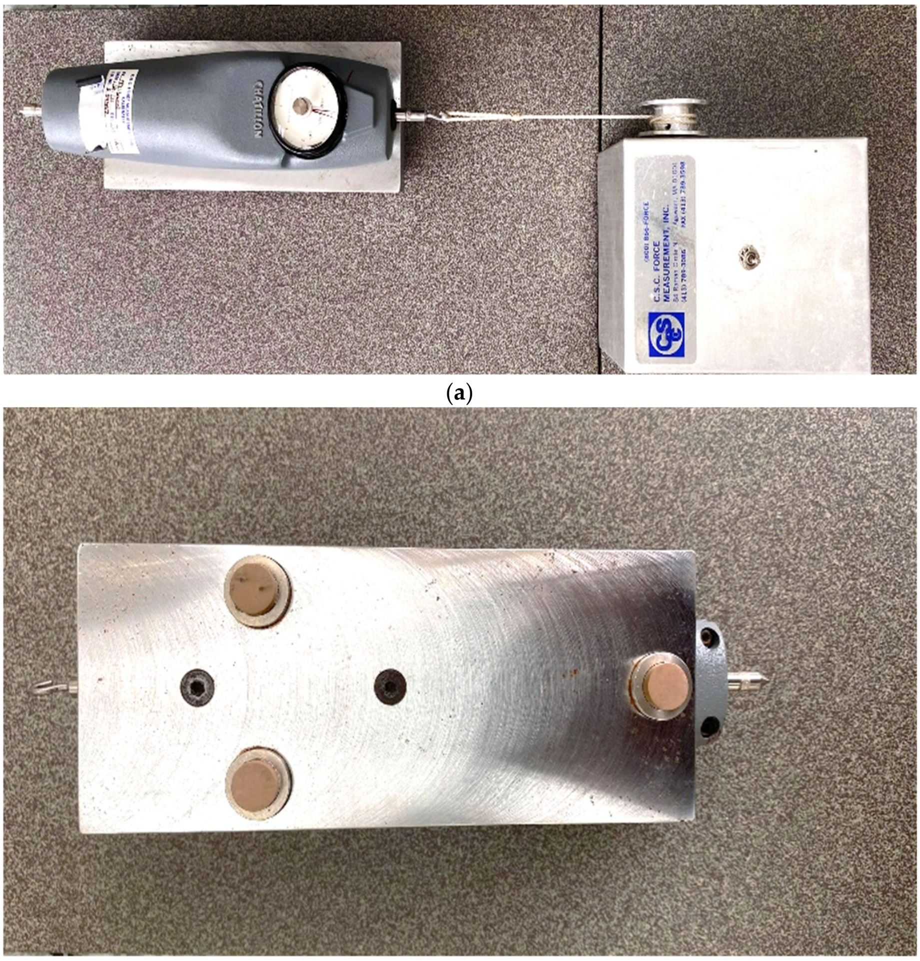
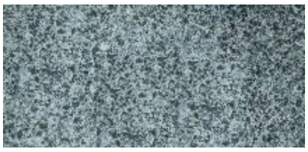
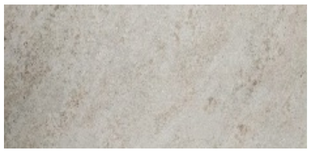


Figure 1. Horizontal pull slip meter: (a) power and weight units, (b) footwear sample on the bottom of the weight unit.

2.2. Floor Tiles

Twelve floor tiles were tested, including six ceramic and six stone floors. These floors are commonly used both indoors and outdoors. Table 1 shows these floors. The stone floors included four sandstones (S1, S2, S4, and S6) and two unpolished granites (S3 and S5). The R_a values of all the floor samples were measured using a Mitutoyo S301 profilometer [42] (Mitutoyo Inc., Sakado, Japan). This device uses a detector stylus tracing the surface of the floor sample. The direction of the stylus movement was parallel to that of friction measurement. The lengths of cut-off and measurement were 2.5 and 12.5 mm, respectively [38]. The R_a was determined based on the movements of the stylus. The literature has shown that friction correlates well with bandpass filtered profile parameters [43]. The Gaussian filter was adopted in processing the stylus tracing data [42]. On each floor, nine R_a readings were collected, each from one location. The average of these readings was used. The R_a of the ceramic and stone floors ranged from 8.9 to 30.4 μm and from 29.0 to 65.1 μm, respectively.

Table 1. Floor samples.

Code	Stone Floor	R_a (μm)	Code	Ceramic Tile	R_a (μm)
S1		31.5	C1		8.9
S2		29.0	C2		18.9
S3		56.8	C3		20.3
S4		38.4	C4		27.2
S5		33.6	C5		27.5
S6		65.1	C6		30.4

2.3. Surface Conditions

The surface conditions included dry, wet, and water–detergent (WD) covered conditions. For dry condition, dry and clean surface of the floor sample was measured. For wet measurements, all the stone floors were immersed in a container full of tap water for 24 h so that the floors were fully moisturized before measurement. For measurements of water–detergent (WD) solution covered condition, all the stone floors were immersed in WD solution also for 24 h before testing. This solution included 30 mL dishwashing detergent (purchased from a local market) mixed with 2 L tap water. For the friction measurement of each of the two liquid contaminated conditions, we poured a small cup (10 mL) of liquid on each of the three footwear pad contact points of the HPS on the floor sample.

2.4. Measurement Procedure

All the friction measurements were performed by the same operator. Prior to measurement, the operator wiped the floor samples with a 3% ammonium hydroxide (NH_4OH) solution and dried them with a clean cloth. The floor sample was sanded using a No. 60 grit abrasive paper. After this, the sample was sanded again using a No. 400 abrasive paper. The operator then brushed the surface to remove loose particles. This procedure followed those in the ASTM [40].

On each floor sample, four locations were selected for friction measurements. These locations were evenly distributed on the floor samples. In other words, each of them was at a distance approximately one quarter of the way to the two adjacent sides of the floor sample. On each location, 6 measurements were performed. On each measurement, the units of the power and weight of the HPS were on the same level. The operator aligned the pulley on the power unit with the hook on the weight unit and then connected the string of the power unit to the hook on the weight unit. The string was parallel with the test surface and was in line with the pulley on the power unit. The operator pushed down the power unit to prevent its moving and then pressed the switch. When the weight unit started to move, the switch was turned off. The reading on the meter was the slip index. The COF was the slip index divided by 10.

2.5. Statistical Analysis

The order of friction measurements on each floor sample was randomized among the three surface conditions. There were a total of 864 COF readings (12 floors $\times$ 3 surface conditions $\times$ 4 locations $\times$ 6 repetitions). The normality of these data were ensured by checking the normal probability plot. Descriptive statistics and analysis of variance (ANOVA) were performed for the measured COF values. Duncan's multiple range tests were performed to compare the differences between any two treatments in a factor if the main effects of the factor reached the $\alpha = 0.05$ significance level. This test is powerful and is very effective at detecting differences between means when real differences do exist [44]. Regression analyses were performed to establish regression models showing the relationship between the COF and R_a using the readings of three out of the six repetitions on the same location of each floor and surface condition. In other words, half of the data were used in establishing the regression models. A mean absolute deviation (MAD) (see Equation (1)) was calculated to determine the prediction errors of the COF values for each of the floor, surface condition, and location. The measured COF values in Equation (1) were the COF readings not used in establishing the regression models. The statistical analyses were performed using the SPSS version 20 software (IBM®, Armonk, NY, USA).

$$\mathrm{MAD} = \frac{1}{\mathrm{n}} \left|\text{predicted COF} - \text{measured COF}\right| \tag{1}$$

where n is the number of pairs of predicted and measured COF values used.

3. Results

3.1. ANOVA Results

Figure 2 shows the means and standard deviations of the COF of all the floor samples. The ANOVA results indicated that both the floor material and the surface condition significantly ($p < 0.0001$) affected the COF. The Duncan's multiple range test results showed that the COF of the stone floors (0.71 ± 0.09) was significantly higher than that of the ceramic floors (0.53 ± 0.12). The COF on the dry surface (0.69 ± 0.11) was significantly ($p < 0.05$) higher than those of the wet (0.61 ± 0.13) and WD solution covered surfaces (0.55 ± 0.15). Duncan's multiple range tests were also performed separately to compare the COFs of the three surface conditions for each of the stone and ceramic floors. For the stone floors, the COF on the dry surface (0.74 ± 0.08) was significantly ($p < 0.05$) higher than those of the wet (0.71 ± 0.07) and WD solution covered (0.67 ± 0.09) conditions. The COF of the wet condition was significantly ($p < 0.05$) higher than that of the WD solution covered condition. For the ceramic floors, the COF on the dry surface (0.63 ± 0.09) was significantly ($p < 0.05$) higher than those of the wet (0.52 ± 0.09) and WD solution covered (0.44 ± 0.09) conditions. The COF of the wet condition was also significantly ($p < 0.05$) higher than that of the WD solution covered condition.

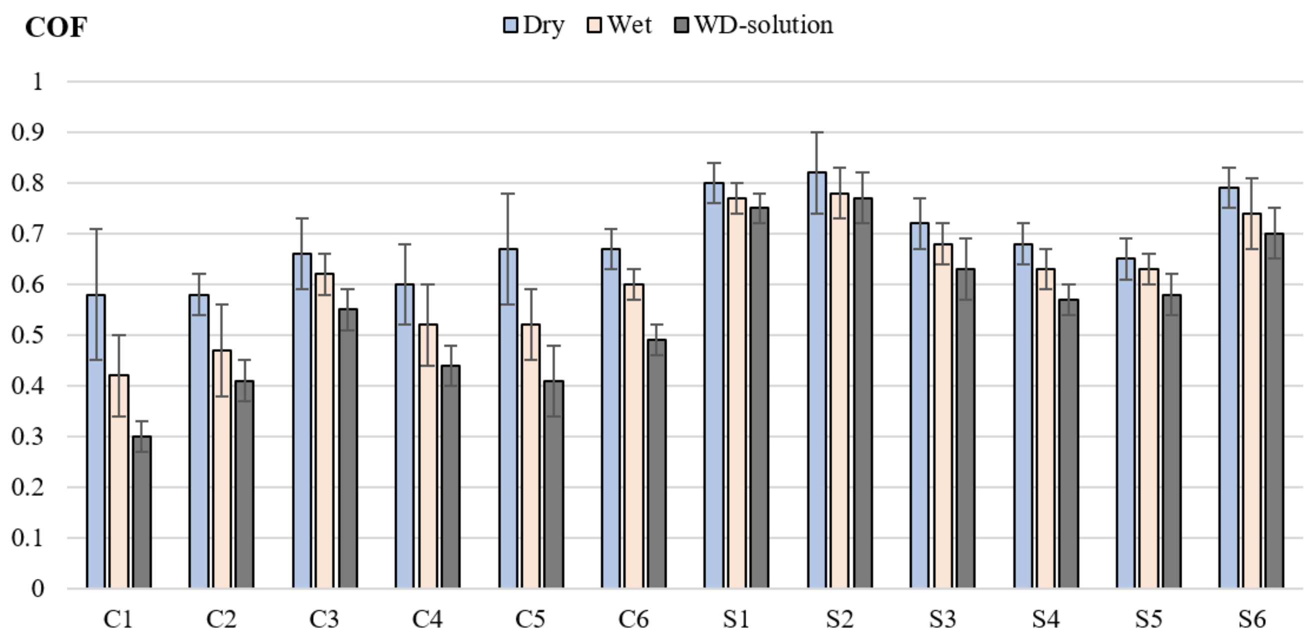


Figure 2. COF values of the floor samples.

Duncan's multiple range tests were also performed separately for the wet and WD solution covered conditions to compare the COF values between any two floor samples. The results are shown in Table 2.

Table 2. Duncan's multiple range test results for floors under wet and WD solution covered conditions.

Floor	R_a (μm)	Wet Mean COF	Grouping *	WD Solution Mean COF	Grouping *
S2	29.0	0.78	A	0.77	A
S1	31.5	0.77	AB	0.76	A
S6	65.1	0.74	B	0.70	B
S5	33.6	0.68	C	0.63	C
S3	56.8	0.63	D	0.58	D
S4	38.4	0.63	D	0.57	D
C3	20.3	0.62	D	0.55	D
C6	30.4	0.60	D	0.49	E
C4	27.2	0.52	E	0.45	F
C5	27.5	0.52	E	0.41	G
C2	18.9	0.47	F	0.40	G
C1	8.9	0.42	G	0.30	H

* Duncan grouping; different letters indicate they are significantly different ($p < 0.05$).

3.2. Correlation Analyses & Regression Modeling

The Pearson's correlation coefficients between R_a and COF under dry, wet, and WD solution covered conditions were 0.63, 0.62, and 0.66, and all of them were statistically significant ($p < 0.0001$).

To establish the relationship between the COF and R_a under a surface condition, a regression analysis was performed using the COF as the dependent variable and the floor roughness parameter R_a and surface condition as the independent variables. It was assumed that the measured COF is a function of R_a under surface conditions, or alternatively:

$$\text{COF} = f(R_a/\text{surface condition}) \tag{2}$$

Initially, a simple linear regression model was fitted to predict the COF using R_a. However, it was found that the curvilinear model may be more appropriate. A polynomial regression model was then fitted (see Equation (3)):

$$COF = ß_0 + ß_1 R_a + ß_2 R_a^2 + ß_3 R_a^3 \tag{3}$$

where $ß_i$ is the regression coefficient, i = 0, 1, 2, 3. The unit of R_a is μm.

The results of the regression analysis are shown in Table 3. The t-test results of the regression coefficients showed that all the regression coefficients were statistically significant at $p < 0.0001$.

Table 3. Results of regression modeling.

Surface	$ß_0$	$ß_1$	$ß_2$	$ß_3$	R^2	$\sqrt{MSE}$
dry	0.508	-4.1×10^{-3}	5×10^{-4}	-6×10^{-6}	0.96	0.022
wet	0.393	-2.5×10^{-3}	5×10^{-4}	-6×10^{-6}	0.94	0.033
WD solution	0.297	-4.4×10^{-3}	6×10^{-4}	-7×10^{-6}	0.93	0.044

The polynomial regression models and measured COF values of the dry, wet, and WD solution covered conditions are shown in Figure 3. The measured COF values are the means of the three readings not used in establishing the regression models. The MADs for the dry, wet, and WD solution covered surfaces were 0.014, 0.021, and 0.025, respectively.

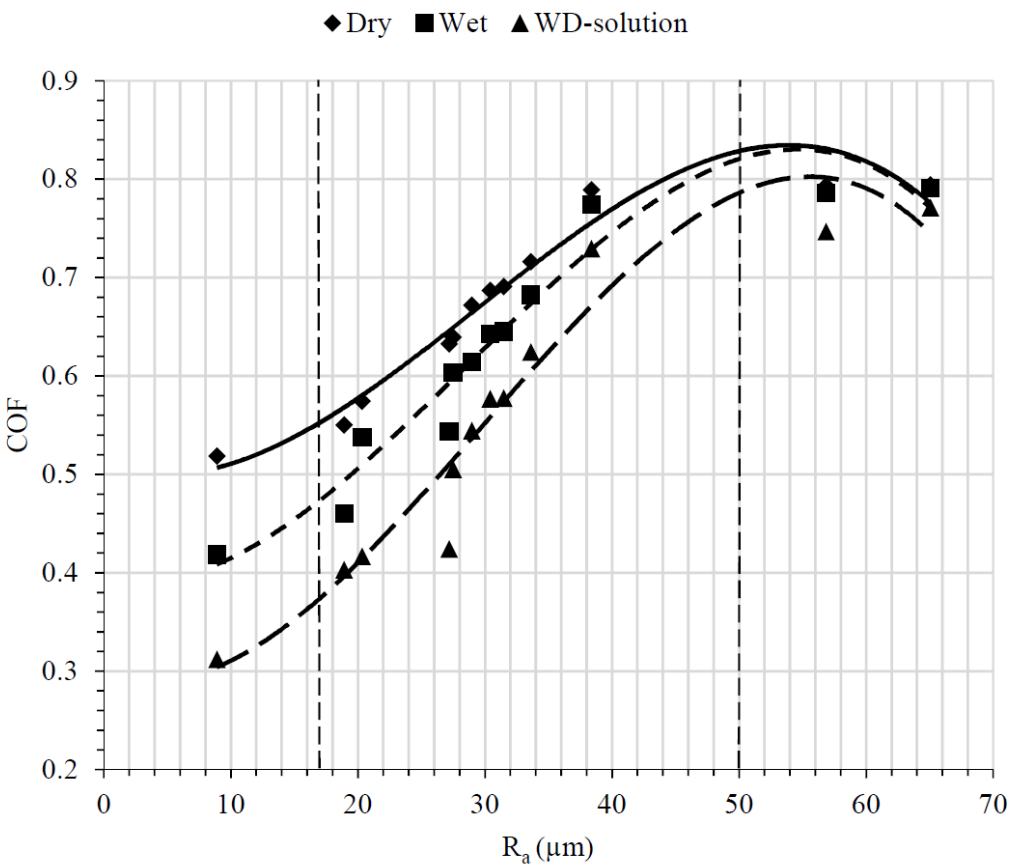


Figure 3. Regression model and measured COF (dot): the curves from top to bottom are for dry, wet, and WD solution covered conditions. The dotted lines indicate the boundaries of the three zones recommended by Kim et al. [26].

The polynomial regression models in Figure 3 support the zones of initial low growth, steady-growth, and plateau concept of Kim et al. [26].

4. Discussion

Friction measurement is one of the major approaches to assess the risk of slip and fall. The result of such a measurement is the available COF. Numerous friction measurement devices have been developed. However, none of them have been accepted universally as a perfect one. All of them have pros and cons. Different friction measurement devices may report different readings. The readings on different devices may, therefore, not be directly comparable. The HPS is one of the friction measurement devices recommended by the ASTM [40] to measure the COF of floor samples. It is not sensitive to operator variability and is easy to use [9,45,46]. These were the reasons why we adopted this device. Due to its drag mechanism design, the HPS is proposed to be used primarily for dry measurement. However, the significance of the surface conditions on the COF in the current study indicates that this device is capable of differentiating the slip resistances among the dry, wet, and WD solution covered surfaces.

Different slip resistance criteria considering pedestrian safety have been used in different countries. Some of the slip resistance criteria pertain to a certain type of friction measurement methodology or device. For example, the Australian and New Zealand Standard [47] adopted a dynamic COF of 0.4 based on a pendulum tester. The Health and Safety Executive of the UK [48] recommended values of slip potential, instead of slip resistance, based on the pendulum test value (PTV). The slip potential is low for a PTV of 36 or higher. Static COF has been adopted to assess the slip resistance more often in the USA than in many other countries. A static COF of 0.5 was adopted as a safety criterion for pedestrian walkways by both the American National Standards Institute (ANSI) [49] and the U.S. Occupational Safety and Health Administration (OSHA) [50]. The Americans with Disabilities Act (ADA) requires the static COF being 0.6 and 0.8 or above for level surfaces and ramps, respectively [51].

Stone floors are widely used in public spaces. Unless they have been ground and polishing processed, stone floors normally have a rough surface and are believed to have proper slip resistance for walking. The COF of these floors was significantly ($p < 0.0001$) higher than that of the ceramic floors. Such results were not surprising and were consistent with the findings in the literature [52]. All the floor samples we tested under the dry condition met the requirement of ANSI [49]. Even on wet surfaces, all the stone floors and four of the ceramic floors had mean COF values higher than 0.5. On the WD solution contaminated conditions, all the ceramic floors except C3 had mean COF values lower than 0.5. This implies that most (five of six) of the ceramic floors we tested are risky under the WD solution contaminated condition.

In tribology, the transmission of friction, as a function of normal load, along a sliding surface depends, at least partially, on the topography of the surface [49,53,54]. The R_a values of the floor samples were adopted in this study to represent the surface profiles of these samples because this parameter is the one that has been used most commonly in slip and fall research [26,37,38]. The estimates of the regression coefficients and corresponding statistics in Table 3 demonstrate the significance of R_a on the COF under the three surface conditions tested. The polynomial regression models of the COF indicate that R_a affected COF in a nonlinear fashion. There are discrepancies between our study and that of Kim et al. [26] in developing the regression models. The first one is that our COFs were static while the COFs in theirs were dynamic. Secondly, we tested only the Neolite footwear sample while they tested one PVC and two Nitrile Rubber soles from three commercially available shoes. Finally, our models considered the dry, wet, and WD solution covered conditions while the cubic function in theirs considered only their soapsuds covered condition. Even with these discrepancies, the curvilinear relationship between the COF and R_a in our models still supports the three-zone concept of Kim et al. [26].

In Figure 3, all three curves reach their peaks at an R_a of approximately 54–55 μm for the three surface conditions. These peaks imply that a further increase of the surface roughness (R_a) provided no extra help in improving the slip resistance (COF). The beginning of the plateau, or, alternatively, the upper bound of the steady-growth zone, should be somewhere before the R_a has reached those peak values. This implies that the upper bound of the steady-growth zone proposed by Kim et al. [26] (R_a = 50 µm) was supported.

In the zone of steady growth, the COF increases almost linearly with R_a. A COF of 0.5 [48] of the safety criterion was adopted to determine the lower bound of the steady-growth zone. R_a values of 19 and 27 µm were obtained for the wet and WD solution covered conditions, respectively. Table 4 summarizes the R_a values of the current study and those in the literature. Our R_a values are slightly higher than that recommended by Kim et al. [26] but are lower than that of Chen et al. [36].

Table 4. Comparison of the lower bound R_a values in different studies.

Study	Friction Measurement Device	Surface Covered by	Safety Criterion	R_a (µm)
Gronqvist et al. (1990)	dynamic step simulator	glycerol glycerol	DCOF = 0.2 DCOF = 0.3	7–9 16–22
Kim et al. (2013)	pendulum-type hydraulic dynamic friction tester	soapsuds	DCOF = 0.4	17
Chen et al. (2015)	Brungraber Mark II	water, soda Liquids: 2 mPa·s < Viscosity < 38 mPa·s	SCOF = 0.5 SCOF = 0.5	28 40
Current study	HPS	Water WD solution	SCOF = 0.5 SCOF = 0.5	19 27

The positive correlation between the R_a and the COF values in our study was consistent with the findings in Chang et al. [9] but was only partially consistent with those in Kim et al. [26]. The Pearson's correlation coefficients between the R_a and the COF for the dry, wet, and WD solution conditions in the current study were approximately the same (0.62–0.66, $p < 0.0001$). This was inconsistent with the results in Kim et al. [26] where they found R_a was significantly correlated with their dynamic COF on soapsuds covered surfaces, but the correlation was insignificant on their dry surfaces. A possible reason for this inconsistency may be that the static COF in our experiment is less sensitive to the variations on the surface profile represented by R_a. The inconsistency could also be attributed to the different footwear and floor samples in the two studies.

A limitation of this study was that only one footwear material (Neolite) was tested. This material has been adopted in many friction measurement studies because of its homogeneity and reliability in physical characteristics [18,19,24,36]. Our results could be different if other footwear materials were used. Another limitation was that most of the floor samples we tested were rougher than the common floors found indoors. Almost all the floor samples (eleven of twelve) had an R_a higher than 9 µm. Our results may, therefore, not be applicable to floors with an Ra less than this level.

5. Conclusions

A friction measurement study was performed on six stone and six ceramic floor samples under dry, wet, and WD solution covered conditions. The COF values of the stone floors were significantly higher than those of the ceramic floors. All the stone floors under all the surface conditions tested had mean COF values higher than 0.5, a safety criterion recommended by the ANSI [49]. Two and five ceramic floors tested under the wet and WD solution covered conditions, respectively, had mean COFs lower than 0.5. Three polynomial regression equations between the COF and R_a were developed. These equations confirmed that the three-zone concept proposed by Kim et al. [26] is valid when static COF values measured using an HPS were adopted. In addition, the concept is valid not only on the WD solution (soapsuds) covered surface but also on dry and wet surfaces. The upper bound R_a values in the steady-growth zone in the current study were equivalent to those in the literature [26]. The lower bound R_a values under our wet and WD solution covered conditions were slightly higher than that proposed in the literature. The findings of the current study can provide insightful implications for the prevention of floor slipperiness and can thus help in reducing slip and fall incidences. Future research may be considered to test commonly used footwear materials not tested in our study, such as blown rubber and ethylene vinyl acetate, to validate the applicability of the three-zone concept on those materials.

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