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The effect of surface roughness on the measurement of slip resistance

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Abstract

Friction coefficient is widely used to measure slipperiness. It is also known that surface roughness affects friction. Surface roughness on quarry tiles was systematically varied by sand blasting. The relationship among slip resistance, tile surface roughness, surface conditions and slipmeters used was investigated. The results indicated that the effect of surface roughness on friction index depends on the slipmeter used, due to the different characteristics among these slipmeters. It was also shown that tile surface roughness could be correlated with the measured friction index. For dry surfaces, surface parameters R_a and R_{3z} (see Table 1 for definitions) had the highest correlation with the measured friction indices among 21 surface parameters evaluated in the study. Surface parameters R_{pk} and R_{pm} had the highest correlation with the measured friction indices for wet surfaces. A rougher surface generally led to a higher friction index. For wet surfaces, moreover, sharper and higher peaks with an optimal high peak density on tile surfaces could increase friction index further.

Relevance to industry

Slips and falls are a serious problem in occupational injuries. A higher slip resistance could potentially reduce the number of falls. This study could help identify the surface features that could increase the slip resistance of a floor.

Keywords: Slip resistance; Surface roughness; Linear correlation

1. Introduction

Slips and falls are a serious problem. Based on the information provided by an earlier study (Leamon et al., 1995), the annual direct cost of occupational injuries due to slips and falls in the US may be as high as 7 billion dollars. The total cost due to slips and falls for the whole population in the US is enormous. The common perception of fall injuries might be related to falls from elevation. However, falls from elevation, usually resulting in a higher claim cost, represented only 35% of all claim cases related to the problem. On the contrary, falls on the same level accounted for 65% of claim cases

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and, consequently, 55% of claim cost in the total direct workers' compensation for the occupational injuries due to slips and falls (Leamon et al., 1995).

Friction coefficient is often used as an indicator of floor slipperiness. Surface roughness plays a role in slip resistance. Proctor et al. (1988) used the hydrodynamic squeeze film theory to demonstrate that certain surface roughness is needed to improve slip resistance. Harris et al. (1988) assessed the subjective opinions of 10 contaminated floor surfaces. In their study, the Spearman rank correlation between opinion ranking in slip resistance and surface parameter R_{tm} (the averaged peak-to-valley distance) was 0.83 with $p < 0.1$. They also concluded that a peak-to-valley roughness of 8–10 μm is required for a wet floor to maintain a proper slip resistance. Stevenson et al. (1989) varied the roughness on steel and concrete surfaces, and measured their slip resistance with a dynamic setup to simulate human walking. They concluded that dynamic friction generally increases almost linearly with the arithmetical average of floor surface roughness (R_{a}), and increases only slightly beyond certain R_{a} values. Manning et al. (1990, 1994) used a traction walking test to assess shoe slip resistance on contaminated floor. They used several methods of abrasion to simulate the polishing effect of walking. They reported that the Spearman rank correlation coefficients between R_{tm} on shoe surfaces and the measured friction were 0.64 ($p < 0.05$) and 0.757 ($p < 0.025$) for wet and oily surfaces, respectively. Grönqvist et al. (1990) used another dynamic apparatus to simulate human walking for measuring the slip resistance of several contaminated floor materials. They reported that the Pearson's product-moment and the Spearman rank correlation coefficients between the measured friction and R_{a} of floor surface roughness were 0.87 and 0.86, respectively, with $p < 0.001$. They also indicated that an adequate R_{a} value should be about 7–9 μm for a proper slip resistance. Lloyd et al. (1992) used the same setup as Stevenson et al. (1989) to measure the slip resistance of several contaminated floor materials. They introduced a roughness index (RI) which contained R_{q} (the root-mean square of surface heights), λ_{q} (the root-mean square of wave length) and R_{sk} (the skewness of surface heights). They reported that the multiple correlation coefficient between friction and RI was 0.983 ($p < 0.001$).

There were two common problems with the results reported in the literature. The first problem was that R_{a} and $R_{t\mathrm{m}}$ are limited representations of surface characteristics, and are highly location dependent. For example, two sine wave surfaces with an identical amplitude but different frequencies have identical R_{a} and $R_{t\mathrm{m}}$ values, but their frictional characteristic could be quite different. The second problem was that several floor materials were used to cover the desired range of surface roughness. As friction is also affected by materials, most of these friction measurements reflected the combined effect of floor materials and surface roughness. Therefore, identical floor and shoe materials should be used in order to investigate the effect of surface roughness. Stevenson et al. (1989) varied surface roughness on identical floor materials. However, they used R_{a} to represent the surfaces. Manning et al. (1990) also varied surface finishes on identical shoe materials, but they only used $R_{t\mathrm{m}}$ to represent the shoe surfaces. They did not measure floor surface finishes. Footwear materials are usually not as hard as floor materials. Shoe materials are likely to have a much larger deformation than floor materials when in contact. Therefore, the surface roughness on footwear is less critical than that on floor.

In this study, the surface roughness on an identical floor material is systematically varied by sand blasting. Several commercially available slipmeters are used to measure slip resistance. A commercially available profilometer is used to measure the surface profiles on floor tiles. A total of 21 surface parameters are correlated with the measured slip resistance. The objective of this study is to identify the surface parameters that have the highest correlation with the measured slip resistance. Also, the number of surface profile measurements required for leading to a satisfactory indication of surface slip resistance is explored.

2. Test apparatus and experimental design

Many slipmeters have been used to assess floor slipperiness. These slipmeters can be quite different in their measurement characteristics. The horizontal pull slipmeter (HPS) and the James machine measure static friction between footwear sample and floor. The Tortus measures dynamic friction. The Brungraber Mark II, the Ergodyne, the Sigler and the British Pendulum measure the impact between footwear sample and floor to simulate a heel strike. The HPS, the James Machine, the Brungraber Mark II, the Ergodyne and the Sigler were used in this experiment to measure slip resistance for representing the diversity of test devices and measurement characteristics.

Unglazed quarry tiles were used as the floor material in this experiment. Sand blasting was used to systematically alter the surface roughness on the tiles. The dimension of the quarry tiles used in this experiment was approximately 15 cm × 15 cm. The exposure time was the only independent variable in the sand blasting process. The air pressure at the inlet for sand particles was 2.76×10^5 Pa (40 psi). The distance between the tile and the exit nozzle of the sand particles was 7.6 cm. The nozzle was kept normal to the tile surface. The sand particles of "black beauty", which consisted of 99–100% of coal slag, were used. The exposure times of 4, 8, 12, 14 and 16 min were selected for the sand blasting process. Ten tile samples were produced under each exposure time for a total of 50 tile samples. After blasting, all the samples were rinsed by tap water. The tile samples were then wiped with a 3% ammonium hydroxide (NH_4OH) solution and then dried with a clean cloth according to ASTM-F-609-79 (1984).

Neolite, a commonly used standard testing material for slip resistance measurements, was selected as the footwear material in this study. The neolite used had an averaged specific gravity of 1.27 ± 0.02 and Shore A hardness of 94. Footwear material pads were polished using a No. 400 abrasive paper followed by a brush to remove surface particles according to the American Society for Testing and Materials F-609-79 (1984).

The surface topography of quarry tiles was measured with a profilometer. The vertical resolution of the profilometer used is 16 nm. A high-pass filtering was performed on the measured profile with a proper selection of filtering length, also known as the cut-off length, to obtain the surface roughness profile, also known as the surface heights. The surface roughness parameters were calculated from the filtered roughness profile. The cut-off length for filtering was 2.5 mm and a commonly used recursive 2CR filter was selected (Whitehouse, 1994). Six surface roughness measurements, each 1 cm apart, in the direction of slip resistance measurement were performed on each tile sample as shown in Fig. 1. The assessed length of a roughness measurement was 4 times the cut-off length (or 10 mm). In this study, the horizontal resolution in the output of roughness measurements was approximately 5 μm. The definitions of 21 surface parameters used in the correlation are shown in Table 1 (Rank Taylor Hobson Limited, 1996; Whitehouse, 1994).

Water was used as a contaminant in this experiment. Slip resistance was measured on every tile sample under both dry and wet conditions. If the contaminant was required, slip resistance was measured right after the contaminant was applied. The contaminant was replenished whenever a slipmeter required repeated measurements to achieve the final value of slip resistance. Sufficient water was poured onto the tile surfaces to form a thin layer. The amount of water put onto the surface was near the maximum that could be retained by water's surface tension without any constraint at the edges

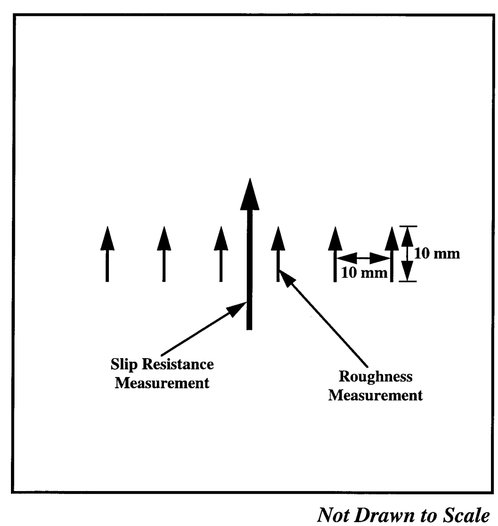

Fig. 1. Locations for slip resistance and surface roughness measurements.

Table 1
The definitions of surface parameters

R_{3y} – the maximum height of the third highest peak to the third lowest valley in each cut-off length
R_{3z} – the mean height from the third highest peak to the third lowest valley in each cut-off length
R_a – the arithmetical average of surface heights, also known as the center line average of surface heights (CLA)
R_k – the kernel roughness depth
R_{ku} – the kurtosis of surface heights
R_p – the maximum height of the profile above the mean line within the assessed length
R_{pk} – the reduced peak height
R_{pm} – the average of the maximum height above the mean line in each cut-off length
R_q – the root-mean square of surface heights
R_{sk} – the skewness of surface heights
R_t – the maximum peak-to-valley height in the assessed length
R_{tm} – the average of peak-to-valley height in each cut-off length
R_v – the maximum depth of the profile below the mean line within the assessed length
R_{vk} – the reduced trough depth
R_y – the maximum of peak to valley in all cut-off lengths
R_z – the average height difference between five highest peaks and five lowest valleys within the assessed length
S – the mean spacing of adjacent local peaks
S_m – the mean spacing between profile peaks at the mean line
λ_q – the root-mean-square measure of spatial wavelength
Δ_a – the arithmetical mean of surface slope
Δ_q – the root-mean square of surface slope

of tile surfaces. The criterion for the amount of water was that pouring stopped when the inflow onto the tile surface was nearly equal to the overflow at all edges of tile surface, based on a subjective measure. All tests were performed at the temperature of 21°C (70°F) and the relative humidity of 30–40%. The only exception was the tests using the James machine where the relative humidity was 65% due to the limitation of test facility.

3. Results

There appears to be no common terminology for the outputs of the slipmeters used in this experiment. The outputs from these devices are called the coefficient of friction for the James machine, slip index for the Ergodyne and the HPS, and friction or slip resistance for the Brungraber. Some of the original designers of these slipmeters wanted to distinguish the measurement based on a particular device from the outputs of other slipmeters and the conventional friction measurements by using a different terminology. In this study, the outputs from these devices were compared. A terminology "friction index" was used here for referring to all the outputs from these devices.

The mean and standard deviation of the friction indices for each slipmeter, each surface condition and each sand blasting duration are shown in Fig. 2 and Table 2. The surface condition for friction index measurements was either dry or water contaminated. Since the slip index taken with the HPS was approximately 10 times the static friction coefficient, the friction index with the HPS was obtained by dividing the slip index by 10. In order to see if the contaminant played an important role in the friction index values, a two-tailed paired t-test was performed on the friction indices under dry and wet conditions taken with each slipmeter. The results indicated that friction index values under two surface conditions had a significant difference for the Brungraber ($p < 0.0001$), the Ergodyne ($p < 0.0001$) and the James machine ($p = 0.026$). There was no significant difference for the HPS ($p = 0.072$) and the Sigler ($p = 0.165$).

Under wet condition, the friction indices taken with the Ergodyne had the largest difference of 0.35 in the mean value for each sand blasting duration, while the friction indices taken with the HPS had the smallest difference of 0.02. Under dry condition, the friction indices taken with the Sigler had the smallest difference of 0.01 in the mean value for each sand blasting duration, while the friction indices taken with the Brungraber had the largest difference of 0.12. The slipmeters based on static measurement methods, such as the HPS and the James machine, always had the highest friction index values under dry and wet conditions. The highest averages of 50 friction index values for dry and wet conditions were 1.04 and 1.06, respectively, taken with the James machine. The lowest friction indices under dry condition had an average of 0.58, taken with the Sigler. The lowest friction indices under wet condition had an average of 0.16, taken with the Brungraber. A paired t-test was performed

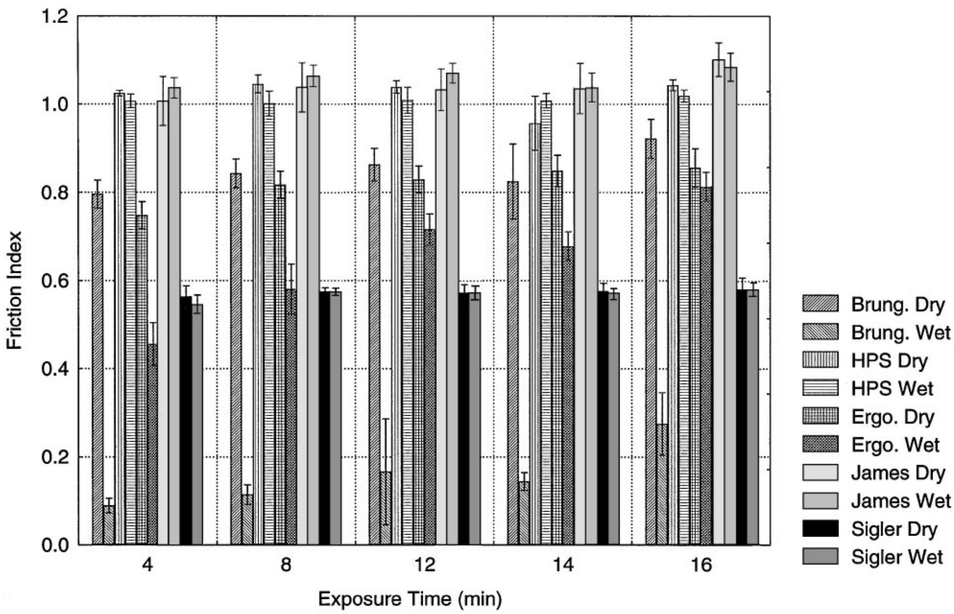

Fig. 2. Mean and standard deviation of friction index versus exposure time.

Table 2
Mean and standard deviation values of friction index

Exposure time (s)		Brungraber		HPS		Ergodyne		James machine		Sigler	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
4	Mean	0.80	0.09	1.02	1.01	0.75	0.46	1.01	1.04	0.57	0.55
	SD	0.03	0.02	0.01	0.02	0.03	0.05	0.06	0.02	0.02	0.02
8	Mean	0.84	0.11	1.05	1.00	0.82	0.58	1.04	1.07	0.58	0.58
	SD	0.03	0.02	0.02	0.03	0.03	0.06	0.06	0.03	0.01	0.01
12	Mean	0.86	0.17	1.04	1.01	0.83	0.72	1.04	1.07	0.57	0.58
	SD	0.04	0.12	0.01	0.03	0.03	0.04	0.05	0.02	0.02	0.01
14	Mean	0.82	0.14	0.96	1.01	0.85	0.68	1.04	1.04	0.58	0.57
	SD	0.08	0.02	0.06	0.02	0.04	0.03	0.06	0.03	0.02	0.01
16	Mean	0.92	0.27	1.04	1.02	0.86	0.81	1.10	1.09	0.58	0.58
	SD	0.04	0.07	0.01	0.01	0.04	0.03	0.04	0.03	0.03	0.01

on the friction indices under wet condition with the Brungraber and those under dry condition with the Sigler. The friction index values with the Brungraber under wet condition were significantly lower than those with the Sigler under dry condition ($p < 0.0001$). With the James machine, the friction indices under dry condition were not that much different from those under wet condition ($p = 0.026$). Therefore, there was a larger difference in the friction indices among five slipmeters used under wet condition than those under dry condition.

To investigate whether five different exposure duration of sand blasting affected friction index, an analysis of variance (ANOVA) was performed on the friction indices measured with each slipmeter under each surface condition. The F and p values for each slipmeter and surface condition are listed in Table 3. The results indicated that the exposure duration of sand blasting had a significant effect on the friction indices for most of the slipmeters used. The exceptions were those taken with the HPS under wet condition ($p = 0.49$) and the Sigler under dry condition ($p = 0.53$). The most significant differences in friction indices under wet and dry conditions for different sand blasting duration were taken with the Ergodyne ($F = 104.28$ and 15.44, respectively). The F values for the friction index taken under wet condition were higher than those under dry condition for all the slipmeters used except the HPS. The maximum differences among the averaged friction indices under wet condition for each sand blasting duration taken with the Brungraber, the Ergodyne and the Sigler were higher than those under dry condition by 0.06, 0.24 and 0.02, respectively. However, the opposite was true for the measurements taken with the HPS and the James machine by 0.07 and 0.04, respectively.

Table 3
F and p values of friction index measurements

Slipmeter	Surface condition	F value	p value
Brungraber	Dry	8.90	0.0001
	Wet	12.47	0.0001
HPS	Dry	15.22	0.0001
	Wet	0.86	0.4924
Ergodyne	Dry	15.44	0.0001
	Wet	104.28	0.0001
James machine	Dry	4.52	0.0037
	Wet	5.60	0.001
Sigler	Dry	0.80	0.5331
	Wet	8.54	0.0001

In order to examine the relationship between friction index and a particular surface parameter, the linear correlation coefficient r (Chase et al., 1986) was calculated. A higher r value indicates a better linear correlation between friction index and that particular surface parameter. For the correlation with friction index, a commonly used approach is to use the averaged surface parameters of several roughness measurements generated from a sample to represent that sample. The surface parameter used by Harris et al. (1988) was an average of up to 50 roughness measurements on each sample. Manning et al. (1990, 1994) used an average of five roughness measurements. An average of 20 roughness measurements was used by Grönqvist et al. (1990). Lloyd et al. (1992) used an average of four to five roughness measurements.

In this experiment, there were six surface roughness measurements on each tile sample. The surface parameters calculated from six roughness measurements from a sample were first used to correlate with the friction indices. The correlation coefficients for all the surface parameters and slipmeters under wet and dry conditions are listed in Tables 4 and 5, respectively. The highest correlation coefficients for the Brungraber, the HPS, the Ergodyne, the James Machine and the Sigler were 0.542, 0.275, 0.724, 0.366 and 0.331, respectively, for dry condition, and 0.633, 0.278, 0.855, 0.294 and 0.552, respectively, for wet condition. For a sample size of 50, the correlation coefficient has to be no less than 0.279 in order to yield statistically significant results ($\alpha = 0.05$) (Chase et al., 1986). The correlation coefficients of the friction indices taken with the HPS under both dry and wet conditions failed to reach this criterion, and, thus, the HPS results were eliminated from further analyses. The friction indices taken under wet condition with the Brungraber, the Ergodyne and the Sigler had a better correlation with the averaged surface parameters than those under dry condition. However, the opposite was true for the friction indices taken with the James machine. Overall, the Ergodyne had the

Table 4
Linear correlation coefficients for averaged surface parameters under wet condition

Surface parameter	Brungraber	HPS	Ergodyne	James machine	Sigler	Average w/o HPS
R_a	0.483	0.210	0.796	0.159	0.546	0.496
R_q	0.448	0.180	0.761	0.168	0.533	0.477
R_p	0.492	0.148	0.742	0.171	0.484	0.472
R_v	0.159	0.080	0.510	0.124	0.496	0.322
R_t	0.335	0.118	0.650	0.154	0.512	0.413
R_{tm}	0.411	0.126	0.747	0.184	0.552	0.473
R_{sk}	0.621	0.191	0.594	0.156	0.182	0.388
R_{ku}	− 0.346	− 0.278	− 0.330	0.039	0.011	0.181
Δ_q	0.134	0.173	0.492	0.266	0.358	0.313
λ_q	0.498	0.168	0.784	0.143	0.551	0.494
S	0.158	0.126	0.515	− 0.028	0.422	0.281
R_y	0.340	0.136	0.642	0.157	0.506	0.411
R_z	0.022	− 0.040	− 0.022	0.098	− 0.123	0.066
R_{pm}	0.558	0.133	0.824	0.195	0.549	0.532
R_{3y}	0.339	0.209	0.657	0.168	0.474	0.409
R_{3z}	0.491	0.220	0.788	0.184	0.543	0.501
R_k	0.521	0.203	0.849	0.191	0.550	0.528
R_{pk}	0.633	0.152	0.855	0.213	0.490	0.548
R_{vk}	0.327	− 0.006	0.587	0.066	0.510	0.373
S_m	0.520	0.172	0.751	0.054	0.546	0.468
Δ_a	0.165	0.175	0.525	0.294	0.386	0.343

Table 5
Linear correlation coefficients for averaged surface parameters under dry condition

Surface parameter	Brungraber	HPS	Ergodyne	James machine	Sigler	Average w/o HPS
R_a	0.440	− 0.181	0.724	0.305	0.322	0.448
R_q	0.415	− 0.180	0.696	0.295	0.324	0.432
R_p	0.430	− 0.127	0.646	0.260	0.304	0.410
R_v	0.270	− 0.148	0.540	0.177	0.268	0.314
R_t	0.363	− 0.144	0.618	0.227	0.299	0.377
R_{tm}	0.389	− 0.175	0.688	0.303	0.307	0.422
R_{sk}	0.345	− 0.034	0.295	0.366	0.150	0.289
R_{ku}	− 0.191	0.0003	− 0.178	− 0.212	− 0.010	0.148
Δ_q	0.293	0.074	0.560	0.252	0.199	0.326
λ_q	0.420	− 0.219	0.693	0.288	0.327	0.432
S	0.188	− 0.275	0.546	0.113	0.284	0.283
R_y	0.363	− 0.158	0.610	0.238	0.310	0.380
R_z	− 0.054	0.259	− 0.201	0.073	− 0.135	0.116
R_{pm}	0.449	− 0.165	0.697	0.343	0.290	0.445
R_{3y}	0.315	− 0.169	0.559	0.219	0.322	0.354
R_{3z}	0.449	− 0.148	0.711	0.309	0.315	0.446
R_k	0.462	− 0.116	0.687	0.287	0.308	0.436
R_{pk}	0.542	− 0.107	0.694	0.323	0.219	0.445
R_{vk}	0.263	− 0.163	0.537	0.164	0.293	0.314
S_m	0.428	− 0.221	0.674	0.228	0.331	0.415
Δ_a	0.293	0.074	0.569	0.268	0.227	0.339

highest correlation under both dry and wet conditions among five slipmeters used. The Brungraber Mark II yielded the second highest correlation coefficients under both dry and wet conditions.

The highest correlation coefficient of 0.855 was obtained between the friction index with the Ergodyne under wet condition and R_{pk} as shown in Table 4. For the Ergodyne, the top five parameters were R_{pk}, R_k ($r = 0.849$), R_{pm} (0.824), R_a (0.796) and R_{3z} (0.788) under wet condition, and R_a (0.724), R_{3z} (0.711), R_{pm} (0.697), R_q (0.696) and R_{pk} (0.694) under dry condition. The top five parameters for the Brungraber were R_{pk} (0.633), R_{sk} (0.621), R_{pm} (0.558), R_k (0.521) and S_m (0.520) under wet condition, and R_{pk} (0.542), R_k (0.462), R_{pm} (0.449), R_{3z} (0.449) and R_a (0.440) under dry condition. The top five parameters were R_{tm} (0.552), λ_q (0.551), R_k (0.550), R_{pm} (0.549) and R_a (0.546) under wet condition, and S_m (0.331), λ_q (0.327), R_q (0.324), R_a (0.322) and R_{3y} (0.322) under dry condition for the Sigler. For the James machine, the top five parameters were Δ_a (0.294), Δ_q (0.266), R_{pk} (0.213), R_{pm} (0.195) and R_k (0.191) under wet condition, and R_{sk} (0.366), R_{pm} (0.343), R_{pk} (0.323), R_{3z} (0.309) and R_a (0.305) under dry condition. Only S_m, λ_q, Δ_a and Δ_q are related to surface horizontal dimension, and all other surface parameters within the top five correlation coefficients are calculated purely from the surface height distribution.

The averaged correlation coefficients calculated separately for wet and dry surface conditions for all the slipmeters except the HPS are listed in Tables 4 and 5, respectively. The top five surface parameters based on their averaged r values were R_{pk} (0.548), R_{pm} (0.532), R_k (0.528), R_{3z} (0.501) and R_a (0.496) under wet condition, and R_a (0.448), R_{3z} (0.446), R_{pm} (0.445), R_{pk} (0.445) and R_k (0.436) under dry condition. R_{pk} versus friction index under wet condition is shown in Fig. 3. R_a versus friction index under dry condition is shown in Fig. 4.

The number of surface roughness measurements required on a tile sample for a satisfactory indication of friction index was investigated. The need arises because the dimension of the contact area between footwear and floor at the critical moments during walking is usually much longer than the assessed length of a roughness measurement. Also, most of surface parameters are highly location dependent. The averaged surface parameters from several roughness measurements are required for

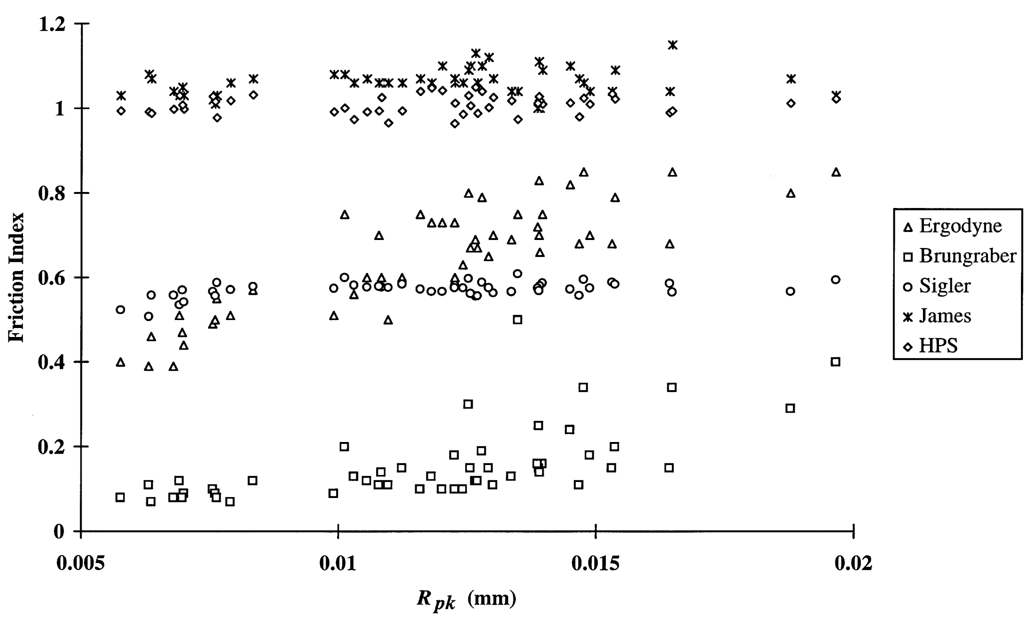

Fig. 3. Friction index under wet condition versus R_{pk}.

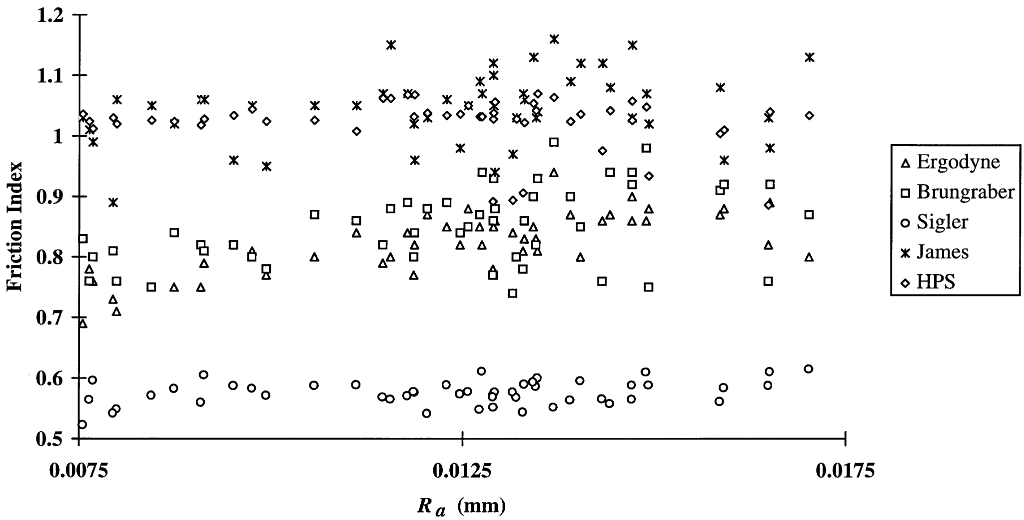

Fig. 4. Friction index under dry condition versus R_a.

a location of interest in order to obtain a good representation of surface characteristics. However, it is not clear how many surface roughness measurements in an area are sufficient. There were six roughness measurements from each tile sample in this study. Each roughness measurement could be used as an independent measurement for correlating with friction index. However, there was only one friction index value for each tile sample with each slipmeter under each surface condition. One reasonable approach was to assign the identical friction index value to all six roughness measurements from the sample. The linear correlation coefficient was calculated between the measured friction index and each surface parameter generated from each roughness measurement. The sample size in this correlation was 300. The r values for all the surface parameters and slipmeters used are listed in Tables 6 and 7 for wet and dry conditions, respectively. The highest correlation coefficients for the Brungraber, the HPS, the Ergodyne, the James Machine and the Sigler were 0.368, – 0.173, 0.556, 0.248 and 0.248, respectively, under dry condition, and 0.418, 0.167, 0.676, 0.190 and 0.438, respectively, under wet condition. Similar to the averages of six roughness measurements, the friction indices measured under wet condition with the Brungraber, the Ergodyne and the Sigler had a better correlation with the parameters from single roughness measurement than those under dry condition. Also the highest correlation coefficients for the James machine and the HPS under dry condition were higher than those under wet condition. Similarly, the Ergodyne and the Brungraber had the highest and the second highest correlation, respectively, under both dry and wet conditions among five slipmeters used.

Surface parameter R_k calculated from single roughness measurements had the highest correlation coefficient of 0.676 with the friction indices taken with the Ergodyne under wet condition. R_k calculated from single roughness measurement versus the friction index taken with the Ergodyne under wet condition is shown in Fig. 5. Under dry condition, R_a calculated from single roughness measurements had the highest correlation coefficient of 0.556 with the friction indices taken with the Ergodyne. R_a calculated from single roughness measurement versus the friction index taken with the Ergodyne under dry condition is shown in Fig. 6. For the Ergodyne, the top five parameters were R_k ($r = 0.676$), R_a (0.611), R_{3z} (0.598), R_{pm} (0.596) and λ_q (0.595) under wet condition, and R_a (0.556), R_k (0.547), R_{3z} (0.540), λ_q (0.526) and R_q (0.507)

Table 6
Linear correlation coefficients for surface parameters from individual measurements under wet condition

Surface parameter	Brungraber	HPS	Ergodyne	James machine	Sigler	Average w/o HPS
R_a	0.371	0.161	0.611	0.122	0.419	0.381
R_q	0.327	0.132	0.555	0.123	0.389	0.348
R_p	0.311	0.094	0.468	0.108	0.305	0.298
R_v	0.084	0.042	0.270	0.065	0.262	0.171
R_t	0.203	0.072	0.394	0.093	0.311	0.250
R_{tm}	0.286	0.087	0.520	0.128	0.384	0.330
R_{sk}	0.284	0.087	0.272	0.071	0.083	0.177
R_{ku}	− 0.150	− 0.120	− 0.142	0.017	0.005	0.078
Δ_q	0.079	0.102	0.289	0.156	0.210	0.183
λ_q	0.378	0.128	0.595	0.109	0.418	0.375
S	0.099	0.079	0.324	− 0.018	0.266	0.177
R_y	0.202	0.080	0.381	0.093	0.300	0.244
R_z	0.009	− 0.016	− 0.009	0.039	− 0.049	0.026
R_{pm}	0.404	0.096	0.596	0.141	0.397	0.385
R_{3y}	0.231	0.142	0.448	0.114	0.323	0.279
R_{3z}	0.373	0.167	0.598	0.140	0.412	0.381
R_k	0.415	0.162	0.676	0.152	0.438	0.420
R_{pk}	0.418	0.100	0.565	0.141	0.324	0.362
R_{vk}	0.191	− 0.003	0.343	0.039	0.298	0.218
S_m	0.385	0.127	0.557	0.040	0.404	0.347
Δ_a	0.107	0.113	0.339	0.190	0.249	0.221

Table 7
Linear correlation coefficients for surface parameters from individual measurements under dry condition

Surface parameter	Brungraber	HPS	Ergodyne	James machine	Sigler	Average w/o HPS
R_a	0.337	− 0.139	0.556	0.234	0.247	0.343
R_q	0.302	− 0.131	0.507	0.215	0.236	0.315
R_p	0.272	− 0.080	0.408	0.164	0.192	0.259
R_v	0.143	− 0.078	0.286	0.094	0.142	0.166
R_t	0.220	− 0.087	0.375	0.138	0.181	0.228
R_{tm}	0.271	− 0.122	0.479	0.211	0.214	0.294
R_{sk}	0.158	− 0.015	0.135	0.167	0.069	0.132
R_{ku}	− 0.083	0.000	− 0.077	− 0.091	− 0.004	0.064
Δ_q	0.172	0.043	0.329	0.148	0.117	0.191
λ_q	0.319	− 0.167	0.526	0.218	0.248	0.328
S	0.118	− 0.173	0.344	0.071	0.179	0.178
R_y	0.215	− 0.094	0.362	0.141	0.184	0.226
R_z	− 0.021	0.103	− 0.080	0.029	− 0.054	0.046
R_{pm}	0.325	− 0.120	0.504	0.248	0.210	0.322
R_{3y}	0.215	− 0.115	0.381	0.149	0.219	0.241
R_{3z}	0.341	− 0.112	0.540	0.235	0.239	0.339
R_k	0.368	− 0.092	0.547	0.228	0.245	0.347
R_{pk}	0.358	− 0.071	0.459	0.213	0.145	0.294
R_{vk}	0.154	− 0.095	0.314	0.096	0.171	0.184
S_m	0.317	− 0.164	0.500	0.169	0.245	0.308
Δ_a	0.189	0.047	0.368	0.173	0.147	0.219

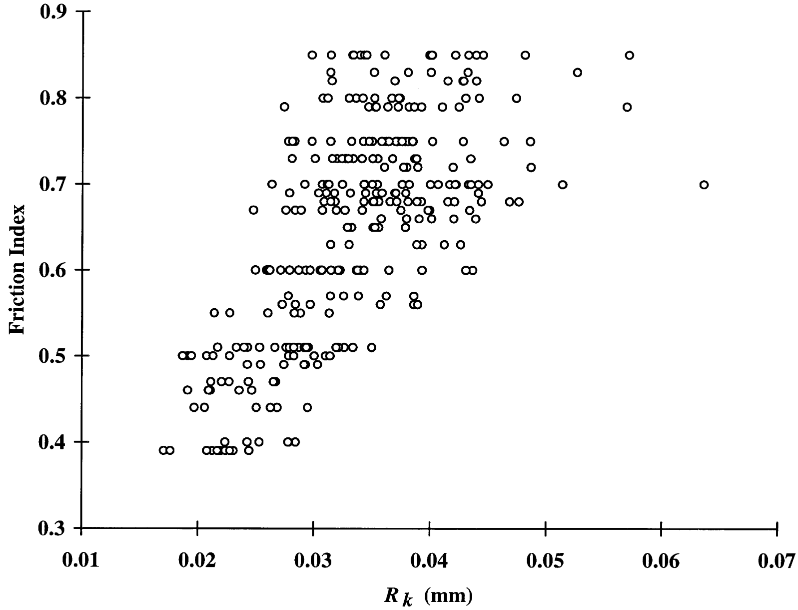

Fig. 5. Friction index taken with the Ergodyne under wet condition versus R_k.

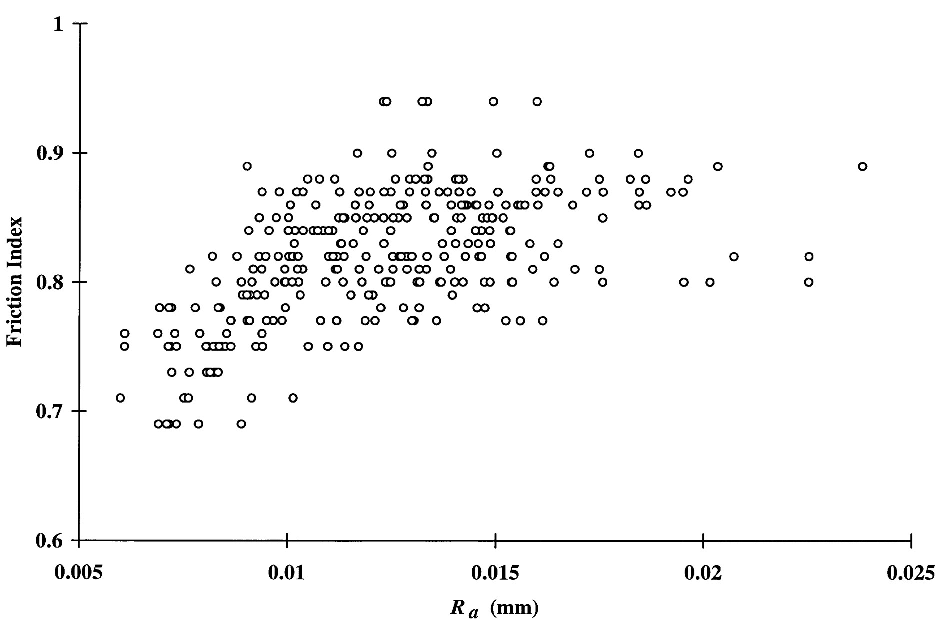

Fig. 6. Friction index taken with the Ergodyne under dry condition versus R_a.

under dry condition. The top five parameters for the Brungraber were R_{pk} (0.418), R_k (0.415), R_{pm} (0.404), S_m (0.385) and λ_q (0.378) under wet condition, and R_k (0.368), R_{pk} (0.358), R_{3z} (0.341), R_a (0.337) and R_{pm} (0.325) under dry condition. The top five parameters were R_k (0.438), R_a (0.419), λ_q (0.418), R_{3z} (0.412) and S_m (0.404) under wet condition, and λ_q (0.248), R_a (0.247), S_m (0.245), R_k (0.245) and R_{3z} (0.239) under dry condition for the Sigler. The top five parameters for the James machine were Δ_a (0.190), Δ_q (0.156), R_k (0.152), R_{pm} (0.141) and R_{pk} (0.141) under wet condition, and R_{pm} (0.248), R_{3z} (0.235), R_a (0.234), R_k (0.228) and λ_q (0.218) under dry condition. For the HPS, the top five parameters were R_{3z} (0.167), R_k (0.162), R_a (0.161), R_{3y} (0.142) and R_q (0.132) under wet condition, and S (-0.173), λ_q (-0.167), S_m (-0.164), R_a (-0.139) and R_q (0.218) under dry condition.

Due to the lack of statistical significance, the friction indices taken with the HPS were eliminated in the previous calculation of averaged correlation coefficients based on the averages of six roughness measurements. The HPS remained the slipmeter with the lowest correlation coefficients when surface parameters generated from single roughness measurement were used. The HPS results were, therefore, eliminated from the calculation of the averaged correlation coefficients based on single roughness measurements for a fair comparison. The top five surface parameters based on their averaged r values were R_k (0.420), R_{pm} (0.385), R_{3z} (0.381), R_a (0.381) and λ_q (0.375) under wet condition, and R_k (0.347), R_a (0.344), R_{3z} (0.339), λ_q (0.328) and R_{pm} (0.322) under dry condition. Surface parameter R_{pk} had averaged correlation coefficients of 0.362 and 0.294 for wet and dry conditions, respectively.

Similar analysis was applied to the averaged surface parameters generated from a different number of roughness measurements. The averaged surface parameters of two and three roughness measurements were used in the correlation analyses. No single roughness measurement was added more than once in each averaging process. Also, an identical friction index value was assigned to all the averaged surface parameters generated from the same sample. The means of the r values for all the slipmeters except the HPS were calculated for dry and wet conditions separately. For the surface parameters generated from two roughness measurements, the sample size was 150. The highest five parameters based on their mean r values were R_k (0.480), R_{pm} (0.459), R_{3z} (0.448), R_a (0.444) and λ_q (0.436) under wet condition, and R_a (0.401), R_{3z} (0.399), R_k (0.396), R_{pm} (0.384) and λ_q (0.381) under dry condition. For the surface parameters generated from three roughness measurements, the sample size was 100. The highest five parameters based on their mean r values were R_{pk} (0.498), R_k (0.491), R_{pm} (0.479), R_{3z} (0.464) and R_a (0.451) under wet condition, and R_{3z} (0.412), R_a (0.407), R_k (0.406), R_{pk} (0.404) and R_{pm} (0.401) under dry condition.

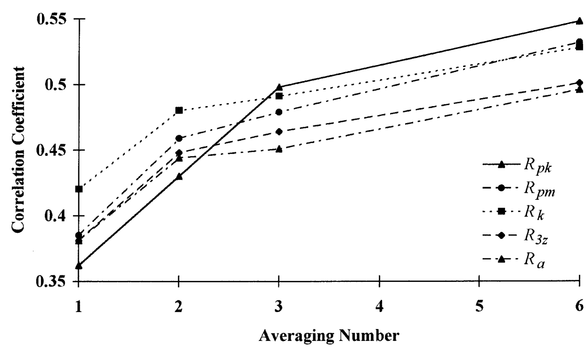

Fig. 7. Linear correlation coefficient under wet condition versus averaging number.

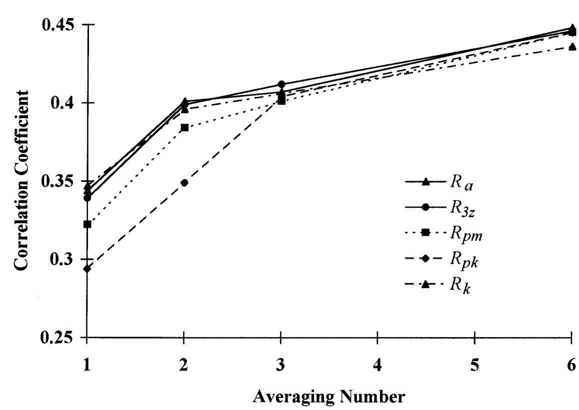

Fig. 8. Linear correlation coefficient under dry condition versus averaging number.

The means of correlation coefficients for R_{pk}, R_{pm}, R_k, R_{3z} and R_a versus the number of roughness measurements used in the averaged surface parameters for wet and dry conditions are shown in Figs. 7 and 8, respectively. The effect of the number of roughness measurements used in the averaged surface parameters on the correlation coefficients was not statistically significant ($p = 0.67$), based on an ANOVA analysis.

4. Discussions

As shown in Tables 2 and 3, the friction indices measured with the Ergodyne, the Brungraber and the James machine had larger differences in value due to the change in the tile surface roughness than those taken with the HPS and the Sigler. Therefore, the Ergodyne, the Brungraber Mark II and the James machine could detect the effect of surface roughness on friction index better than the HPS and the Sigler. The insensitivity of surface roughness on the friction index measured with the HPS could be due to its low contact pressure between neolite and quarry tile. For the Brungraber and the Ergodyne, the squeeze film effect could be the main contributor to larger differences in friction index and lower friction index values under wet condition than those under dry condition. High friction index values taken with the HPS and the James machine under wet condition could be due to the static measurement characteristics of these slipmeters. For the HPS and the James machine, the majority of contaminant was squeezed out of the contact interface before the measurement of friction index was taken. The reduction of contaminant at the interface could result in an insignificant difference in friction indices under dry and wet conditions for the HPS. Since there was a larger difference in friction index values among five slipmeters under wet condition than under dry condition, the measurement characteristics of slipmeters become critical for a contaminated surface.

The Brungraber, the Ergodyne, the James machine and the Sigler use different sizes of single footwear pads for friction index measurement. Therefore, friction index was measured in the area where surface roughness was measured for these four slipmeters. However, the HPS has three footwear pads which have a diameter of 1.27 cm, the smallest linear dimension among the slipmeters used, for friction index measurement. The distances among footwear pads under the HPS are as far as 12.7 cm (5 in) and as close as 5.08 cm (2 in). There was a difficulty in making friction index measurement in the area of surface roughness measurements with the HPS since the tile surface was only 15 cm $\times$ 15 cm. These factors might partly contribute to the lack of correlation between surface parameters and friction indices for the HPS. However, ANOVA analysis indicated that the HPS had a limited capability in detecting the effect of sand blasting duration on friction index for a wet surface ($p = 0.49$ and $F = 0.86$).

When each roughness measurement was treated independently, the results did not yield a higher correlation coefficient even thought it had a larger sample size. The correlation coefficient for the averaged surface parameters increased as the number of roughness measurements used in the averaging process was increased. Therefore, it is necessary that several roughness measurements are taken in an area of interest and the averaged surface parameters are used. When the number of roughness measurements used in the averaged surface parameters was increased, there was no significant improvement in the averaged correlation coefficients in this study, according to the ANOVA analysis. This insignificant improvement could be due to the diversity of correlation coefficients among the slipmeters used, although most of the correlation coefficients appeared significant according to their respective sample sizes. For the averaged correlation coefficient, the largest improvement for different surface conditions and different averaging numbers among the top five surface parameters evaluated under each surface condition was 0.186, while the smallest standard deviation was 0.131. For R_{pk}, the improvement in correlation coefficient was higher when the averaging number was increased from one to three, but it was not as high when the averaging number was increased from three to six for both dry and wet conditions as shown in Figs. 7 and 8. R_{pk} had the highest averaged correlation coefficient when the averaging number of roughness measurements exceeded two.

When the number of surface roughness measurements was equal to or less than two, surface parameter R_k appeared to be a good indicator of friction index under wet condition as shown in Fig. 7. R_a, R_{3z} and R_k had nearly equal correlation coefficients under dry condition as the averaging number was increased from one to six as shown in Fig. 8, and were good indicators of friction index.

Finally, a question that arises is whether these surface parameters with the highest correlation coefficients yield any physical meaning. For a dry surface, R_a and R_{3z} had the highest correlation coefficients. R_a is the arithmetical average of surface heights. A surface with a high R_a value means more surface height deviation from the mean line. A large R_a value could result from large high peaks to support footwear and floor contact or large valleys to contain contaminant. R_{3z} is the mean height from the third highest peak to the third lowest valley in each cut-off length. A high R_{3z} value could result from a surface with high peaks and deep valleys. No information is revealed in R_{3z} value about the surface feature between these high peaks and deep valleys or about the horizontal dimensions of these peaks and valleys. Since R_a and R_{3z} also had high correlation coefficients with friction index under wet condition, it appeared that a rougher surface generally led to a higher friction index. For a wet surface, R_{pk} and R_{pm} had the highest correlation coefficients. R_{pk} is the reduced peak height which represents the height of the top portion of surface for supporting load as indicated by Whitehouse (1994). R_{pm} is the averaged maximum height of the profile above mean line in each cut-off length. R_{pm} represents the averaged void volume among asperities on the surface to contain contaminants during contact. A larger void volume on the surface is more likely to allow more direct footwear and floor contacts for increasing the friction index. High R_{pk} and R_{pm} values could result from a surface with the majority of surface near the valley, and few high and sharp peaks within each cut-off length. For a wet surface, high and sharp peaks are needed to provide space to contain contaminants for achieving more direct asperity contacts between footwear and floor. A surface with many high peaks is going to fill up the spaces among asperities, and there are less spaces for the contaminant. Although fewer high peaks are better, there is a lower limit on high peak density in order to maintain a sufficiently high R_{pk} and R_{pm} values. Therefore, there exists an optimal range of high peak density that could achieve a higher friction index.

The surface parameter used in the previous studies, R_{tm}, also had averaged r values of 0.330 and 0.294 for wet and dry conditions, respectively, for the surface parameters generated from single roughness measurements. It had averaged r values of 0.473 and 0.442 for wet and dry conditions, respectively, for the surface parameters from six roughness measurements. These r values with the corresponding sample sizes also indicated a statistically significant correlation between this parameter and friction index. However, the surface parameters identified in this study, R_{3z} and R_a for dry condition, and R_{pm} and R_{pk} for wet condition, could reveal more surface characteristics than R_{tm}.

5. Conclusions

The Ergodyne, the Brungraber Mark II, the Sigler, the HPS and the James machine were used to measure the friction index between quarry tile and neolite under dry and water contaminated conditions. The surface roughness of quarry tiles was systematically altered by sand blasting. The measured friction indices with each slipmeter were correlated with the surface roughness parameters generated from the tile surfaces.

Due to different measurement characteristics, the Ergodyne, the Brungraber and the James machine were able to detect the effect of surface roughness on friction index better than the HPS and the Sigler. For the Brungraber and the Ergodyne, the squeeze film effect could be the main contributor to larger differences in friction index and lower friction index values under wet condition than those under dry condition. Among five slipmeters used in this experiment, the Ergodyne had the highest correlation between surface roughness parameters and friction index. Among 21 surface parameters evaluated in this study, the highest correlated parameters with the measured friction indices were R_{pk} and

R_{pm} for wet surfaces, and R_a and R_{3z} for dry surfaces. A rougher surface generally led to a higher friction index. For wet surfaces, however, sharper and higher peaks with an optimal high peak density on floor surface, in addition to the increase in surface roughness, could further increase friction index.

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