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Linear regression models of floor surface parameters on friction between Neolite and quarry tiles

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ABSTRACT

For slips and falls, friction is widely used as an indicator of surface slipperiness. Surface parameters, including surface roughness and waviness, were shown to influence friction by correlating individual surface parameters with the measured friction. A collective input from multiple surface parameters as a predictor of friction, however, could provide a broader perspective on the contributions from all the surface parameters evaluated. The objective of this study was to develop regression models between the surface parameters and measured friction. The dynamic friction was measured using three different mixtures of glycerol and water as contaminants. Various surface roughness and waviness parameters were measured using three different cut-off lengths. The regression models indicate that the selected surface parameters can predict the measured friction coefficient reliably in most of the glycerol concentrations and cut-off lengths evaluated. The results of the regression models were, in general, consistent with those obtained from the correlation between individual surface parameters and the measured friction in eight out of nine conditions evaluated in this experiment. A hierarchical regression model was further developed to evaluate the cumulative contributions of the surface parameters in the final iteration by adding these parameters to the regression model one at a time from the easiest to measure to the most difficult to measure and evaluating their impacts on the adjusted R^2 values. For practical purposes, the surface parameter R_a alone would account for the majority of the measured friction even if it did not reach a statistically significant level in some of the regression models.

1. Introduction

Slips and falls are a serious problem. It has been estimated that the annual direct cost of occupational injuries due to slips, trips and falls in the USA exceeded 6 billion US dollars (Courtney et al., 2001). Leamon and Murphy (1995) reported that falls on the same level, where slipperiness is one of the critical issues, accounted for 65% of claim cases and 53% of claim costs in total direct workers' compensation for occupational injuries due to slips and falls.

To prevent incidents of slips and falls, friction is widely used as an indicator of floor slipperiness. Surface texture plays a crucial role in determining surface friction, although the contact interface between shoe and floor is complex (Chang et al., 2001a). Using the hydrodynamic squeeze-film theory, Proctor and Coleman (1988) demonstrated that a certain level of surface texture is needed to increase friction. While the friction measurement related to the problems in slips and falls remains controversial, measurements of surface texture could be a reliable and objective complement to friction measurements (Chang et al., 2001a,b).

The surface textures under consideration in this paper are those on nominally flat surfaces which do not include the macroscopic floor features known as molded surface patterns or profiled surfaces. In addition to surface roughness, surface waviness might play a role in surface friction as shown by Chang et al. (2004a,b). The profile measured with a profilometer is filtered with a selection of a filtering length, also known as the cut-off length, to obtain the surface profile of either surface roughness or surface waviness, also known as the surface heights. The cut-off length is the filtering length that is used as a reference to properly capture important surface features of interest as indicated by Whitehouse (1994). The surface roughness profile contains components with shorter wave lengths compared with the cut-off length, while the surface waviness profile consists of components with longer wave lengths. The surface parameters are calculated from the filtered profiles. The relative importance of surface roughness or surface waviness on the measured friction depends on the cut-off length used and

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contaminants at the interface as demonstrated by Chang et al. (2004a). Their results indicate that some of the surface waviness parameters on floors could have a higher correlation coefficient with friction measured with liquid contamination than the surface roughness parameters when a short cut-off length is used for the surface profile measurements or when the viscosity of the liquid contaminant is high. Among the surface waviness parameters evaluated, as listed in Table 1, $W\Delta_a$, W_a and W_{tm} had strong correlations with the measured friction. The surface roughness parameters measured with a longer cut-off length would contain some of the waviness components measured with a shorter cut-off length. The surface parameters generated with different cut-off lengths reflect different characteristics of the measured surface. The viscosity of the liquid contaminants, besides tread patterns on the shoe sole surface, determines how fast the contaminants will be squeezed out of the shoe and floor interface and, therefore, how close two surfaces approach each other during the contact. The two surfaces will be closer to each other when the viscosity is low compared with the situation when the viscosity is high. Therefore, surface waviness could be more relevant to the measured friction when the viscosity is high (film remains thicker and contact is made only near the crests of the surfaces), while surface roughness could be more relevant when the viscosity is low (film is squeezed thinner and there is more intimate contact between surfaces), as confirmed by Chang et al. (2004a).

Table 1
The definitions of surface parameters.

Parameter	Definition
Surface roughness	
R_{3y}	Maximum height of third highest peak to third lowest valley in each cut-off length
R_{3z}	Mean height from third highest peak to third lowest valley in each cut-off length
R_a	Arithmetical average of surface heights or the center line average of surface heights
R_k	Kernel roughness depth
R_{ku}	Kurtosis of surface heights
R_p	Maximum height of the profile above the mean line within the assessed length
R_{pk}	Reduced peak height
R_{pm}	Average of the maximum height above the mean line in each cut-off length
R_q	Root mean square of surface heights
R_{sk}	Skewness of surface heights
R_t	Maximum peak to valley height in the assessed length
R_{tm}	Average of peak to valley height in each cut-off length
R_v	Maximum depth of the profile below the mean line within the assessed length
R_{vk}	Reduced trough depth
R_y	Maximum of peak to valley in all cut-off lengths
S	Mean spacing of adjacent local peaks
S_m	Mean spacing between profile peaks at the mean line
λ_q	Root mean square measure of spatial wave length
Δ_a	Arithmetical mean of surface slope
Δ_q	Root mean square of surface slope
Surface waviness	
W_a	Arithmetical average or the center line average of surface heights
W_{ku}	Kurtosis of surface heights
W_p	Maximum height of the profile above the mean line within the assessed length
W_{pm}	Average of the maximum height above the mean line in each cut-off length
W_q	Root mean square of surface heights
W_s	Mean spacing of adjacent local peaks
W_{sk}	Skewness of surface heights
W_t	Maximum peak to valley height in the assessed length
W_{tm}	Average of peak to valley height in each cut-off length
W_v	Maximum depth of the profile below the mean line within the assessed length
W_y	Maximum of peak to valley in all cut-off lengths
$W\lambda_q$	Root mean square measure of spatial wavelength
$W\Delta_a$	Arithmetical mean of surface slope
$W\Delta_q$	Root mean square of surface slope

The majority of the published studies on the effects of surface textures on friction related to slip and fall incidents have focused on surface roughness. As reported in the literature, surface roughness parameters R_a, R_{tm}, R_{pm}, Δ_a and R_k, as defined in Table 1, in general had strong correlations with the friction measured at the shoe and floor interface (Chang et al., 2001a, 2004b). It was shown that the parameter R_{tm} had a strong correlation with the subjective ranking of slipperiness (Harris and Shaw, 1988) and with the measured friction on liquid contaminated surfaces (Manning et al., 1990; Manning and Jones, 1994). It was demonstrated that surface parameter R_a had a strong correlation with the measured friction on surfaces contaminated with liquid (Stevenson et al., 1989; Grönqvist et al., 1990). Friction measured with liquid contaminants was shown to have a strong correlation with R_{pm} of the floor surfaces (Chang, 1998, 1999, 2000, 2001, 2002; Chang and Matz, 2000; Chang et al., 2004b). The measurement of R_{pm} on floor surfaces was recommended by Health and Safety Executive (HSE) Food Sheet 22 (HSE, 1999). It was demonstrated that surface parameter Δ_a had a strong correlation with the measured friction (Chang, 1998, 2000, 2001, 2002; Kim and Smith, 2000; Chang et al., 2004b). It was reported that friction measured with liquid contaminants had a strong correlation with R_k of floor surfaces (Chang, 1998, 1999, 2000, 2001, 2002; Chang and Matz, 2000; Chang et al., 2004b).

In the previously published studies on the effect of surface feature parameters on friction, the main focus was to investigate the relationship between individual surface parameters and the measured friction. Based on the results of linear correlation coefficients, surface parameters with higher correlation coefficients with friction were identified. However, collective effects of these surface parameters on the measured friction were not investigated and could provide a broader perspective on the contributions from all the surface parameters evaluated. The objective of this study was to investigate linear regression models of floor surface parameters, including surface roughness and waviness, on friction between quarry tiles and Neolite. Through regression models, the surface parameters that contribute the most to the friction measured could be identified.

2. Methods

The data used in previous publications (Chang et al., 2004a,b) were used as the basis in this investigation. The data for the surface feature measurements were collected with three cut-off lengths, 0.8, 2.5 and 8 mm, while the friction was measured with three different glycerol concentrations, 50, 70 and 85% ratio by weight with water to cover a range of viscosities. Glycerol has been widely used as a contaminant to increase slipperiness in many research activities on slips and falls reported in the literature. Since glycerol can be dissolved in water completely, one can generate a liquid contaminant with a wide range of viscosity from pure water to pure glycerol, and this type of liquid contaminant can be cleaned from the test surfaces much easier than oil-based contaminants. Based on the results reported in an earlier study (Chang, 2001), the correlation between roughness parameters and measured friction coefficient reached the maximum around 70 and 85% glycerol concentrations. Surface roughness was less effective with a glycerol concentration higher than 85% because the contaminant was too viscous to allow a more direct solid-to-solid contact. The roughness effect was also reduced with a glycerol concentration lower than 70% because there would be more than sufficient solid-to-solid contacts at the interface. The average value of each surface