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The Mechanisms of Pedestrian Slip on Flooring Contaminated with Solid Particles

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Abstract

Statistics by the UK Health and Safety Executive (HSE) suggest that slips, trips and falls account for up to one in three major workplace accidents. Many of these accidents are the result of contaminant (fluid or solid) within the shoe-floor contact. Though the lubrication mechanisms for liquid contaminants within the contact are well understood, the same cannot be said for particulate contaminants. This paper considers the key parameters controlling friction in a shoe-floor contact contaminated with various particles of different diameters and shape factors and floors with different roughness values (R_z). Experiments were conducted using a Stanley Pendulum Tester, which is the floor friction tester recommended in the current British standards. Results suggest the adhesive friction is significantly affected by particulate contaminants whilst the hysteretic component is not. Three lubrication mechanisms identified as sliding, shearing and rolling have been observed depending on floor roughness, particle size and shape factor and have been plotted in a simple map to predict behaviour.

1. **Introduction**

Slips and trips in the workplace are one of the largest causes of significant injury in the workplace with Health and Safety Executive (HSE) statistics suggesting that up to one in three major workplace accidents the result of a slip or trip [1]. The tribology of the interaction between the shoe or foot material (simulated using a visco-elastic material) and the floor is crucial to understanding why floors with particular attributes pose an increased slipping hazard.

The most common cause for a slip related accident is the presence of a contaminant within the shoe-floor contact. Fluid contaminants constitute a significant risk and the behaviour of the contact can be predicted using hydrodynamic lubrication theory [2]. In the field, the Health and Safety Laboratory (HSL) repeatedly observe that the introduction of a solid particulate contaminant within the contact can also result in a significant risk of slipping to pedestrians. There is however no clear understanding of the causes to the reduced friction levels observed [3].

The increased contact complexity observed when there are particles at the interface can be attributed to their discrete nature. The relative diameter of a contaminant particle is comparable to the dimensions of the contact geometry and means that they cannot be treated using the same continuum mechanics as fluid contaminants.

This paper outlines experiments performed to ascertain the effects of solid contaminants, the factors controlling friction coefficient and identifies the mechanisms observed.

Human gait and influences on slipping

Gait (or human motion) will depend on factors such mass, body shape and age and will be unique to an individual. The motion in which the foot contacts the floor is equally unique and can be both positive and negative with respect to the overall direction of motion [4]. There are four main stages during foot-floor contact namely impact, foot-flat, propulsion and toe-off. Slips typically occur at the initial impact stage, known as heel strike, where the foot generates a converging wedge and the area of contact is small. In the case of a fluid contaminant this promotes the formation of a fluid film and hydrodynamic lubrication. However the small area of contact and relatively large size of contaminant particles means any effect reducing friction will be significant.

Redfern *et al* [5] suggest that during walking on a horizontal surface the peak load (expressed as impact force per unit body weight) is approximately 10 NKg^{-1} (or roughly equal to body weight) occurring at 25% into the stance phase. However, the foot reaches the 'foot-flat' (FF) position approximately 15% into the stance phase at which point the reaction force is around 8.5 NKg^{-1}. The position of highest risk is likely to be just prior to this point, when the foot is still inclined to the floor. The pressure generated will depend upon the area of shoe in contact with the ground of which little literature is available (highly shoe and gait dependant).

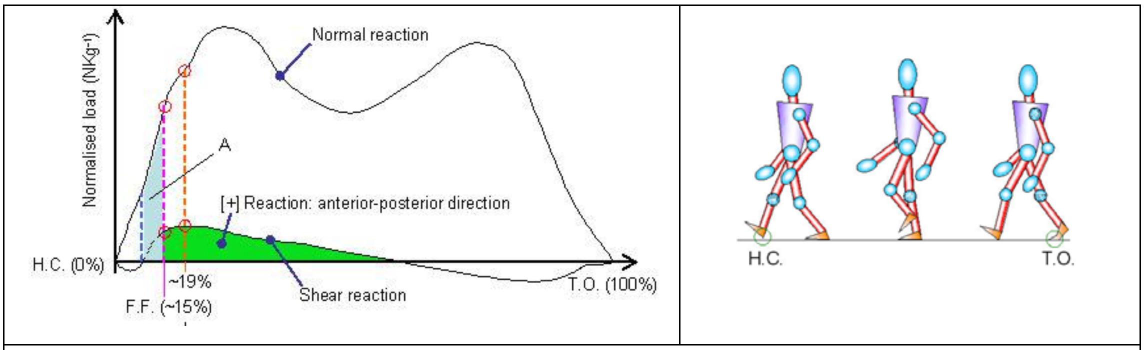

Figure [1]: Relative variation of normal and shear reactions over a single step [4]

Though the maximum shear force of approximately 1.5 NKg^{-1} occurs at a position 19% into the stance [5], the critical position in the stance where the shear to normal load ratio is largest and contact area smallest is likely to occur within the blue shaded region (A) of figure 1 (before FF), when the shear stress ranges from 0 to around 1.25 NKg^{-1}.

2. Apparatus – The Pendulum Friction Tester

Though there are many devices that have been developed to measure shoe floor friction [6] the pendulum friction tester (figure 2) is the standard piece of equipment used by the HSL to measure the friction characteristics of flooring materials. Though a complex device that requires a competent operator, the results are sufficiently repeatable and it performs adequately in both wet and dry conditions despite a high impact velocity of 3.2ms^{-1} [7] compared to actual human measurements of between 0.14 and 0.24 ms^{-1} [8]. The device consists of a tubular arm pivoted at one end and a foot and pad assembly at the other. The pad forms a converging contact with the floor with only the trailing edge in contact and has a width of 76mm and maximum length of 4mm. The materials used for the pads are dependant on the floor and shoe type being tested. The dominant materials used are the four-S and TRL grade elastomers with IRHD hardness of 96±2 and 55±5 respectively [9a]. The four-S type is used for cases where pedestrians will be wearing shoes and has properties that correspond to a typical shoe sole material. The TRL rubber is a softer compound, developed to mimic the behaviour of the softer human tissue of the heel and is used in such cases where the pedestrians will not have shoes (e.g. along the side of a swimming pool).

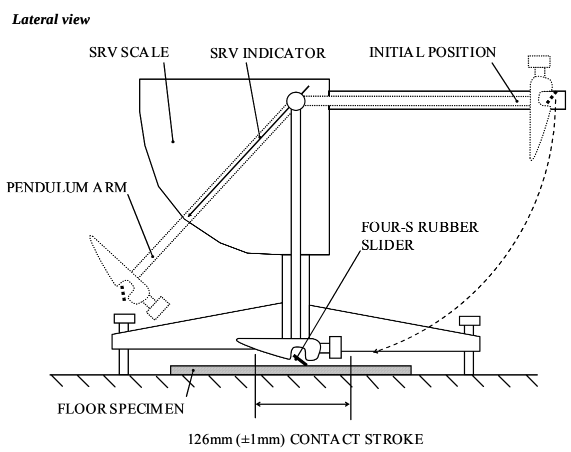

Figure 2: Schematic of the Pendulum tester

Normal loading of the pendulum

A long spring fitted within the tubular arm is linked to the pivoted pad, which is held in position by a stop. The length of the spring allows the assumption that the deflection of the pad over the contact strip causes negligible variation in the contact load. The load that is applied by the foot is fixed by the spring at 24.5N [9a] and corresponds to an applied contact pressure of 126KPa when the pad has a contact edge length of 2.33mm.

Operation of the pendulum

The device is set up on the floor and pivot height adjusted until the contact strip made by the pad has a length of 126 ± 1mm [9a]. The arm is held in a horizontal position and released via a mechanical catch. The pad then makes contact with the floor and is retarded according to the friction between floor and pad. The arm continues to rotate and the position of rest (marked by a needle) corresponds to a specific friction value termed the slip resistance value (SRV). The dynamic coefficient of friction can be calculated from the measured SRV using the empirical correlation:

$$\mu = \left(\frac{110}{SRV} - \frac{1}{3} \right)^{-1} \tag{1}$$

This method of measurement is essentially by energy loss meaning that accurate set-up is crucial to effective measurement. The catch release ensures that no variation in starting energy occurs which could cause false measurement.

Conditioning of the pendulum pad

In order to ensure repeatability between tests a conditioning procedure is applied to the elastomer pad. This involves setting the pendulum apparatus over a sheet of P400 abrasive paper and releasing the pad assembly several times. Following this the same procedure is carried out using 3μm lapping paper. The combined abrasion of these conditioning passes generates a reproducible surface finish to the impacting portion of the pad [9b].

Roughness measurements

Roughness measurements of the floor components were measured using a Mitutoyo profilometer. The roughness parameter R_z was used to characterise the floorings based on standard HSL procedure and suggestions that it correlates well with many floor friction apparatus measurements [10]. The value of R_z represents the mean peak-to-valley height of the asperities of the surface. It should be noted however that this does not have any information regarding the geometry of the asperities, nor their spatial frequency.

3. Particle Contamination of Smooth Floors

Smooth floors (R_z < 3μm) typically present the largest risk in water contaminated conditions where a full thickness hydrodynamic film can develop. In the context of particles a smooth, stiff floor presents the least resistance case. A floor of a roughness R_z of 0.5μm was tested to identify how the variation of particulate diameter affected the friction coefficient without the influence of roughness.

Test conditions and methods

The pendulum tester was positioned on a flat rigid surface and conditioned using HSL standard procedures. A section of tile was positioned below the slider assembly and pendulum strike length set to 126mm. The pendulum and slider were then thoroughly cleaned and dried. A dry, wet and contaminated test was carried out for each contaminant to act as controls. Thorough cleaning of contact surfaces was performed between each test to prevent cross contamination.

Particles were positioned on the surface of the tile using specially manufactured depth combs (0.5 – 2.0 mm) at the point of impact of the pendulum slider. Contaminants having mean diameters ranging from 5μm to 200μm were tested. All particles tested were calcite except for largest, which were silicon. An average of four sequential strikes was taken for each case (dry, wet and dry contaminated) and the mean recorded.

Results

Introduction of a small volume of contaminant into the shoe floor contact can have a significant effect on the available friction. Figure 3 shows the reduction in SRV for dry, water contaminated and solid particulate contaminated conditions. All contaminants tested caused a significant reduction in the friction with an average drop of 55 SRV points from a CoF of 0.93 to 0.21. The effect of the water contaminant is to lower the SRV by an average of 61 points which corresponding to a CoF drop to 0.15. This shows that particulate contaminants can have a comparable effect to fluid contaminants on smooth floors. All contaminants showed evidence of sliding with the pad during the contact period with the tile surface suggesting that no new material is entrained into the contact during the sliding process. The silicon generated a significantly larger friction than that seen with the calcite (35 as opposed to ~19). This is probably due to the friction coefficient of calcite against the counter-face being greater than that of the calcite, showing that the limiting friction is no longer dependent on the properties of the elastomer and only on those of the particles.

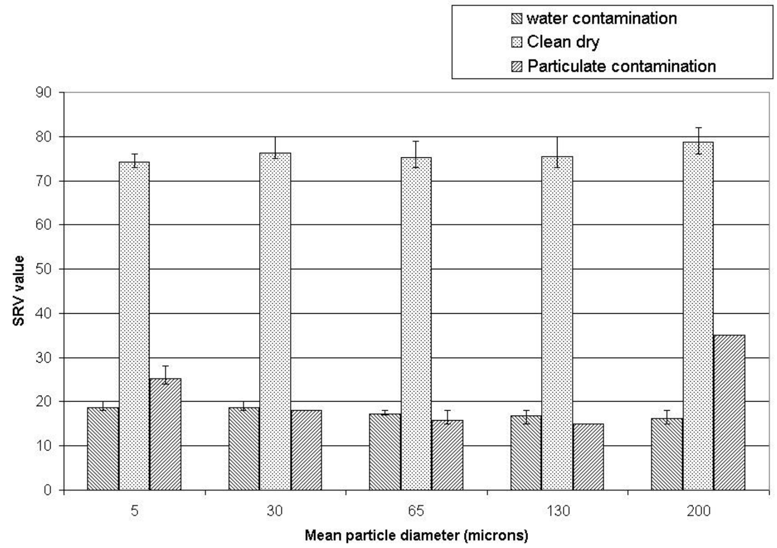

Figure 3: Effect of water and solid contaminant on SRV using pendulum method

4. The Effect of Floor Roughness

In the case of fluid contaminants roughness can help prevent full film hydrodynamic lubrication. In this boundary lubrication regime the asperities break through the film and make contact with the pad surface significantly increasing the available friction. Tests were carried out to prove a similar effect occurs with solid contaminants and how the particles can interlock with the roughness to increase the available friction.

Test conditions and methods

A set of tiles with increasing R_z roughness (0.51 to 34.2 microns) were tested using the pendulum tester with bicarbonate of soda particles having a mean diameter of 50 microns. The pendulum was set up in the same manor as for the smooth floor tests and subject to the same conditioning cycle. The conditioning cycle was repeated between each floor material to prevent any abrasive damage to the pad affecting the results of the next floor surface. Prior to tests with the contaminant, the tiles were tested in clean and dry conditions. The particles were spread with an even layer over the entire surface of the tile and a series of tests were carried out for each tile to generate an average SRV.

Results

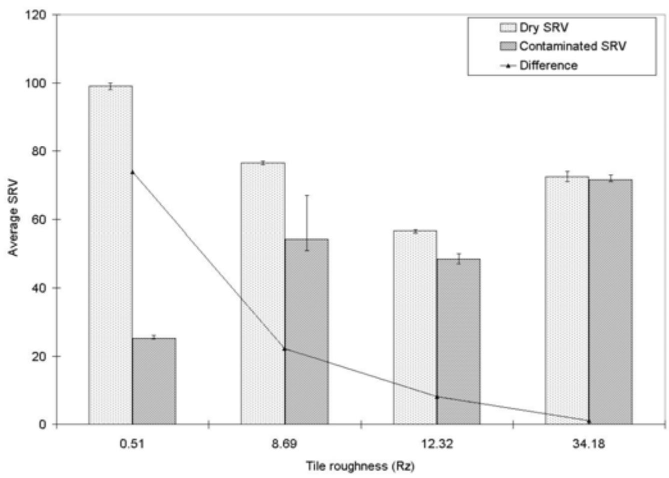

Figure 4: Effect of surface roughness (R_z) on contaminant significance

Floor surface roughness has a significant affect on available friction when contaminated with solid particles. Results suggest that though the available friction in the clean and dry conditions will be greater for a smoother surface, the effect of the contaminant on the reduction in friction will be more significant (figure 4). In the case of the smoothest tile, the reduction in friction was 73 points of the SRV scale (CoF 1.28 to 0.25) while in the case of the rougher tile this was a single SRV point (a CoF change of less than 0.02). A rough surface is able to cope much better than a smooth surface in the presence of a contaminant with the CoF being far more predictable. Once again the smooth tile showed signs of sliding on a layer of contaminant, however as the roughness of the floor surface increased this transitioned into a shearing type mechanism. This was characterised by abrasion of the layer and particles exiting at the rear of the pad.

5. Investigation of Lubrication Mechanisms

In tests carried out to identify the effect of particle size and roughness two different lubrication mechanisms were observed to occur. The first was pad sliding on a layer of contaminant and occurred for a smooth floor material. This was characterised by the formation of a clean path behind the pad where none of the contaminant was passing through the contact. When considering rougher floors, it was observed that the contaminant layer is subject to a shearing mode of lubrication with particles ending up in the path behind the slider. Here, the roughness acts to interlock with, or hold back the contaminant and abrades the lower surface of the layer. The final sets of experiments were performed to observe these different mechanisms occurring within a contact.

Test conditions and methods

A high speed camera was mounted below a plate of toughened float glass upon which the pendulum was set up. Contaminant powder was spread over the surface of the float glass and the pendulum was released while recording the impact region of the pendulum. Two focal distances were used enabling a wide field view of the strike from pad impact to lift off and a close-up view of the impact point only. Video was recorded at a rate of 2500 frames per second. Several different powder contaminants were tested including typical workplace contaminant such as flour and talcum powder. In addition to these, contaminants with certain shape factors were used. Glass ballotini (small spherical glass balls) having a shape factor greater than 0.95 and mean diameter of 500μm and sand having a shape factor closer to 0.8 and mean diameter of 1000μm were tested to identify the effect of shape for stiff particles. (XXX define shape factorXXX). The shape factor for a perfectly circular shape (in profile) is 1 whilst for a square profile this is 0.785.

Results:

Three mechanisms were identified depending on the size and shape factor of the particles and the floor roughness, sliding, shearing and rolling / tumbling. Figure 5 schematically shows these mechanisms. For the finer powders below a diameter of approximately 50 – 60µm, the sliding mechanism dominated with a layer of contaminant forming on which the pad would slide. Very little contaminant was observed in the wake of the slider and any that was present came from being picked up by the turbulent air currents immediately following the pendulum.

This contrasts with the particle layer shearing mechanism. Here the relative motion between the pad and the floor was accommodated by the contaminant layer itself shearing. Though the shearing method was less pronounced owing to the fact that the smoothness of the float glass (<0.5µm), a certain degree of shear thinning was still observed for particles above a mean particle diameter of 50 – 60µm.

The larger ballotini particles showed a further mechanism type by rolling through the contact patch and emerging to the rear of the pad. No layer was able to form and instead the distance between pad and floor was maintained at the diameter of the ballotini.

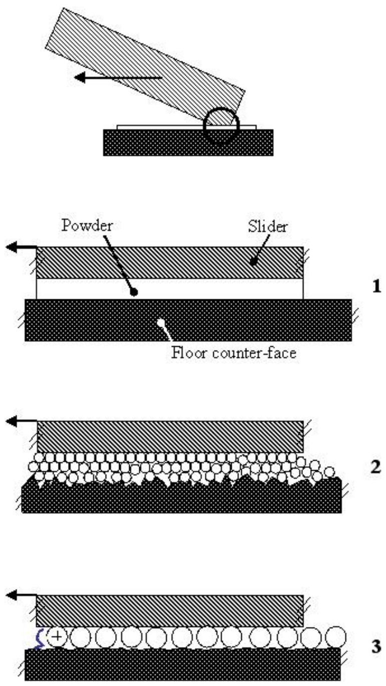

Figure 5: Lubrication mechanisms observed in the pad – floor contact: 1. Sliding, 2. Shearing, 3. Rolling

6. **Discussion**

Particle size and floor roughness

The results observed on floors of varying roughness and for particles of varying diameter can be explained using the idea of adhesive and hysteretic friction. Adhesive friction between an elastomer and surface is the result of material interactions at a molecular scale. Electrostatic interactions between an elastomer and a counter-face are typically strong due to their molecular chain structure and ability to conform to a corresponding surface [11]. Adhesion is particularly strong in the case of very smooth materials, where this compliance of the elastomer creates a large contact area. The introduction of contaminant particles acts to separate the elastomer from the surface and if there is a sufficient particle covering to prevent deformation allowing contact between particles, there is the potential for no elastomer-floor contact at all. In these cases the limiting friction coefficient will be that between the particle and floor and if the particles are sufficiently stiff, the total contact area between floor and particle has also the potential to be small.

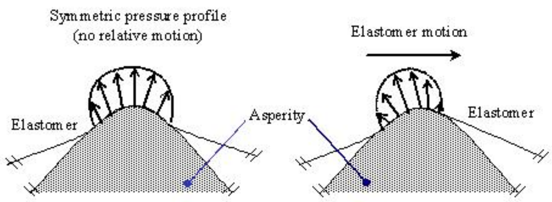

Figure 6: Asymmetric contact pressure generating hysteretic losses

Experiments considering variations in roughness suggest that hysteretic friction is far less sensitive to the introduction of contaminant particles. A rough floor will typically have a smaller contact area than the equivalent smooth floor. The asperities of a rough surface will cause separation of the surface and elastomer. Though the compliance of an elastomer allows a degree of deflection around the asperities and to partially conform with the roughness, there can still be a significant area of elastomeric surface that is not in contact. However this deflection around the asperities creates a contact pressure profile that is not entirely normal to the overall direction of the applied load. When the elastomeric surface is stationary, any lateral loads generated are balanced. As a load is applied in a direction that is parallel to the overall line of the surface, the pressure profile around the asperities must skew to balance the applied lateral force (figure 6). If the limiting frictional force is reached and the elastomer starts to slide, material ahead of the asperity must compress, while material behind must expand. Since the majority of elastomers exhibit strong visco-elastic behaviour, the energy required to compress the elastomer ahead of the asperity is less than that released behind the asperity. This loss of energy (together with phenomena such as abrasion) are macroscopically realised as friction.

The introduction of particles into a rough contact (where the diameter of the particles is comparable to the dimensions of the roughness) means that they cannot simply slide over the flooring surface. A degree of mechanical interlocking occurs which either requires the continual deformation and release of the elasomer as the particles slide over the asperities or can prevent the particle from moving at all, in which case a shear thinning effect occurs and the layer of contaminant particles thins to the point where elastomer-asperity contact is remade. In both cases energy is lost, which manifests itself as an increase in friction coefficient. As roughness increases, the dependency on the adhesive component of friction decreases and this is why the introduction of a contaminant has a much smaller effect on the level of available friction.

Cohesion of powders and its affect on the mechanisms of lubrication

The cohesiveness of a powder is a measure of its mechanical shear strength along a line within the powder. When the shear strength is reached, relative particle motion occurs and particles move relative to each other on either side of the shear plane. Orband *et al* [12] documented that there was a critical particle diameter below which the shear strength rapidly increased (between 50 and 60μm). Simple uniaxial compression tests used to measure the volumetric strain were performed on the contaminants used in this study and the results backed up this finding. Figure 7 gives the volumetric strain against particle size for the different contaminants.

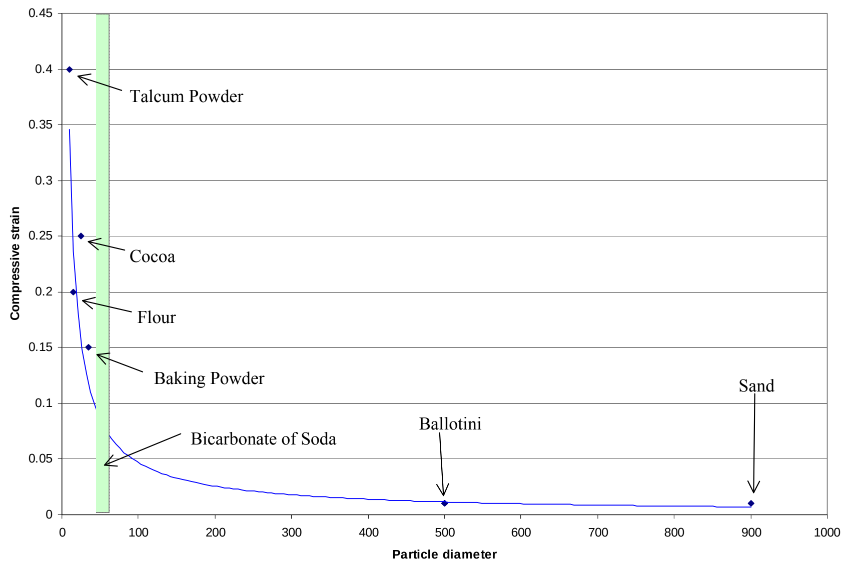

Figure 7: Cohesion strength of typical contaminant particles

This has direct implications for the mechanisms of lubrication as below this limit, the particles are unable to act as individual entities and instead form layers of high inter-particle shear strength.

Lubrication mechanisms observed

Sliding

Powders with a mean particle diameter below 50-55μm showed a sliding lubrication mechanism on floors. This involved the compression of the particles at impact into a thin layer capable of maintaining its structure. This ability to maintain structure is likely to be due to the cohesiveness of the particles where each is electrostatically attracted to its neighbour. In forming this layer structure, no contact between the elastomer and surface occurred. The friction coefficient of the contact was dependant upon that of the floor and powder material only. In addition to this, it was observed that the compressive layer of powder prevented the entrainment of new powder with any material ahead of the pad being simply swept forward. In the wake of the pad, there was no contaminant on the glass surface at all meaning that whatever material was under the pad at impact remained so until lift off. This is a significant finding as it implies that contaminant is required only at the point of impact of a shoe with a sufficiently smooth floor. If a slip is initiated, the pad does not require a continuous entrainment of new contaminant to maintain the reduced friction coefficient.

The limiting shear strength is that between the floor and particles

$$\tau_{p\text{-}e} > \tau_{p\text{-}f} < \tau_{crit} \tag{2}$$

Where $\tau_{p\text{-}e}$ is the interfacial shear strength at the particle-elastomer boundary, $\tau_{p\text{-}f}$ the interfacial shear strength at the particle-floor boundary and τ_{crit} is the inter-particle shear strength of the compressed powder layer.

Shearing

As the roughness of the floor increases a shearing mechanism starts to take place. The contaminant is compressed at the contact and if the friction coefficient between floor and contaminant is less than contaminant and elastomer, it will move with the shoe. However, the roughness of the floor prevents the sliding of particles and acts to abrade particles from the lower surface of the layer. This abrasion reduces the thickness of the layer and can cause re-contact of the elastomer and floor. This mechanism is not self-sustaining – it would require the continual entrainment of new material for the slip to be maintained.

The shear yield stress of the powder controls the available friction

$$\tau_{p\text{-}e} > \tau_{crit} < \tau_{p\text{-}f} \tag{3}$$

Rolling / tumbling

As particle size and shape factor increases, a rolling or tumbling mechanism dominates. Particles roll beneath the shoe, which in the case of highly spherical particles, can cause a significant reduction in available friction. As with the shearing mechanism, continual entrainment of particles is required for the slip to be maintained. In all cases where there is rolling motion of the particle, the forward velocity of the particle will be lower than that of the elastomer. In the test involving ballotini (very high roundness), particles could be seen to be travelling through the contact and were visible in the track behind the swept path of the pad.

Slip Mechanism Map

Figure 8 maps the regions of slip mechanism observed during the tests outlined. The critical diameter, d_{crit} represents the limiting diameter above which the cohesive forces of many powders become less important and their behaviour is more discrete in nature. Findings suggest that the critical diameter tends to determine whether a particle is able to behave discretely or whether it is strongly affected by the particles surrounding it. In the case of $d<d_{crit}$ on a floor of sufficient roughness the particles tend to clump together and pass through the contact in a shearing action. However above this limit, the particles behave in a more discrete fashion and are able to roll / tumble through the contact independently of other particles. There is an additional roughness limit, observed empirically, of around 15μm below which both the shearing and tumbling mechanisms transition to the sliding mechanism. If the roughness is small it cannot generate the sufficient 'interlocking' forces required to abrade a layer that has formed, or allow all but the roundest particles to roll/tumble. Shape factor is likely to shift this roughness dependant transition. Particles of higher roundness will have a tendency to shift the roughness boundary downwards (rolling becomes more favourable) and the converse is true for 'squarer' particles of lower shape factor. It is also suggested that below d_{crit} shape factor will have much less of an effect.

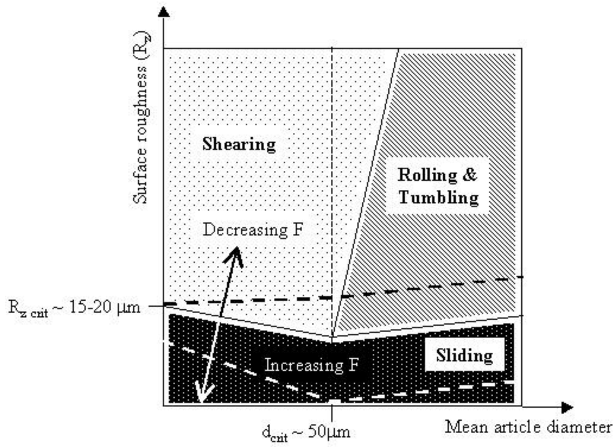

Figure 8: Map of lubrication regions observed in the experiments for a range of floor roughness, *Rz*, particle size, *d* and shape factor, *F*.

7. **Conclusions**

The adhesive component of friction between the elastomer and floor is significantly disrupted by the presence of the contaminant particles. Without the molecular interaction that occurs in clean, dry conditions on smooth floors (in the order of a few microns), the available friction is governed by the interaction between particles and floor material (which can be significantly less). As the roughness of the floor increases, the deformation of the elastomer around the asperities causes hysteretic losses as the loaded elastomer is passed over the floor. Though in clean dry conditions the available friction generally varies inversely with roughness (due to the smaller real contact area), so to does the difference between clean, dry conditions and contaminated conditions. This suggests that it is roughness that plays the dominant role in determining slip resistance of a floor (assuming that the floor material is significantly stiffer and harder than the elastomer).

Small particles are able to adhere to the soles of shoes allowing transference of the contaminant and increased risk of slipping for many steps. This results for high adhesion force between particles and elastomer.

Three significant lubrication mechanisms were observed within the contact; sliding, shearing and rolling/tumbling. Sliding occurs when the surface is smooth typically with a surface roughness (R_z) of less than 15 – 20μm. In this case, the contaminant on which the pad sits forms a layer that moves with the pad. This is due to the higher shear strength at the particle-elastomer boundary than at the particle-floor boundary. For a layer of depth greater than the diameter of the particles the inter-particle shear strength must also be greater than that at the particle-elastomer interface. Due to the contaminant remaining fixed with respect to the pad, contaminant is required only at the point of impact and no new material will be entrained into the contact.

Shearing of the contaminant layer typically occurs when the floor roughness increases past 20μm. In this case, the floor is sufficiently rough to prevent the particles passing over the asperities and a proportion will become trapped in valleys and not move with the pad. In this situation, particulate material will be lost to the rear of the pad as it passes and so the layer will reduce in thickness. This essentially means that either a constant supply of contaminant will be required to maintain lubrication or the pad will eventually break through the layer and make contact with the floor. Of the three mechanisms, shearing has the least effect on friction and presents the lowest risk to a pedestrian.

Rolling or tumbling occurs when the particles are sufficiently large so as not to clump together, this occurs past the cohesive limit which has been observed in particles of mean diameter above 50 – 55μm. In addition, for all but the most spherical particles a degree of roughness is required to generate a interlocking effect allowing the particles to roll over the surface of the floor, rather than sliding. The particles will move relative to both floor and pad and will be ejected from the rear of the pad. As a result a constant supply of contaminant is required to maintain the reduced friction.

Larger depths of particles can cause transitions in mechanisms, commonly shearing to sliding and shearing to rolling/tumbling.

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