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A study of Pendulum slider dimensions for use on profiled surfaces

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Research Report

A study of Pendulum slider dimensions for use on profiled surfaces

Mr Kevin Hallas
Mr Graeme Hunwin
Health and Safety Laboratory
Harpur Hill
Buxton
Derbyshire
SK17 9JN

In the UK, slip and trip accidents lead to more RIDDOR reportable major injury accidents in the workplace than any other type of accident. Approximately three quarters of these accidents are slips, and the remaining quarter are trips. In order to understand the underlying causes of these accidents, it is important to be able to accurately assess the slip resistance of floor surface materials. The Health & Safety Executive (HSE) currently favours the 'Pendulum' coefficient of friction test for the assessment of pedestrian slip risk in 'on-site' conditions. In some workplace situations, more complex floor surfaces are specified, these can include profiled floor surfaces, where a raised pattern is perceived to give enhanced slip resistance. The materials tend to be resistant to contaminants and corrosion, so they are often used where significant contamination occurs. It is appreciated that the slip resistance reading obtained with the pendulum can be erroneously influenced by the pattern of profiled surfaces, unless used by an operator with significant expertise.

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EXECUTIVE SUMMARY

In the UK, slip and trip accidents lead to more RIDDOR reportable major injury accidents in the workplace than any other type of accident. Approximately three quarters of these accidents are slips, and the remaining quarter are trips. In order to understand the underlying causes of these accidents, it is important to be able to accurately assess the slip resistance of floor surface materials. The Health & Safety Executive (HSE) currently favours the 'Pendulum' coefficient of friction test for the assessment of pedestrian slip risk in 'on-site' conditions. In some workplace situations, more complex floor surfaces are specified, these can include profiled floor surfaces, where a raised pattern is perceived to give enhances slip resistance. The materials tend to be resistant to contaminants and corrosion, so they are often used where significant contamination occurs. It is appreciated that the slip resistance reading obtained with the pendulum can be erroneously influenced by the pattern of profiled surfaces, unless used by an operator with significant expertise.

Objectives

To gain a better understanding of how the squeeze-film thickness changes when the dimensions of the Pendulum slider are changed

To evaluate the adjustments needed to enable the pendulum to be operated with reduced slider dimensions.

Main Findings

The thickness of the squeeze-film is far more dependent on the slider length than the slider width. The change in the film thickness allowed by the current UK Slip Resistance Group guidelines could affect readings on floor surfaces with surface microroughness comparable with the squeeze-film thickness.

To compensate for a reduction in the width of the pendulum slider from 76mm to 38mm, the slider length must be increased by 1mm. No further adjustment to the pendulum operation is required.

When measuring profiled surfaces, the slider width and direction of travel should be selected to minimise the interaction of the slider with the profile.

The reduced width slider would allow small areas of other types of surface to be evaluated such as stair nosings, which are often less than 76mm wide.

Recommendations

The UK Slip Resistance Group guidelines should consider the change in squeeze-film thickness over the allowed slider length range, as it can significantly affect slip resistance readings on certain surfaces.

The UK Slip Resistance Group should consider including the use of reduced width sliders in future guidelines for the operation of the pendulum tester.

1 INTRODUCTION

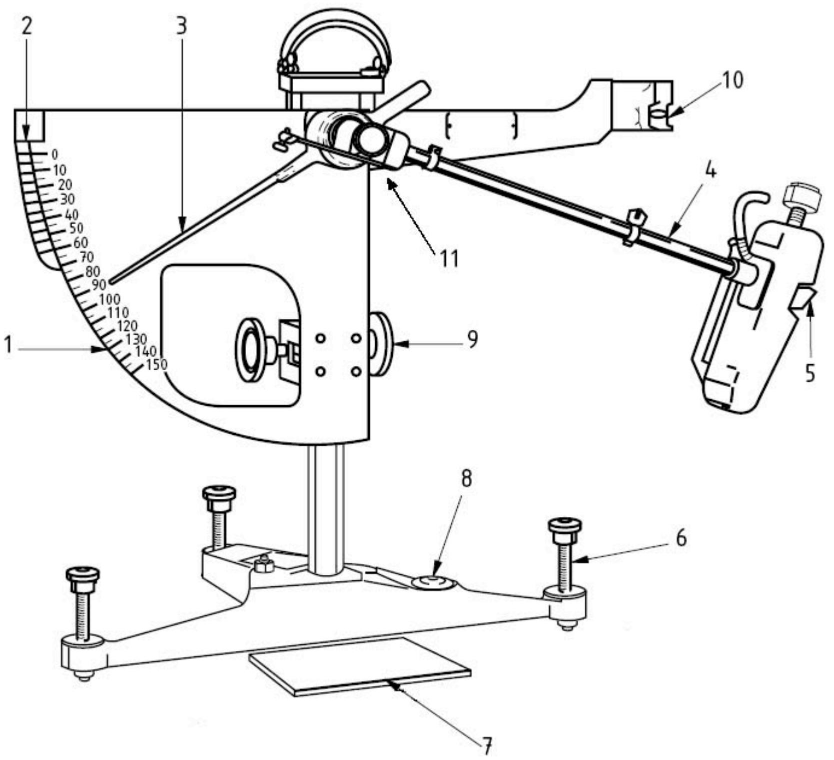
In the UK, slip and trip accidents lead to more RIDDOR reportable major injury accidents in the workplace than any other type of accident. Approximately three quarters of these accidents are slips, and the remaining quarter are trips. In order to understand the underlying causes of these accidents, it is important to be able to accurately assess the slip resistance of floor surface materials. On simple surfaces that are flat and homogeneous, measuring the slip resistance is relatively simple. The Health & Safety Executive (HSE) currently favours the 'Pendulum' coefficient of friction test for the assessment of pedestrian slip risk in 'on-site' conditions. As such, HSL scientists routinely use the pendulum instrument during forensic assessments following workplace slip accidents. In some workplace situations, more complex floor surfaces are specified, these can include profiled floor surfaces, where a raised pattern is perceived to enhance slip resistance. Quite often these materials are used for steps, stairs, platforms and ramps, as they are readily available and easy to work with. The materials tend to be resistant to contaminants and corrosion, so they are often used where significant contamination occurs, for example, as access ramps and fire escapes outside buildings or raised platforms in abattoirs and other food premises. It is appreciated that the slip resistance reading obtained with the pendulum can be erroneously influenced by the pattern of heavily profiled industrial surfaces, such as durbar or five-bar chequer-plate, unless used by an operator with significant expertise. This work, as requested by the HSE client, will serve to increase the validity of the information produced by the pendulum in such conditions, and so will increase the confidence of HSL forensic scientists during the assessment of heavily profiled surfaces.

2 THEORY

The TRL Pendulum (Fig. 2.1) is a portable instrument used to assess floor surface slip resistance. During a measurement, a weighted Pendulum arm (4), which rotates about a spindle at the Pendulum head (11), is released from a horizontal position via a release mechanism (10). A sample of prepared test rubber (known as a slider), attached to the pendulum arm by the slider assembly (5), is drawn a fixed distance across the test surface (7), as the arm swings through an arc. The loss of energy experienced by the Pendulum arm as the slider passes across the test surface is indicated by the height the arm reaches during the upward phase of the swing. A pointer (3) indicates the measurement result, known as the Pendulum Test Value (PTV), upon a scale (1). The PTV is closely related to the Dynamic Coefficient of Friction (which is a measure of the frictional force necessary to maintain sliding, and is a ratio of the frictional (or shear) force to the normal load). The PTV is normally expressed as a measure of slip resistance, as the test is usually carried out on contaminated surfaces.

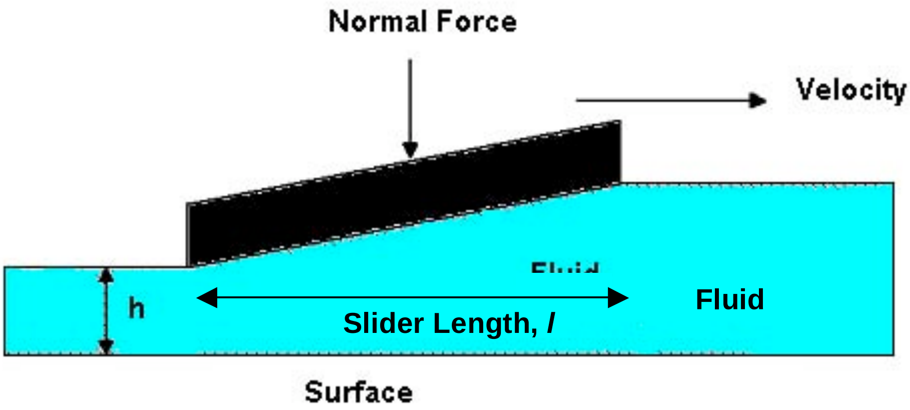
Measurements of floor surface PTV were made using a pendulum calibrated by the British Standards Institution. The test slider material used was Slider 96, also known as Four-S rubber (Standard Simulated Shoe Sole), developed by the UKSRG to represent a footwear material of moderate performance.

Figure 2.1 Slipperiness assessment test methods; the TRL Pendulum CoF test. (Diagram adapted from BS 7976-1:2002 Pendulum testers – Part 1: Specification).



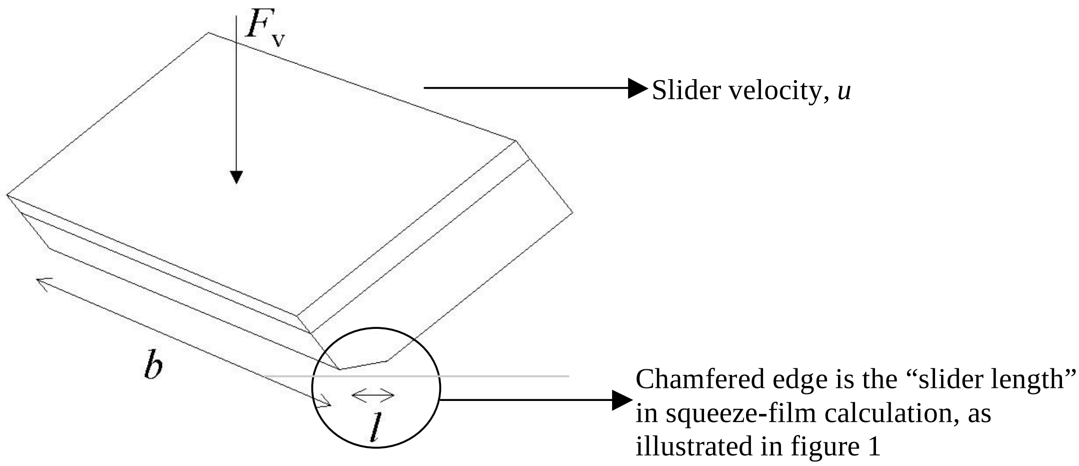
The theory of squeeze-film formation, with respect to the Pendulum, was developed from the hydrodynamic theory of a tapered wedge described by Fuller (1956). In hydrodynamic lubrication, the two surfaces, between which the fluid film forms, are not parallel, i.e. they converge (see figure 2.2). If the inclined surface moves relative to the stationary surface below, which is covered with a lubricating fluid, the liquid is drawn into the converging gap between the surfaces. If the relative velocity of the two surfaces is sufficient, the hydrodynamic pressure generated within the fluid supports the load of the upper surface, reducing the contact between the two surfaces, and therefore reducing the friction between them. When the relative velocity is high enough, the thickness of the fluid film is enough separate the two surfaces completely.

Figure 2.2 Squeeze-film formation



When applied to the action of the Pendulum, the conditioned edge of the slider forms a very small converging gap with the test surface. As the slider passes over the test surface, the fluid film partially reduces the contact between the slider and the asperities of the test surface, thus reducing the dynamic friction measured.

Figure 2.3 Schematic showing slider dimensions, vertical force and velocity terms



This is the model Proctor and Coleman (1988) used for predicting how the fluid film is affected by changes to the surfaces, relative velocity and lubricating fluid. The equation below has been used to estimate how changing the slider dimensions affect the formation of the fluid film, and thus the measured friction, or PTV. In this simplified model it has been assumed that there is no deformation of the slider during the formation of the fluid film. The thickness of the fluid film produced, h, is described below;

$$h^2 = \frac{6u\eta l^2 b K_E}{F_v} K_p$$

where;

h = thickness of the fluid film at the exit of the converging surfaces

u = velocity of the slider relative to the surface below

η = viscosity of the fluid

l = slider length

b = slider width

K_E = correction factor dependant upon the ratio of the slider width to the slider length

K_p = correction factor to allow for the pressure variation

F_v = vertical force of the fluid

In applying the model to the Pendulum, with water as the lubricating fluid, the following variables were used; u = 2.7 ms^{-1}, η = 1 x 10^{-3} Nm^{-2}, K_E = 1, K_p = 0.025, and F_v = 24.5N. The terms b and l were varied to explore the effect on the squeeze-film thickness.

Firstly, the effect of slider length was calculated. The UKSRG guidelines used currently limit slider length to the range 1mm – 4mm. Slider lengths shorter than 1mm are not practical so were not considered, but slider lengths much longer than 4mm were considered (see figure A1, appendix A). The squeeze-film thickness is relatively sensitive to the changes in slider length, even within the current 1mm – 4mm operating range. It should be considered that the practical implications of this are only significant on floor surfaces where the roughness of the floor is comparable with the thickness of the fluid film.

The effect of slider width was then considered at four slider lengths. The squeeze-film thickness is not particularly sensitive to slider width (see figure A2, appendix A). This indicates that reducing the slider width need not unduly alter the squeeze-film thickness, and any change could be compensated by a small increase in slider length.

3 EXPERIMENTAL INVESTIGATION

Experimental work was undertaken to test the theoretical predictions of the squeeze-film thickness when both slider width and slider length were varied. Measurements were made using the pendulum tester, set up in accordance with BS7976: 2002 and the UK Slip Resistance Group Guidelines (UKSRG) 2005. Deviations from the standard operating protocols were made in order to explore the effects of slider length (the guidelines limit slider length to the range 1mm – 4mm) and slider width (the guidelines set this at 76mm). All measurements were undertaken in either dry or water-wet conditions, more viscous contaminants were not considered. Slider 96 rubber, also known as Four-S rubber (Standard Simulated Shoe Sole) was used throughout the study.

On a very small scale almost all surfaces are irregular or rough. The surface roughness is made up of asperities (higher regions or peaks) and valleys, which can be measured and used to characterise the surface through a number of different roughness parameters. The Rz surface roughness parameter is a measurement of the sum of the vertical distance between the largest peak height and largest valley depth within a single sample length. A single measurement is the mean Rz value from five separate sampling lengths.

Lapping films consist of a polyester backing film coated with particles of a mineral, such as aluminium oxide, and are used in a variety of applications to produce a precisely controlled surface finish. The precise control of the coating produces a surface that has a relatively homogeneous surface roughness. The lapping film was therefore selected because it would be a consistent surface between different samples, and sensitive to any variation in the thickness of the squeeze-film. The slider comes into greater contact with the lapping film at lower squeeze-film thickness, and less contact with greater squeeze-film thickness. Therefore, the level of friction measured with the pendulum should vary as the water squeeze-film is manipulated.

The effect of slider width on the squeeze-film thickness was then studied across a range of surfaces. Two slider widths were evaluated, the standard 76mm slider and one at half that width, 38mm. The slider length was carefully controlled to ensure that the slider length of the 38mm slider was always 1mm greater than the slider length of the 76mm slider. This compensation in the slider length gives the closest squeeze-film conditions for each surface. The floor surfaces used for this comparison ranged from 1.1μm Rz to 33.5μm Rz (see Table 1). The PTVs measured with the two sliders showed good agreement. A difference of 9 PTV was seen in the dry condition and of 6 PTV in the wet condition. Only two of the eleven readings showed a difference greater than 3 PTV between the measurements taken with the two sliders. The inhomogeneous nature of some of the samples, such as the conglomerate stone and terrazzo flooring would be expected to give some variation in the results, as the sliders sweep subtly different areas of the surface.

The effect of varying the slider length on the squeeze-film thickness, thus the PTV, was investigated using a slider 76mm in width and a slider 38mm in width. The slider length was carefully controlled to ensure that the slider length of the 38mm slider was always 1mm greater than the slider length of the 76mm slider. This compensation in the slider length gives the closest squeeze-film conditions for each surface. The floor surfaces used for this comparison ranged from 1.1μm R_z to 33.5μm R_z (see Table 3.1). The PTVs measured with the two sliders showed good agreement. A difference of 9 PTV was seen in the dry condition and of 6 PTV in the wet condition. Only two of the eleven readings showed a difference greater than 3 PTV between the measurements taken with the two sliders. The inhomogeneous nature of some of the samples, such as the conglomerate stone and terrazzo flooring would be expected to give some variation in the results, as the sliders sweep subtly different areas of the surface.

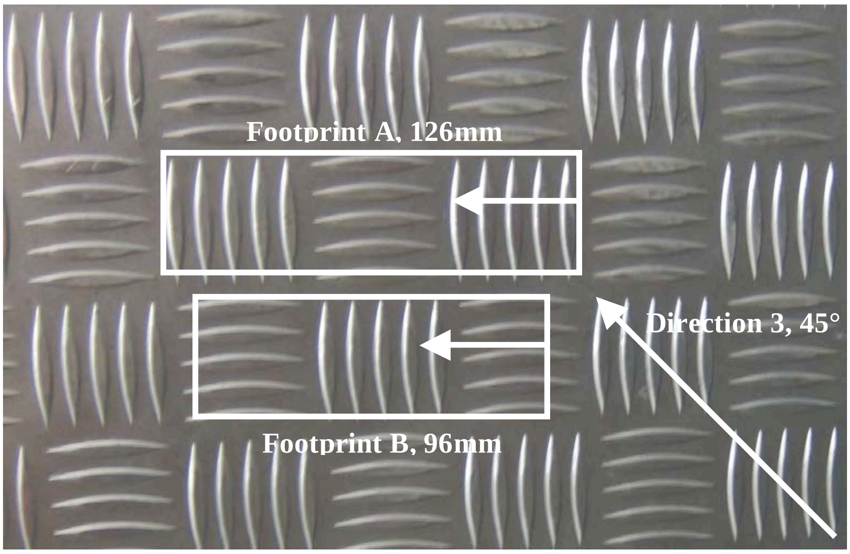
The results discussed above are considered to be validation of the theoretical predictions made in section 2. The results show that using a 38mm slider to measure the slip resistance of a flat floor surface gives broadly the same readings as using the standard 76mm slider. In addition to the work detailed below on profiled surfaces, the reduced width slider could be used on surfaces where the 76mm slider is wider than particular surface features. For instance, when measuring the slip resistance of stair nosings, feature tiles or defects in epoxy / aggregate coatings.

Table 3.1 Comparison of the PTV of a range of floor tiles with 76mm and 38mm sliders

Surface	Surface ID (Figure 4)	Rz (μm)	Mean PTV			
			Dry		Wet	
			76mm	38mm	76mm	38mm
White Granite	1	1.1	101	106	7	5
Conglomerate stone	2	1.7	62	71	8	5
Conglomerate stone	3	5.0	62	59	24	19
Ceramic	4	10.4	59	61	37	40
Terrazzo	5	11.2	62	63	38	32
Ceramic	6	11.2	60	57	33	34
Ceramic	7	11.6	61	62	36	35
Quarry tile	8	14.3	61	61	49	50
Textured ceramic	9	19.1	55	55	29	30
Textured ceramic	10	24.7	61	60	19	21
Ceramic	11	33.5	66	68	60	63

The raised patterns on flooring can challenge the pedestrian, where the slip resistance of the floor can be quite different from one heel-strike to the next. The surface where this is most obvious is on aluminium chequer plate, where five ridges run parallel, with adjacent sets of five ridges perpendicular to the next. Heel strike along the length of the ridge may give little slip resistance, whereas heel strike across the ridge may give greater slip resistance. In order to measure a single feature within the surface, the 38mm slider was used with two footprints:

Figure 3.1 Showing footprints of pendulum tests



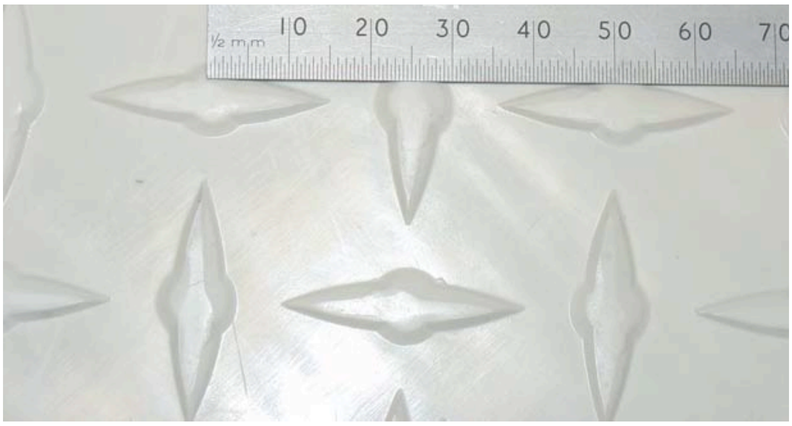
Pendulum measurements using the 38mm slider with footprint A (see figure 3.1) gave a PTV of 42 in water-wet conditions. Measurements with footprint B gave a PTV of 26, which when corrected for the length of the footprint, gave a PTV of 34 for this combination of features. The short footprint was necessary to avoid striking the perpendicular ridges at either end. Based on these two sets of readings, the PTV has been calculated for the following theoretical surfaces to understand how the different features behave:

Figure 3.2 All ridges perpendicular to direction of travel of the slider, calculated PTV = 50 in water-wet conditions

Figure 3.3 All ridges parallel with direction of travel of the slider, calculated PTV = 26 in water-wet conditions

Measuring the PTV of this surface at 45° with either the 76mm or 38mm slider in water-wet conditions gives a reading of 27, suggesting that the 45° measurement is very close to the worst-case scenario for this flooring material. The narrow slider may be useful in separating the slip resistance effects of small regions of other profile patterns.

Figure 3.4 Durbar surface



The two widths of slider were used to measure the slip resistance of the durbar surface shown in Figure 3.4. The material is a white plastic flooring with raised bars in alternating directions. In the water-wet condition, the 76mm slider gives a PTV of 24, suggesting that the surface presents a high slip potential. When measured with the 38mm slider in the water-wet condition, a PTV of 30 was obtained initially. It was noted that the slider rolls about its mounting point on the pendulum arm, perpendicular to the direction of travel. When the position of the slider was reset between each swing, the PTV in wet conditions was 27. It would appear that the reduced width of the slider allows greater interaction with the surface profile; therefore the pendulum looses more energy as it traverses the floor material. On this type of material, the ability of the standard 76mm slider to bridge several raised bars minimises the interaction with the profile and is likely to give a reliable worst-case reading for these floor surfaces.

4 CONCLUSION

The thickness of the squeeze-film is far more dependent on the slider length than the slider width. The change in the film thickness allowed by the current UK Slip Resistance Group guidelines (1mm – 4mm slider length) could affect readings on floor surfaces with surface microroughness comparable with the squeeze-film thickness.

To compensate for a reduction in the width of the pendulum slider from 76mm to 38mm, the slider length needs to be increased by 1mm. The adjustment to the slider length required for other slider widths can be taken from figure A2. No further adjustment to the pendulum operation is required.

When measuring profiled surfaces, the slider width and direction of travel should be selected to minimise the interaction of the slider with the profile.

The reduced width slider would allow small areas of other types of surface to be evaluated, such as stair nosings, feature tiles and defects in epoxy aggregate floors, which are often less than 76mm wide.

Recommendations

The UK Slip Resistance Group guidelines should consider the change in squeeze-film thickness over the allowed slider length range, as it can significantly affect slip resistance readings on certain surfaces.

The UK Slip Resistance Group should consider including the use of reduced width sliders in future guidelines for the operation of the pendulum tester.

5 APPENDIX A

Figure A1 Predicted variation of water squeeze-film thickness with slider length

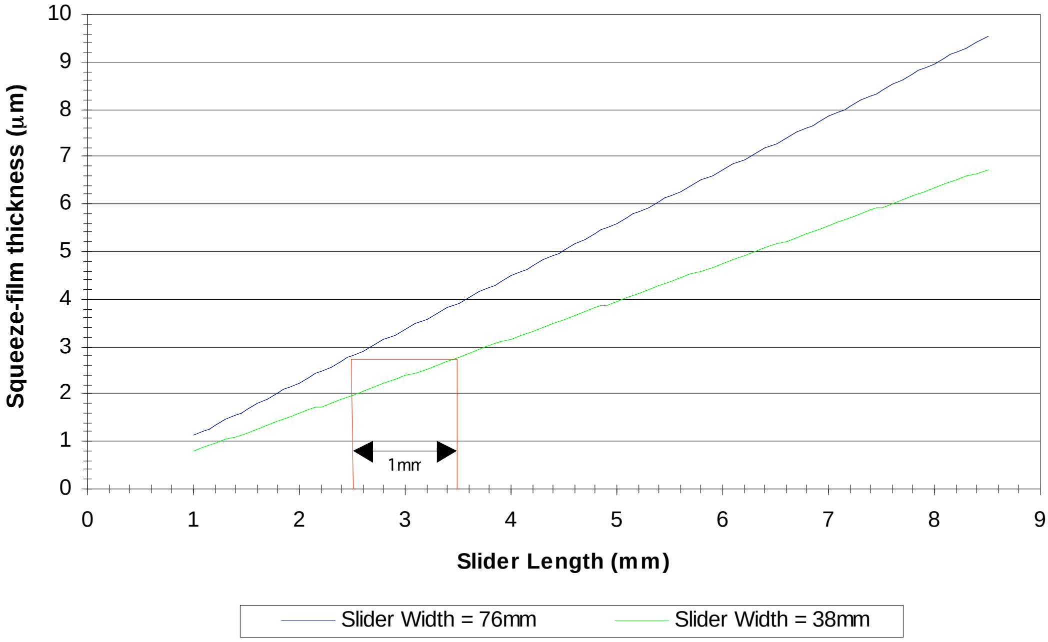


Figure A2 Predicted variation in water squeeze-film thickness with slider width

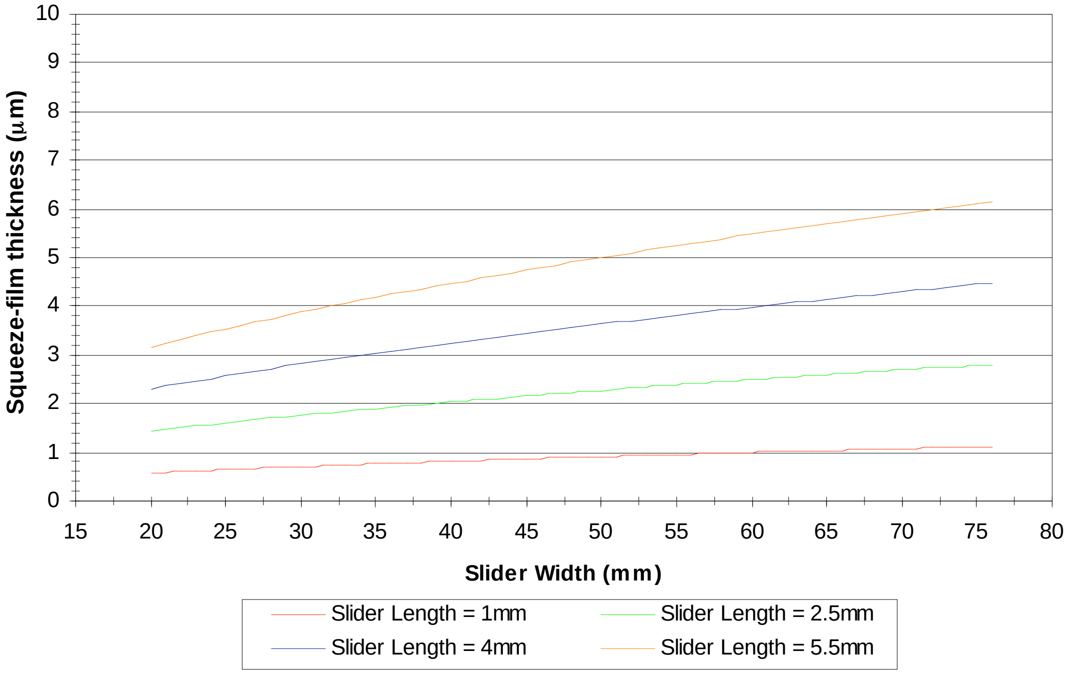


Figure A3 Variation of PTV in wet condition with Slider Length
on Lapping Film of R_z = 2.0 µm and Ceramic Tile of Rz = 8.0 µm

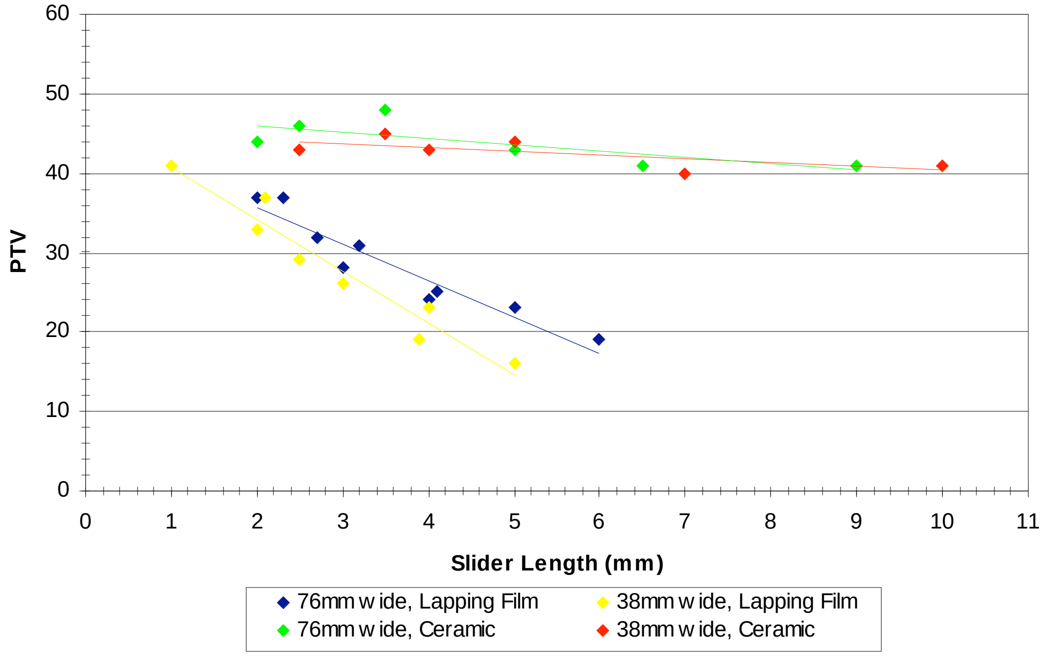
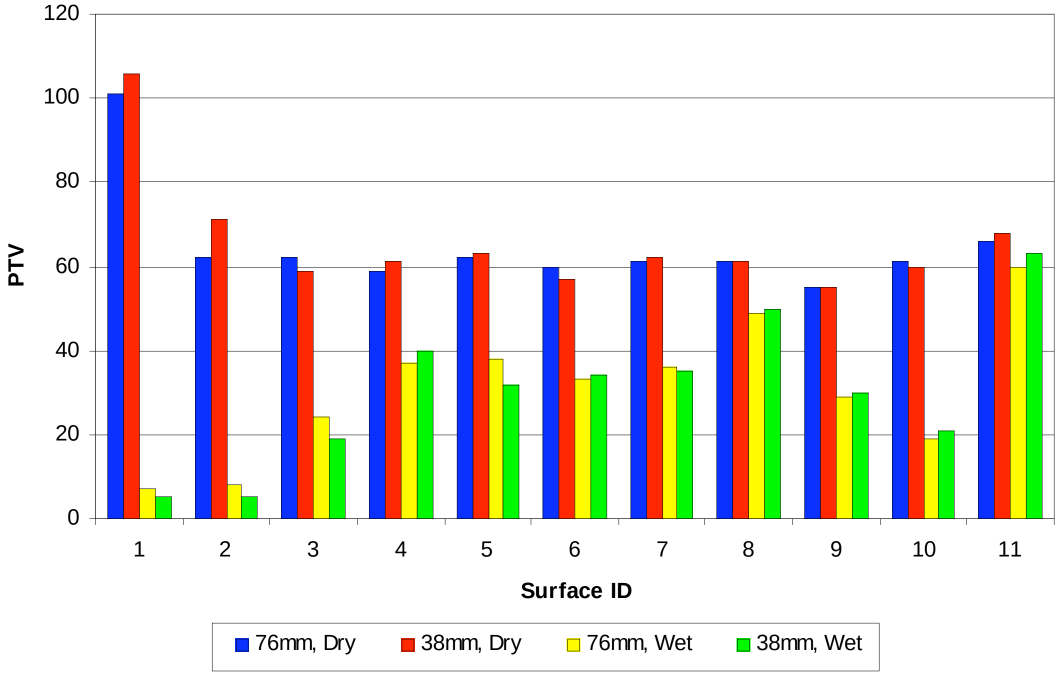


Figure A5 Comparison of 38mm and 76mm slider PTVs
upon surfaces of various R_Z surface roughness values



6 REFERENCES

BS 7976-1:2002 Pendulum Testers - Part 1: Specification, British Standards Institute, ISBN 0580401448, 2002.

BS 7976-2:2002 Pendulum Testers - Part 2: Method of Operation, British Standards Institute, ISBN 0580401456, 2002.

BS 7976-3:2002 Pendulum testers. Method of calibration, British Standards Institute, ISBN 0580401464, 2002.

Fuller, D.D., 1956, Theory and Practice of Lubrication Engineers, WILEY, New York.

Lemon P. and Griffiths S., 1997, Further Application of Squeeze Film Theory to Pedestrian Slipping Research, HSL Internal Report, IR/L/PE/97/9.

Proctor, T.D. and Coleman, V., 1988. Slipping, Tripping and Falling Accidents in Great Britain – Present and Future, Journal of Occupational Accidents, 9: 269-285.

Richardson M.T. and Griffiths R. S., 1996, The Application of Squeeze Film Theory to Pedestrian Slipping Research, HSL Internal Report, IR/L/PE/96/4.

UKSRG, The assessment of floor slip resistance, The UK Slip Resistance Group Guidelines, Issue 3, 2005.

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