Understanding Pedestrian Slipping

A guide by Dr Malcolm Bailey

Contents

2

Introduction

Pedestrian slipping accidents cost the UK over £1 billion each year.

In addition, the victims of such accidents often receive life changing injuries as they tend to land heavily on the base of their spine and can suffer irreparable nerve damage. The sad thing is that many of these accidents are avoidable if only those who are responsible for specifying and maintaining floors understood why such slips take place. This booklet has been written to bring such understanding to those who have such a responsibility including those responsible for the general safety of the building's occupants.

Pedestrian slipping is all about friction. Many people can remember being taught about friction at school in physics lessons. In the first chapter the fundamental aspects of the subject as it relates to pedestrian slipping will be described. Subsequent chapters discuss the problems when water or another lubricant becomes involved and the complications this introduces in measuring the resistance a particular surface may provide against a pedestrian slipping over.

The subject of how much friction a pedestrian needs is set out in chapter 3, and chapters 4, 5 and 6 include advice as to how you can use testing to ensure that your floors are safe and kept safe for people to walk over.

Appendix A describes a number of slip test machines in common use. No doubt someone will suggest that a specific machine should be used; this will help to explain why that machine may not do what it claims. Appendix B explains in detail how the hydrodynamic film works and how it relates to the proportional uplift discussed in Chapter 3.

1. Friction

When two surfaces are placed in contact with each other, for instance a block of metal on a table, if one tries to slide that block of metal across the surface of the table, then friction is brought into play. Essentially, friction is generated in order to try to prevent the two surfaces sliding relative to each other. The block of metal will only move or start to move when a sufficiently large horizontal force is provided to overcome the maximum value of friction that the combination of the block and the table can provide.

The amount of friction critically depends firstly on the force which is holding the two surfaces in contact, in this example, the weight of the metal block, and secondly a very complex relationship between the two materials. It is so complex that the only practical way of discovering what that relationship is in that particular set of circumstances is to physically carry out a test. However this does not hinder us from being able to calculate and predict what level of friction will be involved in a similar set of circumstances.

The way that this is done is via a parameter called the coefficient of friction. This is the amount of friction provided by the two sliding components along the plane of contact, divided by the force which is holding them together. It is essential to understand that the coefficient of friction (CoF) is not a physical property of either or both of the materials involved – it is simply a tool that can estimate the level of friction likely to be involved in a particular set of circumstances.

There are essentially two values for which the coefficient may be used in any calculations, and it is important to understand the difference between the two. The first is defined as the **limiting static coefficient of friction** for a particular pair of materials. This is numerically the maximum amount of friction that the system can provide before the two surfaces start to slide relative to each other, divided by the force holding them together. The second is the **dynamic coefficient of friction**. This is the amount of force which is developed between two surfaces when they are moving at a particular speed, divided by the force holding the two surfaces together. Thus it is the amount of force which needs to be provided to keep the two surfaces sliding at a particular speed.

In practical terms, although the dynamic coefficient at 1m/s sliding speed may be slightly different from that at 2m/s, the difference is in most cases insignificant and in practical terms inconsequential. In pedestrian slipping it is the dynamic coefficient which is the most relevant.

A large number of materials, generally those which are hard, e.g. metals, timber, ceramics, etc are known as Coulomb materials. Providing both surfaces are Coulomb materials neither the force holding the two surfaces together nor the area of contact affect the value of the coefficient. The combination of both these parameters, namely the pressure between the two surfaces, has no effect on the value of the coefficient.

As an example, for a block of metal measuring 5cm x 10cm x 20cm, it would not matter which side was used in contact with the surface across which it was sliding in order to determine the coefficient of friction – the force needed to pull it along would be the same in all cases. Similarly it would not matter if a second block weighing twice that of the first block was used – the pull force would simply double, with the calculated coefficient remaining the same.

This is of significant benefit for designers and test machines. A test machine does not have to replicate the full load in a system, which might be many tonnes, the coefficient can be determined using only a kilogram or so in the test.

Unfortunately materials such as rubber and plastics are not Coulomb materials and one cannot rely on the coefficient of friction being independent of the contact pressure. This problem tends to affect the higher levels of contact pressure and which cause deformation of the materials. If the contact pressure is small and such as to cause hardly any deformation, small differences in contact pressure between the test machine and the real life situation are often insignificant.

This is particularly relevant in pedestrian slipping where the heel material is often plastic or rubber. These heels are normally hard and do not deform significantly at the level of pressure found in pedestrian usage, hence test machines do not have to reproduce the levels of pressure found in the real-life situation. Softer rubbers, such as those used for the heels of trainer type footwear, need however to be considered a little more carefully.

Over the last hundred years or so several hundred machines have been designed to measure the coefficient of friction between sole/heel materials and floorings. In general the results which they have obtained in the dry of the dynamic coefficient of friction are relatively consistent. Indeed one could argue that the results verify the principles relating to friction as set out in this booklet.

2. Wet friction

It was generally thought that when the floor was wet the friction produced would be similar in terms of the way it was produced to that when the floor was dry. It was therefore held that there was a unique wet coefficient of friction which could be measured in a similar fashion to that used to measure the dry coefficient. The major problem was that all machines, whilst giving general agreement in the dry, gave widely inconsistent results in the wet.

The matter was brought to a head in the 1980s when the UK's Ceramic Research Centre designed a new machine, the Tortus, which by all accounts ought to have given the definitive answer. At that time another machine, the TRL Pendulum was also being used by several members of the UK Slip Resistance Group (UKSRG), and whilst the two machines agreed in the dry they differed widely in the wet. The pendulum often suggested that a floor was potentially very slippery in the wet, while the Tortus suggested that it was almost as safe as in the dry.

The matter was investigated by the UK's Health and Safety Laboratories (HSL) who suggested that the problem was all to do with lubrication theory. They put forward the hypothesis that the test machine should have the same value of a hypothetical parameter known as the **critical film thickness** as that calculated from a slipping pedestrian. The critical film thickness is the thickness of the lubrication film at which the sliding object is fully supported by the lubrication film and thus has no contact with the surface and can therefore move frictionless across the surface. It is calculated from a number of dimensions, speeds and forces employed by the test machine or the slipping pedestrian.

HSL calculated that neither the Pendulum nor the Tortus gave a value corresponding to a slipping pedestrian and that both were wrong – the pendulum gave too high a value while the Tortus gave too low a value. N.B. Too high a value of h(crit) would mean that the test machine would suggest that the floor was much more slippery than it really was. At that time, a group of eminent forensic engineers actively condemned the Pendulum claiming that it gave misleadingly low values of slip resistance. The HSL report thus clearly supported their view and presaged the demise of the Pendulum as a floor testing machine. From re-checking the calculations, it was found that the HSL were not using the correct value for some of the parameters. When the correct values for those parameters was used, the Tortus had an even lower value for h(crit) but the Pendulum almost exactly matched that of the slipping pedestrian. This helps to explain why the Greater London Council and several UKSRG members had found a very good correlation between the readings from the Pendulum and wet slipping accidents when floors were measured with that machine.

However the hypothesis did not explain why the critical film thickness was so important, particularly as full lubrication was not involved and floors generally had a roughness well in excess of the 2µm critical film thickness which was calculated for a slipping pedestrian.

SlipAlert was designed to have a 2µm critical film thickness, however the Pendulum was never designed to do so: it got there by accident. One of the reasons for designing SlipAlert was to show that if two machines did have the same value of critical film thickness, then if the hypothesis was correct they would give the same value for the wet coefficient of friction on any floor. Tests have shown that SlipAlert has a 95% correlation factor with the Pendulum, and which is almost as good as one gets comparing two Pendulums.

So why does this hypothesis work? This has been set out in detail in a paper to a conference in Madrid in 2020 (see Appendix B). Basically, when two surfaces slide relative to each other in wet conditions, the fluid separating them is caused to be pressurised because the fluid cannot easily escape. This is the essential principle of lubrication theory. If the upper surface is not fully supported by the fluid film, the surfaces are essentially still in contact and developing friction, but the fluid pressure reduces the force by which the surfaces are held in contact and thus less friction is developed. This is called partial lubrication and is the normal situation in pedestrian slipping. Whilst a fully lubricated slip can occur, it is very rare and will only happen on a very smooth surface such as glass.

It is thus possible to show that if two machines or systems (e.g. a slipping pedestrian) both experience the same proportional uplift from the fluid then they will indicate the same dynamic coefficient of friction when testing a particular floor (see *Appendix C*). In order to develop the same proportional uplift it can be shown that both machines/ systems must have the same value of critical film thickness (see *Appendix B*). The HSL were correct in that, but not due to a proper analysis of the matter. This is not to criticise them for that – it took a further 20 years or so to fully understand what was going on and how the various factors were linked.

3. The friction that pedestrians need

Most of us are fortunate enough to be able to take for granted our ability to walk safely. When we step forwards the leading foot usually lands on the back of the heel. Unless it gets immediate vertical support and, because both the foot and the body are moving forwards, is also able to develop frictional forces to bring the heel to a rapid stop, then a slip is likely to occur. The situation can rapidly become uncontrollable because as the foot slides forwards at an increasing speed, the angle which the leg makes with the ground is also increasing. This increases the forward force provided by the leg on the foot, leading to yet greater acceleration, thus exacerbating the slip.

With good reactions, it is possible to halt an incipient slip before it becomes uncontrollable. However, as we get older our reactions become slower which is why slip related falls are more common in elderly people. Also, if we see that the floor is wet and likely to be slippery, we can walk defensively by taking smaller steps. This ensures that the angle to the vertical of the forward leg as its foot meets the ground/floor is smaller than usual. This angle plays a critical part in the amount of friction we need. In general terms, those who take long strides tend to require more friction to be developed. In understanding pedestrian slipping, we need not only to discover how much friction a particular floor can develop against typical heel materials, but also how much friction people need in normal walking.

The definitive work on discovering how much friction pedestrians need was carried out in the 1960s at the UK's Building Research Establishment. Interestingly, it was not done with slipping in mind but as a means to formulate a method of measuring and predicting wear in flooring. They realised that there was no reliable data on what forces pedestrians actually exerted on the floor on which they walked.

The tests were done using volunteer members of staff who were required to walk along a catwalk and in so doing to step onto force plate on which both the vertical and horizontal force which they were applying were measured. Although the measurement was relatively crude by today's standards it was sufficiently accurate to be regarded as reliable today. The 70 people (both men and women, all aged between 20 and 70 years) first walked in a straight line and then on subsequent walks made a turn to the left or right when they placed their foot on the force plate.

It was realised that the work was important for pedestrian slipping and that the critical moment in the stride was when the heel of the foot swinging forward first met the floor. At that point, if the floor does not provide enough friction the foot which is in practice still moving forwards and indeed being potentially propelled forwards by the force which is being transmitted directly down the leg will continue to slide across the floor, rapidly becoming uncontrollable.

The forces involved in this first heel strike were analysed. It was found that the coefficient of friction needed in straight walking varied across the sample group from 0.08 up to 0.28 with the peak in the distribution occurring at 0.19. The distribution of the results was a skewed Gaussian distribution. It was subsequently analysed to provide the coefficient of friction that would have been the most that any of the volunteers would have needed if 1 million of them had been available to do the test. This was found to be 0.36. When turning was taken into account this increased to 0.40. The UK adopted a minimum criteria for floors of 0.40 and organisations such as the Greater London Council used this data and arrived at the following overall criteria:

Test value of CoF	
0 to 0.19	The floor is unsafe – i.e. a high risk of slip
0.20 to 0.39	The floor is Marginal in respect to slip and users should be warned to take great care. Measures should be put in place as soon as possible to mitigate the risk.
0.40+	The floor is low risk- i.e. safe

:

Other international organisations have subsequently confirmed that the 0.40 figure is the correct level at which to set out that boundary.

It was also discovered that when walking down a slope people needed additional friction equivalent to adding the value of the tangent of the slope angle, hence to be safe on a slope of say 6 degrees, the floor should be able to develop a CoF of (0.4 + Tan 6º).

In the 1980s, the UK Slip Resistance Group changed what was then the generally accepted boundary points. They decided to introduce a new testing rubber named FourS (now called Slider 96) to take over from the rubber which had been traditionally used on the Pendulum, known as TRL rubber. FourS was more representative of the hard rubber heels found on men's shoes at the time although the softer TRL rubber was not dissimilar to that used on trainer type footwear. RaPRA (Rubber and Plastics Research Organisation), who controlled the UKSRG at that time and who supplied the rubber test sliders, carried out a small number of comparative tests and stated that FourS would give a result of 0.36 on a floor which gave 0.4 when using TRL, and 0.25 on a floor which TRL gave 0.20. The UKSRG was thus persuaded to change the criteria boundaries.

Subsequent comparative tests using over 600 different floorings have produced a completely different result and shows that whilst the results fit into a relatively wide band, that band indicates a one-to-one relationship in terms of the coefficient of friction as measured. There is no doubt that the different boundaries cause confusion, but the UKSRG argued that it would cause more confusion to change them back to what they should be. Dr Bailey's opinion is that the UKSRG did not wish to admit that it made a mistake. This is similar to the HSE calculating the pendulum critical film thickness and for ten years or so failing to acknowledge that the Pendulum gave reliable results.

It will be noted that SlipAlert always has and will continue to use the original BRE/GLC criterion.

It has to be recognised that floors that have a wet SRV of 40 or more can be more difficult to clean and keep clean. Specifying flooring is often a compromise between aesthetics, ease of cleaning, durability, slip resistance and cost. There are occasions when slip resistance can reasonably be less than the ideal but in such cases the risk of slip should be carefully thought through. The BRE work on the frictional needs of pedestrians lends itself to this. It can be set out as follows.

For safety…

	Straight	Turning
1 in 2 people need a CoF of at least	0.19	0.20
1 in 20	0.24	0.29
1 in 200“	0.27	0.32
1 in 10000	0.29	0.34
1 in 100000	0.34	0.38
1 in 1000000	0.36	0.40

In a small office building where, for example, 10 people work and only a few visitors are likely to walk over a particular floor, then it would not be unreasonable to work on the 1 in 200 value of the CoF given above.

Many buildings which are open to the public however have a significantly larger number of users. A shop in a small village could well work on a population of 1000 whereas a supermarket in a large town would probably need to work on a population of 100,000 potentially using the floor. Unfortunately there are no hard and fast rules, and it is a judgement call.

4. Measurement of the coefficient of friction

Many machines or methods can reliably measure the dry coefficient of friction but since 95% of accidents take place in wet conditions it is important to use a machine or method which can reliably predict the coefficient of friction that a slipping pedestrian would experience in wet conditions. Only two test machines in practice do this – SlipAlert and the Pendulum. The Pendulum is an excellent machine which is discussed later in Appendix A. SlipAlert, also in Appendix A, is easy to use and is in use in many countries throughout the world. Both machines will reliably predict the risk of a pedestrian slipping over on a floor. Do not be persuaded that tests or methods which rely on people walking on the floor, e.g. the DIN ramp test, must therefore give similarly reliable results – they do not and for very good reasons as set out in Appendix A.

Two other measures apart from the Coefficient of Friction are frequently used in relation to Pedestrian Slipping, namely the slip resistance value (SRV) and the pendulum test value (PTV). PTV simply relates to the coefficient of friction of the surface as measured using a Pendulum test machine. Up to a coefficient of friction of 0.40 the pendulum test value is 100 times the coefficient of friction, i.e. a PTV of 40 relates to coefficient of friction of 0.40. Above 0.4 the relationship diverges as can be seen on the chart on the SlipAalert ramp which enables you to use either measure.

SRV is the same as PTV but relates specifically to pedestrian slip, whereas PTV is used in other applications such as vehicular situations. In both cases however it is important that the rubber type which is being used as a slider is stated. If it is not then one must assume that it is the hard Four S/Slider 96 rubber which has been the standard rubber for use in floor measurements.

In relation to rubbers use for testing floors, in an ideal situation a sample of all the different types of heel material likely to be used by pedestrians walking on the floor would be used. This would take a great deal of time and be very expensive. It is generally agreed that the FourS/Slider 96 rubber typifies the harder type of rubber heel whilst the TRL/Slider 55 represents the softer trainer type of rubber heel and also the barefoot situation. This slider is usually the most appropriate for testing swimming pool surrounds and changing room floors. SlipAlert's Durable Rubber slider has the same rubber hardness value as Slider 96 but is more durable. There is very little difference in performance between the two rubbers, however the SlipAlert rubber is significantly cheaper than Slider 96, so for everyday use it is the rubber of choice. When investigating accidents, FourS/Slider 96 slider can be used as it circumvents any arguments being put forward about which is the most appropriate slider.

Many floor surfaces are isotropic meaning that their frictional properties are equal in all directions. Other floors, particularly those with regular raised profiles often have very different values of slip resistance depending on which direction they are tested. On such floors it is important to test the floor in several different directions to establish the lowest value of slip resistance and the direction in which this occurs.

One advantage that SlipAlert has over the Pendulum is that it enables special nonslip footwear to be tested in situ. The shape of the SlipAlert slider allows the intricate pattern used in the heels of these shoes, for instance Shoes for Crews, to demonstrate their effectiveness. In such cases a slider can be fabricated from the heel of the particular footwear and used on SlipAlert in order to check if it might be the best way to overcome problems associated with an unavoidably wet floor in a factory rather than replacing the floor.

Most slip test machines need verification and calibration. If the machine uses springs either internally or externally or is in any way adjustable it will almost certainly need one or both of these operations. Verification is a test carried out on a carefully selected sample of material which is tested before testing the floor. It has a known SRV and the operator needs to ensure that the test correctly registers that value. Depending on the machine, he may need to make an adjustment or alternatively cancel the tests on the floor and get the machine professionally adjusted. Calibration is normally carried out annually by a third party laboratory who checks all the items which can go out of adjustment.

SlipAlert is unique in that there are no springs or adjustments to be made and has simple user checks to ensure that it is working correctly.

5. How to keep pedestrians safe

The owner of a floor or the organisation legally responsible for that floor has a duty to pedestrians walking over the floor to ensure, as far as reasonably practicable, their safety. There are in practice five ways to achieve this.

The first and optimum solution is to have a floor which provides a slip resistance of 40 SRV (CoF 0.40) or more in both wet and dry conditions, to maintain it in that condition and to check on a regular basis that it is providing that level of slip resistance.

The second and third solutions recognise that whilst most floors in the dry give the necessary slip resistance, many floors simply do not provide that level of slip resistance in wet conditions. In such cases steps need to be taken to ensure that the floor does not get wet or should it do so, the liquid is wiped up in as short a time as is reasonably practicable and pedestrians prevented from walking in that area. The most problematic source of water is that brought onto the floor by the pedestrians themselves from outside on their clothes, feet and umbrellas. The usual way to combat this is to provide adequate barrier matting at entrances. This is normally permanent but often supplemented by temporary matting. It is essential to provide a sufficient length of mat and to ensure that people cannot take shortcuts to avoid stepping on the mats. Some mats can become saturated in very inclement weather and act as a source of water, hence staff need to be vigilant to raise the alarm if they notice that the floor adjacent to the mat is starting to become wet.

In the case of kitchens, washrooms and toilets, it is impossible to prevent water getting onto the floor. Mats are not a solution and the only sensible option is to have a floor in those areas which is slip resistance in wet conditions.

One further cause of water in shops and offices which frequently have floorings which are not slip resistant in wet conditions, is the accidental spill. This also occurs around coffee vending machines, but in that particular situation matting is a viable solution. In relation to the other areas where accidental slips can occur, the solution which most shops adopt is to train staff to be vigilant and to have a system whereby a cleaner can be summoned whilst a member of staff stays to warn and divert customers around the wet area.

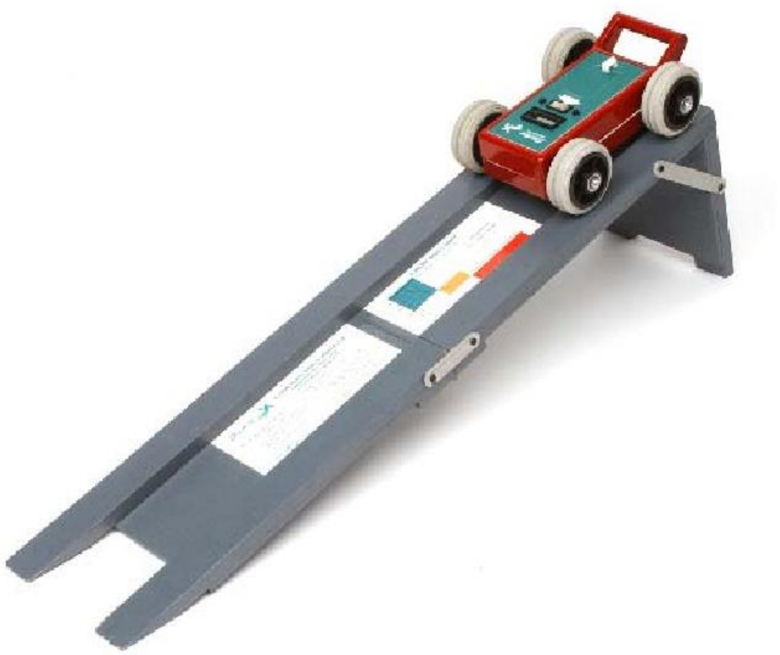
Whilst the second solution above relates to rainwater and accidental spills the third solution relates to the deliberate wetting of the floor during the cleaning process. If this is carried out whilst the building is occupied, then it should be done in such a way that a dry path is available for pedestrians around the wet area. This dry path should be properly signed, ideally using temporary barriers around the wet area. Just relying on the ubiquitous wet floor sign is not good enough. In practice it simply shows that the organisation acknowledges that the floor is slippery and that it cannot be bothered to ensure that pedestrians are properly warned and directed to a dry path around the wet area.

The fourth solution applies to factories where the previous solutions are not viable, usually because the contaminant on the floor is greasy and often all over the floor area. In such cases nonslip footwear can overcome the problem. There are a number of brands which really do work, Shoes for Crews being one such brand. The only caveat is that everyone who goes onto the floor, visitors included, must wear that brand of shoe and that the shoe soles/heels need regular thorough cleaning and inspection by a trained supervisor.

The fifth solution is the one which no one wants to face. If the floor is frequently wet, for instance in changing rooms, and the floor does not have or has lost its original adequate wet slip resistance, then renewal or possible rejuvenation (see Chapter 8) is the only answer. Whilst this is clearly the most disruptive and expensive solution, in some cases it can be the only viable solution.

A cautionary word about microporous heels and floorings. These work by reducing the pressure in the hydrodynamic film because they contain tiny capillaries into which the water can be forced during the sliding process. It has been found that these capillaries can become saturated such that they can no longer accept any further water from the surface and thus lose their initial effectiveness. For an occasionally wet and low traffic area they may represent an acceptable solution.

6. Monitoring slip resistance



Either the Pendulum or SlipAlert can be used to monitor the slip resistance of floors on a regular basis and also to react to incidents and complaints. If the Pendulum is used, the operator must be properly trained in the use of the machine and should rigorously follow the specified operating procedure. If the floor is large, it can be a lengthy and tedious operation. Many organisations find that their staff members are much happier using SlipAlert for monitoring their floors.

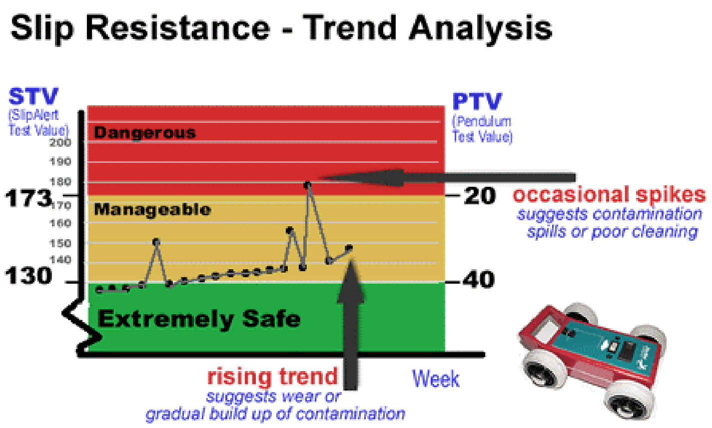
A number of test locations should be chosen which are tested on every occasion in order to monitor changes to the slip resistance which may or may not be taking place. Changes can take place due to wear, modifications to the cleaning regime and contamination. A variety of locations should include those subjected to high, medium and low levels of pedestrian traffic.

The results from each set of tests should be recorded and if possible transferred to a spreadsheet so that it is easy to compare results from previous tests. This will help to see trends or sudden changes. It may also give an indication as to whether it would be reasonable to test more or less frequently. In order to show due diligence it may be wise to get an independent testing organisation to test the floor annually in the same locations as currently used in order to verify the results you have obtained. Slip Test (www.sliptest.info) is an organisation that carries out such audits – they operate throughout the UK.

If it is found that that the floor is losing its original slip resistance, either generally or in certain locations, it will be necessary to investigate what is causing it. The first step is to thoroughly clean the area concerned using a cleaner which is designed to loosen any contaminant which may be causing the problem. Such cleaners often need to be left on the floor for several minutes in order to work effectively.

If cleaning the floor makes no difference, this would suggest that traffic is wearing the floor. This should mean that less trafficked areas are not as badly affected. If wear is the problem, it will be necessary to monitor the floor more closely until such time as it is essential to do something about it before it becomes a slipping risk.

If the floor is returned to its original slip resistance state by the cleaning it will be necessary to investigate whether the problem is due to poor day-to-day cleaning or because some contaminant is being brought onto the floor and which needs either to be either prevented from getting onto the floor or the day-to-day cleaning modified in order to combat it. As an example, one organisation found that the cleaners were using silicone-based polish to polish a sales counter and the overspray was landing on the floor near the counter making it slippery.



7. Slopes and stairs

Slopes

The work in the 1960s at the UK's Building Research Station established that people needed additional friction to be generated when they walked down a slope. This additional amount is numerically equal to the tangent of the slope angle. Thus a person who on the level needs a coefficient of friction of 0.20 will need 0.20+Tan10° (0.38) when they walk down a 10° slope. This is fairly demanding for many types of flooring in wet conditions, although in the dry many floors will give this level of friction.

The Pendulum is able to measure the slip resistance value on slopes and will indicate the same value whether one measures up the slope or down the slope. SlipAlert on the other hand should ideally be used across the slope, or if one can only measure up and down the slope because of lack of width across the slope, the instructions included with the machine should be followed.

N.B. People require less slip resistance walking up a slope and slipping accidents involving people walking up a slope are almost unheard of.

Stairs

In spite of an intuitive feeling to the contrary, stairs generally do not cause slipping if designed and used correctly. The reason is that provided a sufficient depth of tread is provided to be able to place the foot on the tread with only 2cm or 3cm of toe overhanging the leading edge (nosing), and that the user ensures that he uses that part of the tread, the forces that the foot imposes on the tread are all vertical and with almost no horizontal forces which might induce slipping.

Ideally treads should be 275mm to 300mm in depth (called the going) which is measured from the front of one tread to a virtual plane based on the front of the next or one before. Essentially the ball of the foot needs to find a horizontal surface on which to land. Goings can be shorter than 275mm but those stairs are more susceptible to slipping accidents because if the ball of the foot lands beyond the edge of the flat section, the user's weight causes the foot to slide forward. Users tend to counteract this by splaying their feet outwards so that their feet will fit onto the shorter goings.

Square section nosings are generally best as rounded section nosings reduce the available horizontal section of the tread; also, since users tend to lower their foot with a downward angle, the first point of contact is on the rounded section which immediately induces a forward force on the foot. Providing the ball of the foot then lands reasonably well back from the edge this will quickly become the main area of contact and the initial forwards force will be inconsequential. If however the ball of the foot lands on the rounded section a significant forwards force can be generated and to prevent the foot sliding forwards and downwards is frequently beyond the frictional capacity of the materials used in the stair's construction.

It will be appreciated that winders, that is stairs which turn a corner using three or four steps rather than a quarter or half landing, can be a problem. In these, whilst the going around the outside is usually very adequate, the going on the inside of the turn is often virtually non-existent. In housing, such winders are often at the top of the flight which is the worst possible place to slip and fall.

8. Cleaning and rejuvenating the floor surface

Cleaning

In normal circumstances, the cleaner the floor, the more slip resistant it is when wet. Dirt and grease tend to mask the roughness of the surface which plays an important part in how the surface generates slip resistance in the wet.

There are however a number of factors to be considered in relation to cleaning. It should not be so abrasive that it causes the surface to become smoother and lose its natural roughness, nor should it leave a residue or greasy film over the surface.

It is recommended that tests are carried out on the floor by the cleaning organisation in order to establish which cleaning agent and method of cleaning not only cleans the floor most effectively but also leaves the floor in its optimum/least slippery state. Testing with SlipAlert will help to establish this.

It is important that cleaning staff recognise the importance of using the correct cleaning agent on the floor and follow the instructions set out by the manufacturer. If the wrong agent is used it can lead to the floor becoming more slippery than when the original testing was carried out.

Having established the optimum or least slippery state of the floor, this data should be then used as a baseline for future tests in order to establish whether the cleaning is continuing to be effective and how often it needs to be done in relation to slip resistance. Over a long period it will also show up whether wear is affecting the floor surface.

Some highly recommended machines for cleaning floors are the products of i-team Global (www.i-teamglobal.com). The mop and bucket approach should be avoided as it simply spreads the dirt around.

Rejuvenating

Faced with replacing a ceramic tiled floor that simply cannot be made slip resistant, it is tempting to explore the rejuvenation option. There are essentially two types on offer, either making the original surface rougher using an acid etch or coating the surface with a thin film containing particles which provide roughness – these are often described as nano particles.

The acid etch is usually based on hydrofluoric acid – it is the only acid which can make an impression on glass like surfaces. This acid is very potent and needs careful handling and removal from the floor after treatment using copious amounts of water. Immediately after treatment it can be shown to have caused a marked improvement in slip resistance, but unfortunately many organisations have found that it is short lived, despite using the recommended cleaning product which often contains a weaker concentration of hydrofluoric acid. The problem is that the acid cuts through the very hard top layer of the tile and exposes the softer material which forms the main body of the tile. These treatments are generally not recommended by the ceramic tile manufacturers.

The coating type treatments can be effective and reasonably durable. It is important to research them thoroughly and obtain independent verification that the particular treatment does not only improve slip resistance but continues to do so for a good length of time. Find out where it has been used in a similar situation several years ago and get confirmation from that organisation that it is still effective.

If the floor has to be replaced, do not simply accept the manufacturers value for wet slip resistance, since the tile will almost certainly have been tested in its virgin state. Obtain values which had been found after the tile's surface has been well rubbed over with grout and then cleaned off. This will be more in line with the level of slip resistance which will be achieved once the tile has been installed. Do not be tempted to accept the 'R' number designation – it does not correlate with SlipAlert or the Pendulum (see Appendix A).

9. In the event of a slipping accident

When a slipping accident occurs, it is important that reliable data is gathered as soon as possible. This will ensure that if the victim makes a claim for damages a carefully reasoned decision as to whether to defend such a claim can be made. To gather the necessary data it is important to have a member or members of staff who have received the necessary training to be available so that one of them can be sent to attend the scene of the accident as quickly as possible after the accident.

The following advice will form the basis of such training.

i) Be kind, gentle and sympathetic towards the victim. You are likely to get more information than being defensive – however do not suggest or imply that it was in any way the fault of the organisation.
ii) Get the name, address etc of the victim and a rough estimate of age.
iii) Get a description of how the victim fell. For example was it a slip or a trip. A slip will invariably mean that they fell backwards, whereas a trip will cause them to fall forwards. If possible, ascertain what the victim was doing when they slipped, were they distracted, in earnest conversation with a friend, in a hurry, etc.
iv) Have a look at the footwear and if possible the sole/heel of the shoes on the foot which slipped. A photograph is helpful but may be considered inappropriate.
v) People who slip usually land on their bottom right on the spot where the slip started. If they get to their feet, check if there are any signs of dampness or contamination visible on their clothing around their bottom.
vi) When they have got up or have been taken away, check the floor very carefully for signs of wetness or other contamination.
vii) Carry out a SlipAlert test in the immediate area where the slip took place.

A report with the above information should be written as soon as possible and any notes taken at the scene carefully preserved so that the report cannot be challenged on the basis of the passage of time having clouded the memory.

10. Standards and the courts of law

Standards are a useful tool, providing they are used sensibly and are not detrimental to innovation. In relation to slip resistance testing, being described in a Standard does not necessarily mean that the method or device is a reliable indicator of the slip potential of the floor to be tested. Similarly, not being in a particular Standard does not mean that the method or device does not reliably indicate the slip potential of a floor surface.

To give an example: The relatively new European Standard EN 16165 describes four test methods, one of which is the Pendulum. In the UK version of the Standard, warning is given in the Foreword which clearly states that the UK only accepts that the Pendulum (out of the four methods described in the Standard) is a reliable indicator of slip resistance. The UK version also includes a Technical Informative Annex which lays out why the UK has taken this stance. The arguments set out in the Annex are identical to those found in this booklet.

SlipAlert is described in BS8204 (In situ floorings) but was rejected by the European committee for the following reasons:

- It was submitted too late to be included (despite the standard not being published until ten years later and was in a Britsh Standard).
- They considered that four tests was enough. If they allowed it, they would have to allow in other tests.

No proper technical evaluation of any of the methods/devices was ever made by the committee even though it was well known that there was no correlation between them.

In relation to Courts of Law it must be emphasised that whether or not they rely on the results from a particular test is entirely based on the evidence that is presented to them. One or two forensic engineers in the UK have publicly stated that the UK Courts only accept the Pendulum which is misleading as SlipAlert has also been accepted as evidence in the UK. In Ireland it is used significantly more than the Pendulum by forensic engineers in that country.

In the 1980s a similar group of six well respected UK forensic engineers signed a letter which was frequently produced in Court and stated that in their opinion results from the Pendulum did not represent a reliable indication of the slip resistance of a floor. In a landmark case, using the work done by the GLC and BRE, the Court was shown that the Pendulum was indeed reliable and that the opinion of the six as expounded in their open letter was founded on poor understanding of the technical issues relating to pedestrian slipping which were commonly held at that time.

Whilst Courts may well take cognizance of a test method being in a particular Standard, they do not automatically rule out a test method if it is either within another Standard or evidence is produced to show that it is an equally reliable indicator of slip resistance, for example a correlation with a test which is deemed reliable.

Conclusion

Friction is arguably one of the first material properties which humans acknowledged and made use of. Without it mankind could not exist on this planet. Many inventions, like the wheel, have been concerned with offsetting friction, however, in spite of being able to send men to the moon, friction is still not fully understood such that we can forecast its value in a given situation.

It is only very recently that it has become possible to understand friction in wet conditions as pertains to pedestrian slipping. So much so, that many who consider themselves experts in pedestrian slipping still rely on test machines and methods to determine the slip resistance of a floor which do not replicate the hydrodynamic film as found under the heel of a sliding shoe.

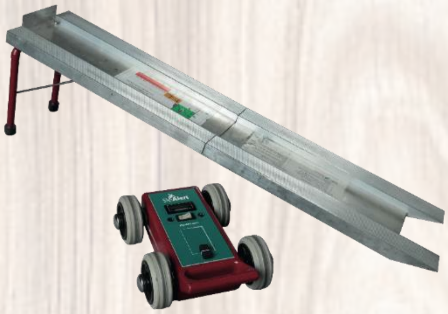
This booklet will bring about a better insight into pedestrian slipping. Just like SlipAlert, it was designed for the ordinary person rather than the expert.

If something has not been explained in sufficient detail or has raised further questions, please contact the author at drmalcolmbailey@gmail.com

Appendix A - Test machines and methods

SlipAlert

SlipAlert was designed to correlate with both a slipping pedestrian and the Pendulum, by using the hydrodynamic film theory. The fact that it does correlate with the pendulum helps to show that the hypothesis is correct. It was also designed to be simple to use so that anyone could use it and get a reliable result.



It works by running down a ramp in order to obtain the correct speed of travel, and when it reaches the floor it is supported by its front wheels and the slider pad at the rear. The friction generated by the slider pad brings SlipAlert to a halt. The front wheels are connected to a counter and which measures the distance SlipAlert has travelled from the top of the ramp. This counter reading is used by reference to a graph to determine the coefficient of friction and/or the slip resistance in Pendulum units (SRV).

It is described in British Standard BS 8204, In situ floorings, but was omitted from the European standard EN 16165 because that committee decided to limit the number of test machines/methods in that standard to four. The UK version of EN 16165 contains a Technical Annex which is worth reading – much of it is included in this booklet.

Advantages – easy and quick to use and reliable

Disadvantages – is best for in situ floors rather than laboratory use as it requires a minimum length of flooring of 900 mm for a safe floor system. N.B. this is less than required for the DIN Ramp which is purely a laboratory test, and equally the GMG/tribometer.

Slopes are best tested across the slope rather than down the slope although it is possible to test down the slope using the instructions included with the machine.

The Pendulum

The pendulum was originally designed in the 1930s by Percy Sigler in the US. He used it to test all the flooring in government offices in Washington DC. It was noted by Barbara Sabey of the U.K.'s Transport and Road Research Laboratories on a trip to the US in the 1950s. It was redesigned by TRL to the current configuration and was used for testing roads to determine the Sideways Force Coefficient throughout the UK.

The Greater London Council thought that it would be a good idea to use it to test floors not realising that that was its original purpose. They tested 3500 floors throughout London in the 1950s and 60s and saw a very close correlation between the readings of the machine and the known accident record for that floor.

In the 1980s its emerging trustworthiness was almost destroyed by the U.K.'s Health and Safety Laboratories when they put forward their hydrodynamic film hypothesis. They pronounced that the Pendulum gave far too high a value for the Critical Film Thickness and should therefore be disregarded in future. It was by chance that Dr Bailey noticed an error in their figures and was able to show that the Pendulum did in fact have the same critical film thickness as a slipping pedestrian. It thereafter became almost universally accepted in the UK and had its own British standard BS 7976. This has been superseded by BS EN 16165.

In Dr Bailey's opinion it is a fine instrument and he has taken in excess of 150,000 readings with the machine.

Advantages. – It can be very reliable when used by a skilled/experienced operator. It measures the slip resistance of a small area of flooring (125 mm x 75 mm) and thus is ideal for measuring individual tiles. The instrument can measure the SRV both up and down the slope on an inclined floor.

Disadvantages. – It is a heavy and cumbersome machine which takes some time to set up and take readings. It is essential that it is used by a trained/experienced operator who follows a very strict and somewhat onerous operating procedure.

It is possible to cheat using the machine. One well-known expert boasted to a journalist from the New Scientist that he could get any reading he liked from the machine and indeed he has demonstrated this in his training sessions.

The DIN Ramp

One of the ways of measuring the coefficient of limiting static friction in the dry is to tilt the surface on which an object is resting until the object starts to slide. The value of the coefficient is the tangent of the angle when sliding occurs. This is the essential principle of the DIN Ramp, and by using a person actually walking up and down the ramp surface might well appear to be a perfectly legitimate way to determine the slip resistance. The big problem with the DIN Ramp is that the slip resistance value, that is the coefficient of friction relating to pedestrian slipping in wet conditions is a dynamic coefficient and is not directly related to the dry coefficient as explained in Chapter 3. The action of walking on the ramp is far removed from normal walking – for instance it uses very short step lengths, the foot is placed almost flat down onto the surface, the soles and heels have a highly profiled surface which frequently gives mechanical interlock with some floor surfaces, and the subject is not walking at a normal pace. Oil is used as the lubricant rather than water since it was found that using water gave very poor consistency of results.

The changing angle of the Ramp also means that the force from the foot acting at right angles to the flooring surface is likewise changing. Hence the proportional uplift is changing and such that the ramp may well only equate to a slipping pedestrian at a specific angle for a specific flooring, if at all. That angle is not the angle at which the operator slips and the relationship between the two angles is not by any means straightforward. Hence the angle at which the operator slips is meaningless in relation to real pedestrian slipping.

Indeed there is no correlation between the DIN Ramp and the Pendulum or SlipAlert, both of which have been shown to correlate with slipping accidents.

The other problem is that the DIN Ramp is laboratory-based and cannot be used to test the floor in situ. N.B.it might be reasoned that if a flooring when tested on the ramp caused the operator to slip at say 10° then that flooring can safely be used up to that angle on a slope. Unfortunately for the reasons mentioned above, this is not correct albeit it appears a logical proposition..

The Tortus

This is one of several “drag sled” test machines. The Tortus was designed by CERAM, the UK’s ceramic tile research organisation, in the 1980s. When it first appeared it seemed to do all the right things. Because it’s results in the wet were found to be inconsistent with known slipping accidents, this instigated the research by the UK’s Health and Safety Laboratories. They correctly found that the Tortus had a critical film thickness which was well below that of a slipping pedestrian and which explained why it only indicated a slip risk on very slippery surfaces.

The original machine applied a fixed weight to a small circular slider which is restrained to move in a vertical direction within the machine and used a cantilever/strain gauge to measure the frictional force acting on the slider assembly. The machine had four wheels which slowly moved it across the floor. The horizontal force developed by the slider was shown on a meter on the top of the machine as the coefficient of friction. This could be recorded on an external plotter. Later models included a continuous paper printout.

The machine is still used albeit very rarely in the UK. Whilst it can be used to determine the dry dynamic coefficient of friction, it tends to suffer from stick/slip which can make it difficult to assess the usable value of the coefficient.

The BOT3000

This is an American machine which is used widely in the US. Like the Tortus, it is a drag sled machine and while from an engineering/technical aspect it is a very sophisticated piece of kit it fails to indicate surfaces which are inherently slippery. It's critical film thickness is well below that of a slipping pedestrian and thus only detects surfaces which are very slippery. In other words, the slider does not experience the same uplift from the hydrodynamic film proportional to the vertical force compared to a slipping pedestrian. It is widely supported by manufacturers of floorings who wish to see their products shown by such machines as being safe and a low risk of a pedestrian slipping.

The GMG/Tribometer

The GMG is basically a drag sled like the Tortus and BOT3000, but unlike those is not propelled along the floor using wheels. Instead a metal tape is pulled from the machine and its end anchored by standing on it. The machine then pulls itself along the tape towards where it is anchored. The tape is wound onto a drum inside the machine and it uses this to measure the force needed to pull the machine along. The machine is supported on three sliders and the coefficient of friction is measured by dividing the force required to pull the machine along by the overall weight of the machine. Like the BOT3000 and the Tortus it fails to detect many surfaces which are slippery in wet conditions; its proportional uplift from the hydrodynamic film is significantly less than that experienced by a slipping pedestrian.

The Pull- along Spring/Electronic balance method

One of the first ways of determining the horizontal frictional force was to pull an object along a flat plane using a force measuring device, for example a spring balance or a set of weights attached by a cord to the object which passed over a pulley. People still use this method to determine slip resistance using an object of known weight, often a block of metal, placed on the floor and with shoe sole/heel material fixed to the underside. Electronic balances have tended to replace spring balances.

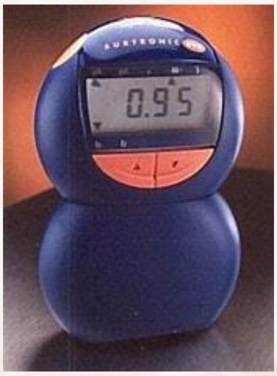
Even in the dry, this method is not very reliable as the results can vary with the way that the object is pulled along. The stick/slip situation caused by the fact that the limiting static coefficient is higher than the dynamic coefficient makes it difficult to get a consistent reading. In the wet, the film thickness bears no relation to that under a slipping pedestrian's heel.

The English XL and the Brungrabber machines

The English XL projects a slider forcibly onto the surface to be tested at an angle which can be varied until the slider slips forward as in a normal pedestrian slip. Whilst the principal has some merit, this author has significant doubts as to how well it simulates the actual forces involved and the way that the hydrodynamic film behaves particularly at the initial impact.

The Brungrabber is also a variable incidence machine. A variable incidence strut is used to apply a force to the slider until the slider slips and shoots forwards. In the dry, it measures the static limiting coefficient of friction, whilst in the wet it does not take into account the forward and downward movement of the heel at heel strike and which provides an uplift on the slider.

Surface Roughness measurement



When the U.K.'s Health and Safety Laboratories first published their paper on the hydrodynamic film and mistakenly stated that neither the Tortus nor the Pendulum developed the same thickness of film as a slipping pedestrian, they put forward the suggestion that surface roughness might be a way of establishing slip resistance in wet conditions. The UKSRG thought that there might be some merit in this and urged members to measure the surface roughness when they took Pendulum readings. Unfortunately this became a means to an end and for many years they insisted that the surface roughness was of itself a valid measure by which the surface should be judged.

This author tested some 600 different floorings surfaces and plotted the results of Pendulum SRV against surface roughness (both Rz and Ra) and found that there was no usable correlation whatsoever. For many years his results were ignored by the UKSRG until fairly recently when it is understood one or two members whose results showed a similar lack of correlation insisted that the UKSRG changed its policy towards the use of surface roughness.

User measurement

For many years, and particularly prior to the more general use of the Pendulum in the UK, experts, particularly those employed by Defendants in a slipping case, would assess the floor by walking across it. If they happened to slip over then they would agree that the floor was slippery. If not then they would tell the court that the floor was perfectly safe and that the Claimant slipped over due to their own fault.

There are two reasons why this is a flawed assessment. People vary in the slip resistance they require and almost certainly none of the experts had physically measured the coefficient of friction they required when walking. Hence anyone who required a higher coefficient than the expert was potentially at risk from the floor which that expert had deemed safe. Secondly, because when walking across a wet floor there is a tendency to walk slightly or moderately defensively, meaning that one requires less friction to be developed. Hence such an expert assessment in practice only meant that a floor had an SRV which is in excess of say 15 but which could be significantly less than the 40 required for safety. N.B. the average person needs an SRV of 19 when walking normally but can reduce this to between 10 and 15 or even lower when walking defensively.

Rather than walk across the floor, some experts would simply swing their leg over the floor making contact over a short distance. They would make their assessment based on how slippery the floor felt. Fortunately today, any expert using such methods of assessment would be given short shrift in a UK Court.

Appendix B - Hydrodynamic Lubrication and the Measurement of Pedestrian Slip Resistance

A paper written by the author which explains in more detail how partial lubrication and the hydrodynamic film need to be understood in relation to pedestrian slipping

Abstract

In the author's experience, most slipping experts do not understand how the film of water trapped between the floor surface and the heel of a pedestrian or test machine slider actually works. Most experts are only too well aware that whereas test machines give comparable values of slip resistance for a particular floor surface in dry conditions, in water wet conditions the results for different types of test machine can be significantly different. Some test machines will suggest that the floor surface is "safe" whereas others will suggest that it is "dangerous". This paper provides an answer as to why this occurs, and that when fully understood it is possible to design a test machine that gives similar readings to another type of test machine, even though the machines are completely different in the way that they measure slip resistance, for example using different vertical forces on the slider and different areas of contact. Based on this it is thus possible to ensure that the test machine replicates the characteristics of the film generated under the slipping heel of a pedestrian, and thus a truly realistic value of the slip resistance of the floor surface.

Keywords: Slip, measurement, hydrodynamic, lubrication

Introduction

Most researchers into pedestrian slipping are aware that machines designed to measure slip resistance will generally give reasonably close agreement in terms of the result for any particular dry surface. If the surface is wet however the results can vary significantly, and since most slipping accidents tend to occur in wet situations, this has led to an unsatisfactory situation. Those who market flooring products tend to favour those devices which give high values of slip resistance in the wet as it makes their product look safe or safer, whereas others question this, as such an approach does not correlate with actual slipping accidents.

The problem was partly solved in the UK back in the 1980s when it was realised that the crux of the matter was that the water on the floor was acting as a lubricant. Although this was generally accepted in the UK, the precise way that the water acted was not understood in a clear and unambiguous manner. It was thus simply described as ‘Hydrodynamic lubrication’ as if this explained everything. In practice the term ‘Hydrodynamic lubrication’ is itself misleading as it implies full lubrication whereas in practice in pedestrian slipping it should correctly be referred to as ‘Partial hydrodynamic lubrication’ as will be evident from this paper.

It will also become clear that using these principles, not only can one deliberately design a machine to give similar results in the wet as another machine, even though they may use different approaches to measurement, but also to ensure or check that they replicate the lubrication conditions which occur when a pedestrian’s heel slides across the floor in a slip.

Lubrication

Full lubrication occurs when a film of liquid exists between two surfaces. The film needs to be continuous and such that it prevents one surface contacting the other. Such a film can exist under certain special circumstances when there is no movement between the surfaces but generally movement is involved; it is this movement which creates the film and keeps the two surfaces apart.

The fundamental factors which cause this to happen are …

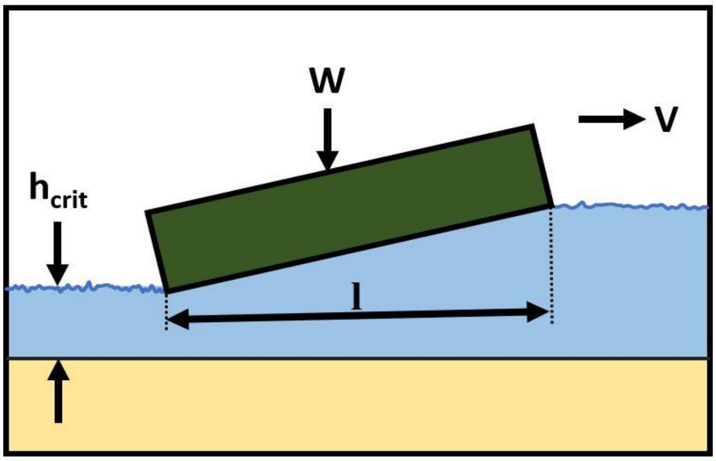
i) Liquid is forced into the gap between the two surfaces at the ‘leading edge’ of the sliding surface due to the relative movement.

ii) It can only escape around the sides and rear edge of the slider.

iii) Because the escape route is very limited, it needs pressure in the liquid to cause the liquid to flow from the leading edge to the sides or rear. This pressure is caused and maintained by the movement between the two surfaces and as a result of the liquid being forced into the gap at the leading edge.

iv) In full lubrication this pressure fully supports the weight of the sliding object, and the film thickness will adjust itself in relation to the weight imposed, the velocity of the slider, and the dimensions of the slider in contact with the film.

The following diagram and equations are taken from traditional lubrication theory.



$$h = ((6\eta l v K_e K_p)/P_{av})^{1/2} \quad \text{or} \quad h = ((6\eta l^2 b v K_e K_p)/U)^{1/2}$$

which, when U = W becomes $h_{crit} = ((6\eta l^2 b v K_e K_p)/W)^{1/2}$

Where
η is the viscosity of the liquid in the lubricating layer
l is the length of the slider in the direction of motion
b is the width of the slider
v is the relative velocity of the slider relative to the floor
K_e is a constant relating to the b/l ratio of the slider
K_p is a constant relating to the geometry of the film wedge
P_{av} is the average pressure in the film
U is the Uplift force provided by the film
W is the downwards force exerted by the slider

In practice the angle of the slider is often only a degree or so – it is shown here with a much larger angle for clarity.

Partial lubrication

In pedestrian slipping, the only time where one is likely to get full lubrication is on a very smooth surface such as glass. The value of h_{crit} in pedestrian slipping is around 2*µm (*2 microns). In almost all other floorings the roughness of the floor itself is greater than 2 microns and there is no continuous film separating the floor and slider (or heel).

However the film of water still exists but is contained in a myriad of tiny passages or tunnels which are formed between the slider and the floor. The forward movement of the slider or heel still forces the liquid to enter the system at the leading edge and the liquid is forced through the labyrinth of passages and out at the rear or sides. On very rough floors the passages are large, the liquid flows easily and requires very little pressure to do so. On more shiny floors, the passages are small, the liquid does not flow easily and requires much larger pressures to do so.

Full lubrication is self regulating and the thickness of the film adjusts itself to ensure that the pressure generated in the film exactly equals that necessary to support the full weight of the slider. In partial lubrication, the value of h is determined by the characteristics of the floor surface. Hence, whereas in full lubrication the film thickness will vary in response to variations in the forward velocity, in partial lubrication the value of h stays roughly constant and the pressure in the film varies in relation to the forward velocity.

The same basic equation as used in full lubrication applies to partial lubrication except that two further constants are required. The first, K_r, is similar to the Reynolds number used in fluid mechanics and aerodynamics and relates to the ease/difficulty with which the water can flow through the tunnels and escape along the sides and rear of the slider. The harder it is for the water to flow, the greater the pressure which will be generated in the film.

The second constant, K_a, relates to the proportion of surface area which is available on the slider (or heel) on which the pressure in the film can act. For instance, a soft rubber will not only sit lower onto the asperities on the floor surface, thus reducing h, but will also cloak the asperities to a greater extent leaving less free area in contact with the water film.

It is worth noting that it is these two constants and particularly K_r which upset the hypothesis that one could measure slip resistance by measuring surface roughness. Certainly surface roughness is a guide (and only a guide) to the value that h (the average height of the passages) might be, but that is only one of the parameters which determine the upward pressure on the slider and hence the slip resistance to be measured.

In Partial Lubrication, the equation becomes…

$$h = ((6\eta l^2 b v K_e K_p K_r K_a)/U)^{1/2} \quad \text{or} \quad U = 6\eta l^2 b v K_e K_p K_r K_a/h^2$$

Where *h* is the average height of the passages between the floor and slider

Effect on μ

The effect of this pressure in the partial lubrication film is to support a proportion of the weight of the slider (or heel) leaving the remainder of the weight to generate friction. It is this reduced value of friction which is thus used to calculate the wet slip resistance and is based on the full value of *W.* Hence any uplift caused by the film will register as a lower value of *μ* than that found in dry conditions.

The frictional force (F) which will be developed by the slider will be …

$F = (W-U)\mu$ and from this the value of μ_{wet} will be calculated thus

$\mu_{wet} = (W-U)\mu / W$ By replacing U and W in terms of the equations previously mentioned gives…

$$\mu_{wet} = (1 - (h_{crit}/h)^2 K_r K_a)\mu$$

This equation is critical in relation to both comparing one machine with another and with a slipping pedestrian. For a given floor surface K_r will be the same as it relates to the ease/difficulty with which liquid flows through the passages formed by its inherent roughness. Similarly h is a function of the surface roughness and the available height of the passages, and K_a will likewise remain at a particular value; these are all dictated by the floor surface and/or the slider/heel material rather than the test machine itself or the sliding dynamics of the pedestrian.

The only other component which dictates the proportion of weight supported by the film, and thus μ_{wet} , is the value of h_{crit} for the measuring machine (or the slipping pedestrian).

Hence, whereas in the UK it was correct to postulate in the 1980s that the measuring device should have the same value of h_{crit} as a slipping pedestrian, it was based on a less than full analysis of what really takes place during lubrication.

The slipping pedestrian

Because all the parameters in the equation for h_{crit} relate to physical dimensions and/or characteristics of the test machines (eg. speed of travel) it is possible to calculate the h_{crit} for the machine itself. This is the thickness of the water film that the machine would develop on a perfectly smooth surface to fully support the slider and thus give full lubrication.

The calculation for h_{crit} for a pedestrian is based on work in the early 1980's by Christer Bring at the UK's Building Research Station whilst on a sabbatical. His experiments with slipping using real slips showed that the average velocity of a slip was around 1.5m/sec that is, starting at a relatively low velocity and rising to between 2.4 to 3.0m/sec at the end of the slip path which on average was around 600mm in length..

Based on this and average weight of pedestrians and heel contact dimensions an h_{crit} of 2 microns can be calculated using the formula.

Likewise if one calculates h_{crit} for the TRL Pendulum, a figure of 2 to 2.2 microns can be found depending on what one takes as the mean velocity and value of *l.*

The Ramp Trolley method as detailed in BS 8204 aka SlipAlert was designed specifically to have an h_{crit} of 2 microns.

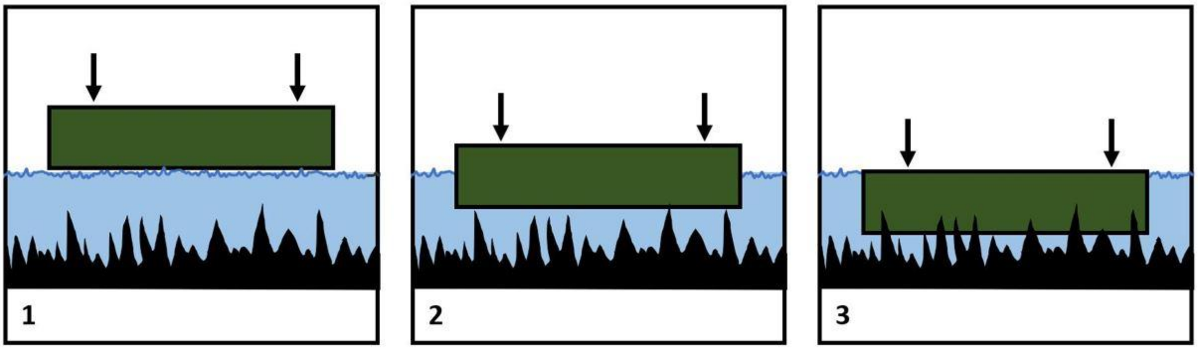
It was thus not surprising that SlipAlert and the Pendulum show good correlation (0.95 correlation coefficient). The main reason for the differences is that the Pendulum measures over a 125 mm path length whereas SlipAlert measures over a much larger path length. Tests have shown that slip resistance as measured by the Pendulum can vary over the typical SlipAlert path length.

The importance of designing the test machine around h_{crit} can be seen from the equation. If a device has an h_{crit} of say 1 micron the proportional uplift it will experience is only 25% of that of a machine with an h_{crit} of 2 microns. As a result the wet coefficient of friction will be significantly greater for the 1 micron machine than the machine with the 2 microns h_{crit}. It is thus critical that the machine h_{crit} is as close to the average person's h_{crit} as possible.

Some devices when used on wet floors indicate a slightly higher value of μ_{wet} than in the dry or a very similar value. The problem is almost certainly due to the velocity of the slider which is insufficient to force the liquid under the slider and it is simply pushed around the slider on the surface. If one calculates the value of h_{crit} for those machines it will be found that it is significantly less than the 2 microns found from a slipping pedestrian.

Start of the slip

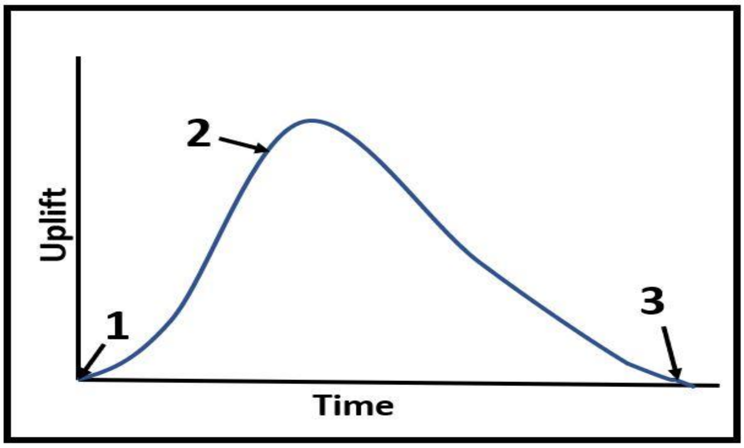
it may be argued that when a pedestrians heel first contacts the ground, that there is no or little forward velocity. In practice high-speed filming carried out in the 1960s showed that there is generally forward velocity at the moment of impact. Indeed this accounts for the wear on the back of the heel that most people find on their shoes. Also as the heel lands on a wet surface the water under the contact area has to be displaced before the heel surface first contacts the asperities in the surface and then for it to settle fully onto those asperities in order that the surface can support the full weight of the heel.



1 – The heel first encounters the wetness on the floor

2 – The heel first encounters the asperities of the floors roughness

3 – The surface now fully supports the heel



Diagramatic representation of the variation in uplift as the heel settles onto the floor in the situation described in the three drawings shown. It assumes no horizontal movement of the heel.

It is during this time that friction is being sought by the pedestrian, and it is not until Point 3 in the diagrams above that the full extent of the friction that might be available can be realised. The potential danger zone between Points 2 and 3 is exacerbated by the pressure increase in the film caused by forward movement. A full analysis of the pressures and uplift during that period when the two systems interact is complex and is not part of the analysis in this paper. It will depend on the height of the liquid layer on the floor and the range of velocities, both vertical and horizontal, which pedestrians employ when lowering their heel onto the floor. The author is not aware of any published research which has established the ranges of these velocities in normal pedestrian activity.

In the UK it is generally accepted that a floor can only be regarded as safe if it can prevent a slip which has started to take place from developing into one which is uncontrollable. Hence h_{crit} for a pedestrian is calculated using the velocity halfway along the slip rather than at the start or end. This approach would appear to be vindicated by the GLC work which in the 1960s tested some 3500 floors in London and found good correlation between the pendulum and the known slip history of the floor concerned. Such a correlation would be impossible if the actual film thickness generated by the pendulum was not similar to that which is generated by a slipping pedestrian. In other words the pendulum would have suggested many more floors were at risk than their slip history suggested; this was clearly not the case.

Conclusions

Lubrication theory is by no means new. It is clear how it works with the fluid film providing sufficient pressure to keep two sliding surfaces separate. Partial lubrication is a relatively straightforward extension of that theory and explains why the apparent coefficient of friction in the wet is generally less than the dry coefficient and can vary significantly depending on how it is measured. It is important that the uplift which is exerted on the test machine slider by the partial lubricating film relative to the downward force on the slider (proportional uplift) is the same as experienced by a slipping pedestrian. Unless this occurs, the value of μ_{wet} indicated by the test machine is of little intrinsic value in relation to pedestrian slipping.

Whereas certain authorities consider that the most important factors of a test are its repeatability and reproducibility regardless of the intrinsic value of the measurement it gives during the wet test, most responsible authorities would wish to have a test method whose wet slip resistance values correlate with the known slip potential characteristics of a wide range of floorings. In that respect, the Greater London Council in the 1950s and 1960s tested some 3,500 floors in London where the accident history was known and found a good correlation with the Pendulum wet readings. Their results and the criteria they were thus able to set out showed agreement with research at the UK's Building Research Station into the level of forces that people need when walking.

References

American Standard for Testing and Materials (1983), *Standard Method for Measuring Surface Frictional properties using the British pendulum test*, (ASTM Designation: E303 – 83), 595-599

Bailey, M. (1988), *The measurement of slip resistance of floor surfaces*, Construction and Building Materials,

Bailey, M. (2005), The *TRL pendulum slip resistance tester, the reasoning for its acceptance in the UK*, Proceedings of the Annual Conference of the Ergonomics Society, April 2005

Bring, C. (1964), *Friktion och Halkning*, Rapport 112, Byggforskningen, Stockholm

Bring. C. (1982), *Testing of Slipperiness*, Swedish Council for Building Research, Stockholm

British Standard BS8204, (2011), *In-situ Flooring*, BSI, London

British Standard BS7976, (2002), *Pendulum Testers*, BSI, London

Fuller, D. D. (1956), *Theory and practice of lubrication engineers*, John Wiley and Sons, New York.

Giles, C.G., Sabey, B.E., Cardew, K.H.F. (1964), *Development and performance of the portable skid resistance tester*, HMSO Road Research Technical Paper No 66, (HMSO, London)

GLC (1971), Bulletin 43 (Second series) Item 5*, Slip resistance of floors, stairs and pavings*, GLC Department of architecture and civil design

GLC (1985), Bulletin 145, Item 2*, Sheet safety surfaces for floors, methods for evaluation*, Building Technical File No 9, 916-922

Harper, F. C., Warlow. W. J., Clarke, B. L. (1961), *The forces applied to the floor by the foot in walking*, National Building Studies Research Paper32 (HMSO, London)

Proctor, T.D., Coleman, V. (1986), Slipping tripping and falling accidents in Great Britain – the present and future. HSE (UK)

Sigler, P. A. (1943), *Relative slipperiness of floor and deck surfaces*, US Department of commerce, National Bureau of Standards, Building materials and structures, Report BMS100, (US Government Printing Office, Washington)

Sigler, P. A., Geib, M. N., Boone, T. H. (1948), *Measurement of the slipperiness of walkway surfaces*, Journal of Research of the National Bureau of Standards, Research Paper RP1879, 40, (US Government Printing Office, Washington), 339-346

Appendix C – Worked example of Proportional Uplift

Consider three test machines, A, B, and C. When testing a particular floor, machines A and B develop a proportional uplift (PU) of 0.4 whilst machine C develops a PU of 0.1. The dry CoF of the floor is 0.5.

	A	B	C
1. Normal weight on the machine’s slider	2kg	4kg	3kg
2. Friction experienced by machine in the dry (Line 1 x 0.5)	1kg	2kg	1.5kg
3. Uplift caused by water film in the wet (Line 1 x PU)	0.8kg	1.6kg	0.3kg
4. Slider weight less the uplift (Line1 – Line3)	1.2kg	2.4kg	2.7kg
5. Friction experienced by machine in the wet (Line4 x 0.5)	0.6kg	1.2kg	1.35kg
6. Apparent CoF in the wet (Line5 / Line1)	0.3	0.3	0.45

About the author

Dr Malcolm Bailey trained as a civil engineer at Imperial College London where he went on to obtain his Ph.D. in structural engineering. He joined the construction industry and got experience in design and management. He joined Harry Stanger Ltd, a highly respected testing laboratory as its senior Engineering and Construction Materials consultant. During this period he was introduced to the Pendulum and pedestrian slipping. He set up his own Forensic Engineering consultancy in 1992.

He has been involved as a technical expert in numerous court cases in particular those involving pedestrian slipping accidents.

He was carrying out research into why the Tortus and the Pendulum gave differing values of wet slip resistance when the HSL published their hypothesis in relation to the hydrodynamic film. It was he who noted that HSL had got their figures wrong.

He was a member of the UKSRG and became its secretary after it voted to leave RaPRA. He subsequently resigned from the group when they refused to acknowledge the total lack of correlation between surface roughness readings and Pendulum SRV values. One or two members, who having founded their reputations on their promotion of surface roughness, became most unpleasant and such that it was no longer comfortable to attend meetings.

Whilst at Harry Stanger he joined the BS 8204 – In situ floorings BSI committee, and subsequently became its chairman and remained so for some 30 years. He persuaded BSI to set up a committee which subsequently wrote BS 7976 the UK Pendulum standard and became the mirror committee for TC 339 the CEN committee for slip resistance testing. He helped to set up that committee and was the U.K.'s Head of Delegation. He wrote the UK Foreword and Technical Annex for the UK version of EN 16165: the UK voted against publication of that document as it considered that three of the four tests described within it were fatally flawed and gave totally misleading results.

He has championed the Pendulum and written a number of papers in relation to that machine. He was the originator of the concept of Proportional Uplift in relation to partial hydrodynamic lubrication as described in this booklet.

He realised that the way to reduce slipping accidents was for floor owners to be able themselves to monitor their floors. He invented / designed SlipAlert to enable them to do this using the principle that the machine should be simple, reliable and easy to use. Many hundreds of SlipAlerts are in use throughout the world.