DISCRETE PROGRESS IN THE DEVELOPMENT OF AN INTERNATIONAL SLIP RESISTANCE STANDARD

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ABSTRACT

Although slip resistance is only one of several characteristics that should be considered when selecting ceramic floor tiles, it has become the sole or primary technical consideration for many architects. Ironically, it is the only principal tile characteristic that does not have an associated ISO standard, and this has led to much confusion. This paper considers why there is no standard, and the relative merits of some test methods, in the context of past and current developments. It concludes that an ISO standard, based on a revision of the Australian slip resistance standards, could be introduced quite soon. Past European difficulties could be overcome by means of national variations. Other proposed initiatives would help to overcome the poor quality assurance that is sometimes associated with the slip resistance of tiles, a few examples of which have been provided.

1. INTRODUCTION

When health and safety is universally accepted as a paramount issue, one must wonder why it has been impossible so far to develop an ISO standard for the slip resistance of ceramic tiles. Does the problem relate to the absence of a substantial forum to determine where the disagreements exist and how they can be resolved? Perhaps partly, but difficulties will naturally arise when sovereign nations have adopted particular test methods into mandatory regulations. If such measures have been found to work successfully, it is difficult to overturn them, and to replace them with something unfamiliar, particularly if it is perceived that it may not work as well. However, the paramount issue is to provide consumers with reliable information, which will not lead to an unfortunate choice of a product that will be potentially hazardous in the expected environmental conditions.

There are a multitude of slip resistance test methods. Anybody who has a reasonable grasp of the issues associated with pedestrian slip resistance knows that it is impossible to reliably convert the results from one test method to another, although there may be reasonable correlation between some devices on specific types of floor surfaces. To some extent, different tribometers (slip resistance test devices) will tend to rank a range of different floor surfaces in a similar order, but there will often be significant variations. Who or what determines which is the correct order, or is this dependent on where the product will be used? To what extent does 'fitness for purpose' determine the quality of the product and the quality of the test method?

Individuals have different gaits that vary with activity and relative well-being, and they wear different types of shoes, of different fits, with different soles, and of different slip resistance, which varies with the degree of wear, the nature and quantity of any contaminant, and the nature and condition of the underlying pedestrian surface. Whether or not someone steps onto a small area of spilt liquid will be a function of their attentiveness, the visibility of the spill given the lighting conditions and, to a certain extent, luck: whether they will step over it or onto it. If they do step onto a spill and a slip ensues, whether or not they injure themselves may be a function of their fitness, or the close presence of something that may stop the slide, such as a grout joint. The reasons why we need to determine the slip resistance of a ceramic tile, and how we should best go about it, are as many and as varied as the factors that may lead to a slip.

2. PAST STUDIES

There have been some excellent past studies of the aspects of slip resistance, and it is regrettably necessary to omit many of the best from this paper. The theme of those selected should become self-evident.

In introducing his 1982 study[1] of the forces applied to a floor and movements of the foot in walking and in slipping on the heel, Bring stated, 'In spite of great efforts in many countries, there has been little success in solving the problems connected with slipperiness and the slip resistance of walking persons. No valid test method has been available for this purpose, mainly because of the oversimplified image of frictional phenomena given by the classical laws of friction. In the light of the research literature of the past few decades, these laws appear to some extent incorrect or insufficiently detailed with regard to viscoelastic materials (such as rubber), which comprise the most common heel and sole materials and floor coverings'.

Bring[1] discussed the dependence of the coefficient of friction on different factors (such as load, velocity, temperature, lubrication, surface roughness), as well as the consequences of these variables for different test methods. He drew several conclusions with respect to the range of conditions that were most appropriate for testing the slip resistance of shoe–floor systems during the heel-strike phase of the gait cycle. This was one of a number of studies that led to the development of a number of sophisticated test devices that incorporated force platforms.

3. MACHINE OR MAN?

Jung and Schenk[2] compared six different sophisticated test devices and two walking test methods in an international interlaboratory study. While there were significant interrelationships between the various machine test methods, there were great differences in the absolute values. There was a clear relationship between the average friction value for the six machine test methods and the inclined plane walking test method with the three floor lubricant combinations. A second international interlaboratory study[3,4] again found that results varied widely between individual machines, even though every single machine proved to be acceptably repeatable. This suggests that small differences in the design and operational characteristics of the individual machines were influencing the results. Human walking trials, with adequate standardisation and calibration, had improved precision.

Jung and Schenk[5] used 98 test persons, 6 different types of shoes and 4 different test surfaces to determine a calibration procedure for the oil-wet ramp test. Test persons whose acceptance angle lay outside a statistically stipulated region around the standard acceptance value on each DIN 51130 calibration board were excluded from the test. For accepted test persons, an individual correction factor was determined and included in test result evaluation. Inclusion of the correction factor, which was determined with standard shoes, improved the accuracy and reliability of the test method. The critical difference, which describes the separation characteristics of the oil-wet walking method, was reduced through standardisation to less than 1.5 degrees.

In a further inclined plane walking study[6] involving 61 different floor surfaces, 3 different lubricants and 3 types of footwear, the data for oil-wet conditions indicated a separation characteristic of 2 degrees in the angle range up to 10 degrees, with a detection limit of 3 degrees. This work led to the establishment of a new R9 class within the 1992 revision of the DIN 51130 Standard.

James[7] outlined the theory behind inclining platform (ramp) walking tests in an attempt to dispel some of the trite criticism surrounding them. A principal criticism has been that the walker uses an unnatural gait. However, restrictions on posture and gait, and particularly step length, are necessary in order to obtain reproducible results. Shorter and shorter steps must be taken to maintain equilibrium as the angle is increased. As one walks down a slope, the required coefficient of friction increases as a function of step length. Conversely, if one only takes a short step, the tangent of the angle is equivalent to the coefficient of friction that would be available on a level surface.

Grönqvist[8] produced an excellent literature review and concluded that the assessment of slip resistance was cumbersome due to complex tribophysical phenomena at the shoe–floor interface at the critical heel-strike phase. Grönqvist developed an elaborate friction model for slipping that considered the various phenomena associated with three critical aspects: the drainage capability of the shoe–floor contact surface, draping of the shoe bottom about the asperities of the floor, and true contact between the surfaces. Anybody who wants to develop an appreciation of some of the complexity of this aspect of slip resistance needs to understand this model.

Grönqvist[8] developed a microcomputer-controlled dynamic instantaneous test method for simulating the dynamics of actual slipping at heel touchdown during walking. A series of case studies showed that this laboratory-based method was capable of simulating the relevant squeeze-film and contact pressure effects during slipping on contaminated surfaces. Amongst several other findings, Grönqvist noted that the optimum roughness, hardness and microporosity characteristics of the interacting surfaces should particularly be looked into.

While individual sophisticated test machines may be capable of demonstrating aspects of certain phenomena, friction is, in part, a property of the system (and tribometer) used to measure it[9]. The differences observed between the machines in the studies that Jung coordinated can be attributed to such systemic differences in machine design and operation. This might be overcome if one company were to mass manufacture such devices.

4. A GLOBAL OVERSUPPLY OF TRIBOMETERS

In 1983, Strandberg[10] reported that there were about 70 different test devices for measuring slip resistance (tribometers). Since then, several other tribometers have evolved, some of which have been incorporated into standards, for instance the English XL variable incidence tribometer [ASTM F1679] and the Brungraber Mark II portable inclinable articulated strut tribometer (PIAST) [ASTM F1677]. However, other devices such as the Sellmaier FSC 2000 and the GMG 100 may not yet or ever be covered by standards. One evaluation[11] of the FSC 2000, a digitised self-propelled drag sled, found that wear of the profiled test feet changed the slip resistance results. It has no sanding protocol for test foot preparation, nevertheless it is still widely used. Manually pulled drag sleds are much cheaper and, despite their unsuitability, are more widely used. The establishment of a coherent set of Australian standards for slip resistance, where the accepted tribometers are defined, has seen a slow, gradual reduction in the use of other devices.

5. A LIMITED GLOBAL SNAPSHOT OF SLIP RESISTANCE REQUIREMENTS

There is an Italian national provision (DPR 14, June 1989, No. 236), which, in dealing with the elimination of architectural barriers for persons with disabilities, prescribes that the pavements of residential units in shared or public areas must not be slippery[12]. Although DPR 14 does not extend to public buildings and private buildings open to the public, it requires that the coefficient of friction is at least 0.40, when determined in accordance with British Ceramic Research Association method Rep. CEC 6/81. This requires the use of the (Tortus) floor friction tester with a leather test foot in dry conditions and a standard hard rubber test foot in wet conditions.

As discussed later, there are specific German slip resistance regulations with specific requirements. In many other countries there are requirements that floor surfaces be slip resistant, and different conventions have arisen as to how this should be demonstrated. In the USA, the Americans with Disabilities Act (ADA) Accessibility Guidelines contained a recommendation for minimum levels of coefficient of friction on level surfaces and ramps, but failed to specify a test method. This **has led to the proposed withdrawal of the recommendation**, but where it is still used in a *de facto* sense, it reflects the flawed notion that one can nominate a universal minimum slip resistance threshold value that is applicable to any test method[13]. Marpet[9] refers to this as 'the single-numeric-threshold abstraction'. There is no single threshold at which a transition occurs between safe (certain not to slip) and dangerous (certain to slip) conditions. The probability of slipping will change as the coefficient of friction changes, but the probability of slipping is also a function of the activity being undertaken. It is thus more effective to develop slip resistance classifications, based on slip resistance results, which facilitate improved design and appropriate specification practices.

6. ARE OUR INTERESTS BEST SERVED BY SIMPLE OR COMPLEX SOLUTIONS?

Rowland[14] aptly summarised the situation in 1997: 'No single machine/test method is accepted as a definitive approach to the problem of slipping. They fit into four groups – pendulum devices, sleds which are dragged across the floor, articulated struts that try to imitate walking, and actual walking tests where human subjects walk on test floors on standard or test shoe soles/heels. Much time and effort has been expended on comparisons between machines and arguments for and against dynamic and static friction measurement, without success. Yet regardless of this well documented confusion there is a desire by those who do not have in depth knowledge of the problem, to have one instrument which will give one reading which will cover all situations for all floors, all shoe soles/heels, all seasons, all contaminants, all ages, all infirmities, in fact for everybody, anywhere, anytime. It is perhaps now time to forget the much sought after and now obviously mythical "universal test machine" that will, with one result tell us all we need to know, and to concentrate on a composite solution which in itself may be quite complex'.

Of course, lay people want simple solutions. It is reasonable that they should be able to ask: is this product suitable for this specific purpose? However, the difficulty lies in a general inability to specifically define exactly what the expected conditions of service will be. Furthermore, we continually develop new products and evaluate their characteristics when they are new, as it is virtually impossible to define how they will wear with exposure to different types of scratching dirt, different levels of traffic, and exposure to different chemicals and maintenance regimes. If we leave aside the problem of predicting future slip resistance, is there a simple way in which we can overcome the present impasse?

7. THE ISO SLIP RESISTANCE DRAFT TEST METHOD AND ASSOCIATED MATTERS

Let us firstly consider what happened with respect to slip resistance within ISO Technical Committee 189, Ceramic Tiles. The draft test method has now been long abandoned, but is still sometimes incorrectly referred to as ISO 10545-17. The draft originally contained three test methods. This was a means of reflecting national preferences rather than seeking Rowland's composite scientific solution. The 'dynamic slider' test method was based on the use of a floor friction tester (FFT), which was originally developed in the United Kingdom and is still commonly referred to as the Tortus. The 'static slider' test method was based on the use of a manually pulled drag sled. It generally reflected ASTM C1028, *Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method,* except that the weight of the sled was reduced from 22.7 to 4.5 kg, based on ergonomic considerations. The 'inclined platform' test method referenced DIN 51130 (Testing of floor coverings, determination of slip resistance, work rooms and areas of work with an increased risk of slipping, walking method ramp test), and provided a summary of that test method.

While the ISO draft seemed to reflect a reasonable compromise, Standards Australia and Standards New Zealand were just about to jointly publish AS/NZS 3661.1, *Slip Resistance of Pedestrian Surfaces: Requirements,* for testing both new materials and existing surfaces other than carpets and gratings. AS/NZS 3661.1:1993 adopted the FFT for dry measurements of pedestrian surfaces. Since a clean test foot on a clean surface is an unrealistic situation, and slip–stick phenomena can occur on very flat smooth surfaces (giving high coefficients of friction), one is justified in questioning the worth of the FFT when testing new materials, as the ranking of results can be misleading. A small amount of contamination, as occurs in the real world, will dramatically change the ranking. Hence, it is more sensible to use tests where the surface is contaminated for assessing suitability (and water is a fairly constant, readily available and easily controlled contaminant). However, the FFT is useful for testing existing floor surfaces in dry conditions, as the graphical output of the machine as it moves across the floor will often indicate areas of low slip resistance due to a pick up of contaminants.

AS/NZS 3661.1 adopted the British pendulum for wet testing. AS/NZS 3661.1 also recognised that: 'The inclining ramp test method used in Germany may be more suitable to measure the slip resistance of heavily profiled surfaces under laboratory conditions. Dynamic test machines based on force plates may also be suitable for determining the level of slip resistance for specific applications'. AS/NZS 3661 was a start to a composite international scientific solution, but we still had (and have) a long way to go.

Harris and Shaw[15] had shown that a minimum Rz surface roughness of 8–10 μm was required for safe walking in clean-water wet conditions. The British Health and Safety Executive (HSE) developed a further understanding of the role of roughness by using the squeeze film theory of lubrication, which indicates that hydrodynamic considerations are important in determining slip resistance in the presence of contamination. Proctor and Coleman[16] undertook calculations that showed the effect of various parameters of equipment design, and used these to explain the differences observed in practice between test results from various instruments. Proctor[17] subsequently showed that the Tortus is unable to assess the effect of aquaplaning (squeeze film) on smooth floors (low roughness) and hence overestimates the wet slip resistance (level of grip). Standards Australia Committee BD/44/3 had already rejected the use of the Tortus in the wet based on similar concerns about unrealistically high wet coefficients of friction and the high variability encountered in a 1989 round-robin study[18].

Bailey[19] followed up Proctor and Coleman's theory[16] and found that they had used some wrong values for the pendulum. When the correct parameter values were used, the film thickness that the pendulum test foot generated was almost identical to the hydrodynamic uplift generated by the heel of a slipping pedestrian[19]. This helps to explain why the British have generally perceived that there has been a reasonable correlation between results given by the pendulum and the actual slipping histories of floors, since the Greater London Council introduced requirements in 1971[20].

Rowland[14] acknowledged that some floors have a raised profile that is too large for use of the pendulum or surface roughness meters, although there were exceptions. HSE had thus started to use laboratory-based walking tests, initially the DIN 51097 ramp test, to see if it could assess the slip resistance of profiled floors, which could then be used as a base against which portable instruments could be validated. They found that the ramp test had good repeatability, good reproducibility and could distinguish between floors, and hence was a practical base test method for profiled floors.

Although being generally concerned about the use of the FFT in wet conditions, Bowman[21] was advocating coefficients of friction higher than those proposed by ISO/TC 189 for the wet FFT. In discussing the Australian Standard for slip resistance of pedestrian surfaces, he indicated that the proposed ISO requirements for the FFT would not provide the Australian public with a sufficient degree of safety[22]. He also pointed out that this provided justification, under the GATT Technical Barriers to Trade Code, for Australia to retain AS/NZS 3661.1 rather than adopting the proposed ISO standard.

The death knell for the ISO draft came after the British Standards Institution (BSI) ceded the right to the HSE to vote on behalf of BSI on the draft. The British delegation then refused to accept the use of the wet FFT. However, the Italian delegation was insistent on its inclusion, since it was an integral part of the Italian national provision (DPR 14). The Australian delegation suggested a compromise position, whereby the pendulum test would be added as a fourth test method, knowing that this was the favoured British test method (and it was already then an integral part of AS/NZS 3661.1).

In November 1995, in a statement authorised by the Solicitors Office of the British HSE, Rowland wrote, 'In our technical judgement, we cannot accept the Tortus instrument or instruments using the same principle of test as a basis for a standard test method for assessing the slip resistance of floors in water wet or similarly contaminated conditions. We have reached this decision after consideration of experimental evidence, some of which has been available since 1988, from UK, French and German sources. We further believe that the use of the Tortus could lead to unsuitable floors being classified as acceptable'. ISO/TC 189 subsequently referred the matter to CEN Technical Committee 67 for resolution within Europe. However, such resolution did not occur, and the draft was abandoned due to irreconcilable differences.

8. PROGRESS WITHIN AUSTRALIA

In 1999, AS/NZS 3661.1 was partially superseded by the publication of AS/NZS 4586, *Slip Resistance Classification of New Pedestrian Surface Materials*. AS/NZS 4586 still contains the dry FFT and wet pendulum test methods from AS/NZS 3661.1, but has adopted two new test methods: DIN 51097:1992 (Testing of floor coverings, determination of anti-slip properties, wet-loaded barefoot areas, walking method ramp test), and DIN 51130:1992 (Testing of floor coverings, determination of slip resistance, work rooms and areas of work with an increased risk of slipping, walking method ramp test).

Later in 1999, AS/NZS 4586 was supplemented by Standards Australia Handbook 197, *An Introductory Guide to the Slip Resistance of Pedestrian Surface*

Materials. HB 197 provides tile merchants, architects and others with recommendations for general design guidance. This includes republishing the mandatory German requirements that were given in German regulation GUV 26.17, *Code of Practice for Floor Coverings in Barefoot Areas Under Wet Conditions*; and German regulation ZH 1/571, *Floors in Workplaces and Areas with Increased Risk of Slipping*. HB 197 also includes a table where the recommendations for some common public locations are based on both pendulum and ramp classifications. A few of the German requirements were increased because of concerns about the R9 classification starting at 3 degrees. HB 197 suggested that the R9 class should begin at 6 degrees to prevent the use of products (in the 3–6 degree range) that would be too slippery under water-wet conditions.

It is significant to report that DIN 51130 is currently being revised so that class R9 will now commence at 6 degrees. Furthermore, the specified Bottrop boots, which have not been available for some years, will be replaced with Lupos Picasso S1 shoes. AS/NZS 4586 is being revised to include these changes, based on confirmatory testing that there is a minimal difference in the results[23].

German regulation ZH 1/571 was replaced by a new regulation BGR 181 in May 2003. One significant change was an increase to R10 in entrances to buildings that are likely to become wet (in accordance with HB 197). Furthermore, BGR 181 has introduced requirements for external work areas and stairs. The normal minimum requirement for such areas is R11 (or R10 if the surface has at least a V4 volumetric displacement). These and other changes will be included in a revised version of HB 197.

The other significant pending revision to AS/NZS 4586 is the inclusion of Rz surface roughness measurements as a means of determining how the Four S rubber test feet should be prepared when conducting wet pendulum tests. This is in accordance with BS 7976-2:2002, *Pendulum Testers – Method of Operation*, and also the UK Slip Resistance Group 2000 Guidelines for the measurement of floor slip resistance. Although the Rz surface roughness of one surface may have the same measured value as another, the surface characteristics may be quite different. One surface may have a jagged saw-tooth pattern and the other smooth sinusoidal curves. Thus, surface roughness readings should not be used in isolation.

The other companion Standard to AS/NZS 4586 is AS/NZS 4663: 2002, *Slip Resistance Measurement of Existing Pedestrian Surfaces*. This Standard only contains wet pendulum and dry FFT test methods. It is also undergoing a minor revision to harmonise it with the revisions being made in the relevant portions of AS/NZS 4586.

9. EUROPEAN DEVELOPMENTS

It is important to reflect on ongoing international developments. In Europe, CEN/Technical Committee (TC) 339, *Slip Resistance of Pedestrian Surfaces – Methods of Evaluation*, is attempting to unify the slip resistance testing of floorings other than road surfaces and sporting surfaces. CEN/TC 339/Working Group (WG) 1, *Determination of the Parameters of Slip*, has now met on two occasions. They have basically determined that a test device should react in the same way to the film of water under its slider or test feet as a heel does when a pedestrian slips. This essentially reflects the importance of the parameters that are used in the equation to determine the thickness of the hydrodynamic lubricating film. Based on past work[16,17,19 etc.], one may anticipate that the pendulum will qualify as a test device for determining wet slip resistance. It has already been adopted as the sole instrument for use in the standards for clay pavers (BS EN 1344), slabs of stone for external paving (BS EN 1341), setts of stone for external paving (BS EN 1342), concrete wearing surfaces (BS 8204-2), stairs and walkways (BS 5395-1), road and airfield surfaces (DIN EN 13036-4), etc.

CEN/TC134, *Resilient, Textile and Laminate Floor Coverings*, is preparing a draft European Standard prEN 13845, *Resilient Floor Coverings – Polyvinyl Chloride Floor Coverings with Enhanced Slip Resistance – Specification*. It is intended that this standard will call up three inclining platform (ramp) walking test methods: DIN 51097, DIN 51130 and a shod water-wet test method that is being derived from the RAPRA CH0001 test method and the British Health and Safety Laboratory (HSL) 'HSL DIN ramp' test method. The test method basically uses two human subjects wearing flat-soled shoes (without a heel), soled with 3 mm thick Four S rubber, which is prepared before testing with P400 silicon carbide paper in an orbital sander. The test board is wetted with a 0.1% solution of sodium lauryl sulfate. It is encouraging to see American laboratories participating in the associated interlaboratory study, and it is anticipated that this test method will be considered for use as the new ASTM test method for evaluating the slip resistance of walkway surfaces, with standard footwear, using the acceptance angle from a variably inclined ramp.

Bowman *et al.*[24] found there was a consistent difference between three ramp walkers when wearing shoes shod with Four S on wet specimens. In order to facilitate interlaboratory comparisons, ramp tests must have calibration boards – standardised ramp surfaces – whereby results can be corrected to allow for differences between walkers. It has been shown that this enables a significant reduction in the variation of the results[25]. The shod wet ramp (RAPRA CH0001) test results were very similar to the wet Four S pendulum test results[24]. This is not surprising since the RAPRA test uses footwear shod with smooth Four S rubber, as used with the pendulum. This tends to validate the use of the pendulum where the soling materials and contamination conditions are very similar. However, even though the coefficients of friction for the different tiles were so close as to be almost interchangeable (within the presumed limits of reproducibility for each test), the correlation coefficient was only 0.88 due to suppression by multicollinearity effects.

The seemingly high degree of correlation between the RAPRA CH0001 and the Four S pendulum tests may imply the potential redundancy of the RAPRA test, but this overlooks the potential use of the ramp test on those surfaces deemed to be too profiled to be classified with the pendulum. However, where both tests are conducted, the initial pendulum test establishes a benchmark that can then be used to monitor any changes in slip resistance with time. Furthermore, since any slip resistance test only provides an indication of slip resistance, the more indications one gets, the more confident that one can become in eliminating potentially hazardous situations.

HSE have used the HSL DIN ramp test extensively and has found that it correlates well with the pendulum test[26]. The HSL DIN ramp test will shortly be submitted to BSI as the basis of a new (draft) British Standard. Although the HSL DIN ramp test is generally more time and labour intensive than the pendulum test, and can only be used in the laboratory, one advantage is that it can also be used to assess other footwear for expected workplace conditions. The HSL DIN ramp test is HSE's preferred test method for assessing the slipperiness of footwear.

The HSL has expressed two reservations about the oil-wet DIN 51130 ramp test, partly because of a misconception by some that the R classification scale runs from R1 to R13, rather than from R9 to R13, with highly slippery products failing to obtain a classification[26]. This is a matter for proper education of those who need to know, where documents like HB 197 and HSE information sheets can certainly overcome this.

The second HSL reservation is more important: that the use of high-viscosity (SAE10-W-30) motor oil might not always provide a good indication of the slip resistance of water-wet floors. CSIRO has found that when one looks at a wide body of data that relates to different types of surfaces, there is relatively poor correlation between water-wet Four S rubber pendulum test results and oil-wet ramp test results. This can be seen in Figure 1, where class R10 includes tiles of the five pendulum classifications. Pendulum class X includes tiles from R9 to R12. Any result is an indication of slip resistance rather than a guarantee. Two or more positive indications are obviously better than one. However, tests are not infallible. One should always consider that there might be some particular feature of a product that causes it to perform uncharacteristically well or poorly when evaluated by one of the recognised test methods. Liquids tend to be dispersed through channels. The DIN 51130 boots are highly profiled, whereas the HSL DIN ramp test uses harder flat, smooth Four S rubber soles. It is the combined roughness of the floor and footwear surfaces that will determine the ease with which the lubricant can flow out from their interface.

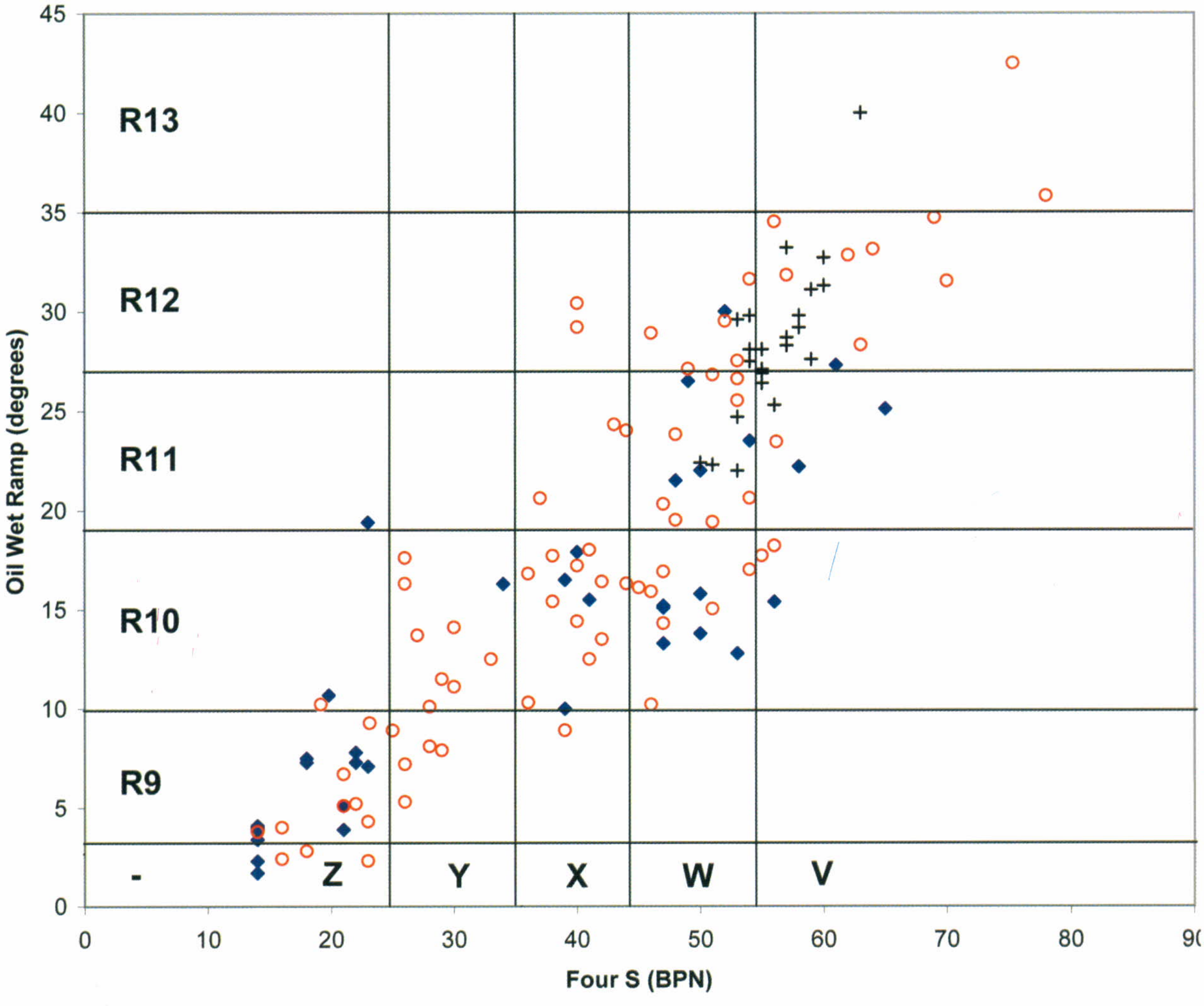

Figure 1. A comparison of oil-wet ramp and wet pendulum slip resistance results for some ceramic tiles, in the context of the AS/NZS 4586 classifications: glazed tiles (◆); porcelain tiles (O); and terracotta tiles (+).

In terms of Figure 1, the further a product is to the top right-hand corner of the diagram, the more slip resistant it is likely to be. The closer that a point is to the diagonal, the more likely the tile is to be slip resistant in a broader range of conditions. When individual points are considered, several important principles can be demonstrated[27,28]. One of the difficulties in looking at Figure 1 is the need to rely upon generic descriptions. Many glazed porcelain tiles appear to have less glaze than so-called surface-modified unglazed porcelain tiles. The Australian delegation to ISO/TC 189 has called for a revision of the definitions of glazed and unglazed, and for a reconsideration of the requirements that should apply to each class of tiles. While there are several different types of porcelain tiles depicted in Figure 1, we lack a precise language to convey their finish and texture.

We still need a better understanding as to which test methods will overestimate the potential slip resistance of which type(s) of surfaces, or the corollary is: which surfaces are suitable for testing by a specific test method, and where should extreme caution be used in interpreting results derived from individual test methods?

As can be seen from the above, the momentum in Europe for wet slip resistance testing has principally been towards the pendulum and inclining platform walking methods. What has been going on in the USA?

10. AMERICAN ACTIVITIES

The ASTM C1028 horizontal drag sled test method has been widely deemed inappropriate for use in wet conditions. Manually operated horizontal pull testers permit the test foot to substantially reside on the surface before applying the lateral test force. As such, any lubricant will tend to be expelled before the test pull commences. As the vertical force increases, viscoelastic test feet deform around asperities, expelling further lubricant, as well as interlocking with the asperities. This phenomenon increases as a function of time. Consequently, drag sleds are not suitable for making wet slip resistance measurements of footwear or walkway surfaces. Furthermore, manually operated horizontal pull testers are technically inappropriate due to uncontrolled, non-uniform and non-normal application of force and rate of force application. The problems associated with wet testing where there is not a simultaneous application of the vertical and lateral forces is often referred to as 'sticktion'.

Bowman *et al.*[24] found that the manually pulled (ASTM C1028) 50-pound drag sled was incapable of satisfactorily distinguishing between the wet slip resistance of ceramic tiles. The results were much higher than pendulum and ramp test results, particularly on the smoother surfaced tiles. Considering that the wet coefficients of friction were all above 0.5, such a universal static coefficient of friction threshold was too generous to be a reliable indicator of safe or acceptable wet slip resistance, when using ASTM C1028. The withdrawn ADA recommendation of 0.6 for the static coefficient of friction of level floor surfaces was little better. Since this drag sled test method significantly overestimated the wet slip resistance of tiles that offer little available traction, it should be withdrawn, in line with previous theoretical recommendations[29-31]. Although the ASTM C1028 results were higher than the English XL variable incidence tribometer (VIT) results on smooth tiles, and comparable with them on rough surfaced tiles, there was a 0.9 correlation coefficient between the test methods, when using either the hard Neolite® test liner or Four S rubber test feet in the XL VIT[24].

McIlvain[32] once wrote: 'Based on 14 years of testing ceramic tile and marble floors where people have slipped and fell and filed litigation, I have found that the static coefficient of friction usually exceeds 0.6, and some exceeded 0.8 when the floors and walkway surfaces were tested according to ASTM C1028. None tested less than 0.5'. While there may be some attraction in having all products pass, it doesn't bode well for manufacturers if people consistently slip on products that have been declared to be slip resistant. The reputed situation in the UK was that, in the case of accidents, tile manufacturers and suppliers stated that they should be investigated with the Tortus, while plaintiffs' advocates favoured the use of the pendulum.

In 2001, the Ceramic Tile Institute of America (CTIOA) approved *Endorsement of improved test methods and slip prevention standards for new flooring*[33], reflecting a desire to adopt more realistic test methods than ASTM C1028. While there were ASTM test methods that they could have chosen, they chose to adopt the DIN 51130 and DIN 51097 ramp test methods, the pendulum test method and the Tortus test method. This is very similar to the AS/NZS 4586 test methods, except that they permit use of the Tortus in wet test conditions.

However, the main American slip resistance 'action' is occurring within ASTM Committee F13 on Pedestrian/Walkway Safety and Footwear. The past tactics of some factions within this committee inspired a paper on ethical behavioural principles within the voluntary consensus standards development process[34]. Attempts by some participants to skew standards to favour specific products and practices led the ASTM Board of Directors to form a Task Group to recommend fundamental steps for the development of standards related to slip resistance, including acceptable approaches to achieving precision and bias statements. This reflects a concern about the possibility that a proliferation of proprietary device standards would allow those who are trying to prove a point (rather than trying to objectively determine the relative safety of a given flooring material or walkway) to 'shop' for a tribometer that will give them the results they desire[9].

Marpet[9] has considered the issues involved in the development of modern non-proprietary performance-based walkway-safety tribology standards. He recommended the development of a series of standards:

- a standard guide for the characterisation of required friction as a function of various activities;
- a set of standard reference material pairs, used to calibrate equipment and to classify the slip resistance of a shoe-bottom material or a surface being tested;
- a standard for the validation of tribometers;
- a standard test method for determining walkway/shoe-bottom slip resistance; and
- a standard guide for conducting walkway-safety tribometer precision and bias determinations.

The basic concept is that a valid tribometer would be required to rank the standard reference materials in the correct order. This would enable a calibration curve to be developed for any apparatus. This curve would then be used to verify the instrument and measure the slip resistance of other surfaces relative to the standard reference materials. In some respects, the last aspect is not unlike the way in which calibration boards are used in the DIN 51097 and DIN 51130 inclining platform tests.

The ASTM Board of Directors Task Group approach is classically academic, and is apparently needed, in part, to overcome past factional problems. It may provide Rowland's desired complex solution, although the speed of obtaining this solution is likely to depend on the amount of funding provided to independent parties, and this appears to be minimal. The solution of national problems should not be left to the public spirit of individuals.

Bowman *et al.*[24] showed that there was a wide divergence in the rankings obtained by various variants of different test methods (ASTM C1028, ramp, pendulum, SATRA STM 603 and English XL VIT). The English XL tended to underestimate the slip resistance of relatively smooth surfaces and to overestimate that of coarse surfaces. Bowman *et al.*[24] considered the proposition that the relative slip resistance of materials can be determined by ranking them against standardised materials. Some surfaces may cause some tribometers to overestimate the available traction, leading to potentially dangerous situations. It was recommended that if such a ranking system is to be introduced, tribometers should undergo a rigorous qualification process with respect to the types of surfaces that they are fit to test. A set of five standard reference materials is probably far too few. If a tribometer passes on the primary standardised materials, it could be submitted to further qualifying tests on subgroups of materials. ASTM F13 has now formed a Surface Response Task Group, which is examining the variability in results of different tribometers as a function of the position where tests are conducted on a limited range of profiled surfaces.

Fendley[35] has considered what is necessary to gain valid consensus for slip resistance standards, recognising that conflicts will exist between stakeholders, since no existing tribometer can evaluate every aspect of pedestrian friction. Fendley recognises the philosophical positions of stakeholders on the ASTM F13 Committee, which has some 270 members, including at least 20 independent experts of excellent repute and 5 representatives from the tile industry. Over half the ASTM C21.06 Ceramic Tile Committee has a slip resistance background, i.e. external slip resistance interests almost dominate the Committee. It is easy to understand why the tile industry members of C21.06 would be wary of having standards imposed on them by factional elements of the F13 Committee. Some might perceive F13 as being dominated by those who conduct tests for the purposes of litigation. In such investigative circumstances, quasi-legal recognition of the device they use and getting a quick answer based on a single pass/fail criterion may be perceived as being more important than a consideration of the possible limitations of the device used, or an adequate investigation of other possible causal factors. The device used is simply a means to achieving an end.

In considering ways of working towards a solution, Fendley[35] mentions useful approaches to slip resistance standards writing, specifically citing a number of positive examples from AS/NZS 4586 and the associated Handbook 197. Singapore has chosen to base SS 485:2001, *Specification for Slip Resistance Classification of Public Pedestrian Surface Materials*, on AS/NZS 4586 rather than on other available standards. The scope of SS 485 only covers public trafficable areas and excludes industrial work areas. As such, it does not provide for the measurement of displacement volume. The other major difference between the Standards is that SS 485 contains some other design guidance from HB 197, including Table 3, *Pedestrian Flooring Selection Guide – Minimum Pendulum or Ramp Recommendations for Specific Locations*.

Before considering a possible global solution to the current ISO/TC 189 impasse, based on Australian and New Zealand slip resistance standards writing experience, it is important to consider some basic objections that are likely to be raised. These are likely to come from two sources.

11. A REAR ATTACK

Di Pilla and Vidal[36] have attempted to brainwash American safety engineers about overseas (non-USA) standards in their review of 'current slip resistance measurement standards and continuing developments'. While they are justifiably critical of some ASTM standards, such as C1028, they recognise the Brungraber Mark II PIAST (ASTM F1677) and the English XL VIT (ASTM F1679) as being the only sticktion-free tribometers that are suitable for testing in both wet and dry conditions. One of Marpet's papers[29] that they reference (out of context) indicates that pendulums are also sticktion-free. Pendulums are also non-proprietary in that there are at least two British and one Italian manufacturer.

However, in introducing overseas slip resistance standards, Di Pilla and Vidal[36] allege, 'Often, these standards are not developed by consensus, but rather are funded, written and published primarily by commercial groups with vested interests in industry-friendly standards. While such organisations may welcome the participation of all parties, they are not required to maintain a specific balance of interests'. Although this material was attributed to Bowman[37], reference to[37] reveals a gross misrepresentation. Bowman was not critical of the committees of any national standards organisation, and described the Australian standardisation process (which is typical of other ISO member bodies, such as the British Standards Institute and DIN), emphasising how consensus and transparency are critical elements of the process. In the context of their introductory remarks, Di Pilla and Vidal[36] effectively belittle DIN by describing it as 'a nongovernmental standards-making organization in Germany'. DIN, Standards Australia International and ASTM International are all excellent non-governmental standards-making organisations.

They then immediately criticised the DIN ramp tests, where all of the developmental work was done under the auspices of the principal German national health and safety institute, BIA. In making such criticism, it would seem that they are unaware of the research that was undertaken in Germany and elsewhere[2–7,14,25 etc.], even though some of these references were also given in Bowman[37], which they referenced. They quote Hughes and James[38] out of context, and would appear to be unaware of James' later paper[7] that demonstrates why a changed gait is necessary, when walking on an incline, for determining the available traction on level surfaces. In an extended version of[38], Hughes and James state: 'At RAPRA we use an inclined ramp and indeed this is the only test available for barefoot applications'. How well does Neolite (as used in the ASTM test methods Di Pilla and Vidal advocate) simulate human skin? In discussing rubbers, as commonly used in 'overseas standards', Di Pilla and Vidal[36] state: 'The impact of wear on rubbers is another variable'. However, they fail to acknowledge that wear is also a factor with Neolite. This has been well demonstrated and has led to revised sanding protocols for Neolite. The surface roughness of the Neolite test foot changes during testing as a function of the roughness of the surface being tested, and this changes the slip resistance results[39].

Di Pilla and Vidal[36] rely upon the support of Adams[40], a private consultant, who was arguing against the AS/NZS 4586 test methods, in order to advocate the use of manually pulled drag sleds, which Di Pilla and Vidal condemn. Di Pilla and Vidal also failed to mention the existence of an ASTM Ramp Test Task Group comprised of members of Committees F13, F6 and an array of international associates, that is seeking to develop a new ASTM *Standard Test Method for Evaluating the Slip Resistance of Walkway Surfaces, With Standard Footwear, Using the Acceptance Angle From a Variably Inclined Ramp.*

In arguing against pendulum testers, Di Pilla and Vidal[36] correctly indicate that the original pendulum tester, the Sigler pendulum, has fallen out of US standards considerations. However, they failed to reveal the existence of ASTM E303, *Standard Test Method for Surface Frictional Properties Using the British Pendulum Tester*, which was first published in 1961. Significantly, ASTM E303 is one of only a few ASTM slip resistance standards to have a precision and bias statement. Their arguments against the pendulum date from the 1970s and are easily countered by subsequent research. Here is not the place: the wide recent acceptance of the pendulum in Europe speaks for itself.

Despite these and other shortcomings, it is worth reinforcing one of Di Pilla and Vidal's introductory remarks: 'Another problem is that the output of these instruments doesn't always agree and no method exists to correlate the results of one class of tribometer with another. Compounding this problem is the misinformation used to market several instruments and the inaccurate literature provided with certain flooring, floor treatments and footwear'. They also reference Marpet[29] when explaining why there is no known correlation between devices: 'test methods have their own set of biases and operator variability issues, and also because friction is, in part, a property of the system used to measure it'. A correct reference for this would be[9], where Marpet considers the 'perfect-test abstraction'.

12. INTERNAL POLITICS

Some ISO TC189 delegates want a portable slip resistance test that can be rapidly conducted. Some delegates are only concerned with testing freshly produced tiles and do not consider in situ variables such as angles, grout and dirt as being relevant, which would seem to render the need for portable equipment for testing outside the factory irrelevant. Some delegates may consider that the problem with multi-instrument methods is that the various methods do not correlate, and that this lack of correlation may lead to more lawsuits. While they might desire consistency, we know that this is not achievable, and that there is no magic device that is capable of testing all surfaces for all readily foreseeable usage scenarios.

In many respects, the lack of consistency can be an advantage. If one test indicates that a tile has good wet slip resistance, and another test indicates that it is marginal, what does it tell us about the tile and where it should and should not be used? So do we invest in further product development or are we cautious with our marketing?

In the end, national committees that fundamentally represent manufacturers must consider whether it is in their best long-term interests to develop standards that are perceived as safeguarding their interests, or is this outweighed by the ethical need to safeguard the interests of the public. A lesson might be learnt from the fact that the HSL still has the British vote on CEN and ISO committees with respect to slip resistance.

13. A PROPOSED SOLUTION

Let us consider what might happen if ISO were to base a new standard on the current draft revision of AS/NZS 4586 for testing new tiles.

The presence of the DIN 51097 and DIN 51130 Standards would fulfil German needs, as well as other countries, such as France and Belgium, that have grown accustomed to using these Standards and the associated German regulations as their own *de facto* standards. Many Italian companies have been providing DIN ramp results and details of the ZH 1/571 and GUV 26.17 requirements in their product literature for years. Leading international architects have become accustomed to using such data.

There would seem to be no reason why a third ramp test, the HSL DIN ramp test, could not also be introduced to cater for British interests. Although we are only concerned with ceramic tiles, if the standards for flooring materials were to be unified, this initiative would be welcomed by the resilient flooring industry. However, bearing in mind that the ramp tests can only be conducted in the laboratory, there will always be a need for at least one portable slip resistance test.

The presence of the wet pendulum test would largely fulfil British needs, particularly since it would include the use of two rubbers, the conditioning of which would be based on surface roughness measurements. The pendulum test might be extended to include dry testing, since one would not expect significant opposition to this, or this might be achieved by means of a British national variation.

The presence of the dry FFT (Tortus) test would partially fulfil Italian requirements, but given the significant British opposition to the wet Tortus test (and wide scientific condemnation of it), there would probably need to be an Italian national variation to include a wet Tortus test. However, this might only be a temporary measure if the Italian regulators can be persuaded that there are better means of protecting public pedestrian safety.

The above solution would certainly satisfy the CTIOA, but what of the Tile Council of America and other American interests? The existing ASTM C1028 has been pilloried. Manually pulled drag sleds are widely regarded as inadequate for wet slip resistance testing. Digitised self-propelled drag sleds, such as the Tortus, are also poorly considered when it comes to wet slip resistance measurements. If these options are discarded, do American tile manufacturers want to propose adoption of the (F13) English XL VIT or the Brungraber Mark II PIAST, or have they found that these devices discriminate unfairly against (some) ceramic tiles? The English XL VIT performed very poorly in a comparative ranking of ceramic tiles (against ramp and pendulum tests)[24].

While ISO/TC 189 is concerned with ceramic tiles, it cannot overlook the international trend towards harmonisation of slip resistance standards. Will the Committee act before external circumstances overtake it? Past problems have been due to national requirements and, being essentially political in nature, they require a political solution. There is also a need to identify the limitations associated with any candidate test instrument and for any potential limitations to be well broadcast. However, most of this work has been done for the AS/NZS 4586 test methods. Is it not better to try to improve something that is working than to start afresh?

Global research has shown that picking a favourite test method to assess slip resistance and using a single result to select a product or to condemn or accept a floor is no longer appropriate. CSIRO recommends that products be selected on the basis of wet pendulum results (using an appropriately prepared rubber slider, as determined by Rz surface roughness measurements) in conjunction with results from the appropriate ramp test (wet barefoot for wet barefoot areas, and oil-wet for other areas). When CSIRO is engaged as a consultant on specific projects, other types of ramp tests may be undertaken, and the SATRA STM 603 (a sophisticated dynamic laboratory-based test machine that has multiple load cells) is often used to assess new and laboratory-abraded specimens. Further work may help identify the most appropriate footwear for specific contamination situations.

While some people will initially be confused by the seeming complexity of this proposed 'complex solution', well-constructed education packages will eventually provide higher levels of public safety, thus reducing the industry's exposure to litigation. Standards Australia Committee BD/94 is continuing to develop further guidance material, based on risk management principles, for inclusion in Handbook 197. However, it is important to note that HB 197 is intended to start or assist the thought process, not to replace it. It cannot anticipate or cover every possible design situation.

The final aspect is that of testing existing floors. The Australian approach was to use the same portable test methods, but to place them in a separate standard (AS/NZS 4663) to minimise opportunistic claims that tiling should be reinstated. We know that slip resistance changes with time as a function of wear and contamination. Testing of existing floors is principally for routine auditing purposes, to assess the effectiveness of maintenance regimes, or to investigate accidents. Such standards need sufficient flexibility to enable people to conduct the testing in accordance with the reason for testing. However, this is one aspect that ISO/TC 189 should not have to spend too much time on: there is exceedingly limited international trade in used tiles.

14. A FURTHER FUTURE PERSPECTIVE

Once we have an ISO standard for the slip resistance of ceramic tiles, what will be the drivers for future developments? I would anticipate that this would relate to ensuring the consistency of product. CSIRO has tested a number of ranges of glazed tiles where there has been a difference of at least 10 British Pendulum Numbers (a coefficient of friction of at least 0.10) between different coloured tiles within individual product ranges[41-43]. The difference can be as high as 0.25[41]. We have found that the coefficient of friction can vary by as much as 0.20 between different batches of unglazed tiles. The classification of individual batches of tiles are often downgraded because the variation within the five tile test sample is so high that individual tiles have a result that is less than 20% of the sample mean. This all points to an unacceptable degree of variation, poor quality control and an insufficient quantity of product being tested.

Why do the results vary? If we consider tiles that have a uniform planar surface, we can detect different levels of gloss, which may correlate with the slip resistance[44]. Gloss differences imply a difference in the degree of vitrification. Changes in Rz surface roughness can also be detected, but since this is only one of several surface texture parameters, it will often correlate poorly. The surface roughness parameters that correlate best with slip resistance have been found to vary with type of tile[45].

Since such parameters are obtained by filtering electronic signals, it is quite possible to process the raw data in other ways to develop new hybrid measures that would provide a better correlation with slip resistance.

Bowman and Bohlken[41] raised the possibility of real-time automated process control of slip resistance by combining a suitable packaging of optoelectronic measuring systems and intelligent software. However, given Australia's geographical separation from the global centre of tile manufacturing, there has been little incentive to apply existing CSIRO multidisciplinary intellectual property to this task.

Another desirable initiative would be the automation of those mechanical test devices, which are found to react in the same way to a film of water under its test foot as a heel does when a pedestrian slips. This might again be accomplished relatively easily. However, a lack of planarity in the tile surface[41] can also cause a change in the measured slip resistance, but without changing the traction that is available to the pedestrian. A combination of simple and long wavelength measures of topography could resolve aspects of variable physical measures of slip resistance due to poor surface conformity between the test foot and the ceramic tile. Matters become more complex when looking at profiled tiles, but again there are potential existing solutions.

When the necessary technology is developed, tile manufacturers will be able to assess a reasonable percentage of the tiles produced, and to test a sufficient quantity of them, so that they will be able to state the minimum coefficient of friction for any batch of tiles with a high level of confidence. Mean slip resistance values might provide a useful indication, but it is the outliers with low slip resistance values that are most likely to cause problems.

15. IN CONCLUSION

1. ISO standards are intended to create free and fair trade, building a bridge between manufacturers and consumers, while enhancing public safety.
2. The building industry needs slip resistance test results in a format that allows their most sensible use.
3. Ceramic tile manufacturers need test methods that will allow them to rapidly and reliably assess the slip resistance potential of tiles. They cannot afford to use methods that may misrepresent wet slip resistance.
4. There is no single slip resistance test device or method that will cover every possible situation.
5. Products will often be ranked in different orders of slip resistance by different test methods.
6. One cannot convert the slip resistance results from one test method to that of another.
7. Multiple indications of slip resistance will best characterise the slip resistance potential of a tile.
8. Slip resistance devices may impart a systemic influence on the test results.
9. Some types of tribometers are considered unsuitable on technical grounds.
10. Test methods should react in the same way to a film of water as a heel does when a pedestrian slips.

11. In wet slip resistance tests, the vertical and horizontal forces should be applied simultaneously.
12. Wet drag sled test methods should be withdrawn.
13. Vested interests have sometimes inappropriately misrepresented other test devices and methods.
14. The ceramic tile industry needs to consider which test methods best characterise the slip resistance of tiles, rather than being diverted by consideration of devices that others are using for litigious purposes. However, where devices are portable, they may be used for auditing and litigious purposes.
15. The ceramic tile industry should bear in mind the trend towards harmonisation of slip resistance standards, and the benefits that this brings to architects and specifiers.
16. The revised versions of AS/NZS 4586 and Standards Australia Handbook 197 (due in March/April 2004) will provide a basis for an ISO slip resistance standard, where established test methods are well defined, and the resultant classifications (largely based on practical German experience) can be sensibly used.
17. National variations could accommodate past problems that prevented publication of an ISO standard.
18. There is an unacceptable variation in the slip resistance of some tile manufacturers' product ranges.
19. The future development of automated measuring systems should enable manufacturers to better meet their obligation to supply tiles with consistent slip resistance characteristics.

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