THE CORRELATION OF SLIP RESISTANCE AND DURABILITY WITH SURFACE TOPOGRAPHY

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1. ABSTRACT

The replacement of the European Building Products Directive by the European Building Products Regulation in 2013 [1] has put more pressure on the manufacturers and installers of flooring materials to concern themselves with the aspects of durability in use of such essential characteristics like slip resistance [2]. Experts as well as testing institutes like the FGK Forschungsinstitut für Anorganische Werkstoffe - Glas/Keramik - GmbH in Höhr-Grenzhausen, Germany, are increasingly commissioned to evaluate slip resistance as a function of the wear to be expected on the tile surface in private and occupational areas. This publication addresses the potential of the surface classification scheme developed in the european SlipSTD Project [2, 3, 4] and of significant new developments regarding the interpretation of slip resistance using the results of non-contact optical profilometry. These developments have led to an enhanced possibility to differentiate between surfaces and to explain their functional behavior before and after wear. A major impact of these results is that significant differences in the slip risk assessment using slip measurement methods and the consequences regarding their suitability for different surfaces can be evaluated. It also will support the choice and development of new adequate, reproducible and durable reference systems for the slip resistance tests.

2. INTRODUCTION

When addressing the slip resistance and its durability of a surface, the discussion strongly depends upon the test method used. Even the use of the methods summarized in the European Technical Specification CEN/TS 16165 [5] for slip resistance measurement on pedestrian surfaces (including the ramp method, the measurement of the dynamic coefficient of friction by using a tribometer and the pendulum test (figure 1)) does not give a consistent and comparable basis for the actual slip risk assessment of a pedestrian surface, let alone a basis to evaluate its durability.

Different methods are known to give contradicting results and corresponding risk evaluations on the same surface, dependent on its structure. This was the incentive for the development of a surface classification based upon the use of optical topography measurements [3, 4]. Every slip resistance measurement method is a different functional interpretation of these surface characteristics. The impact of these differences is even more critical, when due to the wear of a surface its roughness profile changes, influencing the interpretation. A practical example is the effect of the shift of a micro rough surface into a smooth one due to wear, thus decreasing the slip resistance measured on the ramp, but increasing the slip resistance as measured by the dynamic coefficient of friction measurement. To complicate matters further this also depends on the equipment used. This effect also has to be taken into account when looking at the current reference systems for slip resistance testing of the mentioned methods and its possible re-development, which will be addressed in a separate publication [6].

Figure 1. *The methods included in the European Technical Specification CEN/TS 16165 for slip resistance measurement on pedestrian surfaces: the ramp method (left), the measurement of the dynamic coefficient of friction, here by using the GMG 200 equipment (middle) and the pendulum test, here used on site (right).*

This situation motivates the ongoing investigation of correlations between slip resistance and the surface characteristics as derived from optical topography measurements. This publication is based on the results of a cooperative research project regarding the development of new reliable and durable reference systems for the slip resistance measurement methods by FGK and the Test and Research Institute Pirmasens PFI Germany [7]. New insights from these investigations support the development of a laboratory based wear simulation and new concepts for designing reference systems, not only addressing the surface and its durability but also the behaviour of the shoe or slider used.

3. SURFACE GROUPING AND ITS IMPLICATIONS

The lack of a single harmonized test for slip resistance, being an essential characteristic for the CE marking of floor tiles, motivated the European standardization committee CEN/TC 339 (on measurement of slip resistance in pedestrian areas) to put forward the mentioned technical specification in 2011, including the walking method on an inclined ramp, the pendulum test method and a method for the measurement of the dynamic coefficient of friction. These methods, which address different slip mechanisms, are the basis for the discussed research.

The ramp method is based on the determination of a critical inclination angle at which a person slips on a sample. The test for occupational areas with oil / reference shoes (DIN 51130), ranging the tested surfaces in R-classes (using reference slabs), is related to application areas with different amounts and sorts of contamination. In the test for barefoot applications (DIN 51097) samples are flooded with (surfactant added) water and walked on with bare feet, to classify the surfaces as A, B or C-class, related to areas with different water load. The tribometer-method measures the dynamic coefficient of friction, i.e. the resistance to move a defined slider over the surface in dry or wet (with water or surfactant added water) conditions. Safety threshold values have been established to evaluate and control slip resistance on site under occupational conditions. The pendulum test is based upon the deceleration of a rubber slider, mounted on a spring-loaded slider unit on a pendulum arm, which swings over a surface with a defined contact path, measuring in fact the loss of energy during the contact. These values are also compared to specified thresholds, each indicating a different expected slip risk.

As mentioned before, the results of these methods can differ strongly dependent on the surface tested due to different measurement mechanisms:

The operator-based ramp approach incorporates static as well as dynamic friction during human walking, with high uncertainty at lower angles, but the possibility to measure highly profiled surfaces. It however only can be used in the laboratory. The measurement of the dynamic coefficient of friction can also be performed on site using portable self-propelling or pulled devices. It is less dependent on human influences. On smooth surfaces it however can lead to an overestimation due to adhesion of the slider on the surface, as well as an underestimation at a higher profile depth due to the loss of contact area of the slider. As the pendulum originally was developed to simulate the braking effects of car tires on roads, it is a portable measurement device, but puts high demands to the experience and training of the operator. Here smooth surfaces can also be easily overestimated due to adhesion effects, whereas highly profiled surfaces require operator expertise and can be underestimated due to the loss of contact area.

A major break-through of the the European SlipSTD project [3, 4] was the use of a novel surface evaluation method based upon optical topography measurements. It is applicable to the wide range of ceramic surfaces and quantifies the surfaces' aspects relevant for the differences in the behavior of the slip resistance measurement methods. Thus, a new approach to evaluate the suitability of the methods on different surfaces can be developed.

For standard measurement and evaluation tasks regarding surface roughness 2D tactile measurements are commonly used. They however reach their limits on often heterogeneous and structured ceramic surfaces. Thus, state-of-the-art optical 3D-measurement methods for surface topography characterisation provide significant advantages. Sensors using chromatic aberration (surface height differences are calculated from the measurement of the intensity-peak-shift of the reflected wavelength-spectrum of focussed white light) generate a 3D-topography-measurement with a height range relevant for ceramic floor tiles (up to 1 cm). At the same time the handling of a necessarily large measurement area (up to 100 mm x 100 mm) with a required lateral resolution, together with an acceptable time effort is provided.

Within the SlipSTD Project a specifically tailored measurement and evaluation procedure for the topography measurement of ceramic surfaces was developed. Its initial version is designed upon the international 2D-based Geometrical Product Specifications (GPS) - Surface texture Standards ISO 4287 and EN ISO 4288 [8, 9]. From 2010 on a new standard for 3D optical measurement methods has been presented, with relevant parts implemented in 2013, ISO 52787 [10], which led to further improvements of the developed method by specification of relevant settings for measurement and evaluation of structured surfaces. At the time FGK investigates the transferability of the method in cooperation with the Centro Ceramico in Bologna, using high definition confocal microscope. This shows promising results, indicating that the method can be transferred to other systems, thus enabling the necessary further establishment of this method as a significant tool to characterize the tile surface.

The ongoing research has shown and confirmed that by using topographic data, mainly the unfiltered profile data, an interpretation and classification of the surface, independent of the slip resistance as determined by different methods, is possible. It showed that filtered roughness values like the well-known Ra and Rz can hide actual relevant differences in the surface profile. To interpret the characteristics of a surface, amplitude parameters, shape factors as well as parameters, specifying the material ratio curve in the depth of the profile, were incorporated [11]. After an extensive statistical correlation analysis the core roughness Pk, defining the main load carrying part of the profile as well as the parameter Pp, the height of the profile above the mean line, representative for protruding peaks in the profile, were established as significant parameters, defining respectively the “friction” and the “grip” of the surface (Figure 2).

Figure 3 shows the mentioned differentiation of the surfaces using these parameters, and the specification of the suitability of the different slip test methods on different surface types as derived during the project tests, confirmed by ongoing research. This result indicates the lack of correlation between these methods over the complete span of the available surface topography. Some methods show a limited span, like the tribometer used, others, like the ramp, address a large part of the total span. On smooth surfaces (group 1, including polished tiles) other parameters like medium, measurement speed and slider type are found to be more significant than the actual topography, so adhesion aspects can influence the slider measurements. Only when roughness increases (in group 2), correlations between the methods can be established, until the loss of contact surface impairs the reliability of the tribometer measurement in group 3 and of the pendulum at an upper level of group 3.

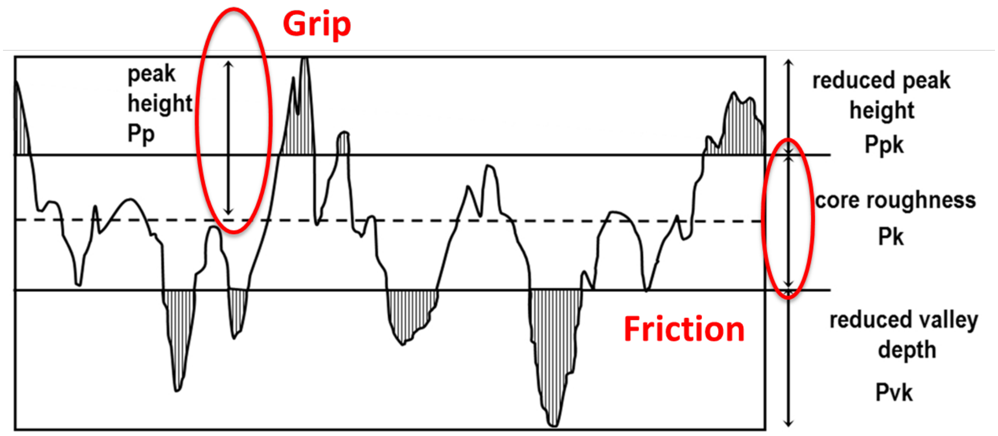

Figure 2. *Relevant topography parameters as established to be defining the slip resistance [11].*

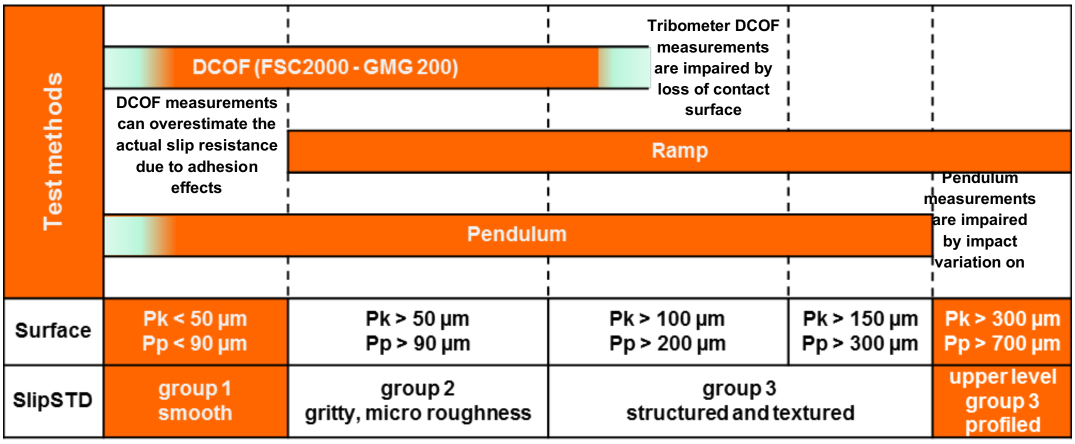

Figure 3. *Suitability of different slip test methods dependent on the surface characteristics according to the SlipSTD Research [3, 4].*

This has also an important impact on the use of the reference systems for these measurement methods. In a separate publication [6] the inadequate use of reference surfaces and the development of new reference systems for the slip resistance measurement methods by FGK in cooperation with the Test and Research Institute Pirmasens PFI Germany for shoe slip resistance testing will be highlighted. An important observation to be mentioned here is that at the moment for tribometer as well as for pendulum measurements reference materials are used, whose surfaces without exception are within group 1. This fact incorporates as mentioned the risk of misinterpretation of the actual slip resistance. Furthermore these methods in practice are used on surfaces from group 2 or even group 3, in which there is the risk of underestimating the slip resistance. These preliminary results here imply that reference surfaces should represent the surface groups also measured in practice, or even that methods might be disqualified for a certain surface range. This implication will need further investigation and discussion.

4. SLIP RESISTANCE, WEAR SIMULATION AND TOPOGRAPHY

The aims of the ongoing research project are to develop robust, reproducible and controllable reference systems, a method to evaluate the durability of surfaces as well as footwear and to evaluate application areas for slip measurement methods. As a technical base, the development of a reliable and practice–oriented laboratory wear simulation is being investigated [7].

The basis for these investigations is the previously by FGK developed radial abrasion method for larger scale samples up to of 50 cm x 100 cm using abrasive pads in a single-pad cleaning device [2]. This testing area enables the performance of all relevant described slip measurement techniques as well as cleaning tests. This method has been optimized and validated using topography measurements, to compare the laboratory results with identical surfaces in use on site, using a duplication technology with a two-component silicone material to eliminate the need to extract of tiles from the actual floor. This comparison indicated that specified abrasion patterns (quantified as cycles) lead to changes of the profile as found in the surface on site. Thus, they can be correlated to actual wear effects: 20 abrasive cycles in laboratory correspond to the effects of wear after 1.5 years in a highly trafficked area with abrasive dirt (discount store, mall, train station hall). At the moment this method is being transferred into a laboratory device, which enables a uniform abrasion of up to 50 cm x 50 cm surfaces. It will serve in future projects to investigate parameter settings relevant to surface changes in different application areas, to differentiate it from the worst case approach and to enable further standardization. This development will be the topic of future publications.

The first results of the investigation also showed that most surfaces designed for slip resistance requirements, show a significant decrease in their slip resistance properties in their first 1.5 year of use (reductions of 30 % up to 70 % for the results of the ramp method, dependent on the surface profile). Slip class thresholds might possibly be superseded, implying a reduced slip class, lower than upon installation, thus rendering it unsuitable for the application it was chosen for. This aspect has to be taken into account regarding the required attestation of performance as incorporated in the CE marking requirements. It is furthermore very important for the development of new reference systems, as the current ones are known to deteriorate during use.

To enhance the database on wear effects on ceramic surfaces, tiles from different tile manufacturers from different surface categories and corresponding slip classifications were selected and subjected to the described wear simulation method. The untreated and treated tiles were specified by surface topography measurements as well as by the chosen slip resistance measurements according to DIN CEN/TS 16565, using the ramp method (identical to DIN 51130 for occupational areas and DIN 51097 for wet-barefoot applications), tribometer measurements (in this case by GMG 200) as well as pendulum measurements. The following results are discussed as representative for the measured wear effects.

In figure 4 the mentioned typical strong decrease of slip resistance within the first number of cycles when measured by the ramp method (with oil and reference shoe) can be seen. This phenomenon is even more pronounced when the initial slip resistance of the tile is high. In this case even transitions from higher to lower slip resistance classes, almost up to two classes, can be found. In figure 5 the same surfaces were measured using the GMG 200 as representative for the measurements of the dynamic coefficient of friction. Although other tribometer tests might give different results, a known effect mentioned earlier is observed: In this case the slip resistance of the smooth surface, initially classified as R9 by the ramp method, reaches a higher value than the R10 up to R12 ranked surfaces. The R13 surface could not be measured with the tribometer due to the high profile. In comparison to the ramp test results this indicates an overestimation of the actual slip resistance on these surfaces. Another aspect to be observed is that the slip resistance decrease levels out after 10 cycles, only to decrease again after a large number of cycles (from 20 to 100 cycles).

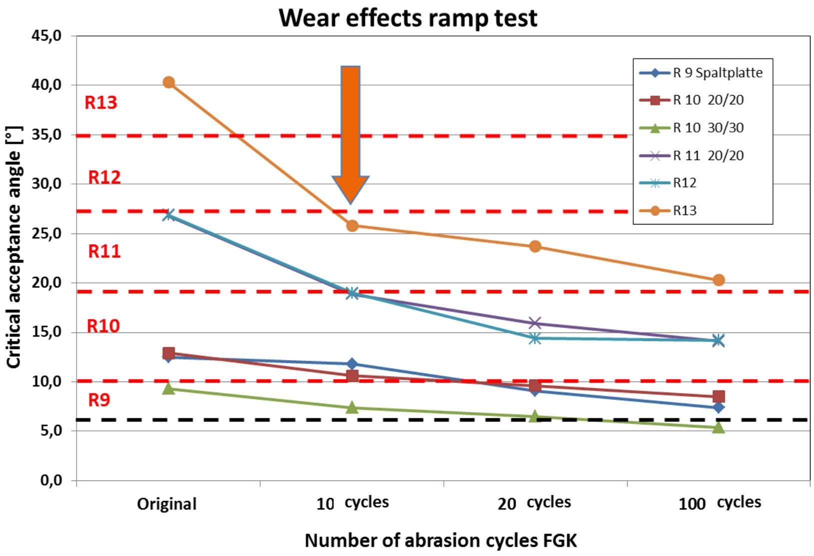

Figure 4. Wear effects on the ramp measurements (DIN 51130)

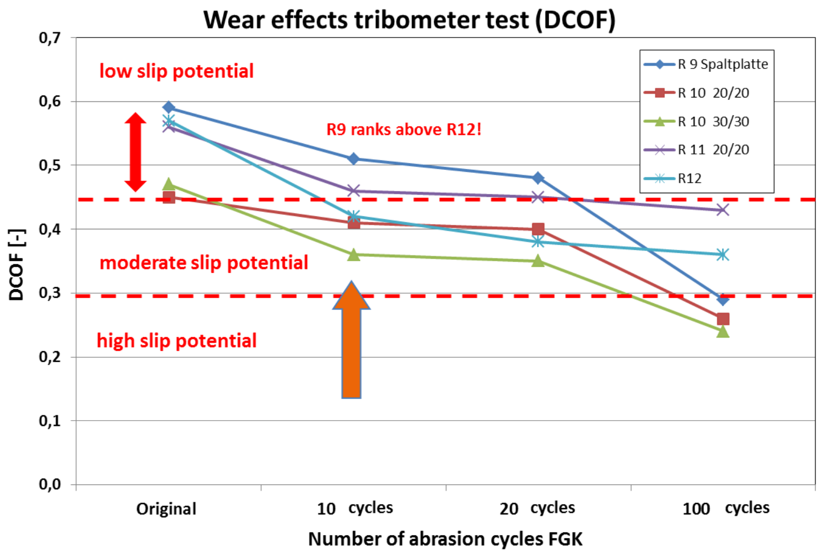

Figure 5. Wear effects on the tribometer measurements with the GMG 200

The pendulum results (figure 6) show a more severe impact of wear on the slip resistance. The effect that the smooth R9 surface also tends to generate higher values than the R10 surfaces also occurs for this measurement method. Moreover, the surfaces, which were indicated to have a certain degree of slip resistance, are after few cycles transferred into the high slip risk range. Besides, the R10 surfaces do not even reach the expected low slip risk range in untreated condition.

These slipperiness characterizations, which are all based upon the same samples and their changes in surface, lead to strongly differing results using the different measurement methods – not only regarding the initial classification of the surface but also in terms ofthe interpretation of the changes in slip resistance. This emphasizes the mentioned need for applicability ranges of the test methods as proposed (Figure 2), as dangerous misinterpretations can be made.

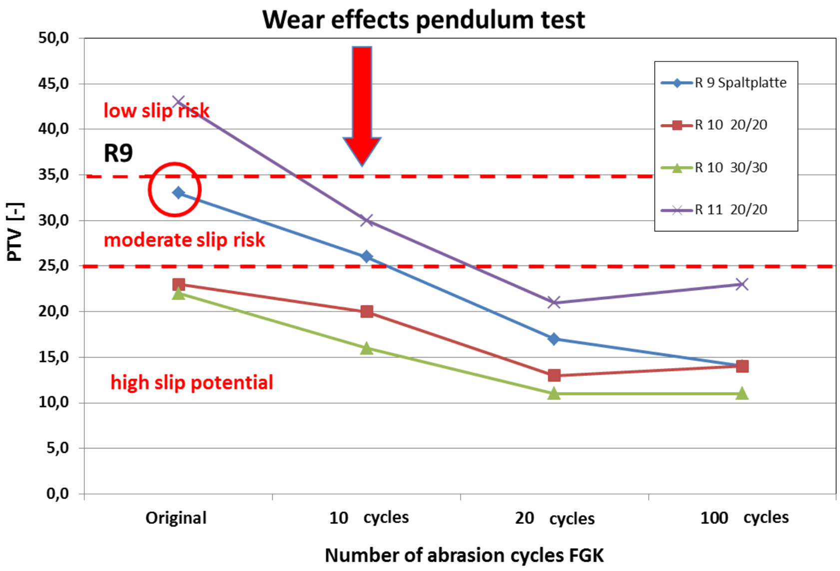

Figure 6. Wear effects on the pendulum measurements

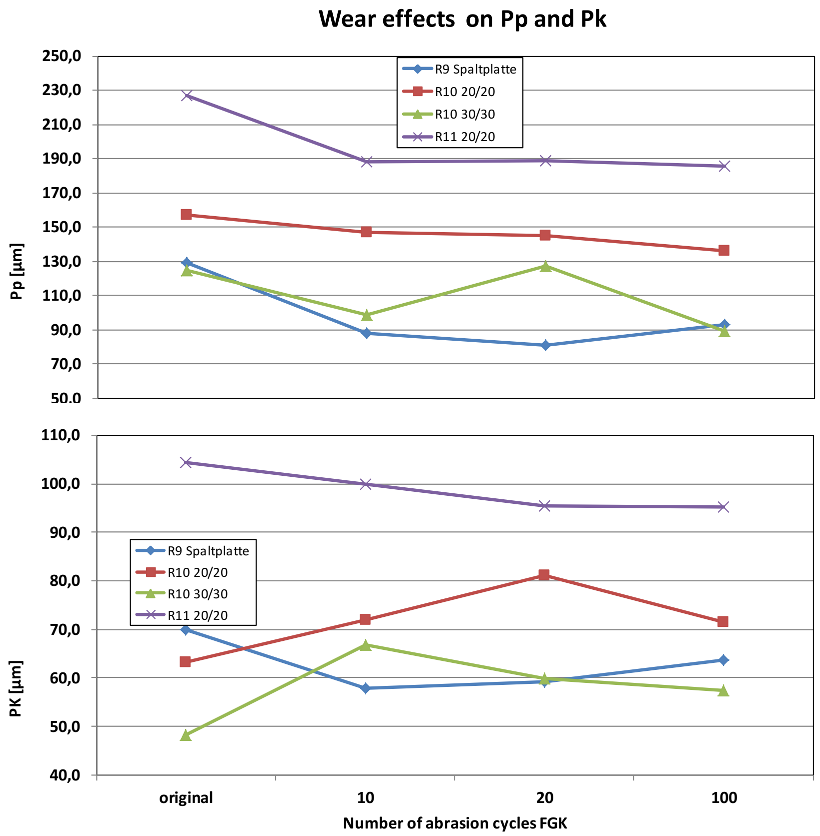

Figure 7. *Wear effects on Pp and Pk values*

In figure 7 the actual surface changes as measured by Pp and Pk are displayed, showing that the correlations with slip resistance and abrasion effects are not linear. Therefore, other aspects than both initially defined parameters might be important to explain the effect of the surface changes. When looking at the behavior of the R10 tile surface, the Pp reduces slightly from ca. 156 µm to 145 µm, while the Pk value even increases from 63 µm to 81 µm, still resulting in a strong decrease of the slip resistance. The cause for these effects could be explained by the heterogeneous character of this specific surface: parts of the surface wear differently, in this case removing parts of the surface matrix without changing the protrusions to create a higher Pk value. This kind of effect has to be investigated specifically for each surface.

5. THE RELEVANCE OF Psk FOR SLIP RESISTANCE

To be able to interpret the wear induced changes in the surface profiles and their correlation to the discussed changes in slip resistance, a new approach had to be developed. As linear correlations between the surface parameters Pp and Pk and the slip results could not be established, further research had to be performed. Spatial parameters were included to explain differences between surfaces with comparable Pk and Pp values, but different slip results, which were expected to originate from the spatial distribution of the protrusions in the profile.

The spatial parameter that explains these effects could be identified as the Psk, the skewness of the profile. It indicates the symmetry of the peak/valley distribution about the mean reference plane of the profile, as derived from the 3D topographical measurements (figure 8). Although direct spacing parameters like RPc, the peak count/distance, seem more logical, these showed too much statistical variation on the examined surfaces, due to their extraction from 2D measurements instead of being calculated from 3D measurements.

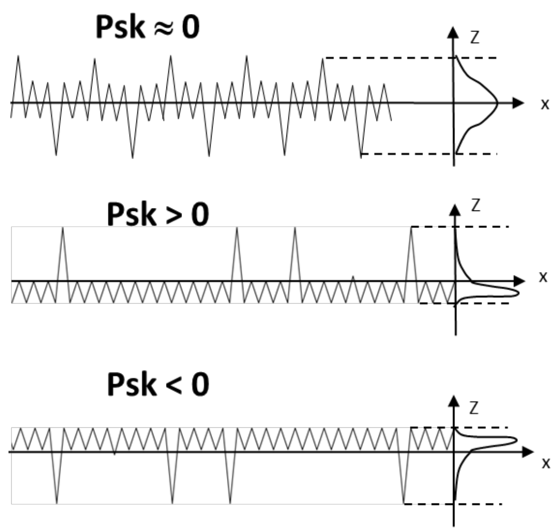

Figure 8. *The Psk parameter as indication for the peak/valley distribution about the mean reference plane of the profile*

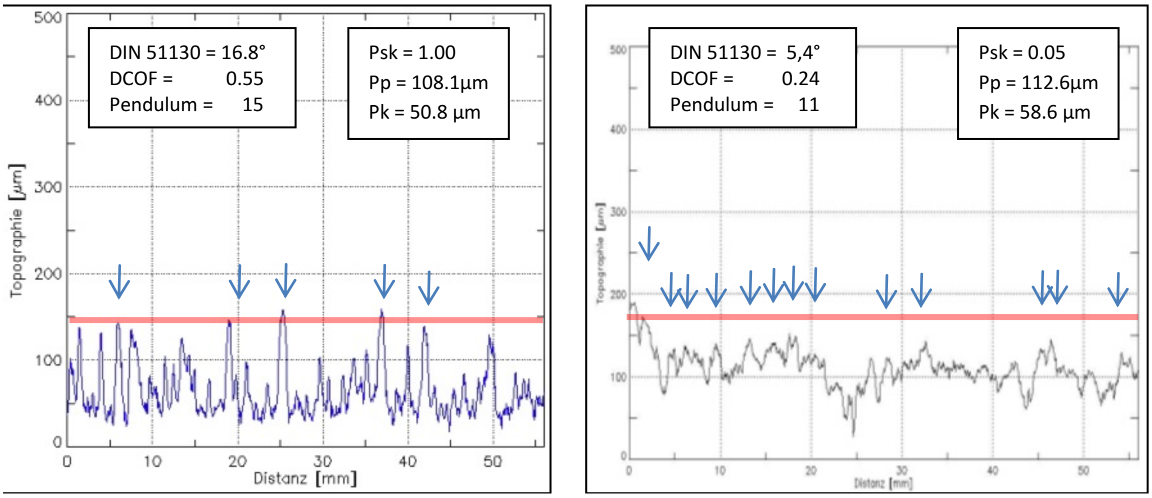

Figure 9. *Impact of Psk differences on the actual measured slip resistance values for a group 2 surface.*

Figure 9 illustrates the impact of Psk differences on the actual measured slip resistance values for a group 2 surface. Although the values of Pp and Pk are comparable, the surface with a higher Psk (distribution skewed towards top, i.e. more high peaks spread on a regular surface) has less contact points in the surface than in the case of Psk near 0. In figure 9 this is simulated by introducing a flat load (red line). In this case there is a significant difference in the measured values on the ramp and the dynamic coefficient of friction, however less pronounced compared to the pendulum test.

A possible explanation can be found in a simplified description of the contact situation of the surface profile with the shoe/slider (figure 10):

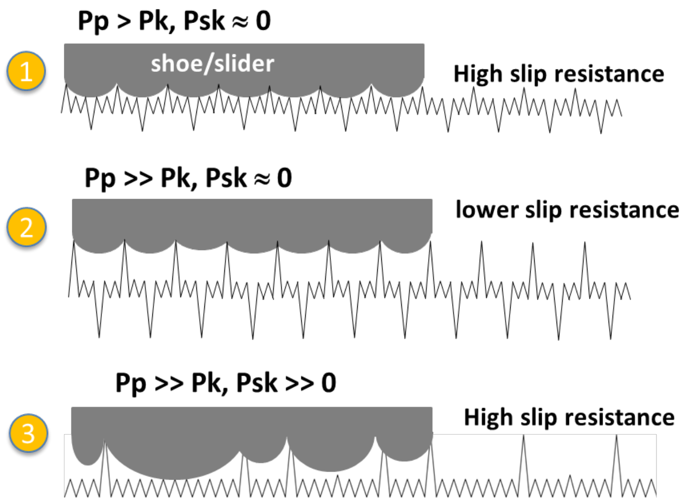

Figure 10. *a simplified description of possible contact situation of the surface profile with the shoe/slider*

If the value of Pp is higher than of Pk and the Psk is near zero (situation 1), there is contact with most of the profile. In this case Pp provides the grip; Pk provides the friction, generating the optimal slip resistance. If the value of Pp is much higher than of Pk, and Psk is near zero (situation 2), there is mainly contact with the protrusions, thus grip, as defined by Pp, which competes with the loss of friction by a reduced contact with the core roughness Pk. This means also that this surface can be susceptible to wear. If Pp is much higher than Pk, but with a value of Psk differing from zero (situation 3), there is contact with the protrusions. Due to the wider distribution of peaks, contact with the core roughness Pk is also provided, so the slip resistance is increased. In this case, like in situation 2, this surface tends to be even more susceptible to wear.

In the discussed project the correlation of the results of slip measurements with surface characteristics of 5 tile types, each abraded in 4 to 5 abrasion stages (0, 10, 20, and 100, in some cases supplemented by 50 cycles) of 4 manufacturers has been investigated. The evaluation of the slip resistance measured with the ramp as related to Pk and Pp for group 2 tiles is shown in figure 11. In this case two different areas in regard to the Psk value can be specified: a line can be drawn between the area of high Psk values (above 0.5, here to the left of the red dotted line) and of low Psk values (right of the red dotted line). This indicates that with regular shaped surfaces with a low Psk value sufficient slip resistance can only be reached with high Pk and moderate Pp values. Higher slip resistance with Psk values between 0.6 and 0.9 can also be reached at lower Pk values, but only with sufficient Pp. In case of high Psk values, there is even a range at lower Pk and Pp values with high slip resistance. The latter however is only a small area, where small changes in the surface lead to a strong decrease in slip resistance, which indicates high sensitivity for wear for these surfaces.

This explains the strong decrease of the mentioned R10 tile surface: the increase in Pk was paralleled by a strong decrease in Psk, suggesting a shift in the profile from situation 3 to the situation 2 according to figure 10.

Zooming in on the group 2 tiles with a Psk lower than 0.5, another effect which has been experienced in practice can be explained (figure 12). In this case increasing the Pp at a high Pk leads to an increase in slip resistance on the ramp (“1” in figure 12). However, at further increase of Pp, according to the description in figure 9, the contact area is reduced and contact with the core roughness lost, leading to a lower slip resistance (”2” in figure 12). This leads to the interpretation that too high peaks reduce the slip resistance.

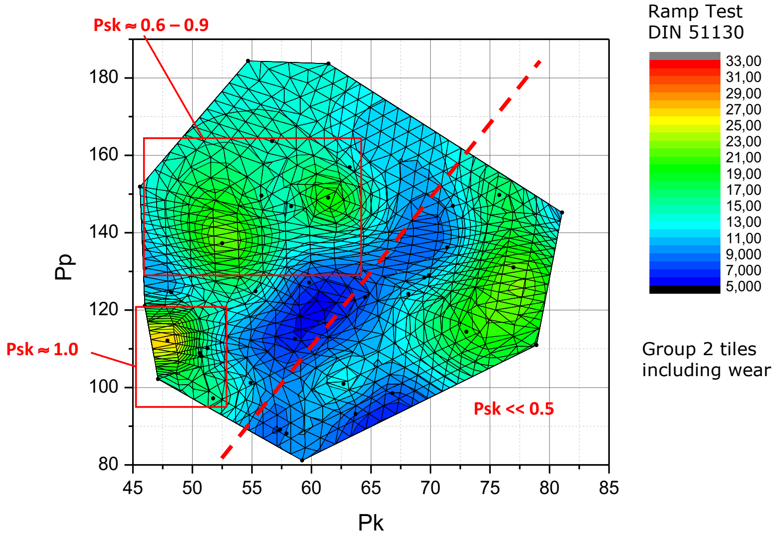

Figure 11. *The correlation of slip resistance (measured with the ramp) to Pk and Pp and the influence of the Psk.*

This representation also shows the differences between the different test methods. In figure 13 and 14 results for group 1 tiles are shown.

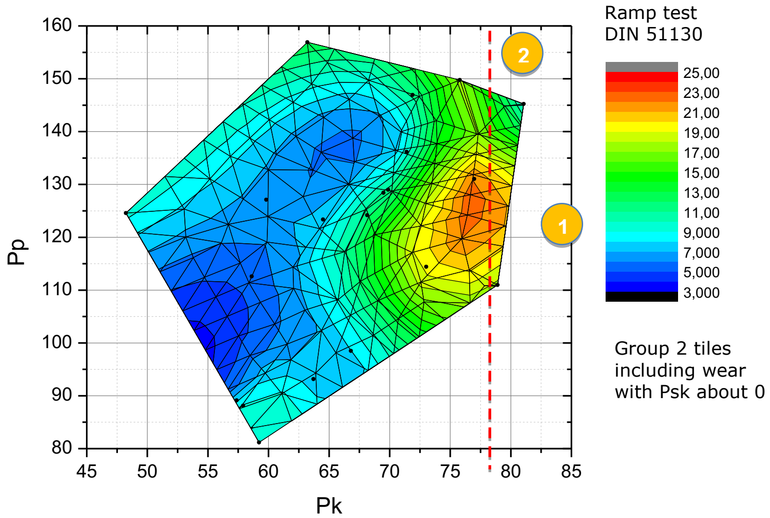

Figure 12. *The correlation of slip resistance of group 2 tiles measured with the ramp to Pk and Pp.*

In the case of group 1 tiles the possible slip resistance as specified with the ramp method is both limited (up to 14° critical angle or R10 resp.) and has a very narrow range, so there is a high sensitivity to wear. Comparing these values to the values obtained with the DCOF measurement (figure 14), there is a significant difference: in this case there is a large region in the diagram with a constant slip resistance value, signifying minimal wear sensitivity. This complies with the results as displayed before in figure 5, where this "plateau"-effect was found during the wear tests. Looking at the results of the pendulum tests (figure 15), the interpretations are again very different. There is high slip resistance at low Pk with moderate Pp values, which however tend to decrease when the Pk value is increased or the Pp value decreased. Here contact loss can also be expected as cause for the decrease in slip resistance.

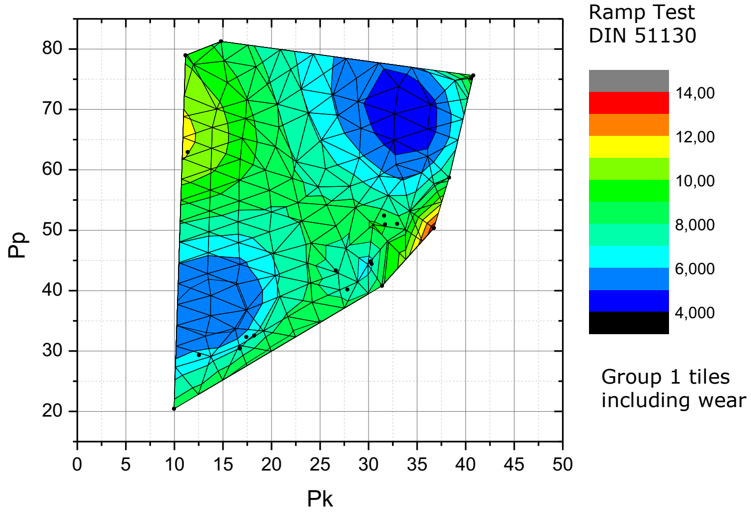

Figure 13. *The correlation of slip resistance of group 1 tiles (measured with the ramp) to Pk and Pp.*

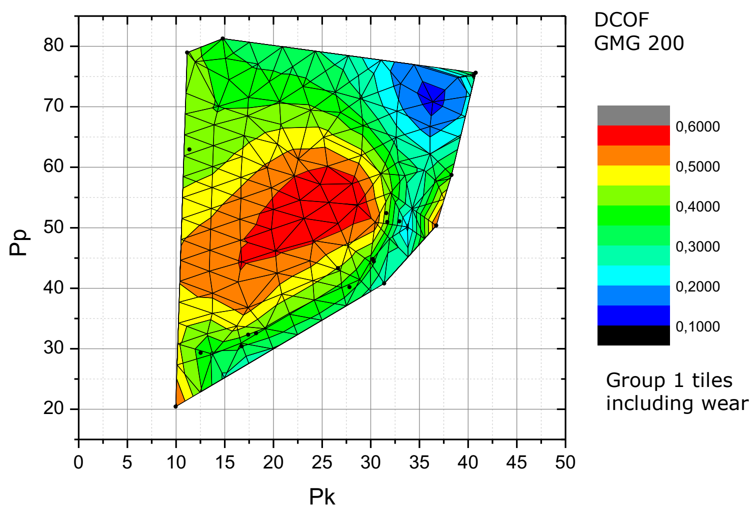

Figure 14. *The correlation of DCOF of group 1 tiles to Pk and Pp.*

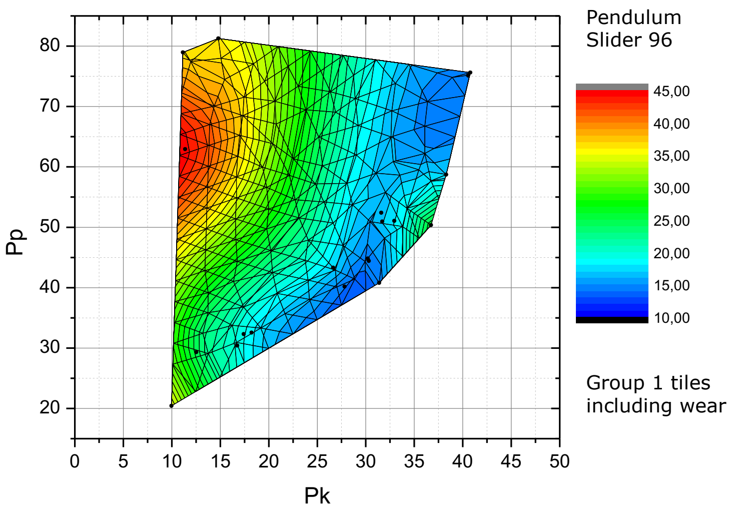

Figure 15. *The correlation of the pendulum tests of group 1 tiles to Pk and Pp*

6. DISCUSSION

The presented results highlight the difference in the interpretation of slip resistance of different methods on the same surfaces, which has to be taken into account when estimating slip risk. The increasing understanding of the surface profile in regard to slip resistance can help to support the present issues when discussing comparability and reliably of slip resistance testing. Of course the results shown always depend on the method used, but the use of surface topography as an objective basis to interpret slip effects as developed in the SlipSTD project is confirmed. Both surface topography measurements and defined abrasion simulation have a high potential to help manufacturers of slip resistant tiles to investigate, develop and control durable slip resistant surfaces. Continuative investigations are essential to live up to growing requirements regarding reliable safety in use, as is included in international and national regulations, and to match these with the high esthetic quality which is required in the market.

Enhancing this database of surface topography and slip resistance measurements will increase the qualitative and even quantitative predictive potential of the shown correlations, also regarding to the possible effects of surface changes to wear. In this regard these results are already being implemented to design optimized surfaces for durable slip resistance. Moreover, these findings are an important input to evaluate the currently used reference systems as well as to develop reliable, controllable and transferable sets of reference surfaces for the slip resistance measurement methods. This development will be the subject of separate presentations.

7. ACKNOWLEDGEMENTS

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