EVOLUTION OF ROUGHNESS AND SLIP RESISTANCE DURING WEAR OF CERAMIC TILE SURFACES

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ABSTRACT:

In academic research, roughness is used to evaluate some technical properties of a ceramic surface, such as its texture, tendency to be impregnated with dirt, and slipping resistance. Many works show the importance of the determination of surface roughness, but this property is not commonly measured in the ceramic industry. Therefore, this work aimed to correlate roughness with the surface wear of ceramic floor tiles. The R_z parameter, determined by contact profilometry, was used to evaluate the wear of nine ceramic surfaces with different coatings: glossy, satin, polished, glazed and unglazed, natural surfaces with and without decoration, and covered with corundum and grit.

The wear of the surfaces was performed in the laboratory according to an adapted procedure of the ISO 10545 standard. Corundum was used as abrasive agent, according to the standard, and also quartz. The abrasion cycles ranged from 25 to 24,000 rotations, with shorter intervals for the smaller cycles and longer intervals for the larger ones. In addition, the slip resistance of the worn surfaces was also determined, for each of the abrasion cycles, according to the Pendulum, BOT, and Dynamic Slip (DS) techniques.

The surface of the samples was analyzed by scanning electron microscopy (SEM) after wear in order to correlate the surface topography with the roughness measurements. The results show that the original surfaces with higher roughness, such as that covered with grit or other coatings, presented a marked reduction in R_z values and also in slip resistance after surface wear. Coated surfaces regarded as 'slip resistant' can be drastically impaired over their life cycle, and therefore great care must be taken in their specification for use. On the other hand, the satin and polished surfaces presented an increase in R_z and also in slip resistance. The SEM analysis showed that samples with higher initial roughness underwent a polishing process, in which the peaks of the roughness profile were worn down by the wear process. The smoother surfaces had their porosity and internal irregularities revealed by the wear processes, resulting in an increase in the R_z values and also in slip resistance. The microscopic analysis corroborated the surface roughness measurements. Therefore, roughness parameters (such as the R_z) can be used by the ceramic industry to determine surface characteristics of ceramic tiles.

1. INTRODUCTION:

Ceramic tiles are widely used as coverings in both residential and commercial environments, including outdoor areas, called wet areas, used in humid / wet conditions. The wet condition requires that the floor (and the environment) show characteristics that increase the pedestrian's safety when walking, that is, ensure he / she will not suffer an accident such as a fall or slip, as the water acts as a lubricant, increasing the chances of falls.

The resistance to abrasion of a ceramic surface is related to its brittleness. Once installed, the ceramic tile will be continuously rubbed against furniture, apparatuses, and pedestrian shoe soles, which cause constant wear on the surface. There is also the possibility that at the interface there are particles, materials that intensify the abrasion process, such as dust, sand, water, etc. This entire abrasion process tends to cause wear on the ceramic surface, reducing its roughness and consequently its friction coefficient.

According to Smithells (2004), wear is the progressive loss of material from the surface of a body, which occurs as a result of the relative movement with this surface. The main types of wear are abrasive wear, adhesive wear, erosive wear, and corrosive wear.

The wear phenomenon is defined as the destruction and separation of material particles from the contact surfaces due to mechanical factors. Abrasive wear occurs when hard particles isolated from the contacting surfaces are moving against each other. This type of wear can be controlled by factors such as increased hardness of the contact surfaces and decreased surface roughness (Arnell, 2010; Burakowski and Wierzgon, 1998; Cohen, 2004).

Since wear is a system response and not a material property, wear resistance can vary within a wide range of different mechanisms that are tested by different test conditions and methods (Adachi e Hutchings, 2003).

Surface texture is considered to be a factor influencing the displacement of the layer structure during the wear and friction control operation. According to research carried out so far, it can be inferred that surface texture is studied to assess the effect on tribological properties during slip conditions (Amini et al., 2016).

Floor surface friction and wear behaviors are the result of many local events and the nature of these events is very difficult to determine. However, the transfer of a material to its surface seems to be a crucial feature of wear mechanisms between the surface of the floor and the sole of a shoe (Kim, 2016). This means that the formation of transfer films on the surface during repetitive sliding plays an important role in the wear and friction mechanisms of materials (Bahadur, 2000).

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Therefore, it can be considered that the transferred wear products are equally important for understanding the tribo-physical behaviors of the floor surfaces (Kim, 2016). In other words, unlike other mechanical properties, the wear properties of materials are not intrinsic, but are specific to the slip system and are modifiable by slip variables (Kim and Nagata, 2008; Kim et al., 2013; Kim and Smith, 2000; Zhao and Bahadur, 1999).

Kim (2004) studied the wear of shoes and floors, and several interrelated mechanisms such as material transfer and film formation were also found to be factors in the phenomenon of friction and shoe wear. The three-dimensional microscopic observations clearly show that each shoe and floor tested experienced various types of surface changes and flaws that evolved throughout the entire test. Overall, the wear of each floor sample showed severe material transfers and film formations from an early stage of friction. From this experimental study, it is clear that there is a relationship between wear effects and slip resistance results.

The friction mechanism between the shoe and the floor surfaces has very peculiar and complex characteristics because of the totally different material properties of both bodies. However, one of the most important features is that the topographic characteristics of both surfaces are continually changing in the process of friction and wear evolution. Therefore, it is vital to systematically monitor the surface state of both bodies (Kim, 2004).

Sidewalks, walkways, and any place that will be subjected to pedestrian traffic must be constructed to provide safety for people. These locations must offer excellent slip resistance throughout their lifetime (Kim, 2017). For Kim (2017) the support and control of the slip resistance properties of the floor surfaces are necessary. That is, with repeated walks, the final surfaces of pavements and sidewalks seem to undergo considerable changes due to the aging of the covering materials, wear, dirt, and maintenance (Leclercq and Saulnier, 2002; Kim and Smith, 2000). As a result, the slip resistance functions of pavements and floor coverings deteriorate over time (Kim, 2017).

These results are confirmed by field studies where floor friction was investigated at different test sites. Mechanical wear, soiling and maintenance strongly affect slip resistance and the complex interaction of these factors can lead to considerable local variations in surface properties (Chang et al., 2003; Chang et al., 2008; Li et al., 2004).

There are two options for maintaining adequate slip resistance and preventing slip accidents. The geometry of the floor surface must be designed and maintained regularly or a shoe surface that does not change with wear must be produced (Kim and Smith 2000). But it is known that under real conditions of use these two alternatives are not possible.

With use, floors are subjected to physical and chemical attacks, especially resulting from human traffic and cleaning operations. These forms of attack can change the state of the floor surface and, therefore, its resistance to slipping (Leclercq and Saulnier, 2002).

Due to the difficulties regarding the determination of the slip resistance of ceramic tiles, the aim of this work was to measure the surface roughness of ceramic tile surfaces during and after wear and relate them to the slip resistance of the material.

2. MATERIALS AND METHODS:

To analyze the wear behavior of different ceramic surfaces, a total of 8 types of products with different finishes were analyzed. Table 1 shows the products evaluated in this work.

Typology	Surface finish	Sample
Stoneware tile (single firing)	Glossy	GG
Glazed porcelain tile	Polished	GP
	Satin	GS
	Covered with corundum	GCC
	Covered with grit	GCG
Unglazed porcelain tile	Polished	UP
	Undecorated	UU
	Decorated	UD

Table 1. *Typologies of ceramic surfaces studied in this work*

The samples were subjected to surface characterization tests such as: 1) Determination of the dynamic friction coefficient using a tribometer, according to ISO 10545 (Gabrielli DS Dynamic Slip); 2) determination of the dynamic friction coefficient using a tribometer, according to ANSI A.137 (BOT Regan Scientific Instruments); 3) determination of slip resistance according to AS 4586 standard using digital pendulum (Munro); 4) determination of the Rz surface roughness parameters by contact profilometry (Mitutoyo SJ 210); and microstructural analysis by scanning electron microscopy (Zeiss EVO).

The surface characterization tests were performed before and after surface wear. In the determinations of slip resistance and roughness, three samples of each surface were evaluated for each wear condition. The microstructural analysis was performed with one sample.

The procedure for the wear test was based on the ISO 10545 standard. The test was performed with the standard abrasive material, corundum and water, with steel balls of various diameters as abrasive load. A second composition of abrasive material, quartz, was used. The number of spins tested were 100 – 20,000 cycles. An abrasimeter (Gabrielli ISO) was used.

To perform the slip resistance test after abrasion, two worn parts were joined so that there was a sufficient area to perform the tests, as shown in Fig.1:

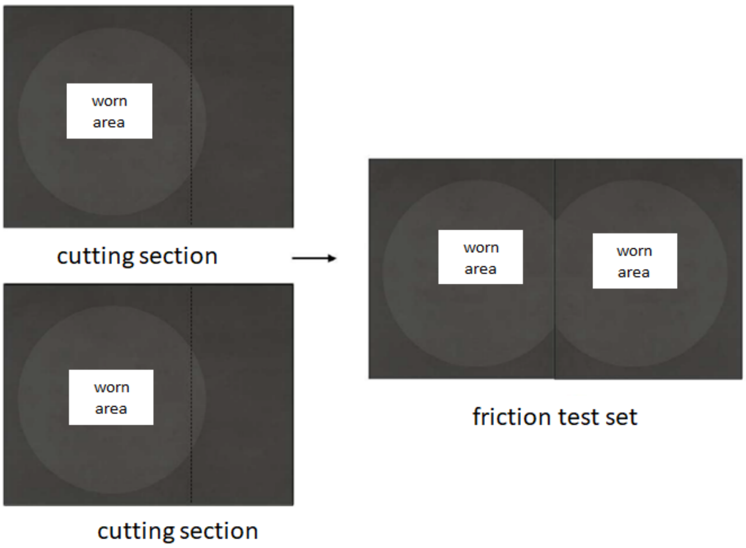

***Figure 1**. Set of tile samples for the slip resistance test after abrasion*

3. RESULTS AND DISCUSSION:

Slip resistance according to ISO 10545 (DS Dynamic Slip), ANSI A.137 (BOT), and AS 4586 (pendulum) in dry and wet conditions is presented as a function of the friction coefficients. Roughness is represented by the Rz parameter. The red lines in the graphics indicate the value established by the respective standard so that the surface can be considered safe.

The coefficient of friction (COF) determined by the DS method is shown in Fig.2(a) for the wear of the satin surface. In the dry condition, the COF did not change significantly during wear. In the wet condition, the coefficient of friction increased during wear. The increase in friction is higher and at fewer cycles when corundum was used as an abrasive material. This behavior is due to the difference in hardness between quartz (Mohs = 7) and corundum (Mohs = 9). That is, the greater the hardness of the abrasive, the faster the wear.

The coefficient of friction measured with the BOT method for the satin surface is shown in Fig.2(b). The trend is the same as observed for the DS method. The coefficient of friction determined by the pendulum method during wear is shown in Fig.2(c). The friction coefficient in the wet condition showed the same behavior as the other methods. As wear occurs, there is an increase in the coefficient of friction. In the dry condition there is a small increase in the measured friction. Therefore, both the DS and BOT methods do not have sufficient sensitivity to detect friction differences in the dry condition. With the pendulum there is greater sensitivity, as it was possible to detect the difference in friction in dry and wet conditions.

The Rz parameter changes during wear, Fig.2(d). The wear-free surface has a Rz = 5 µm. After 20,000 cycles of wear, Rz = 12 µm using corundum as abrasive, and Rz = 6 µm using quartz. That is, the greater the wear, the greater the value of Rz.

As the wear process evolves, the porosity and internal irregularities of the vitreous layer are exposed. The change in the Rz parameter is much more evident in wear caused by corundum than in wear caused by quartz.

The colors in the graph shown in Fig.2(d) show the potential for slippage as per the UK Slip Resistance Guide. The red area indicates a high slip potential, the blue area a moderate potential, and the green area a low slip potential. Therefore, even after the wear and the increase in the Rz parameter, the surface can still be considered to have a high slip potential.

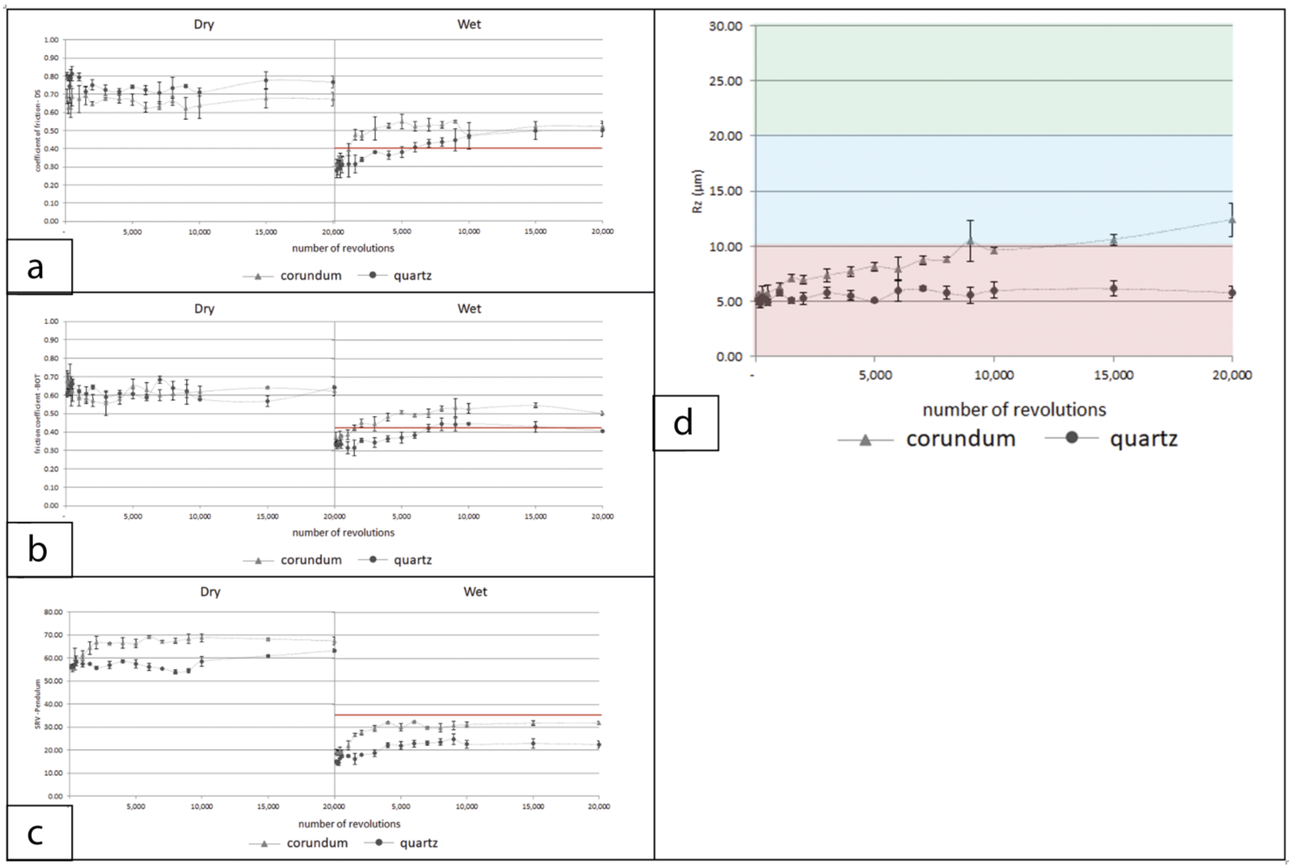

Figure 2. *Coefficient of friction measured by the DS (a); BOT (b); and pendulum (c) methods for the satin surface. Evolution of the Rz parameter during wear for the satin surface (d)*

For the unglazed decorated surface, Fig.3(a) shows the coefficient of friction determined by the DS method during wear. The trend of the friction coefficient was similar to that of the satin surface, as there was an increase in friction, especially in the wet condition. The increase was greater for the corundum-wzorn surface than for the quartz-worn surface.

The COF determined by the BOT method for the unglazed decorated surface is shown in Fig.3(b). Despite a small increase in the friction coefficient for the wet condition, the variability of measurements was very large, which does not allow for precise conclusions.

The coefficient of friction determined by the pendulum method is shown in Fig.3(c). There was an increase in the friction measured in both dry and wet conditions. The surface alteration caused by the surface abrasion process was perceived by the pendulum method in both dry and wet conditions. Therefore, the pendulum method has greater sensitivity to differentiate surfaces with different characteristics. The behavior of the unglazed undecorated surface was very similar to the behavior of the decorated surface, so the results are not displayed.

The evolution of the Rz parameter with wear for the decorated surface is shown in Fig.3(d). There was practically no change for the Rz parameter despite the increased friction coefficient. The Rz parameter is on the threshold between the red and blue areas, with values close to 10 µm.

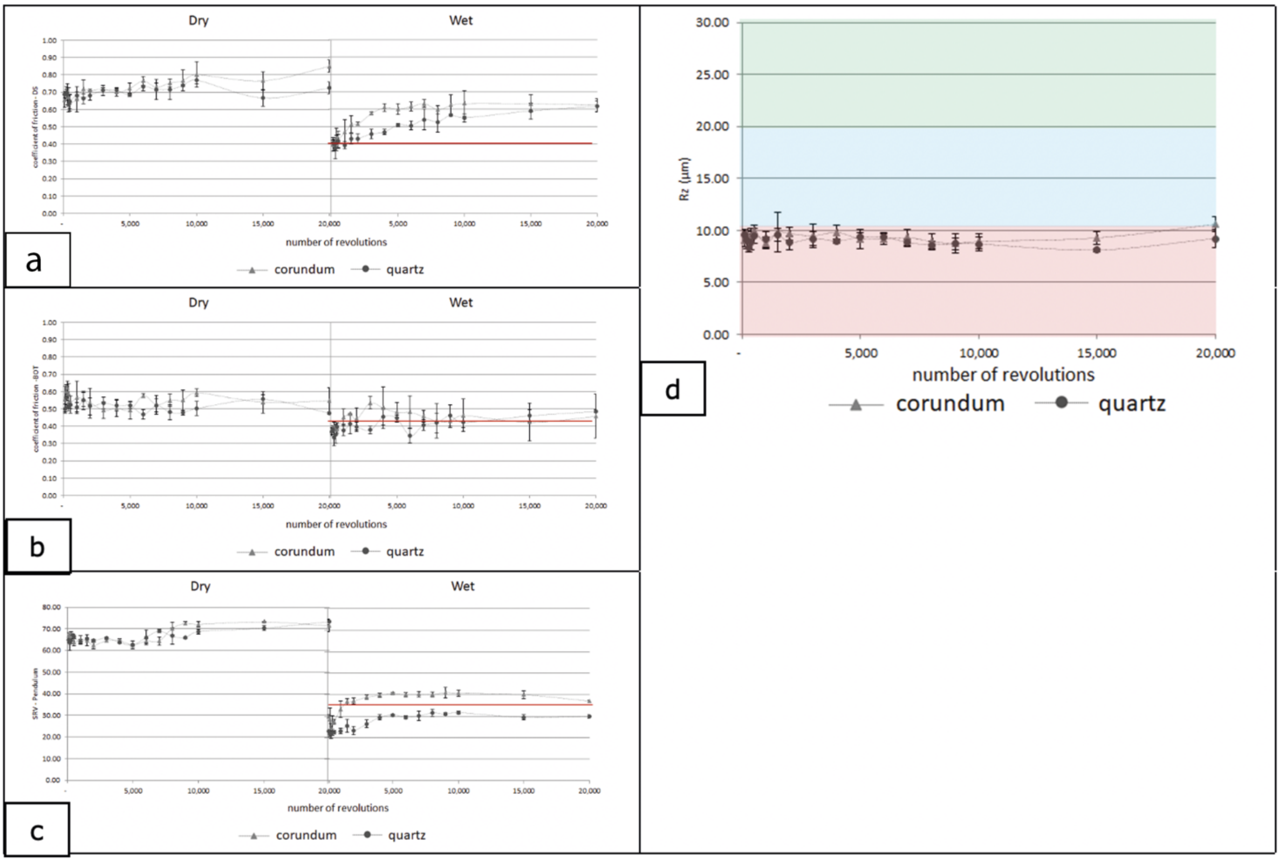

Figure 3. *Coefficient of friction measured by the DS (a); BOT (b); and pendulum (c) methods for the unglazed decorated surface. Evolution of the Rz parameter during wear for the unglazed decorated surface (d)*

For the polished surface, Fig.4(a), the DS method shows an increase in the coefficient of friction with increasing number of wear cycles. The greater the surface wear, the greater its coefficient of friction. This behavior is evidenced in the wet condition, but it is not observed in the dry condition. This effect may be due to the great variability of the results, indicated by the error bars.

Though the friction coefficient measured by the BOT method increased, the variability of the results was large, and perhaps this increase is not expressive, Fig.4(b).

By the pendulum method, polished surface, there was an increase in the coefficient of friction measured during wear, both in dry and wet conditions, Fig.4(c). The increase in friction is more evident in the wear caused by corundum, as it is harder than quartz. The pendulum has greater sensitivity to determine small surface differences in the dry condition, which is not the case with other test methods.

The trends observed in the polished surface were very similar to those observed in the polished glazed surface and the glossy surface, so these results will not be presented.

The Rz parameter during wear for the polished surface is shown in Fig.4(d). For the unworn surface, Rz = 5 µm. With the evolution of wear, Rz = 12 µm for corundum wear and 10 µm for quartz. Therefore, this surface has a moderate slip potential (blue area in the graph).

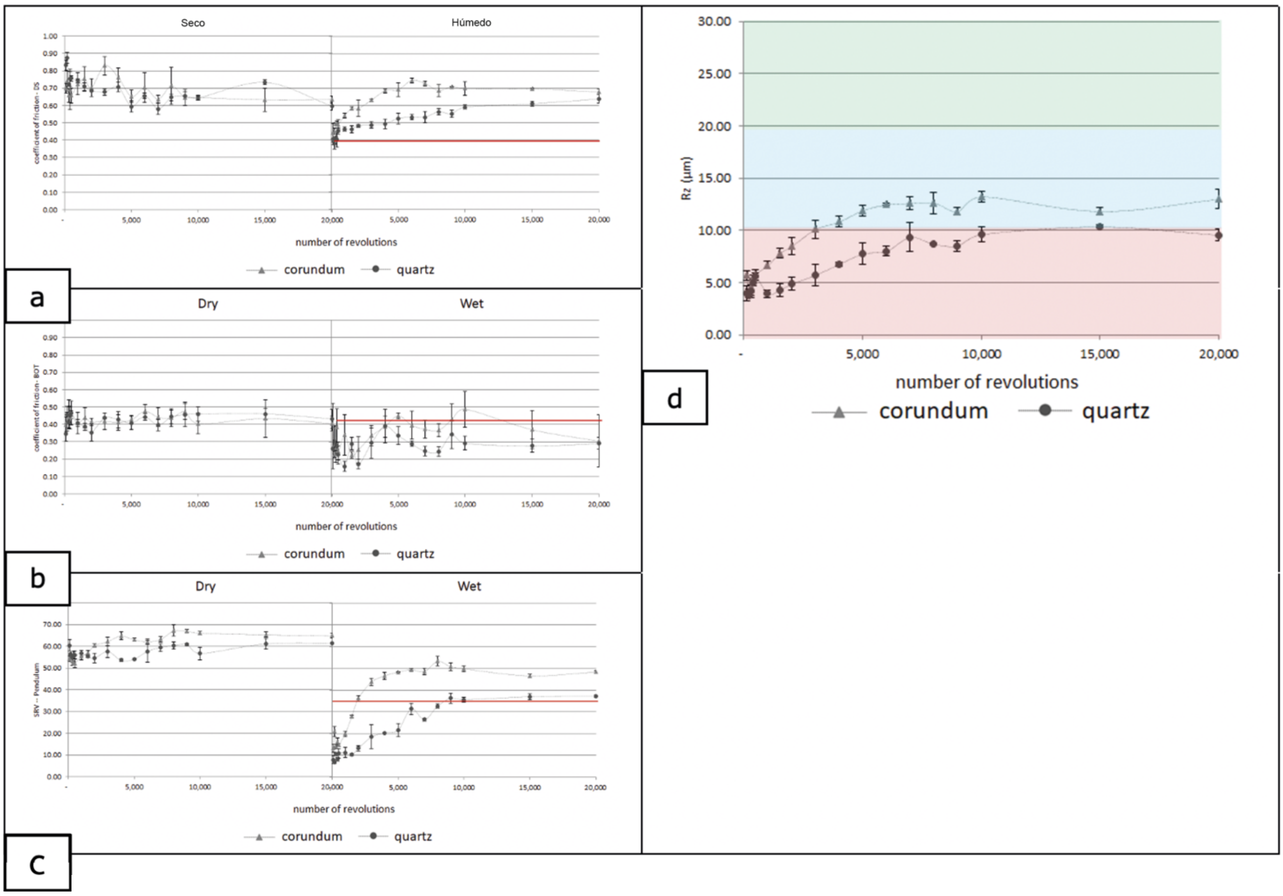

Figure 4*. Coefficient of friction measured by the DS (a); BOT (b); and pendulum (c) methods for the unglazed polished surface. Evolution of the Rz parameter during wear for the polished surface (d)*

For the corundum-covered surface, which is rougher, the variability of results decreased considerably, Fig.5(a). The corundum coating, applied before the firing process, is intended to increase the surface roughness and, consequently, its coefficient of friction.

The tribological behavior for this surface is different from the others. While on the previous surfaces there was an increase in the friction coefficient from the beginning of wear, in this case there was a reduction in the friction coefficient until the first 1,000 cycles, then there was an increase in COF. The results for the BOT method are like those of the DS method, Fig.5(b). Up to the first 1,000 cycles, the coefficient of friction is reduced. Above these cycles there is an increase in COF.

For the pendulum method, the same behavior is observed, Fig.5(c). The initial tendency of decreased friction is probably related to the wear of the corundum coating that is applied to the product surface before the firing process, resulting in greater surface roughness. In this way, the wear process initially acts as a polishing process, removing the coating from the surface of the product, and therefore reducing its coefficient of friction. As soon as this cover is removed, the wear process becomes similar to what happens with other surfaces, providing an increase in the friction coefficient.

The Rz parameter for the corundum coated surface decreases with wear, Fig.5(d). The initial value of 18 μm changes to 12 μm after 20,000 cycles. Even with the reduction of the Rz parameter, the surface remains with the same slip potential rating, rated as moderate.

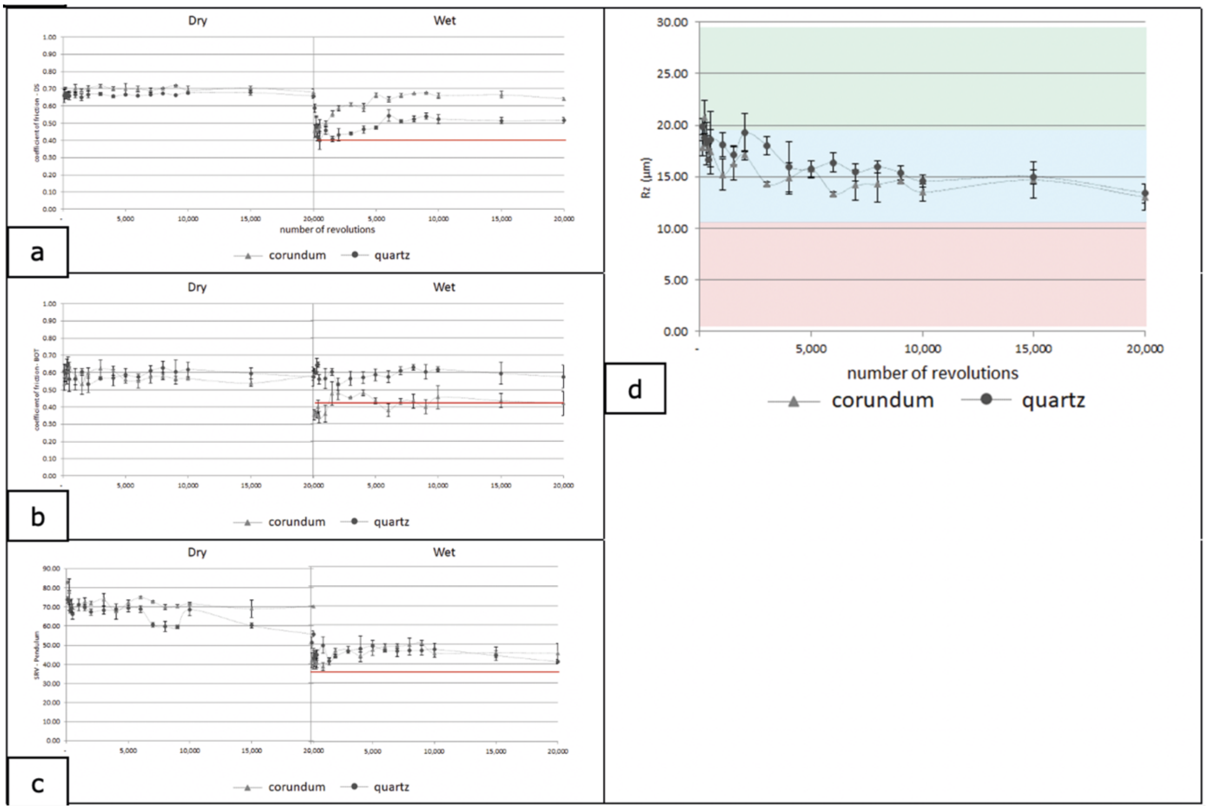

Figure 5. *Coefficient of friction measured by the DS (a); BOT (b); and pendulum (c) methods for the unglazed corundum-covered surface. Evolution of the Rz parameter during wear for the corundum-covered surface (d)*

The COF for the gritted surface, determined by the DS method, is shown in Fig.6(a). The grit causes surface irregularities that aim to make it rougher and, therefore, to increase its friction coefficient. After 1000 cycles, a polishing process begins, indicated by the reduction of the friction coefficient, both in the dry and wet conditions. The behavior was most evident in the wet condition. The COF results obtained by the BOT (Fig.6(b)) and pendulum (Fig.6(c)) methods are similar to those obtained by the DS method. Despite the great variability of the results (error bars), there is a tendency to reduce the friction coefficient.

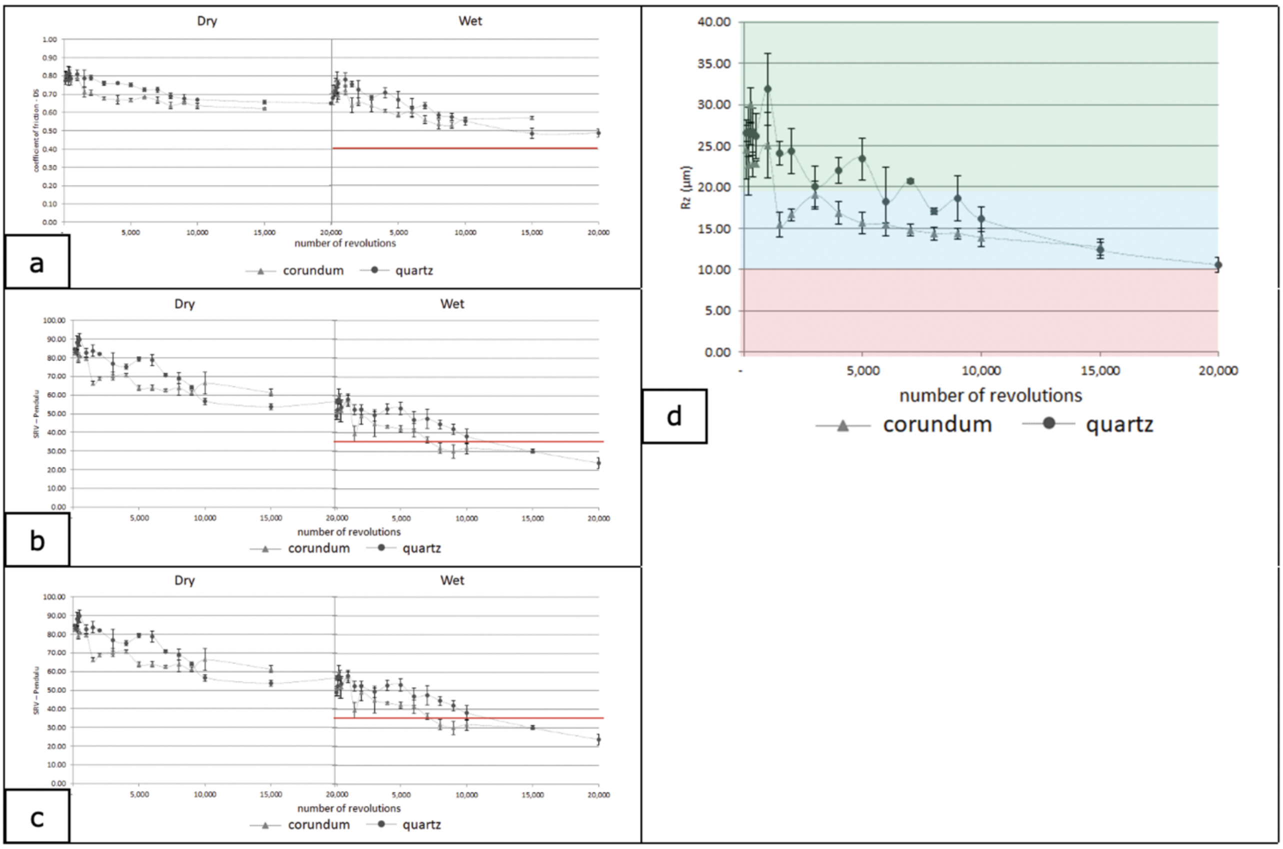

Figure 6. *Coefficient of friction measured by the DS (a); BOT (b); and pendulum (c) methods for the unglazed gritted surface. Evolution of the Rz parameter during wear for the gritted surface (d)*

The evolution of the Rz parameter for the gritted surface shows the tendency of surface polishing, Fig.6(d). As observed for the friction coefficient, there is a surface polishing, where the irregularities of the gritted surface are eliminated by the wear process and the surface becomes smoother during the process. The variation of the Rz value for the gritted surface is greater, as there is greater variability in the surface just because of the lack of homogeneity in the grit application. In this case, the corundum abrasive causes greater wear. The surface that initially presents higher values of Rz, ranging from 25 to 30 µm, and, therefore, has low slip potential, during wear has its roughness reduced and changes to moderate slip potential.

By comparing the methods, the pendulum had better sensitivity to perceive differences in surfaces, especially in the dry condition, while the other methods, DS and BOT, did not show this sensitivity. Originally smooth surfaces, such as satin, polished, unglazed and glossy, showed an increase in the coefficient of friction with wear, as the abrasion process removes the glaze layer, causing the surface to stretch and to have a smooth appearance, in the case of the glazed surface. Wear exposes irregularities present inside the vitreous layer or the ceramic body, the latter for technical porcelain tiles, that is, these irregularities make the surface rougher and, therefore, with a higher coefficient of friction.

Roughness directly influences the friction coefficient. Sariisik (2009) showed that, for marble slabs, the greater the porosity of the marble surface and, therefore, its roughness, the greater the friction coefficient, resulting in greater slip resistance.

Surfaces that already have irregularities, such as gritted and corundum-coated surfaces, underwent a polishing process, where the irregularities were gradually ground away, and the coefficient of friction reduced during wear.

Similar tests performed by Derler et al. (2015) showed that the mechanical wear produced by pedestrian traffic over a one-year period affected the sliding resistance of different surfaces in different ways and to varying degrees. In the tests by Derler et al. (2015), the friction coefficient measurements on rough (slip-resistant) surfaces generally decreased over time, as shown in this paper. The authors also observed an increasing trend in the coefficient of friction for relatively smooth surfaces. On smooth surfaces, an increase in the coefficient of friction values was observed.

Derler et al. (2015) state that the predominant wear mechanism on smooth surfaces is scratches on the surface. These scratches can contribute to the increase in the coefficient of friction. For rough surfaces, typical wear mechanisms are surface polishing and subsequent abrasion by debris. It is believed that the same wear mechanism occurred in the present work, since the results were very similar.

Micrographs (SEM images) of the satin and gritted surfaces at 150 and 500× magnifications are shown in Fig.7. The micrographs show surfaces without wear and after corundum wear with 500, 6000 and 10,000 cycles.

On the satin surface, without wear, a homogeneous image is observed. In wear with 500 cycles, lighter point areas are observed, indicating the pullout of the material caused by the surface abrasion process. With the evolution of wear, with 6,000 and 10,000 cycles, in addition to a very drastic change in surface appearance, large rounded and open pores are observed. Initially, there is a homogeneous surface, and therefore smooth, with a low friction coefficient. After the abrasion process, the surface becomes heterogeneous, with points where part of the material has been torn off, and, therefore, the friction coefficient increases.

On the gritted surface without wear, superficial particles can be observed, which are the grit that was added to the surface in order to make it irregular and consequently to increase its friction coefficient. This surface is, in fact, the ceramic surface that presented the highest values of friction coefficient. With the evolution of the wear cycles, as observed in the micrographs, it is possible to identify grit particles at 500 cycles. But unlike other surfaces with 500 abrasion cycles, there are no spots or areas of material pull-off. In other words, up to this stage, the wear process has the main effect of eliminating irregularities caused by the presence of the grit, and there is practically no damage to the glaze layer. However, at 6,000 and 10,000 cycles, there are no grits on the surface, and the glaze layer has already been drastically affected. Furthermore, the presence of numerous pores is noticed, especially at 10,000 cycles, which were revealed by the abrasion process.

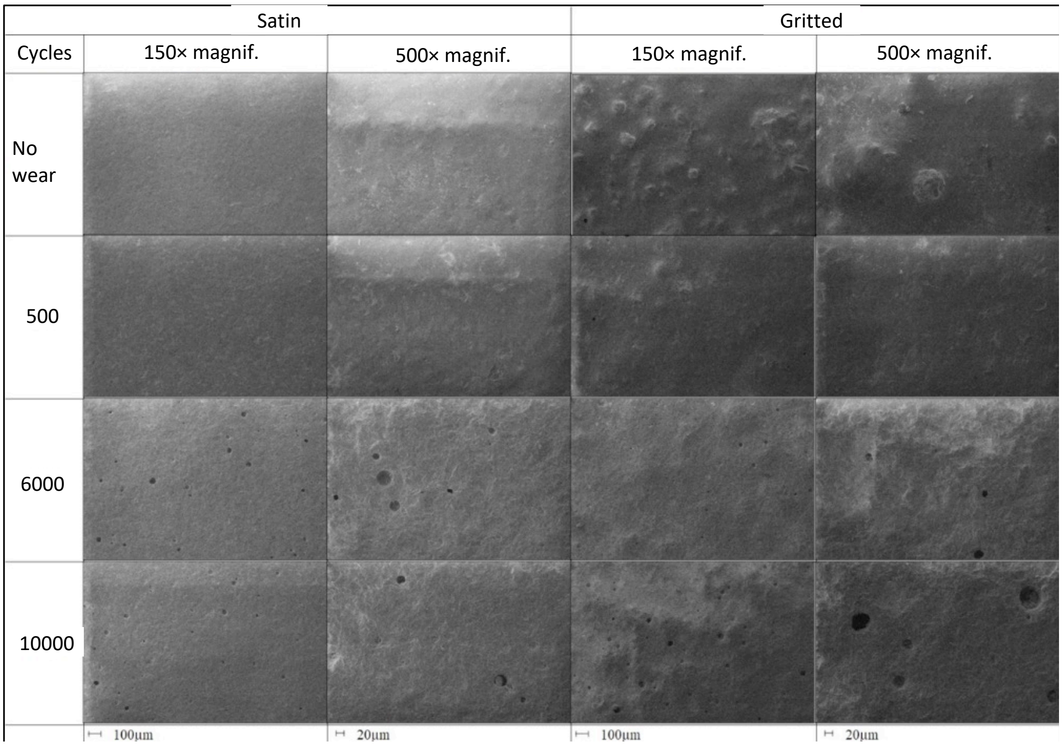

Figure 7*. Scanning electron microscopy images of the satin and gritted surfaces after wear*

Regarding the characteristics of the surfaces studied in this work, there is a relationship between the coefficient of friction and the roughness parameters. However, this relationship is not evident for both unglazed porcelain tile surfaces, as the Rz parameter practically did not change during wear. That is, although Rz is an excellent indicator of the friction coefficient of a surface, the measurement of this characteristic by the DS, BOT and pendulum methods should not be ignored.

Manning and Jones (2001) stated that it is not possible to specify a certain roughness value to ensure maximum safety, but experimental evidence supports the assertion that there will be a greater degree of slip resistance on surfaces with high roughness.

Kim and Smith (2000) studied the roughness of a rough floor before and after the wear process. The results showed that the roughness height and the average depth were significantly reduced after the wear tests. The analyses also showed that the surface parameters underwent large variations initially, but later these changes were less intense. The present work shows similar results for rough, coated, and gritted surfaces, as the roughness of these surfaces, represented by the Rz parameter, was reduced throughout the abrasion process.

4. CONCLUSIONS:

There is a different behavior of the friction coefficient depending on the surface type. Glossy, satin, unglazed and polished surfaces showed an increase in the coefficient of friction during the wear process. The gritted and corundum surfaces showed a decrease in the coefficient of friction after the abrasion process. Harder abrasive materials wear more intensely.

Observing the micrographs, the wear process gradually removes material from the surface of the product. Over time, the irregularities and porosity present in the vitreous layer of the glaze are exposed. This exposed porosity enables the impregnation of dirt into the surface, as it enables the entry of dirt into the porosity.

In addition to the change in the friction coefficient, there are also changes in the roughness parameters, in this case Rz. In general, the microscopy analyses confirmed the results obtained by the roughness measurements. Therefore, the roughness parameters can be better used by the ceramic industry, but not as the only indicator for an analysis of slip resistance.

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