USE OF A PIN-ON-DISK TRIBOMETER FOR STUDYING PORCELAIN TILE POLISHING

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ABSTRACT

A method has been fine-tuned to reproduce porcelain tile polishing by using a tribometer of the pin-on-disk type on a laboratory scale. By this method, test specimens of porcelain tile, in the form of cylindrical rods ("pins"), are subjected to the action of a disk similar to the abrasive tools used in polishing on an industrial scale, and the mass loss is determined of both pin and disk with time. The method is demonstrated to be reliable and repeatable, and analysis of the resulting surface texture has shown that it satisfactorily reproduces the mechanisms by which porcelain tile polishing occurs on an industrial scale.

The use of this apparatus with disks of abrasive material, made by the same procedure as the abrasive tools used in the industrial polishing lines, has enabled studying the effect of certain abrasive tool variables, such as grit size and content, wear in the porcelain tile and in the tool itself, thus allowing efficiency to be quantitatively determined. The study also demonstrates that tests of this type enable establishing the order of advance of grit sizes and grit working times, to provide an optimum porcelain tile polishing curve.

The study shows that the pin-on-disk tribometer can be a useful tool on a laboratory scale, for controlling grinding tool quality and in a more general way, for optimising the polishing operation.

INTRODUCTION

The porcelain tile polishing operation is a complex process in which multiple factors play a part, depending on the properties and nature of the tile, characteristics of the grinding tools used and polishing line design.

To date, industrial porcelain tile polishing line design has been based on knowledge acquired in facilities used for polishing other materials, such as granite. This has similarly been the case of the development of the tools used for tile levelling or planing, and subsequently for the actual polishing phase. Based on this experience, the polishing process has been optimised by trial and error, since there are few theoretical studies on ceramic tile polishing in the literature.

On the other hand, the polishing process is expensive (around one third of total porcelain tile production cost), with high raw materials consumption (grinding tools) and natural resources (water and energy), together with a certain environmental impact (polishing waste). There is hence a need for research aimed at improving the ceramic tile polishing stage.

In the few works found in the literature, analysis has addressed the evolution of the porcelain tile surface as it travels through the industrial polishing train[1,2]. However, the study of the tribological system (workpiece-abrasive-machine) with a view to optimising current polishing cycles requires having a laboratory-scale method, that allows studying the material removal mechanism under conditions as close as possible to those of the industrial process. This method would allow quality control of grinding tools, at the moment carried out directly in the industrial polishing train.

The literature[3-5] describes numerous assemblies for laboratory-scale study of material behaviour under a certain type of wear. Most have been designed based on others, adapting these to the specific nature of the wear process to be simulated and to the specific characteristics of the materials used in the process. Following these lines, in this study a laboratory tribometer has been used to perform porcelain tile polishing tests, using small-size grinding tools, similar to those used industrially. This method, which simulates the mechanisms well by which porcelain tile polishing occurs on an industrial scale, allows studying the effect of the variables of the polishing operation and properties of the materials involved, besides providing a fast and simple method of grinding tool efficiency control in industrial polishing.

2. SELECTION OF THE WEAR METHOD

In this first phase of this study, two of the numerous machines described in the literature for determining material wear rate were tested: a laboratory polishing machine was used that worked with sandpaper, and a tribometer with different configurations. In both methods disk-shaped porcelain tile test specimens were used, of 4 cm diameter and 10 mm thick, made from industrial porcelain tiles.

Given the greater similarity of the industrial polishing process with what happens in the laboratory polisher, this was used first for the wear tests. The method consists of abrading porcelain tile test specimens with silicon carbide sandpaper of a certain grit size. For this, the test specimen underwent successive polishing stages with a certain number of revolutions, at a set velocity and pressure, weighing the specimen before beginning the test and after each test stage. At the end of the test, specimen weight loss was plotted versus polishing stage time. With these experimental points, which should fit a straight line, the slope was calculated whose value gives the wear rate of the tested piece.

However, on plotting the experimental data, it was found that these did not fit a straight line, indicating, together with the lack of result repeatability, that this method was not appropriate for studying the porcelain tile polishing stage. This was because this machine was only designed to prepare samples and not to perform determinations, which prevents carrying out mass loss tests with the required accuracy.

After discarding the laboratory polisher, it was decided to use a tribometer to conduct the wear tests. At first, the wear test was run according to the procedure designed by the maker of the assembly, which consisted of setting a ruby ball, with a 6 mm diameter (loaded with a certain weight), on a disk-shaped test specimen. The specimen was held in a clamp, which rotated at a certain speed. The ball thus made a wear track on the test specimen. As in the previous case, the test specimen was weighed before and after each wear stage, and weight loss was plotted versus wear time. However, the data found by this procedure did not fit a straight line either, because when the ball encountered a protuberance on its travel (e.g. a harder particle or one that stood out more), it jumped on the piece, striking it and causing non-uniform wear, which altered the normal course of the test. Due to these problems, this configuration was discarded for the wear tests.

The configuration of the tribometer was then modified, using prism-shaped porcelain tile test specimens ("pins"), with a cross section of 0.24 cm^2, instead of the ruby ball and placing a small round piece of sandpaper on the bottom area ("disk"). This is known as the pin-on-disk arrangement (Figure 1). The main advantages of using this configuration are first, that the same abrasive materials can be used as in the industrial process (substituting the sandpaper by abrasive disks), which allows varying both abrasive disk and porcelain tile test specimen properties, and secondly, that the contact surface area between the two materials stays practically constant (specimen base).

The tests carried out using this method showed it to be quite reliable, since the experimental points fitted a straight line with a high correlation coefficient and the degree of repeatability of the results was very high, so that small differences in wear rate can be noted without fear of error. For the reasons indicated above, this method was finally adopted to perform the necessary laboratory tests to study porcelain tile polishing.

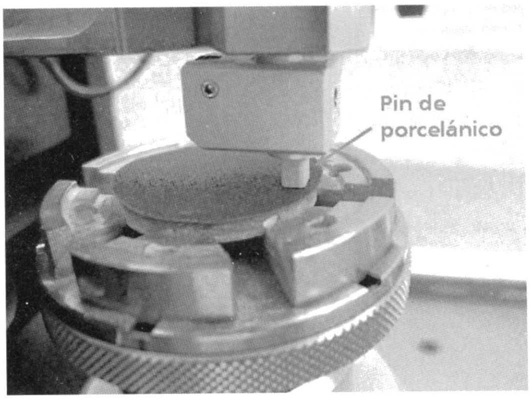

Figure 1. Pin-on-disk arrangement in the tribometer.

3. FINE-TUNING THE PIN-ON-DISK TEST

Having selected the pin-on-disk method to perform the study, a series of tests was conducted to establish the ranges of the working variables, as well as suitable conditions for the studied materials.

In the first place, to determine the degree of machining accuracy required for the porcelain tile test specimens, a first test was done to establish whether a small change in test specimen base area (contact area) could cause some change in the wear mechanism owing to pressure changes in the contact area. The existence of a change in mechanism (ductile-brittle), as a result of modifying pressure in the contact area would be reflected in a change of slope of the mass loss values, which would then not fit a straight line[6-8].

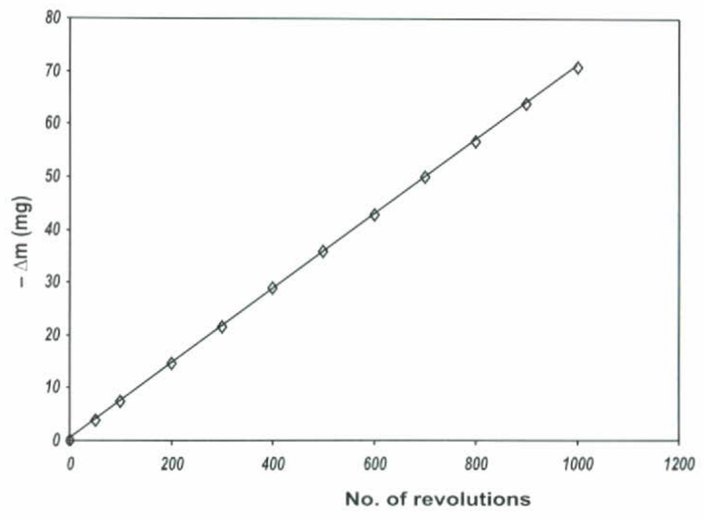

Figure 2. Wear test with a wedge-shaped pin.

For this, a wedge-shaped test specimen was made, so that the contact surface would be very small (high pressure) at the beginning of the test, progressively increasing as the test advanced (lower pressures). Figure 2 shows that the mass loss values (-Δm) found align perfectly, demonstrating that in the tested contact area variation range, much higher than that produced on machining the test specimens, no change took place in the wear mechanism.

In the second place, the effect of the load on the prism-shaped test specimen was studied, using the different weights with which the assembly is equipped (2, 5 and 7 N), in order to establish if, in this range of loads, any change existed in the wear mechanism and to define the most appropriate load for testing. Figure 3 shows that wear rate (W_p), calculated as the slope of each resulting straight line, increases linearly with applied pressure (P). This linear dependence indicates that, though the wear intensity increases with applied pressure, the mechanism producing this does not vary, and hence it is possible to work with any load inside this range.

Finally, as water is used in the industrial polishing process to eliminate polishing wastes and cool the grinding tools and tiles, and since the tribometer can also be used for wet testing with materials immersed in a liquid, a test was carried out to determine the convenience of running the tests in this way. Several materials were chosen for this purpose, which exhibited quite different wear rates in dry testing. These were then put through a wet test. The results revealed that the differences in wear rate observed in the dry tests were also found in the wet tests, although the wet test wear rate values were a little lower. In view of this similarity in the results, it was decided to perform the rest of the tests dry, particularly in view of the greater simplicity and speed of the dry test.

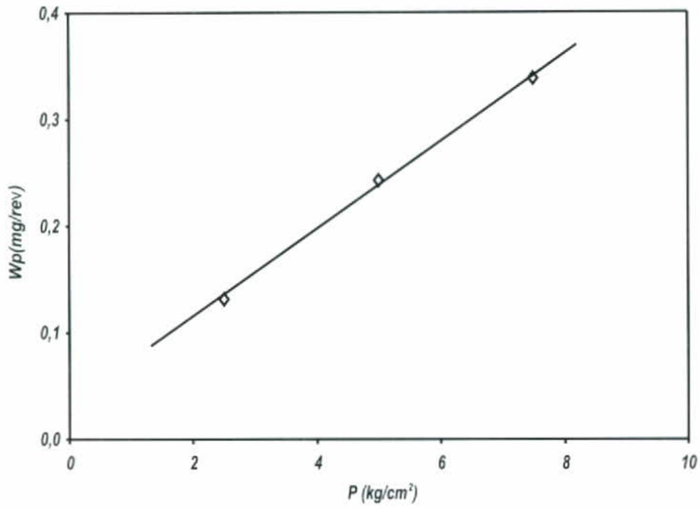

Figure 3. Tests performed at different loads.

After conducting these tests the variables of the apparatus were set as follows:

Linear velocity = 0.27 m/s
Applied load = 5 N
Contact area pressure = 2.12 kg/cm^2
Dry test

4. USE OF THE PIN-ON-DISK TRIBOMETER FOR STUDYING THE POLISHING STAGE

4.1. EXPERIMENTAL

4.1.1 Materials

To perform the wear tests, test specimens were made from industrial porcelain tiles. The tiles came from a single production lot to ensure identical characteristics. The test specimens were machined until producing parallelepiped specimens with a 0.24 cm^2 base and 4 cm height.

The abrasive disks were made by a grinding tool producer with specially designed moulds. These yielded disk-shaped tools, of 4 cm diameter and 5 mm thick, for use in the tribometer. The matrix used for making these was a magnesium cement, widely employed in producing grinding tools for industrial polishing. Silicon carbide was used as abrasive material with three grit sizes, covering the range used on an industrial scale.

Abrasive disks were prepared for each of the selected grits, with three SiC mass fractions around the values typically used in industry:

• Mass fraction A: 5%. • Mass fraction B: 10%. • Mass fraction C: 20%

4.1.2 Experimental procedure

To perform the wear tests a tribometer was used with the pin-on-disk configuration described in section 3 (Figure 1). The test consisted of successive wear stages, cleaning and weighing the test specimen and abrasive disk after each stage to determine mass loss. Test variables were those set out in section 3.

It should be noted that before conducting the wear tests, the abrasive disk surface was eroded by sand blasting so that the abrasive particles would surface in the disk (dressing operation). Otherwise the test specimen would slip over the abrasive disk binder matrix with no wear efficiency.

This operation was also performed after each wear stage so that the abrasive disk would at all times have fresh abrasive particles. This ensured consistent test efficiency.

4.2 RESULTS AND DISCUSSION

4.2. Selection of the grit size to be used

To select three grit sizes that were representative of the different phases that take place in the polishing line, tile gloss and weight measurements were carried out at different points in an industrial polishing facility. Figure 4 shows the evolution of tile surface gloss and mass loss in the polishing line.

It can be observed that high mass loss occurs initially, while tile gloss remains stable at very low levels. These results indicate that in this zone of the polishing facility very severe wear develops, with massive material removal.

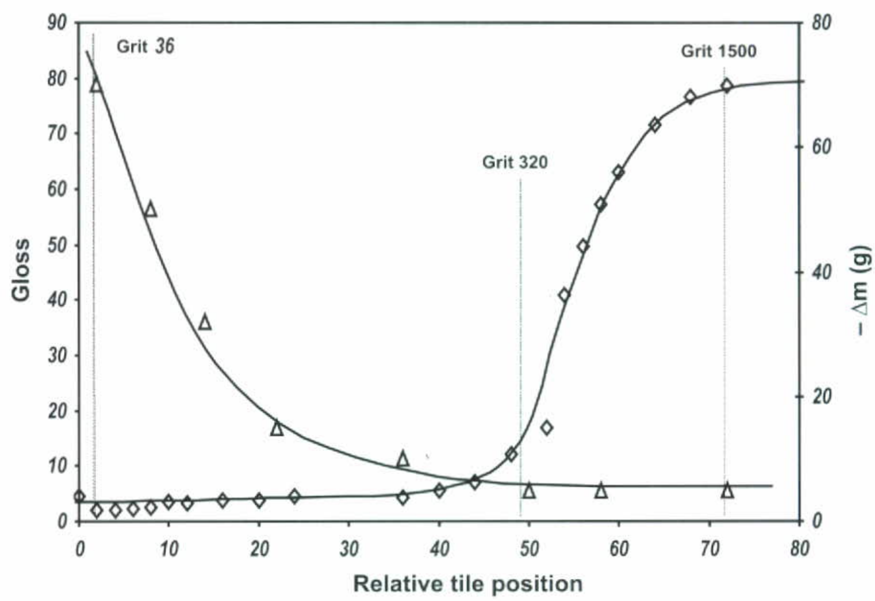

Figure 4: Evolution of tile gloss and mass in the polishing line.

As the piece advances along the polishing line, mass loss decreases progressively whereas gloss values stay very low and stable. From position 40 on, mass loss is very low with a tendency to stabilise, while gloss begins to rise very abruptly. In this zone, the wear mechanism is no longer so severe and its effect is a mixture of smoothing and pullout of small material particles.

Finally, from position 60 on, practically no mass loss is further observed, while gloss has increased considerably, to stabilise at a maximum value. At this point a very gentle wear mechanism is involved, in which plastic strain predominates, with hardly any material loss.

Thus, the industrial polishing facility could be divided ideally into three zones, depending on the type of operation effected. A first zone where massive material removal occurs, a second zone in which the piece begins to gain gloss, and finally a zone in which final gloss is produced. These three zones correspond to polishing tool heads containing abrasive with the following grain size:

- First zone: Grit 36 (d_{50} = 525 μm)
- Second zone: Grit 320 (d_{50} = 33 μm)
- Third zone: Grit 1500 (d_{50} = 5 μm)

Selecting these three grit sizes therefore enabled covering the three phases found in the polishing line.

4.2.2.Effect of abrasive disk characteristics on porcelain tile wear rate

Figure 5 plots test specimen mass loss versus the number of revolutions on the tribometer for the different tested abrasive disks. In the first place it can be observed that wear rate (slope of the straight lines) caused by the abrasive disks corresponding to grit 36 is much higher than that of the disks containing finer abrasives (grits 320 and 1500), independently of grit concentration. These results match the measured mass loss values in the industrial polishing line (Figure 4).

As a curious feature, it may be noted that the test specimens abraded with the abrasive disks containing grit 1500 exhibit a slight mass gain instead of mass loss. This is because rests of the disk matrix remain stuck to the test specimen contact surface, forming a surface layer. This effect, which is not observed in the industrial polishing line, is probably caused by carrying out dry instead of wet wear tests.

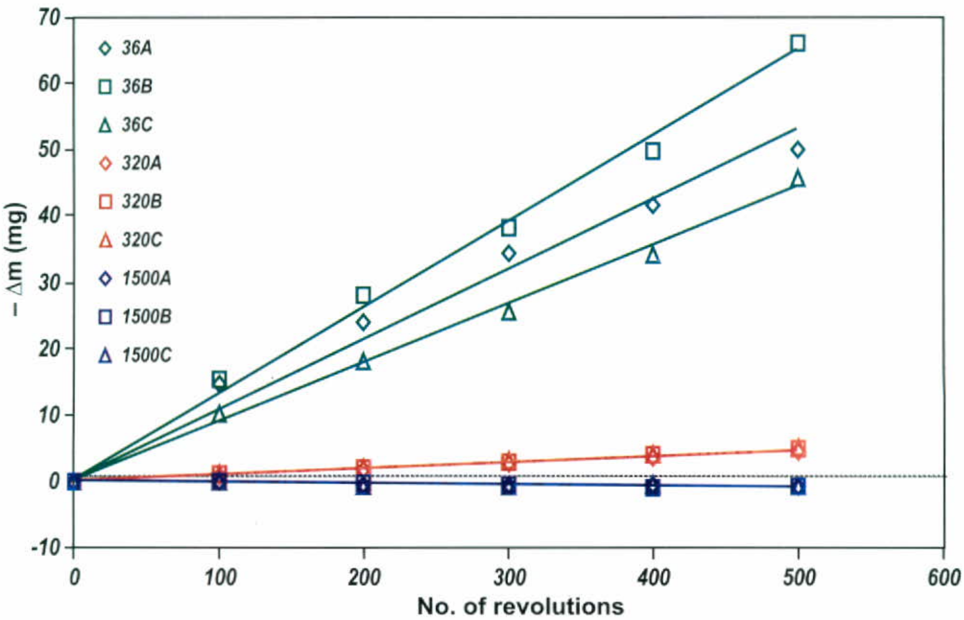

Figure 5. Porcelain tile specimen behaviour during the wear test.

The main reason for the difference in behaviour between disks with different grit sizes is the different real contact surface that each presents. Thus for a certain mass fraction, the larger the grit size, the fewer are the number of particles per unit surface area that enter into contact with the material to be abraded, so that the pressure increases at the contact points. On the other hand, large grains can stand out more from the surface of the substrate that holds them, so that they can have greater penetrating power into the surface of the material to be abraded, and hence more abrading strength than the smaller ones. According to the literature surveyed[8], the mechanism by which wear occurs in brittle materials by abrasive particles depends on the applied pressure, with a transition occurring from a severe wear mechanism (detachment of chips by fracture), to a gentler wear mechanism, in which material is removed in powder form, to ultimately reach plastic strain, as pressure decreases[7].

Using the data in Figure 5 the wear rate was calculated, plotted in Figure 6 versus grit 36 and 320 mass fractions. The results found for the disks with grit 36 show that initially, on increasing grit mass fraction, the wear rate increases until peaking, at mass fraction values slightly below 10%, after which it decreases with the rise in grit content. According to these results, there seems to be a grit content in the grinding tools, which maximises wear. As for the grit 320 abrasive disks, the low weight loss they exhibit does not allow establishing appreciable differences. The values obtained with the fine grit disks have not been plotted for the reasons set out in the previous section.

The increase in grit mass fraction has two opposite effects on wear rate. On one hand it raises the number of abrasive grains that enter into contact with the workpiece, which contributes to increasing wear rate. On the other, it lowers the real pressure that each grain applies, which produces the opposite effect.

The results shown in Figure 6 indicate that at low grit mass fractions, the first effect predominates over the second, leading to a rise in wear rate up to a maximum value, after which the tendency inverts.

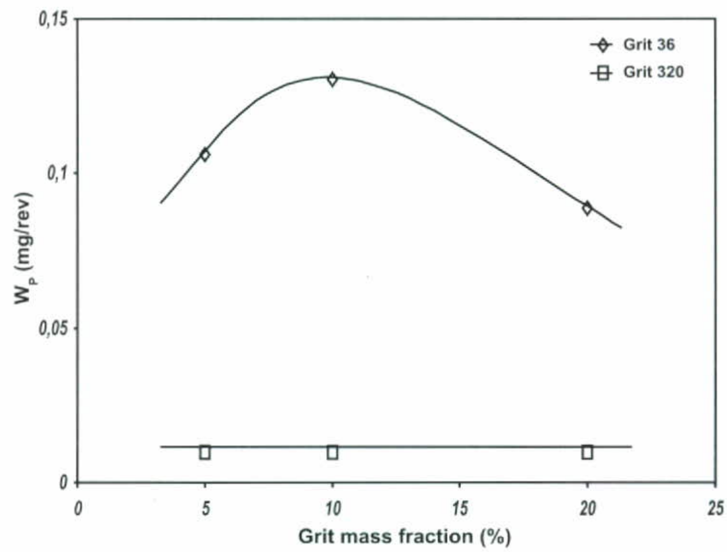

Figure 6. Effect of grit mass fraction on porcelain tile wear rate.

To compare the effect of abrasive particle size on porcelain tile surface texture, topographic maps were made of the abraded test specimen surfaces on two different scales. In those of Figure 7, covering an area of 2.5x2.5 mm, the largest size grit (a) has produced large grooves in the surface, about 100 μm wide and approximately 130 μm deep. The surface produced with the intermediate size grit is much smoother (b) due to the absence of deep grooves, although it is not flat. Lastly, the surface corresponding to the smallest grit (c) is much flatter than the previous ones and does not exhibit large irregularities.

To observe the three surfaces in more detail, smaller topographies were made, this time covering an area of 0.48x0.48 mm (Figure 8). These show that while the larger size grit has left a very rough surface, produced by chipping (a), the intermediate size grit has left a texture in which shallow grooves prevail (b), with much less chipping than in the previous figure. Finally, the texture produced by the fine grit (c) is quite flat, presenting some shallow tracks and small holes. In this surface, owing to its low roughness, the characteristic open porcelain tile pores can be observed. The modification observed in the topographic maps on changing grit size is consistent with the results found in a previous study[1], in which the evolution was studied of tile on its travel through the polishing line. This validates the pin-on-disk method for studying porcelain tile wear in the polishing stage.

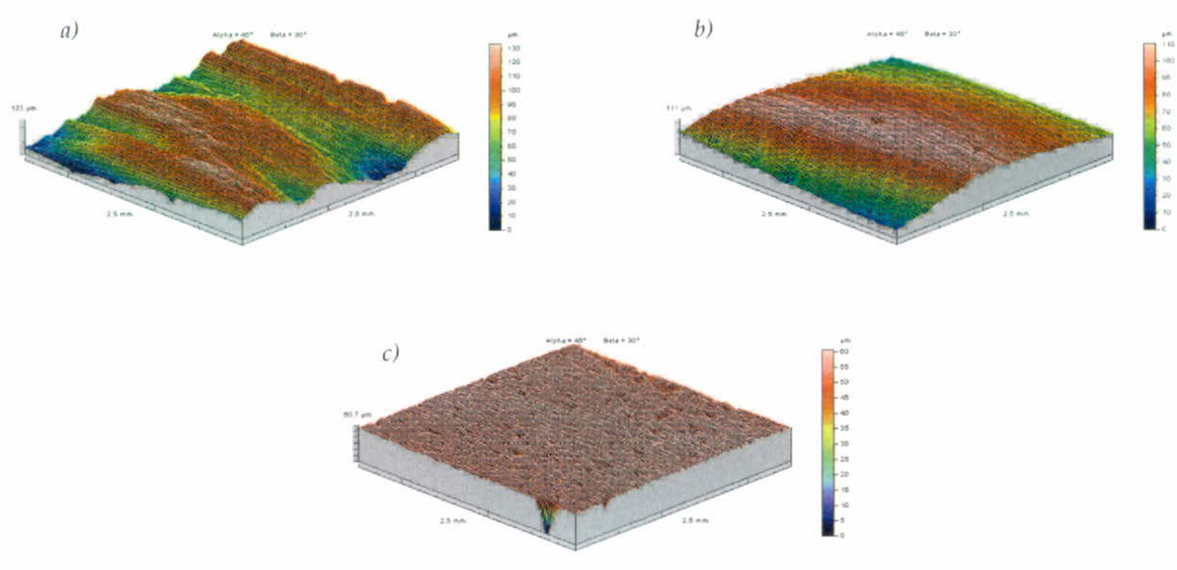

Figure 7. Topographic maps (2.5x2.5 mm) of the test specimen surfaces abraded with disks containing different grit sizes: a) grit 36; b) grit 320; c) grit 1500.

The mechanisms that cause chipping are those described in the literature on the typical behaviour of brittle materials, in which cracks appear at which the removal of portions of material starts. Cracks can occur by static indentation (penetration of a particle without movement) or dynamic indentation (scratching action). The effect of a static indentation, widely studied in the literature, is schematically illustrated in Figure 9[6][8]. It shows how, when a particle exercises pressure on the surface, a region of elastic strain forms with a small zone of plastic strain in the area subject to greatest pressure under the indenter tip, in which a crack is produced that grows as the applied load is raised. On reducing the load the crack closes, but the reduced elastic recovery capacity of this type

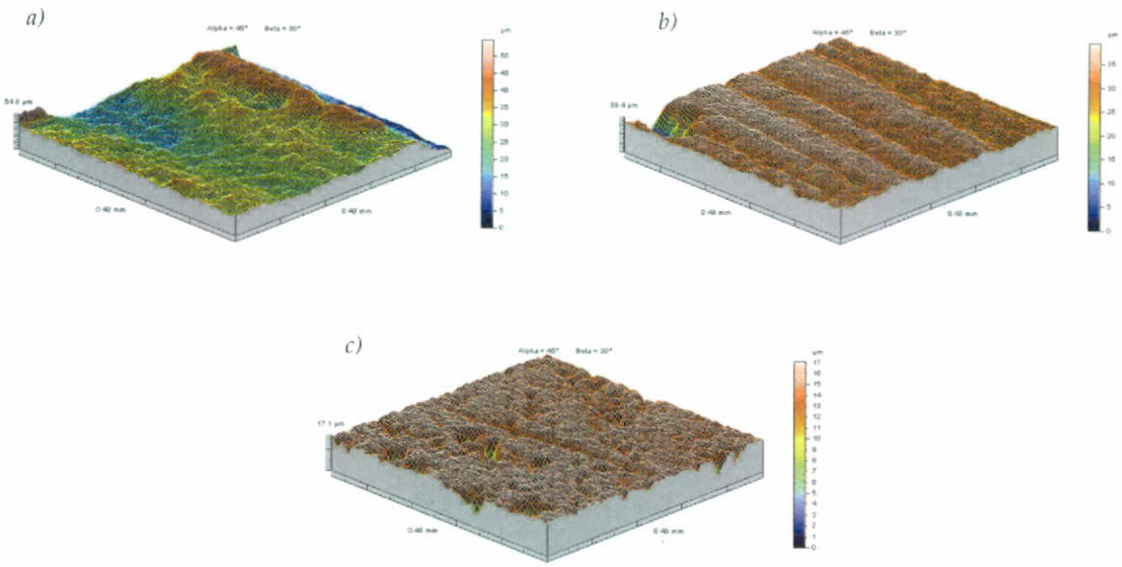

Figure 8. Topographic maps (0.48x0.48 mm) of test specimen surfaces abraded with discs containing variously sized grit: a) grit 36; b) grit 320; c) grit 1500.

of material prevents the arising stresses from being released in the area under plastic strain and may cause separation, generating another crack below this area, parallel to the surface. If the toughness of the material is not sufficiently high, this crack will propagate to the surface when the applied load is withdrawn, causing chipping.

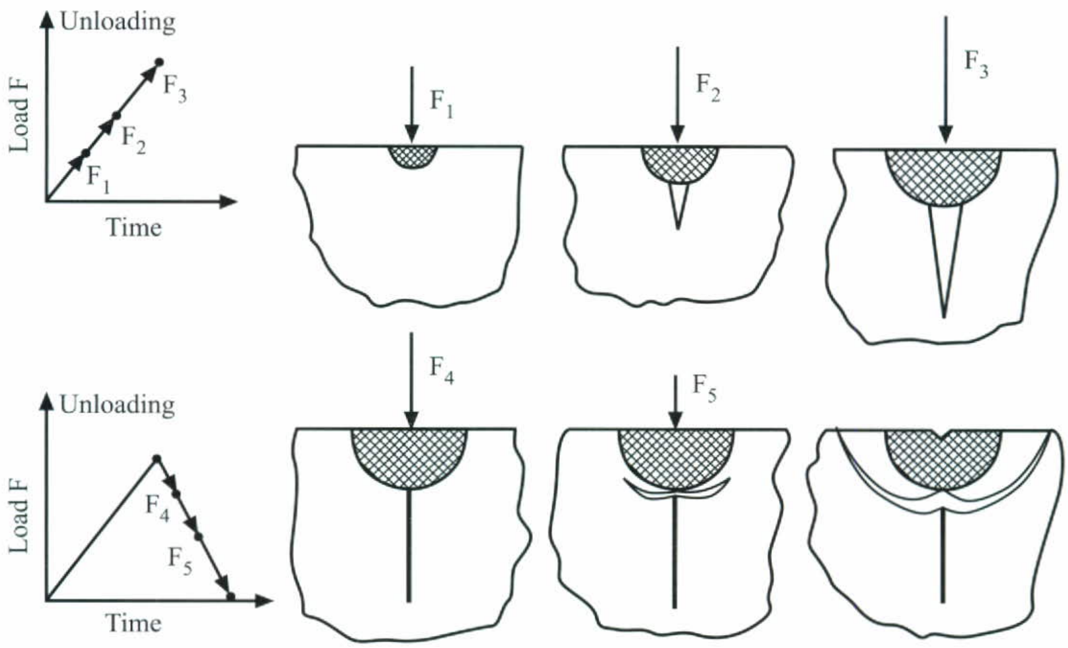

Figure 9. Scratch generation mechanism by static indentation (Source: ref. [6]).

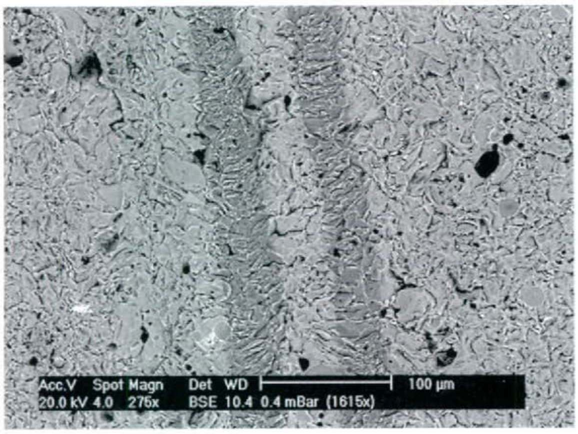

Figure 10. Scratches produced by 320 grit.

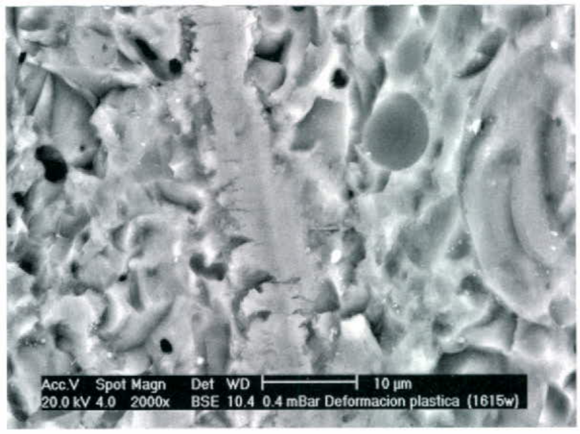

Figure 11. Scratching mechanism by plastic strain.

In Figure 10, corresponding to the surface of the test specimen abraded with the grinding tool containing intermediate abrasive grain (grit 320), two scratches have been coloured, produced by moving abrasive grains. It shows the cracks formed in a perpendicular direction in the grain trajectory. This configuration resembles the cracks described in the literature as characteristic brittle materials scratches[8], which, following the same process as the one described for static indentation, can also cause chipping.

If the scratches produced by the disks with finer grit (320 and 1500) are observed in detail, the brittle fracture and plastic strain mechanisms are found to exist together. This is demonstrated by some shallow scratches in which no crack generation occurred, but only plastic strain of the material (Figure 11).

4.2.3 Behaviour of the abrasive discs during wear

To study the behaviour of the abrasive disks during the polishing stage their mass loss was determined during the wear tests. Figure 12 shows that the disks containing large size grit (grit 36) have worn considerably, while those with intermediate grit (grit 320) practically underwent no weight loss. This difference is associated with the greater pressure at the contact points of the disks prepared with coarser abrasive grain. Thus, the high pressures that develop at the contact point, besides damaging the porcelain tile, also make the grit act as indenters on the matrix that holds them, even producing its deformation. To this is further added the high existing friction force, which also contributes to weakening the matrix (Figure 13). This all affects the anchoring of the abrasive grains and leads to their detachment, thus facilitating progressive disk wear. This form of wear produces the scatter found in the mass loss data.

The grinding tools containing intermediate size grit undergo much smaller deterioration because the pressures at which the contact between the two surfaces occurs and the friction forces are much lower.

The variation of disk wear rate with grit size, determined in the laboratory, matches what happens on an industrial scale. In industrial polishing facilities it is necessary to substitute the polishing tools that contain larger size grit more frequently (every 2-3 hours) than those containing smaller size grit (several days).

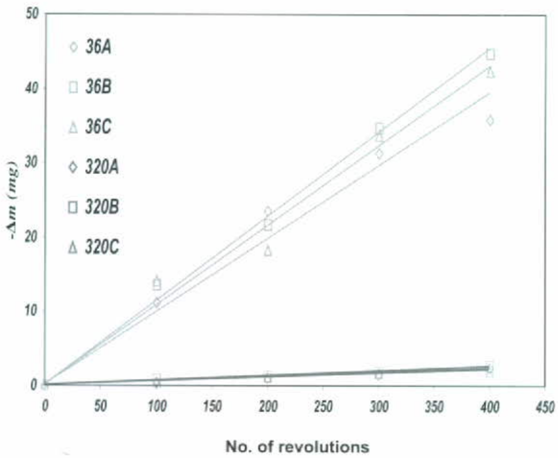

Figure 12. Grinding tool behaviour during the wear test.

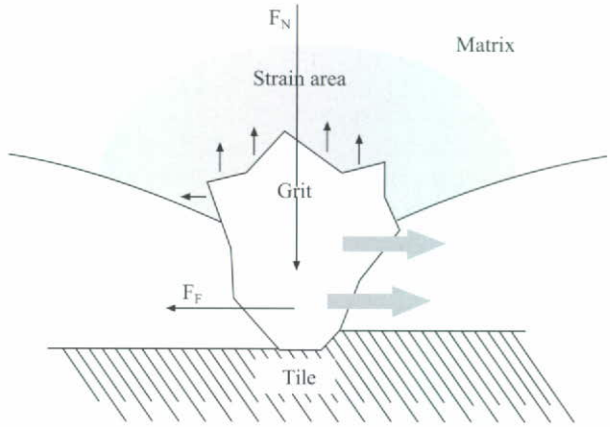

Figure 13. Scheme of abrasive grain action on the cement matrix.

To analyse the effect of grit concentration on disk wear, disk wear rate was calculated (slope of the straight lines), plotted versus grit mass fraction. Figure 14 shows that the disk containing grit 36 exhibits a maximum wear rate value at maximum grit fraction values close to 10%. In contrast, in the disk with grit 320, due to its low mass loss, no difference is observed at all in grit mass fraction.

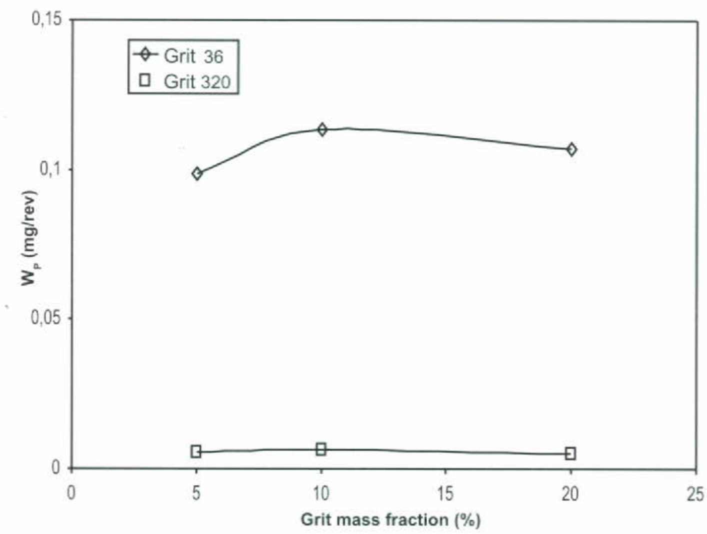

Figure 14. Variation of abrasive disk wear rate versus grit mass fraction in the disk.

It can be observed that for grit 36, maximum test specimen and disk wear rate are located at practically coinciding grit mass fraction values (around 10%). This coincidence indicates that the factors giving rise to the maximum wear rate in the disk are the same as those discussed previously for the porcelain tile test specimen.

4.2.4 Other applications of the pin-on-disk tribometer

4.2.4.1 Determination of polishing tool efficiency

In the foregoing sections the wear rate of the two materials entering into contact on performing the wear test was determined separately. It was found that at a certain grit size, there is a grit concentration that maximises porcelain tile wear rate. However, the disks prepared with this same grit concentration also undergo the greatest wear. Therefore, to determine the abrasive concentration that optimises this process stage, it is necessary to study their combined effect, in order to establish real polishing tool efficiency.

For this purpose, parameter α representing grinding tool efficiency has been calculated from the following expression:

$$\alpha = \frac{W_P}{W_D}$$

where:

- α = efficiency
- W_P = porcelain tile test specimen (pin) wear rate
- W_D = abrasive disk (disk) rate

This parameter allows evaluating grinding tool wear power and the deterioration it undergoes together during the test.

Figure 15 plots parameter α versus grit mass fraction of the disk containing grit 36. It also includes the evolution of test specimen wear rate (WP) and disk wear rate (WD). The values of α are found to fit a curve, which presents a maximum at mass fraction values close to 10%. In fact at this concentration, although disk wear is high, test specimen wear rate peaks, optimising abrasive disk efficiency. At lower mass fractions, disk and test specimen wear rates decrease, the drop in test specimen wear rate being more pronounced, which leads to a decrease in parameter α. Similarly, at mass fractions exceeding 10%, test specimen wear rate falls notably, while disk wear remains stable at high values. This gives a low grinding tool efficiency value.

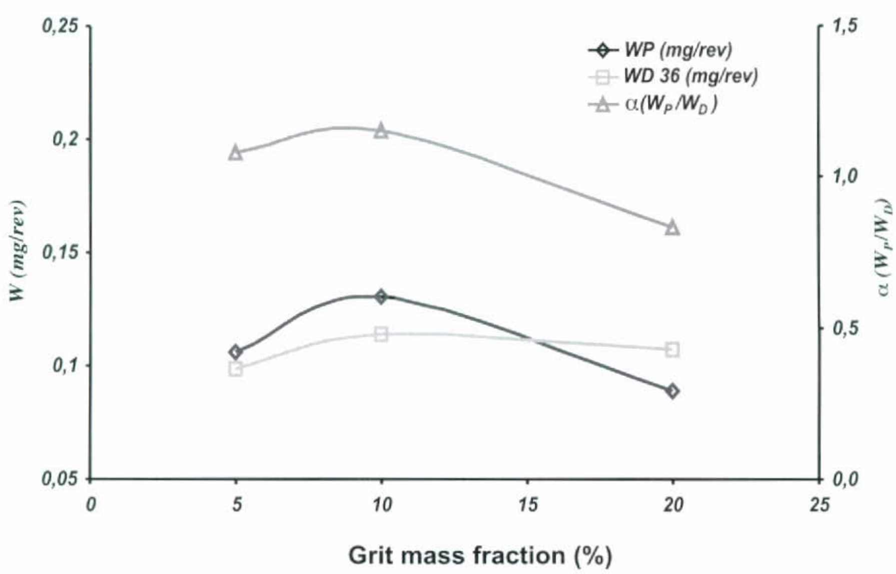

Figure 15. Effect of grit size on grinding tool efficiency.

Conducting these tests for the different grit sizes used in the polishing tools allows determining their efficiency and will therefore enable optimising their grit mass fraction.

4.2.4.2 Optimisation of the polishing cycle

The main industrial polishing cycle variables are: order of grit size and concentration, velocity of tile advance and pressure of the tool heads on the tiles. These variables define the time during which the tiles are subjected to the action of a certain grit, pressure at the contact point and cutting velocity.

The objective pursued on designing a polishing cycle is for each tool to leave the characteristic texture of the grit it contains on the porcelain tile surface with the greatest possible speed. To achieve this surface texture, a grinding tool containing a certain size grit needs to reduce the dimensions of the irregularities produced by the previous one, removing part of the material. This causes the roughness of the piece to evolve progressively from very rough textures to very smooth ones.

To establish the optimum grit size order of advance in the industrial tools and the optimum time spent on each tile to achieve the required final texture, wear tests need to be performed on porcelain tile test specimens using disks with progressively smaller grit sizes. To determine the feasibility of using a pin-on-disk tribometer for this type of tests, an experiment was conducted subjecting a test specimen to the successive action of the available types of disks.

Figure 16 plots mass loss of the test specimen subject to the successive action of disks containing large and intermediate grit sizes. An abrupt change of slope appears on modifying the size of the grit used, caused by the different material removal capacity of each abrasive disk.

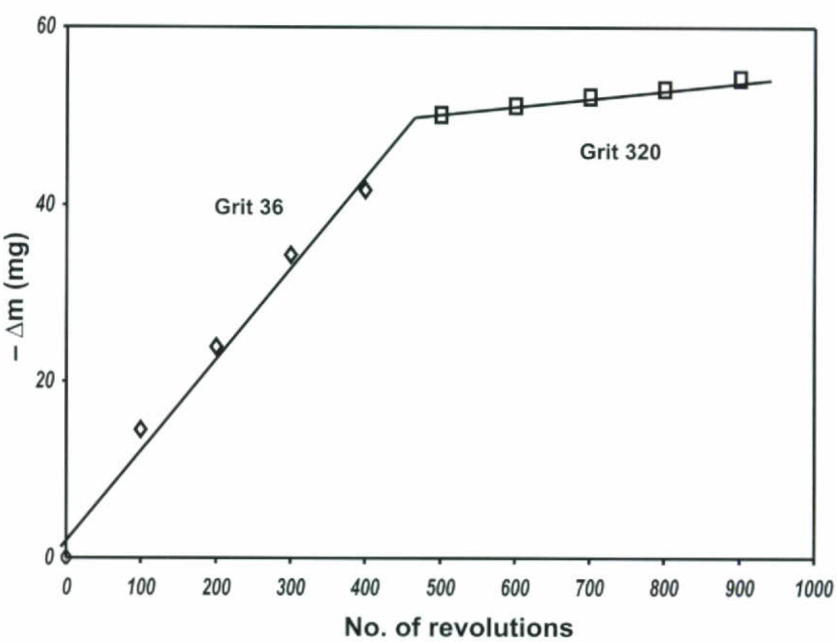

Figure 16. Change of wear rate produced by the different grit sizes used.

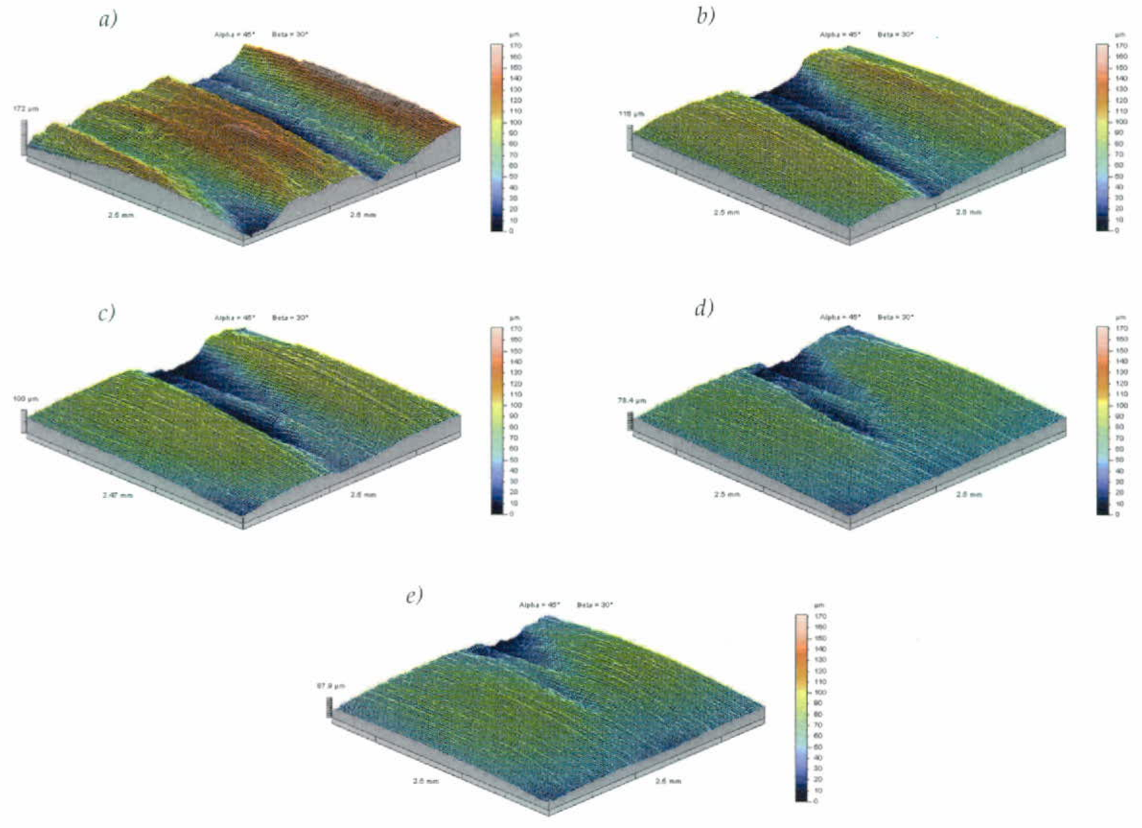

Figure 17. Topographic map of the abraded porcelain tile test specimen surface: a) with grit 36; b) after 100 revolutions with grit 320; c) after 200 revolutions with grit 320; d) after 300 revolutions with grit 320; and) after 400 revolutions with grit 320.

To monitor the evolution of test specimen texture on changing the type of abrasive disk, topographies were made on ending a test with the grit 36 disk and throughout the test with the grit 320 disk. Figure 17 depicts the results. They clearly show the removal process of grooves made during polishing. Thus, on ending the wear process with grit 36, tile topography exhibits a large groove 150 μm deep and 100 μm wide, which gradually decreases in size with removal of the material located in the highest areas (red colour in picture a). Obviously, on ending the test the tile surface still has intact low areas in the grooves produced by the previous disk. This fact, due to the enormous difference between the grit sizes used, indicates that grit size order should be more progressive or that longer periods of time are needed for the small size grit to completely eliminate the irregularities produced by the previous grit size and provide the tile with the sought texture.

These results demonstrate that it is possible to reproduce industrial polishing cycles in the pin-on-disk tribometer, using an order of disks containing different grit sizes. The joint study of the successive changes of slope (wear rate) of the tiles on replacing one abrasive gain by another, together with the changes observed in surface texture, will enable designing an optimum grit size order and optimum grinding tool working times, which on scaling up to industrial scale will allow optimising abrasive materials consumption and polishing cycles.

5. CONCLUSIONS

- It has been shown that the use of a pin-on-disk tribometer enables reproducing porcelain tile wear during the polishing operation.
- Porcelain tile wear rate increases with grit size due to the greater pressure that is generated at the contact points and greater grit penetration capacity in the tile.
- There was found to be a maximum grit concentration at which porcelain tile wear rate maximised. The presence of this maximum is due to the existence of two opposing effects. On increasing the grit concentration the number of contacts rises but the pressure at the contact points decreases.
- The variation of the disk wear rate with grit concentration follows the same tendency as that experienced by porcelain tile, while their maximum values coincide at a certain grit mass fraction. Disk wear occurs by the high stresses that develop in the grit-matrix contact area, causing grit detachment.
- Using this apparatus the mechanisms that produce material removal have been confirmed, proceeding from very severe wear by brittle fracture (large grit size) to gentle wear with predominance of plastic strain (smallest grit size).
- Finally, it has been shown that application of this technique enables determining polishing tool efficiency as well as designing and optimising industrial polishing cycles.

6. REFERENCES

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