LABORATORY SIMULATION OF THE INDUSTRIAL CERAMIC TILE POLISHING PROCESS

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ABSTRACT

This paper reports the design and preliminary use of a laboratory-scale tribometer and its use in tests to simulate the industrial polishing processes for ceramic tiles. The mechanical conditions in a typical industrial polishing process are analysed and the results are used to define the conditions to be reproduced in a laboratory simulation. The tribometer allows the relative sliding speed and contact pressure between the abrasive tool and the tile to be controlled. Measurements can be made of changes in tile surface roughness and optical gloss, as well as of the rate of material removal from the tile and the wear rate of the tool. Preliminary results from the tribometer are presented, in which the evolution of surface roughness and gloss are studied, with different abrasive tools. These results are compared with data gathered from an industrial polishing line, and show that the tribometer accurately reproduces the important features of the process. The results show that surface roughness and gloss are the two most important variables to assess the tile surface and that these are the most useful measures at different stages in the evolution of the surface.

1. INTRODUCTION

Polished ceramic tiles show excellent performance including high mechanical strength, and high chemical, stain and frost resistance, as well as aesthetic advantages over glazed tiles. Polishing is the most important operation step during the manufacturing process, and the polishing process can contribute more than 40% of the total cost of the product. However, current industrial polishing processes are thought to be inefficient, resulting in high wear of the grinding/polishing tools, high energy consumption, excessive wastage of rejected product and poorly controlled product quality. There are clear opportunities to reduce the cost and improve the quality of the final product, through improved understanding of the polishing process.

Most previous studies of the tribological behaviour of ceramic materials have been restricted to deriving empirical models, adapted to the specific system under study [1-3]. The design of tribological test rigs (tribometers) is often concerned with specific experimental conditions, such as thermal conditions [4,5] or lubrication [6,7]. In order to study the polishing behaviour of ceramic tiles, a laboratory-scale tribometer has been designed at the University of Cambridge to investigate both polishing mechanisms and rates. With this equipment the characteristics of both the tiles and of the abrasive polishing media can be quantitatively assessed.

In this work, the industrial polishing process for ceramic tiles was analysed; the design of the new tribometer was related to the industrial polishing conditions, focusing on aspects such as contact pressure and sliding distance. Profilometry and optical gloss measurements were used as the main tools to evaluate the quality of the polished tile surfaces. The experimental results from the laboratory rig were compared with data gathered from an industrial polishing line.

2. INDUSTRIAL POLISHING PROCESS FOR CERAMIC TILES

2.1. POLISHING PROCEDURE

The information used in the following discussion was obtained from various industry sources in Spain and Italy, and is considered to be typical of current European practice.

Silicon carbide is the most common abrasive used in the polishing process, usually in the form of a composite block with a silicate cement binder, with a gradual reduction in particle size from several hundred micrometres to a few micrometres, with as many as perhaps 20 steps. A final, high quality polished surface typically has a surface roughness Ra of about 0.1 to 0.2 mm and gloss (β=60°) up to 80. Current industrial polishing processes are inefficient, resulting in high wear of the grinding/polishing tools (0.5 to 0.6 kg grinding tool per m^2 of polished product), high energy and natural resources consumption (0.02 – 0.04 m^3 of water per m^2 of product), excessive product rejects and limited final product quality.

Figure 1 shows schematically the structure of a grinding tool (swinging head) and the swinging motion of a single abrasive block used in the industrial polishing process. The tool rotates at a speed of 450 rpm while each individual abrasive block also swings. The swinging motion of the abrasive block retains the cylindrical shape of the block surface to avoid edge effects from the abrasive block and to guarantee the flatness of the tile surface.

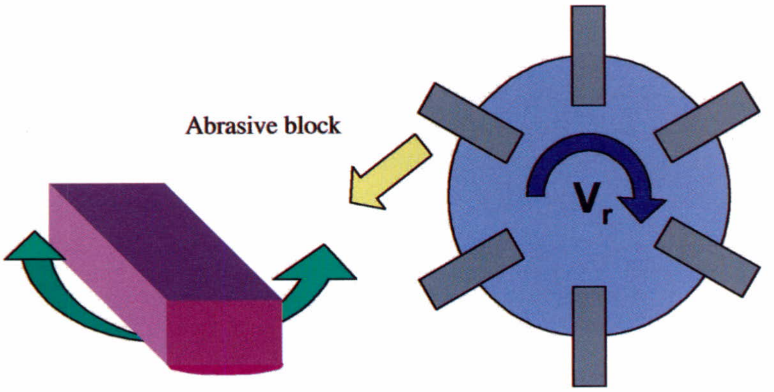


Figure 1. Schematic diagram of typical swinging head grinding tool used in industrial polishing process.

2.2. ANALYSIS OF POLISHING CONDITIONS

Figure 2 (a) shows schematically the dimensions of the grinding tool and the ceramic tile and their relative motion in the polishing process. The feed rate of the ceramic tile is 75 mm s^{-1}. Figure 2 (b) represents the contact conditions between an abrasive block and a ceramic tile during the polishing process. A normal load of 200 N is applied on each abrasive block, and the radius of the abrasive block decreases from 130 mm to about 72 mm due to wear of the abrasive during the polishing process.

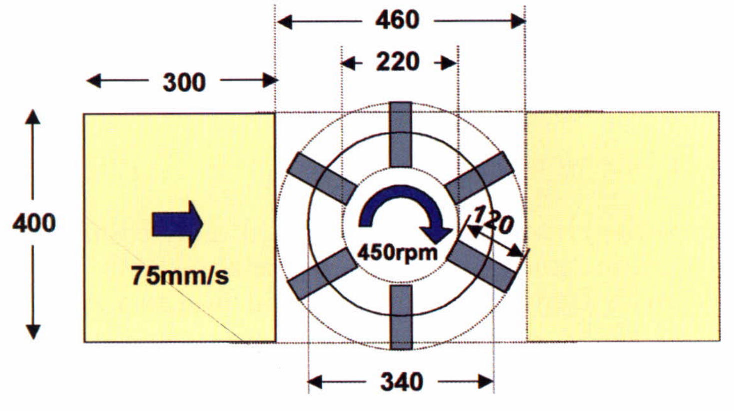


Figura 2. (a) Schematic diagram showing the dimensions of the grinding tool in the polishing process;

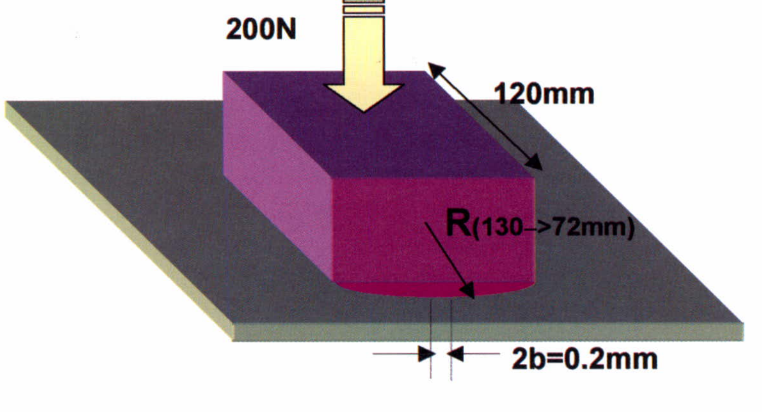


Figura (b) Relative motion between abrasive block and ceramic tile in the polishing process.

In designing a suitable tribometer, important requirements are the use of practically relevant contact conditions and type of motion, high mechanical stability, facilities for inducing a realistic environment, and the use of comparatively simple specimens [8, 9]. Contact pressure is the most important parameter in the polishing process which affects the material removal from both the abrasive block and ceramic tile, and the final surface quality of the product. During the industrial polishing process, the contact length between the abrasive block and the ceramic tile changes with the sliding time, and so does the contact pressure. These two parameters can be estimated from the Hertzian equations for elastic contact between isotropic bodies:

Contact length 2*b*:

$$b^2 = \frac{4PR'}{\pi E'} \qquad (1)$$

$$\frac{1}{E'} = \frac{1-\nu_1^{\,2}}{E_1} + \frac{1-\nu_2^2}{E_2} \qquad (2)$$

Where P = W/L, W is the applied load, L is the length of the abrasive block;
R = Radius of curvature of the abrasive block;
ν_1 = Poisson's ratio of the abrasive block;
ν_2 = Poisson's ratio of the ceramic tile;
E_1= Young's modulus of the abrasive block;
E_2= Young's modulus of the ceramic tile.

Maximum contact pressure *p* is given by:

$$p = \frac{2P}{\pi b} \qquad (3)$$

Figure 3 shows the change in contact length and contact pressure during the polishing process as a function of the radius of the abrasive block. As the radius of the abrasive block decreases from 130 mm to 72 mm due to wear, the contact pressure increases from 10 to 15 MPa, and the contact length decreases from 0.2 to 0.15 mm.

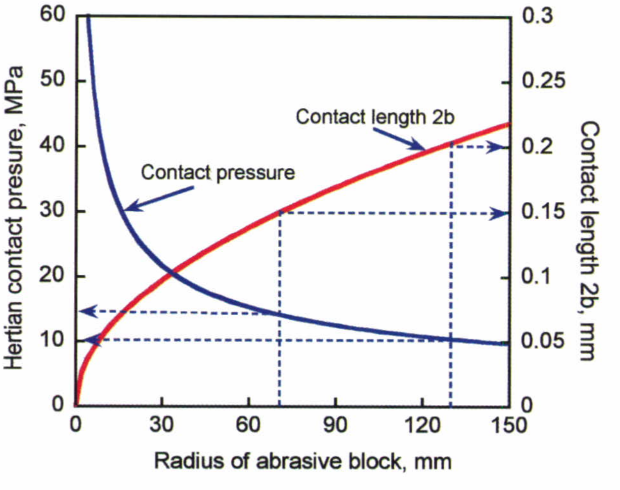


Figure 3. Change in contact pressure and contact length during the polishing process as a function of the radius of curvature of the abrasive block.

Other relevant parameters which need to be considered can also be calculated from the information on geometry and polishing conditions shown in Figure 2 (a). Figure 4 shows the number of contact cycles and sliding distance of a ceramic tile as a function of the position on the tile material. The maximum and minimum contact cycles which a tile experiences during the polishing process are 250 and 130. Figure 5 shows the sliding distance of the abrasive block as a function of the position of the abrasive material with respect to the axis of rotation of the block. It can be seen that both the abrasive block and the ceramic tile experience different sliding histories at different positions.

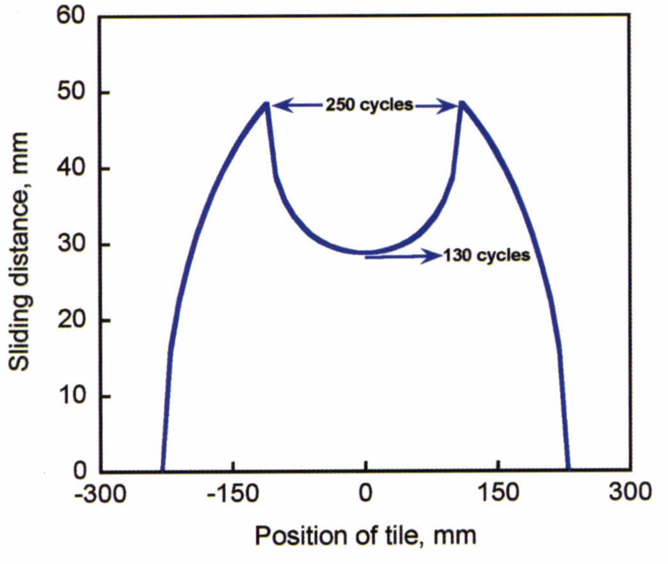


Figure 4 The number of contact cycles and sliding distance of a ceramic tile as a function of position of the material with respect to the centre-line of the tile (axis of rotation of the abrasive).

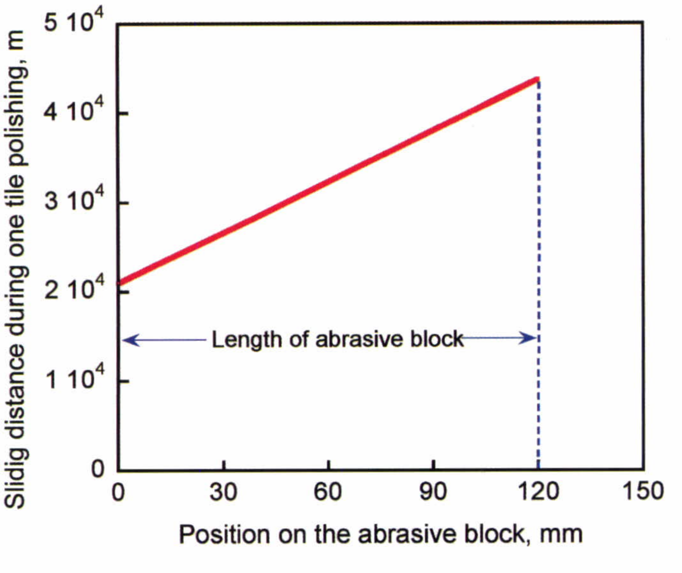


Figure 5 Sliding distance on abrasive block as a function of distance from the end of the block.

The operating conditions in a typical industrial polishing line, derived from the above analysis, are summarised in Table 1.

Contact conditions	Line load (N/mm)	1.7
	Contact pressure (MPa)	10 to 15
	Contact length (mm)	0.2
Ceramic tile	Number of contact (cycles)	130 to 250
	Sliding distance at each point (mm)	30 to 50
Abrasive block	Sliding distance (m per tile)	20 to 50

Table 1. Summary of operating conditions in the industrial polishing process.

3. DESIGN AND CONSTRUCTION OF THE TRIBOMETER

The tribometer was designed to reproduce, as far as possible, the important features of the practical conditions shown in Table 1. An automatic laboratory polishing machine with sample head (Struers RotoForce3 and RotoPol35) was adapted for this purpose. By adjusting the operational parameters of the tribometer (normal load and rotational speeds), relative motion between the abrasive block and ceramic tile which is representative of the industrial conditions can be achieved.

3.1. SAMPLE DIMENSIONS AND TRIBOMETER COMPONENTS

Abrasive pins of size 10 x 10 mm (diameter x length) and ceramic tiles of size 100 x 100 mm were used in the laboratory scale tests. Special abrasive pin holders and tile holders were designed.

Figure 6 shows a schematic diagram of the tile sample holder and a photograph of the actual component. Figure 7 shows the design of the abrasive specimen holder which couples with the motorized head of the polishing machine.

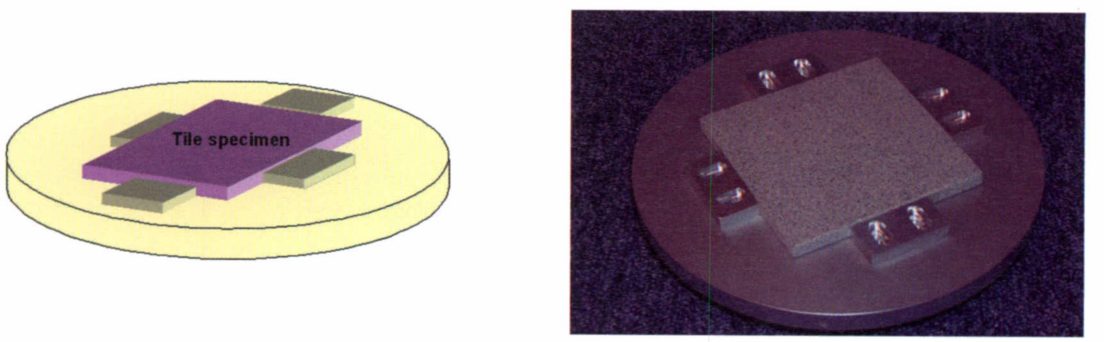
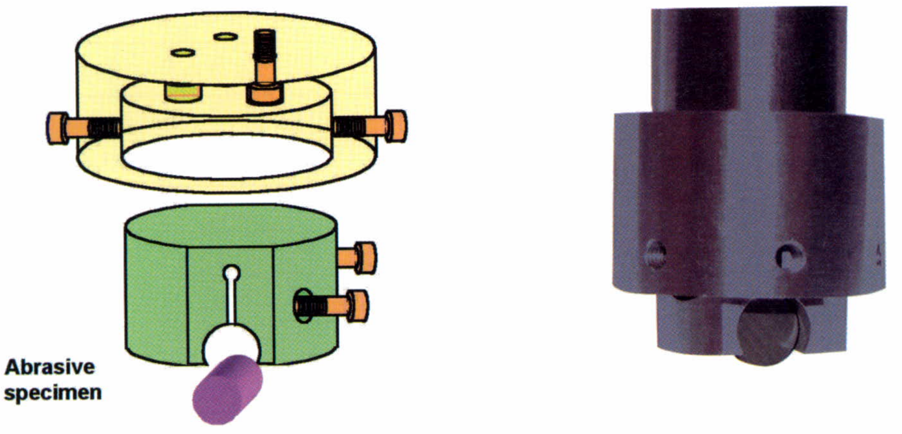


Figure 6 (a) Schematic diagram of ceramic tile specimen holder; (b) Actual part.

(a) (b



(a) (b)

Figure 7 (a) Schematic diagram of abrasive pin, holder and coupling; (b) Assembly of abrasive pin, holder and coupling.

3.2. LABORATORY TEST METHOD

Figure 8 shows the geometry used for the polishing experiments. A single abrasive pin is used in the test, mounted as shown in Figure 7, and pressed against the tile surface and rotated about a vertical axis. The load and rotation speed are controlled by the motorized head. The tile sample also rotates about a vertical axis.

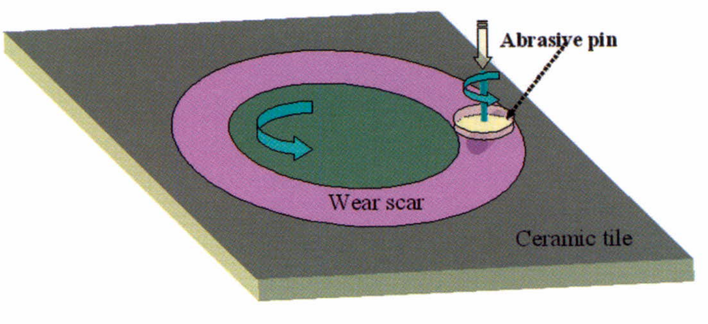


Figure 8 Sample and abrasive pin motion used in the laboratory tests

4. LABORATORY POLISHING TESTS

4.1. EXPERIMENTAL METHOD AND PROCEDURE

The polishing conditions were as shown in Table 2.

The applied load was chosen to ensure that the line load in the laboratory tests was the same as that under the industrial polishing conditions, since load is usually the most important operational parameters in tribological testing. The relative speed of the abrasive pin relative to the tile surface inevitably varied somewhat across the wear track, between 0.96 and 0.80 metres per second, which was however not considered to be large enough to cause a significant difference of the polishing effect on the tile surface.

Line load (N/mm)	1.7 (200 N/120 mm)
Rotational speed of tile specimen, rpm	300 (ω1 = 10π/sec)
Rotational speed of abrasive pin, rpm	150 (ω2 = 5π/sec)
Outer radius of wear scar r1, mm	33
Inner radius of wear scar r2, mm	23
Outer edge speed of abrasive pin, m/sec	0.96
Inner edge speed of abrasive pin, m/sec	0.80
Average speed of abrasive pin, m/sec	0.88

Table 2. Polishing conditions used in the laboratory tests

Standard SiC composite abrasive pins supplied by Abrasivos de Castellón, Castellón, Spain (ABC), with specifications conforming to normal industrial practice, were used in all the tests, with tile samples 100 mm square cut from a single batch of standard porcelain tiles, supplied by Instituto de Tecnología Cerámica, Castellón, Spain (ITC). A single cylindrical abrasive pin 12 mm in diameter and 10 mm long was used in each test.

Surface roughness Ra and gloss G were measured by using a stylus profilometer (Taylor Hobson Talysurf 10) and glossmeter (Rhopoint Novo-curve, 60 degree angle) after each test to evaluate the polished surface quality.

A test sequence was performed to simulate as closely as possible on a laboratory scale the development of the tile surface in an industrial polishing line. A single sample of ceramic tile was polished in sequence by the full range of grit sizes available from the largest grit number (#36C1) to the smallest grit number (#1500C1). (The numbers indicate the grit size designation, while the code C1 indicates that the concentration of grit and nature of subabrasives were in accordance with standard commercial practice).

Before the full abrasive sequence, the specimen surface was initially abraded by a diamond abrasive wheel (250 mm mesh size) in order to obtain a rough initial surface to simulate the real industrial situation. Nevertheless, the initial tile surface polished by the diamond abrasive wheel was smoother than that ground by the diamond roller in an industrial line. All abrasion tests were performed under the conditions shown in Table 2, with the contact region flooded with copious supplies of water.

For each abrasive pin the tile was polished for 15 seconds, then for a further 15 seconds and then for a further 30 seconds. After each increment of polishing, i.e. for a total of 15, 30 and 60 seconds exposure to each size of abrasive, the surface roughness Ra and gloss G of the tile surface were measured.

4.2 EXPERIMENTAL RESULTS

Figure 9 shows the surface roughness (Ra) and gloss (G) of the polished tile surface after each polishing step for each abrasive sample. For each grit size there are three points plotted, corresponding to the data after 15, 30 and 60 seconds exposure to each abrasive pin. The data for the final 1500 grit size are an exception to this; five data points are shown, corresponding to 15, 30, 60, 180 and 300 seconds total exposure.

The test result shows a general decreasing trend in surface roughness and an increasing trend in gloss as the polishing process proceeded from large abrasives to small abrasives. For each grit size, the surface quality depended on the polishing time, i.e. the longer polishing time applied on the specimen the better surface quality obtained, especially for those abrasive grit numbers below #600. Since there are three measurement values plotted for each abrasive pin, this graph cannot show clearly the relation between the effects of two adjacent grit numbers and the effect of each abrasive pin. Therefore, the data relating only to each abrasive pin after 60 seconds polishing time have been extracted and are re-plotted in Figure 10, which shows more clearly the change in surface roughness and gloss caused by each abrasive pin during the polishing process.

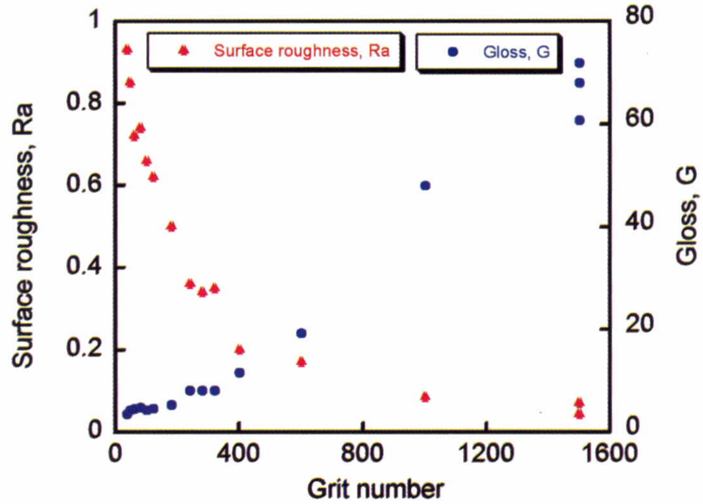


Figure 9. Surface roughness Ra and gloss G as a function of grit number of abrasive pin for the full sequence of polishing steps in the laboratory test.

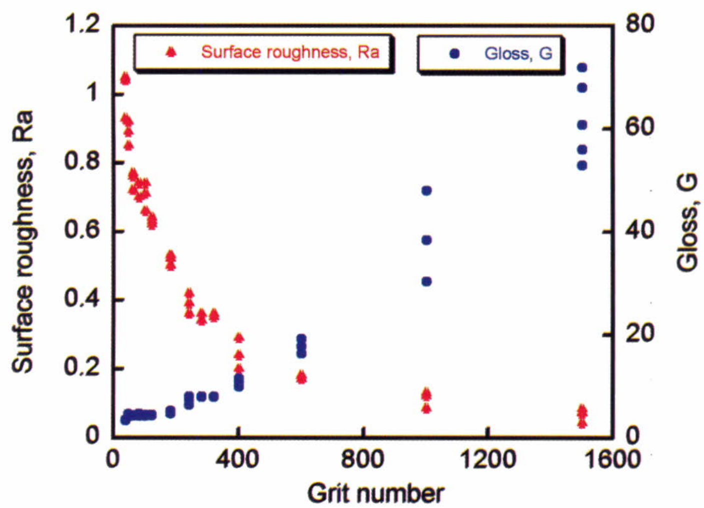


Figure 10. Surface roughness Ra and gloss G of the polished tile surface after 60 seconds exposure to each abrasive pin. In the case of 1500 grit, the three data points relate to 60, 180 and 300 seconds exposure.

5. COMPARISON OF DATA BETWEEN THE LABORATORY POLISHING TEST AND INDUSTRIAL POLISHING LINE

5.1 DATA FROM INDUSTRIAL POLISHING LINE

Data were measured on samples which were taken from an operating industrial polishing line, which was stopped to enable tiles to be withdrawn at different points [10]. The abrasive blocks used in the line ranged from #36C1 to #1500C1. As there were some duplicated or even triplicated polishing heads carrying the same grit number of abrasive block in the line, the data for some samples may relate to different polishing times. In these cases, the polishing times of the samples from the industrial polishing line may have been different from those of the samples polished in the laboratory tribometer.

5.2 COMPARISON AND DISCUSSION

Figure 11 compares the results from the industrial polishing line and the laboratory tribometer. The surface gloss is a more important and sensitive parameter than the surface roughness in the evaluation on surface quality, especially in the later polishing stages. Therefore, only the gloss values from both tests are included and plotted in the graph. It can be seen that the evolution of the tile surface in the industrial polishing line is similar to that of the tile specimens polished by the laboratory tribometer, and that the final gloss values (78.7 compared with 71.8) are of the same order as well.

For both the polishing sequences, the polishing process can be divided into two periods. For abrasive grit numbers below # 400 (i.e. larger grit particles), there was little apparent improvement in gloss, while the smaller abrasives, with grit numbers above # 400, had a significant effect on the gloss.

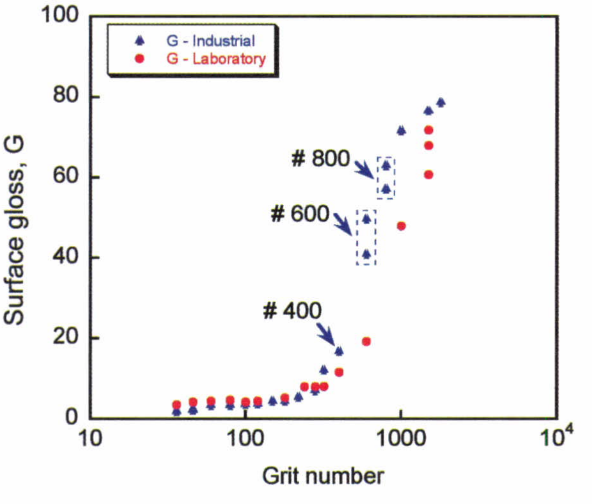


Figure 11 Comparison of gloss values for samples from the industrial polishing line and the laboratory tribometer.

Comparing the two sets of gloss values from the industrial samples and laboratory tribometer, the tile surfaces polished by the industrial polishing method had a somewhat higher gloss than the surfaces polished by the tribometer. The gloss values for tile from the industrial line showed some scatter at the certain grit numbers, e.g. # 600 and # 800, since the gloss values were measured from tile samples polished for different times. This phenomenon is in a good agreement with the results shown in Figures 9 and 10 from the tribometer, implying that the polishing time is a very important factor in improving gloss, especially for the smaller grit particles. It can be concluded that the different polishing times applied in the two polishing methods probably account for the differences in gloss values.

6. CONCLUSIONS

The design and construction of a laboratory-scale tribometer has been completed and tests suggest that the results from this apparatus in terms of tile surface properties are comparable with those observed in the large-scale polishing process employed used in an industrial polishing line. The following conclusions were obtained:

- polishing conditions in the industrial polishing line were analysed, and these conditions were used in the design of a laboratory-scale polishing rig and polishing tests;
- the important aspects of the contact conditions between the abrasive and ceramic tile in the industrial polishing line can be simulated by the tribometer;
- preliminary polishing tests with the tribometer have shown that the polished surface quality was comparable with that obtained from the industrial polishing line;
- both industrial polishing results and laboratory test results showed that there was little effect of polishing on the surface gloss for the larger abrasive particles with grit numbers below # 400, whereas a substantial effect for the smaller abrasive particles with grit numbers above # 400;
- further work is needed to establish an optimum polishing cycle in order to raise the polishing efficiency by changing the polishing conditions, such as applying different polishing time and selecting the most effective abrasives.

7. ACKNOWLEDGEMENT

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