A contribution for an optimization of the polishing quality of stone slabs: simulation and experimental study using a single-head polishing machine

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ABSTRACT

This paper describes recent research regarding: 1) the influence of the water flow and the pressure in order to attain the best polishing in portuguese limestones; 2) the experimental validation of a polishing simulator under development at Instituto Superior Tecnico (Lisbon). The research work was carried out using slabs of calcareous stone Moleanos, from Portugal, and the polishing sequence employed commercial Frankfurt-type abrasive tools applied for the last 3 stages of the process in order to attain maximum surface gloss. The study was conducted with a single-head laboratory-type polishing machine, where all test conditions are adequately monitored and controlled. The polishing head contains 6 Frankfurt abrasives of the same grit size (320#, 400# and 5Extra). The surface quality was assessed, after each polishing stage, by means of a glossmeter. In the end, it was possible to identify the optimum working parameters for each polishing stage. The results obtained also show that indeed a correlation exists between experimental values of gloss and the abrasion data given by the simulator.

KEYWORDS

Polishing, Pressure, Water Flow, Ornamental Stone, Gloss, Frankfurt Abrasives, Modelling

INTRODUCTION

Surface finishing processes alter the surface of a manufactured item to achieve a certain property. Aesthetic characteristics are very important when rocks are used as construction or ornamental materials, and therefore surface finishing processes are considered essential by the stone processing industry. Among the different types of surface finishes (such as: polished, honed, flamed, tumbled, brushed, etc.) the polished finish is perhaps the one which best enhances the rock attractiveness. Roughness (R) and gloss (G), as well as colour (C), are surface properties generally used to assess the rock polishing. The polishing quality depends very much from the type of abrasives used and on the optimal abrasive sequence utilized for a specific type of stone material (marble, limestone, onyx, granite, sandstone, and other natural stones or even engineered artificial stones). Some recent publications appearing in the open literature and dedicated to studies on surface finish evaluation on ornamental stones are listed in the references [1-3].

In industry, polishing is a finishing process, formed by several successive operations aiming to decrease the roughness of the surface and to increase its gloss intensity. This technique uses friction movements of abrasive elements over the material to obtain the required polishing degree. On modern slabs polishing machines, the stone slabs move on a wide belt and are processed by multiple polishing heads installed on the machine's bridge (see Fig. 1).

Fig. 1. Typical multiple head polishing machine used by the ornamental stone industry. [4]

Typically, polishing machines for marble have spindle motors of 10-15 hp and the diameter of the polishing head is 450 mm, installing 6 polishing “Frankfurt” abrasive elements; while for granite, machines are more powerful (spindle motors of 15-20 hp or more) and use 470 mm diameter polishing heads with 6 “Fickert (Tangential)” abrasives. There are machines that allow to process (polish) slabs of both marble and granite. There are also other types of polishing machines which use one single head.

A schematic representation of the polishing process in a polishing line is shown in Fig. 2. The abrasive elements installed at each polishing head, in contact with the stone slab, perform the polishing under well-established operating parameters: conveyor belt speed, V_L; cross-head or transverse velocity, V_T; head rotation speed, ω; water flow, Q; and pressure of polishing head, P. The abrasives have, progressively, a lower grit (between polishing heads), providing a gradual treatment through the belt.

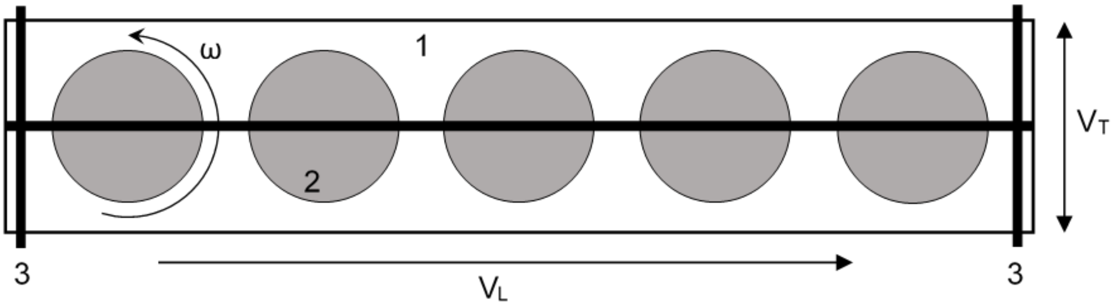

Fig. 2. Schematic representation of the polishing process in a polishing line:
1 - conveyor belt; 2 - polishing head; 3 - crosshead beam.

The water flow, Q, is employed to clean, lubricate and cool the polishing process. The effective pressure P, applied in the polishing head, allows obtaining a permanent and stable contact between the tool and the surface of the stone. As detailed in [5], the vertical movement of the polishing heads is performed by a pair of pneumatic cylinders working in counter pressure. In modern polishing machines, the lifting of polish spindle is controlled according to the stone profile perceived by sensors; and in fact, the control system inspects and optimizes the movement of polish head, crossbeam and belt to expert polishing.

The investigation described in the present paper has two objectives: 1) the optimization of the working conditions, namely pressure and water flow, in order to attain the best polishing in portuguese limestones; 2) to validate a polishing simulator developed at Instituto Superior Tecnico (Lisboa).

For this type of study, the choice of an adequate limestone is relevant and the following stone characteristics may simplify the comparison between simulation and experiment: - minimum mineralogical differences; - absence of tonalities (i.e. great homogeneity); - absence of defects (seen to the naked eye); - easy to be polished (i.e. getting easily high gloss to be measured by the glossmeter).

1. EXPERIMENTAL

1.1 Stone and abrasives used in polishing experiments

The experimental work was carried out using slabs of calcareous stone Moleanos, from Portugal. Figure 3 depicts the typical use in flooring of Moleanos limestone. As it will explained further on, each tile was divided into referenced areas that were used to attain the gloss readings after each stage of polishing.

Fig. 3. An example of typical use of Moleanos limestone in flooring.

Three different Frankfurt abrasives were used throughout this work (see Fig. 4), mounted in groups of six in the polishing head (as schematically shown in Fig. 6). These abrasives, typically applied in the three final polishing stages, were chosen in order to maximize gloss, thus making it simpler to measure and study surface changes after polishment.

320TX is a magnesite abrasive containing silicon carbide particles of grit size 320#; 400T is a resin bonded abrasive containing silicon carbide particles of grit size 400#; and 5Extra is an oxalic acid abrasive containing fine (5 micrometer) silicon carbide particles used on final polishing step to get mirror-like polishing.

(a) (b) (c)

Fig. 4. Frankfurt abrasives used in this work: (a) 320TX; (b) 400T; (c) 5Extra.

1.2 Equipment used for polishing tests and gloss readings

The polishing tests were carried out with a laboratory-type linear polishing machine (see Fig. 5.a) equipped with a single polishing head, so changes in surface characteristics (like, gloss or roughness) can be simply correlated with the local abrasive action applied in each polishing experiment. The machine is instrumented to control and monitor all the most important processing variables: conveyor belt speed, transverse speed, head rotation speed, tool pressures and water flow. The correct knowledge of all these variables is of crucial importance to study and optimize the polishing process [5].

(a)

(b)

Fig. 5. Equipment used in this work: (a) laboratory-type polishing machine; (b) glossmeter.

The surface quality of stone tiles was assessed by measuring gloss values after each polishing stage. The gloss readings were made with a glossmeter TQC PolyGloss [6] allowing measurements at angles of 20º/60º/85º. The readings were taken at different locations of the stone tiles, according to a planned grid, and the results were submitted to statistical analysis.

2. SIMULATION OF THE POLISHING

PAM (Polishing Analysis Modelling) is a 2D geometric simulator aiming to reproduce the macroscopic action of a polishing tool, rotating and moving over a stone surface, both considered flat. PAM is unable to simulate the complex Materials Science mechanisms governing the polishing at a microscopic scale, involving the deformation and wear of the asperities in the stone / tool interface. PAM instead divides the stone and tool surfaces in tiny 2D cells, from now on called pixels, and assumes that the accumulated contact between the pixels of both surfaces, from now on called abrasion, can be used to determine the main aspects of a polishing process. As in many other modelling techniques, the processing time is divided in tiny time steps, small enough to properly simulate the fast changing pattern of the tool over the stone.

Different polishing tools can be simulated simply defining the abrasion intensity for each tool pixel, from 0 (no contact) to any positive number. For example, a tool surface might be designed to have a given distribution of diamond and binder pixels. Tools with relatively simple geometric shapes can be created using PAM own functions. More complex tools can be designed using CAD or image software and then imported into PAM as images. Figure 6 shows three different polishing tools, each formed by six Frankfurt abrasives, mentioned earlier: 320TX, 400T and 5Extra.

Fig. 6. Simulated polishing tools, formed by six Frankfurt abrasives: 320TX (left), 400T (center) and 5Extra (right).

Different simulation sections can be created, with different tools, different rotation and translation tool speeds, even different time steps. Figure 7 shows the polishing results produced by the same tools of Fig. 6, after one rotation at 10 rps (no translation), with a time step of 0.001 s, corresponding to an angular step of 3.6 degrees between each impression.

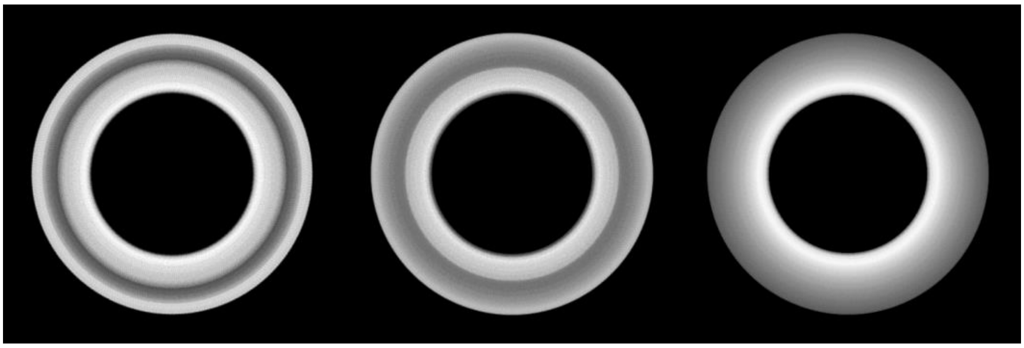

Fig. 7. Simulated polishing by the same tools as in Fig. 6, with abrasives: 320TX (left), 400T (center) and 5Extra (right), after one rotation at 10 rps, with a time step of 0.001 s.

PAM provides a very simple (only five instructions!) but powerful language to define the path followed by the tool over the stone, including multilevel loops and arbitrary sequences of linear segments and circumference arcs, powered by a wide range of parameter options. This functionality allows users to study a virtually unlimited number of trajectories, certainly covering the small subset of interest for the industry. Figure 8 shows the polishing results produced with a simple tool disk for two different polishing trajectories: a mostly linear polishing path and a more complex, mostly circular, path.

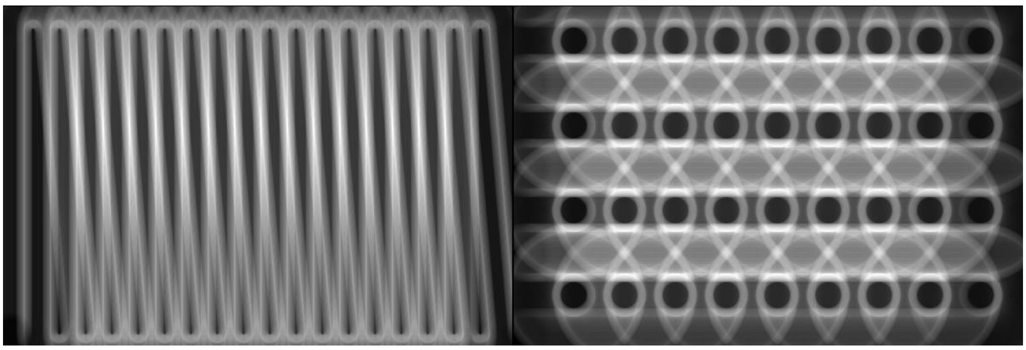

Fig. 8. Simulated polishing by a simple circular disk, for two different tool trajectories. Left: a mostly linear, up-and-down trajectory, circular on the borders. Right: a complex, four-row trajectory, mostly formed by circular movements, simulating multi-level circular hand polishing.

The accumulated simulation results for each stone pixel are stored in files describing the five properties that so far we identified as useful to assert the quality of a polishing process: 1) the total abrasion; 2-3) the shift in pixels (in horizontal and vertical directions) between each polished pixel and the tool central pixel; 4-5) the mean distance and standard deviation between the polished pixel and the tool central pixel. The data thus acquired throughout the entire simulation (or just during a single section) can then be reported in image and statistical formats, including different colour schemes, different statistical treatments, histograms, etc.

To obtain a properly polished stone surface, is not enough to achieve high levels of abrasion throughout the stone surface: abrasion should be as homogeneous and randomly applied as possible to avoid scratches and other visual defects on the surface. For economic reasons, polishing trajectories should be as short and quick to process as possible, and stone surface should not be unnecessarily over-polished.

The main goal we want to achieve with PAM is to create a modelling laboratory that help us optimize: 1) the polishing trajectories automatically generated by algorithm-controlled cutting machines (robot-based and CNC-based) in industrial contexts; 2) the shape and texture of new polishing tools, that can be simulated first to eliminate bad designs, before real tool prototypes are made and experimental tests begin.

3. RESULTS AND DISCUSSION

3.1 Influence of water flow

The assessment of the influence of water flow, Q (litre per minute), was made by varying Q (litre per minute), while keeping the pressure constant (P = 3 bar). Figure 9 summarizes the results obtained after conducting this series of polishing tests.

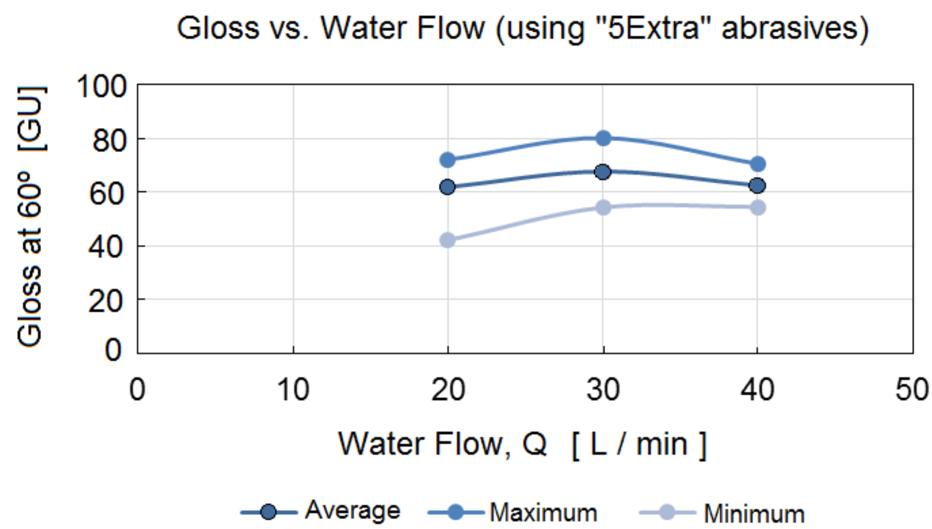

Fig. 9. Results of gloss (average, maximum, and minimum values) after the tests with “5Extra” abrasives at different water flow: 20, 30 and 40 litre per minute.

3.2 Influence of pressure

Polishing tests were conducted at pressure P = 1 bar, 2 bar, 3 bar or 4 bar, but keeping the water flow constant (Q = 30 l/min). Figure 10 shows the average values of final gloss found at different positions (along the stone tile) after tests with “5Extra” abrasives.

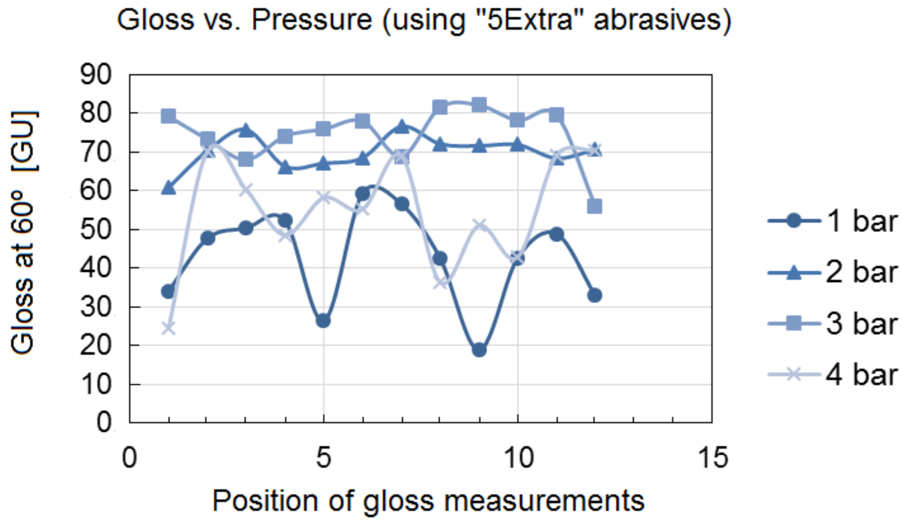

Fig. 10. Results of average gloss after the tests with “5Extra” abrasives at different pressure: 1 bar, 2 bar, 3 bar and 4 bar.

It is noticeable from Fig. 10 that there is a better polish (i.e. higher average-values of gloss) when P = 2 bar or P = 3 bar, compared to the results for P = 1 bar or P = 4 bar. The high variation of gloss across the stone tile found for P = 1 bar is attributed to vibrations occurring at the Frankfurt abrasives installed at the polishing head. The vibrations appear due to the low pressure contact between tool and stone. On the contrary, the variation of gloss for P = 4 bar is attributed to a high pressure contact. In this case, average values of gloss are higher compared to those for P = 1 bar; but the variation between minimum and maximum values for P = 4 bar is of the same order of magnitude as for P = 1 bar. The reason is that for P = 4 bar the contact areas between the Frankfurt abrasives and the stone tile are probably overloaded and this originates a less homogeneous polishment and premature deterioration of the abrasives. Table 1 summarizes the results of the total average value of gloss (for the whole area under study), as well as it presents the values concerning the standard deviation of the gloss measurements.

Table 1. Results of gloss (total average value, standard deviation, and % of standard deviation) after the tests with “5Extra” abrasives at different pressures.

	Pressure in the polishing head			
	1 bar	2 bar	3 bar	4 bar
Gloss at 60º, average [GU]	42.7	70.0	74.6	54.6
Standard deviation [GU]	12.4	4.3	7.4	14.7
% of standard deviation	29%	6%	10%	27%

Based on the results of the experiments described here before, we may consider that pressures in the range of 2–3 bar are suitable for a high gloss polishing. Note that P = 2 bar causes a slightly lower (circa 6%) final value of gloss (70.0 GU) compared to P = 3 bar (74.6 GU) but the deviation in gloss values is lower in P = 2 bar i.e. the gloss is more homogenously distributed along the stone tile. Therefore, we have considered that the best conditions for polishing the stone material under consideration are P = 2 Bar and Q = 30 liter/minute.

3.3 Some results showing the validation of the simulator

Figure 11 shows the PAM simulated abrasion produced by a polishing head equipped with six 400T abrasives that is rotating only, suggesting that abrasion is higher in the inner region, decreases in the middle and increases slightly in the outer region. A comparison between abrasion measured along the indicated radial region and equivalent gloss experimental values is shown in Fig. 12.

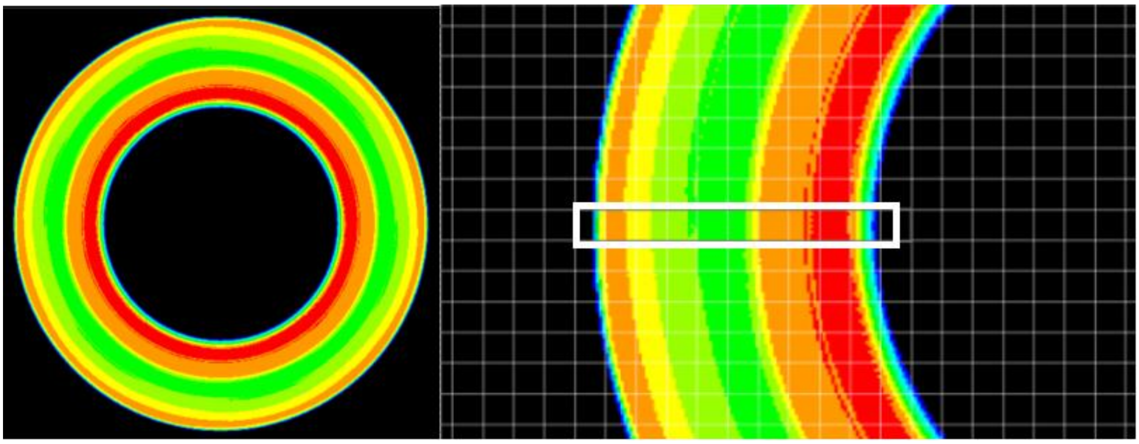

Fig. 11. Abrasion simulated with PAM for a polishing head with six 400T abrasives that is rotating only, showing the radial measuring region. Colour scheme: from blue (low abrasion) to red (high abrasion).

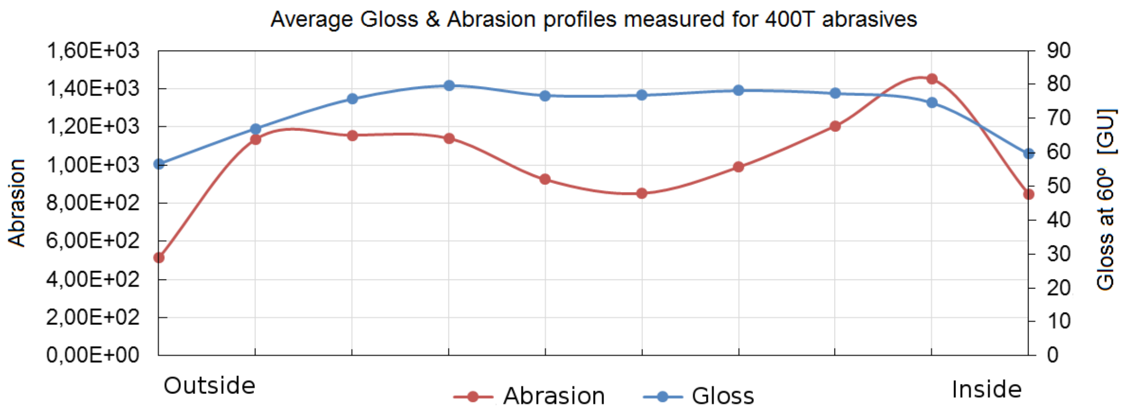

Fig. 12. Comparison between simulated abrasion and experimental gloss for a polishing head with six 400T abrasives that is rotating only.

Although changes in experimental gloss are much smaller than in simulated abrasion (because gloss tends to an asymptote and abrasion increases linearly), the same trend can be observed in both: a decrease in the middle region that is easily explained considering the geometry of the 400T abrasive used in this experiment (see Fig. 13).

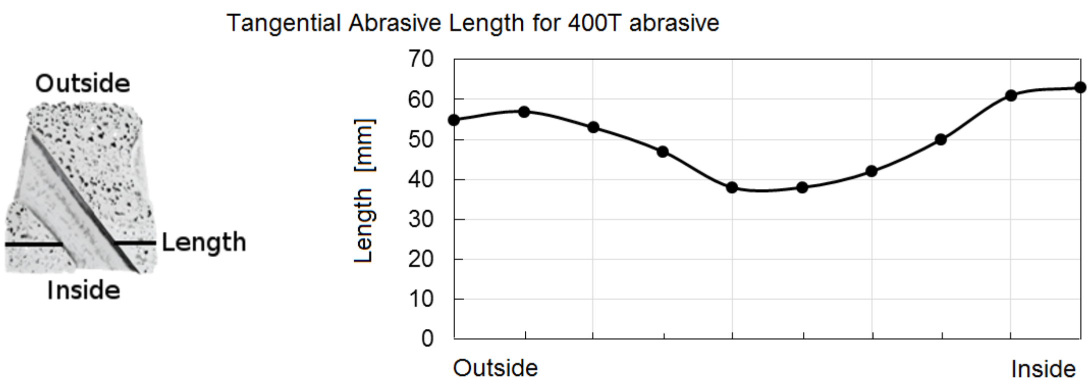

Fig. 13. Abrasive length for 400T abrasive, measured from outside to inside, in the tangential direction, showing a minimum in the central region.

Measuring the effective abrasive length along the radial direction, every 10 mm, from outside to inside, the length increases in the beginning, then decreases until the central region, where it increases again until the end. Although this abrasive tangential length cannot be directly compared with the abrasion simulated from inside to outside (because the perimeter is smaller in the inside than in the outside region, so equal tangential length abrasives are more effective in the inside region), it clearly shows the same trend observed before in experimental and simulated results. So PAM simulations of polishing tools (as shown in Fig. 7) seems to be effective in predicting the polishing behaviour of new tools.

A comparison between abrasion and gloss for a complete polishment sequence, with the three types of abrasives (320TX, 400T and 5Extra) is shown in Fig. 14. Clearly there is a good correlation between experimental gloss and simulated abrasion although, as mentioned before, gloss tends to an asymptote while abrasion just increases linearly. This explains the flat regions observed in experimental measures of gloss while accumulated abrasion always seems to increase or decrease linearly. The whole result for the polished surface, as simulated with abrasion and in agreement with gloss results, is shown in Fig. 15. The colour code uses “blue” for gloss values from 40 up to 50 GU; “green” for values from 50 up to 70 GU; and “red” for values higher than 70 GU.

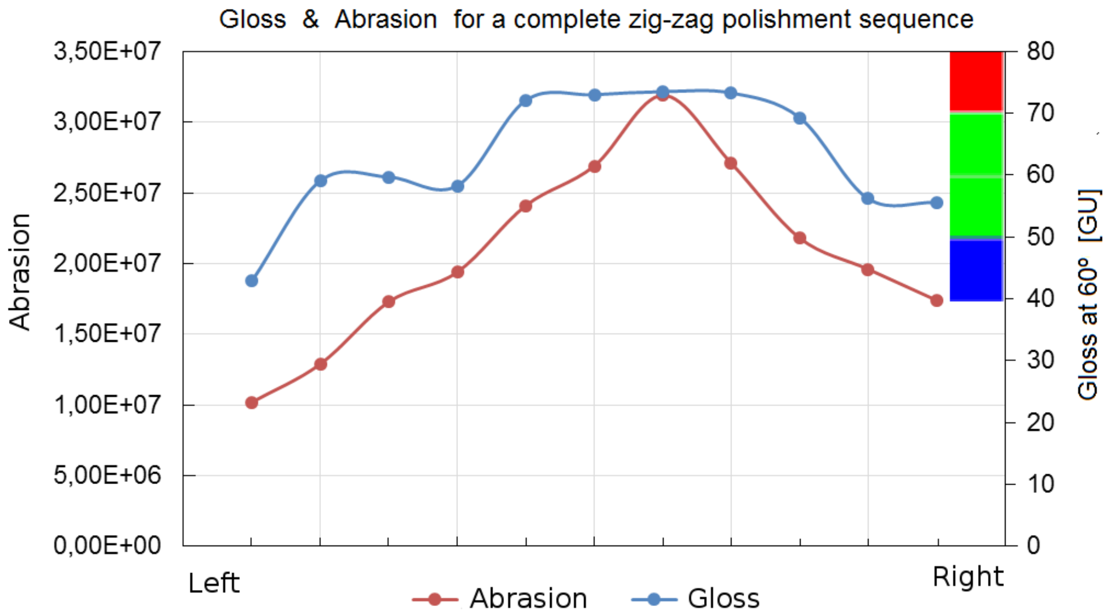

Fig. 14. Gloss and abrasion measured for a complete zig-zag polishment sequence, using the three types of abrasives (320TX, 400T and 5Extra).

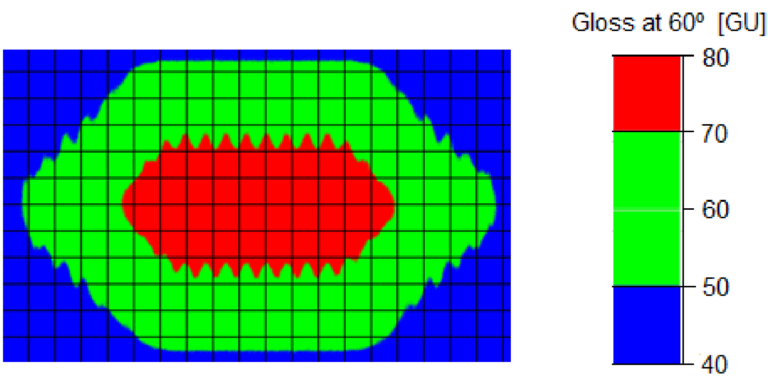

Fig. 15. Prediction of average gloss distribution, given by PAM, for the entire polished surface of a stone tile, considering a complete zig-zag polishment sequence with the three types of abrasives (320TX, 400T and 5Extra) as simulated with abrasion.

4. CONCLUSIONS

This study was conducted with commercial Frankfurt-type abrasive tools applied for the last 3 stages of the process in order to attain a maximum surface gloss in a portuguese limestone (Moleanos). The first part of the work was dedicated to the assessment of the influence of the water flow (Q) and the pressure (P) on the distribution of gloss over the polished area. Concerning to this part, we may conclude that the best conditions for polishing the stone material under consideration are attained with values of P and Q which are close to P = 2 Bar and Q = 30 liter/minute.

The second part of the work was devoted to the experimental validation of the polishing simulator named PAM. Systematic comparison tests between experimental and simulation results have been done so far only in limestones and marbles (tests on marbles were not included in this paper), with Frankfurt-like tools and linear polishing machines. The results show that indeed a correlation exists between experimental values of gloss and the abrasion data given by the simulator.

Despite the fact that the results obtained so far are positive and several correlation effects could be established, it is clear that much more research work and effort is needed to fully assert the validity of the PAM simulations, namely testing different types of stone and more complex polishing trajectories than those provided by simple linear polishing machines.

Although PAM has been specifically designed for the ornamental stone processing industry, the simplicity of the fundamental ideas behind its 2D geometric model should made it equally valid for a wide range of other polishing processes, involving different materials and polishing techniques.

These studies also lead to a better understanding of the influence of the polishing process parameters, namely the polishing time and contact area between tool and polishing surface.

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