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Assessment of the Polishing of the Aggregate Microtexture by Means of Geometric Parameters

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ABSTRACT

The paper dealt with the use of geometric parameters to measure the degree of polishing of road surface aggregates. Microtexture asperities were characterized by two angular parameters related to their shape and relief. The polishing action was simulated in laboratory by means of a French device, which was developed as an alternative to the British Accelerated Polishing Test. Three road stones were studied. Friction and microtexture measurements were carried out at different polishing stages. The friction was measured by means of the Skid Resistance Tester. The microtexture profiles were measured by means of a very high-resolution laser sensor, providing profiles with a 1 μm sampling length. The variations of the friction could be satisfactorily explained by the evolutions of the microtexture parameters with the polishing time. Two microtexture scales were defined to take into account the roughening effect, which occurred on polymineral stones in the beginning of the polishing process. Interpretations from the profile analyses of the effect of polishing on the characteristics of microtexture asperities such as the size, shape and density were corroborated with the polishing mechanisms based on petrography examinations.

INTRODUCTION

The tire/road friction, which is essential for the safety of road users, decreases when the road surface is worn. For highway engineers, it would be valuable to be able to predict the long-term skid resistance of bituminous surfaces before the pavement was constructed. Wear of road surfaces involves the polishing of the microtexture of aggregates due to the repeated actions of traffic. The microtexture is defined as surface asperities less than 0.2 mm-height and 0.5 mm-width. These asperities are required mainly under wet conditions to breakdown the thin water film and to enhance the creation of effective areas of contact with the tire treads. Previous works (1)(2)(3) reported models to relate the long-term skid resistance of pavements to the polishing resistance of aggregates. The long-term skid resistance was measured on long service life pavements by means of dynamic devices. The polishing resistance was characterized commonly by the Polished Stone Value (PSV), when the polishing action was simulated by the British Accelerated Polishing Test (1)(2). When specific polishing devices were developed to simulate wheel passes, the polishing resistance was characterized by the friction values measured after a predefined number of passes (3). The correlation between the polishing resistance and the long-term skid resistance was generally low ($r\text{-squared} < 0.5$), although the relations obtained were statistically significant.

Petrography examinations were performed also to relate the mineralogical composition to the polishing resistance (2)(4)(5). Observations of pictures of road stones taken by means of the Scanning Electron Microscope (SEM) (4)(5) showed how the polishing actions, as simulated in laboratory by the British Accelerated Polishing Test, affected the microtexture of the aggregates. Comparisons of the SEM pictures before and after polishing showed significant evolutions of the topography of aggregate particles which could be related to the variations of friction, as measured by means of the Skid Resistance Tester (SRT), before and after polishing. Generally, the decrease of the friction was attributed to the decrease of the microtexture harshness. From their comprehensive study (5), Tourenq and Fourmaintraux emphasized two polishing mechanisms: a “general” polishing, which tends to round off the asperity summits, and a “differential” polishing, which tends to create residual relief. Existence of the relief is only possible on polymineral stones where soft minerals, on which the polishing actions is significant, define the valleys and hard minerals, which are affected to a lesser extent than the soft minerals, define the peaks. Tourenq and Fourmaintraux proposed also in (5) a formula to calculate the PSV values of stones from their mineral hardness. The petrography examination is a valuable tool to understand the polishing process and to state recommendations for the use of aggregates. However, good technical skill is needed in interpreting the pictures of aggregate facets. Results are mainly subjective and no quantitative descriptor could be defined.

In order to complete this state of knowledge and improve the prediction of the variation of skid resistance with the polishing time, a geometric description of the microtexture asperities is needed. Previous works reported methods to calculate the shape, size and density parameters from the microtexture profiles (6). However, no further result was reported on the application of the proposed parameters to the determination of the degree of polishing of road aggregates. Recently, LCPC developed a method for measuring the microtexture profiles by means of a high-resolution laser sensor (7). A profile analysis method was also proposed to characterize the geometry of microtexture asperities by means of two angular parameters (7)(8). Results obtained on surfaces composed of aggregates and road surfaces showed that these parameters are well correlated with the SRT friction (8).

The aim of the study dealt with in this paper was then to assess the evolution of the microtexture with polishing by means of the two angular parameters mentioned above.

RESEARCH METHODOLOGY

The polishing process was simulated by means of a laboratory device on laboratory-made specimens composed of aggregates. The same specimen was used to survey the evolution of the microtexture with the polishing time. The polishing machine was stopped at predefined stages and the specimens were taken out for measurements. Then, the specimens were replaced in the machine and the polishing process was pursued.

Microtexture profiles and friction were measured at defined polishing states. Care was taken to measure the profiles always at the same locations. The angular parameters were calculated from the profiles and their evolution with the polishing time was compared to that of the friction.

EXPERIMENTAL PROGRAM

Materials

Aggregates from three road stones were used : a limestone, a diorite and a sandstone. The PSV of the three stones were respectively 0.39, 0.51 and 0.67. Results from a preliminary petrography study (unpublished results - Hardy) showed that :

- The limestone is made of calcite. The crystal sizes are mainly between 1 and 5 μm . Occasional coarse crystals (size exceeded 50 μm) are present ;
- The diorite is made of an imbrication of crystals from different minerals : amphibole, feldspar, and quartz to a lesser extent. Crystal sizes are in the order of 300 μm to 500 μm ;
- The sandstone is made of 50 - 300 μm quartz particles strongly linked to each other by a matrix. The matrix is mainly made of needles-like or sheets-like soft clay minerals.

Polishing Device

The polishing actions were simulated in laboratory by means of the equipment called “GRAP”, which was developed in France by the LPC network (Public Works Regional Laboratories) as an alternative to the British Accelerated Polishing Test (9). The polishing action is achieved by the projection of a water and very fine abrasive mix under a pressure of 10 MPa by means of a nozzle with a 60 degrees incidence angle (Fig. 1). The surface is swept by the displacements of the projection nozzle. Twenty sweep cycles are necessary to obtain the GRAP limit polishing state. The degree of polishing is assessed by the SRT friction, which is measured under the same test conditions as those used for road surfaces. The test method is detailed in (9). Results from (9) showed that the limit polishing states of the GRAP and British Accelerated Polishing Test methods are quite comparable.

Polishing states

Analyses and observations were done at the initial (without polishing) and four polishing states, expressed as the number (n) of sweep cycles of the GRAP nozzle : 1 – 5 – 10 – 20 cycles. The initial state was considered as the 0-cycle polishing state.

Specimens

Specimens used for the GRAP polishing are 100 mm \times 150 mm rectangular plates. Specimen surface is composed of coarse aggregates of similar sizes and fixed in a resin matrix (Fig. 2). The aggregates were first placed as close as possible to each other in a flat rectangular mould by means of a vibrating device. Only a single layer of aggregates is required. Space between aggregates was then filled with fine sand before resin was spread out. About half an hour is required for setting of the resin. Detailed procedure for fabrication of specimens may be found in (9). For each stone, two specimens were made.

Friction Measurement Device

Friction was measured by means of a Skid Resistance Tester. This device is widely used in order to assess the skid resistance properties at low speeds of a surface either in the field or in the laboratory. The tester incorporates a spring-loaded 76.2 mm × 25.4 mm slider made of a standard rubber attached to the end of a pendulum. On releasing the pendulum from a horizontal position, the loss of energy as the slider passes over the test surface is measured by the reduction in length of the upswing using a calibrated scale.

The surfaces were wetted before release of the slider. Measurements were done in laboratory where ambient temperature was kept constant (20°C). Thirteen releases were made, the last three readings being taken for calculating the SRT friction values.

Microtexture Measurement Device

Microtexture profiles were measured by means of a high-resolution laser sensor. The working principle of the sensor as well as its use for the measurements of road microtexture profiles was already discussed in (7). On every specimen, profile measurements were carried out in the friction area of the rubber pad on about 15 aggregates, which were selected in order to be representative of the aggregates composing the specimen. The measurements were carried out along the sliding direction of the rubber pad. Ordinates of the starting point of each profile were registered. By this way, it was possible to measure the profiles always at the same location on the aggregates at every selected polishing state. When the aggregates are broken by the projection actions, the profile length measured at subsequent polishing states was reduced. The sampling interval was of 1 µm. Profile lengths varied between 6 mm and 12 mm, depending on the surface topography of the aggregates. The cumulative profile lengths varied between 120 and 150 mm.

RESULTS

Definition of the Angular Parameters

The analysis method developed at LCPC is focused on the significant features of the microtexture profiles, that is, the asperities called “indenters”, which are required to breakdown the water film and deform the rubber of the tire. Profile indenters were defined as being composed of a profile peak and its two neighboring left-right valleys (Fig. 3). The indenters analysis was derived from the motif combination technique (10) which was developed and used in the French automobile industry. A motif is composed of a valley and its two neighboring left-right peaks. The notions of “indenter” and “motif” are then quite similar. However, indenters were preferred for their geometry is closer to that of road surface asperities. The indenter shape was defined locally as the cotangent of its summit semi-angle (α). In order to take into account the relative positions of the indenters, the indenter relief was defined locally as the angle (θ) between the segment connecting the summits of two consecutive indenters and the horizontal.

Beside the angular parameters, it was also possible to define the density as being the number of indenters per unit length and the indenter width as being the distance between two valleys composing an indenter.

Peaks and valleys were defined as points respectively higher and lower than their neighboring left and right points. Formulae for calculating the shape and relief are the following :

$$\theta = \tan^{-1} \left| \frac{z_{p+1} - z_p}{x_{p+1} - x_p} \right| \quad (1)$$

where z_p, x_p : height and abscissa of the p^{th} peak.

$$\alpha = \frac{1}{2} \times \left[\tan^{-1} \left| \frac{x_e - x_{e-1}}{z_e - z_{e-1}} \right| + \tan^{-1} \left| \frac{x_{e+1} - x_e}{z_{e+1} - z_e} \right| \right] \quad (2)$$

where z_e, x_e : height and abscissa of the e^{th} extremum.

The profile analyses were performed by means of a Matlab® program developed at LCPC. The profiles were re-sampled at a sampling interval of 5 μm , meaning that the smallest indenter width that could be detected is 10 μm . On each profile, the indenters were detected and the related shape and relief values were calculated. On each stone, since profiles were measured on two specimens, values of cotangent (α) and (θ) obtained on both specimens were regrouped, then the respective mean values were calculated to characterize the microtexture of the aggregates. This choice was supported by the fact that for each stone the friction values obtained on the two specimens are quite similar (Tab. 1).

Evolution of the Aggregate Microtexture with the Polishing Time

Evolutions of the cotangent (α), (θ) and density are presented on figures 4, 5 and 6 for respectively the limestone, diorite and sandstone. Evolutions of the friction are also shown on the same graphs. Values at n-cycle polishing states were normalized by the values at the initial state. The individual values were reported in table 1.

The polishing actions induced a decrease of the cotangent (α) and (θ) values on the three stones, meaning that the indenter summits were progressively rounded off and their relief became less pronounced. At any polishing state, the microtexture harshness of the three stones, which might be characterized by cotangent (α) and (θ), was ranked in the following decreasing order : sandstone, diorite, limestone (Tab. 1). This classification was corroborated by the friction values (Tab. 1). The ranking order based on the density was reversed. The high-friction aggregates seemed then to be composed of a small number of harsh asperities, and the low-friction aggregates by a greater number of flattened asperities. On the limestone, the density was not affected by the polishing actions. On the diorite and the sandstone, there was a decrease of the density. These results should mean that on the diorite and the sandstone, the polishing not only affected the geometry of the indenters, as it did on the limestone, but also removed the indenters by means of the projection action.

Variations of the microtexture parameters were important during the first 5 cycles, then they became stable until the end of the polishing process. There seemed to be a relationship between the polishing resistance and the variations of the indenters shape and relief during the first 5 polishing cycles. Indeed, the decrease of cotangent (α) and (θ) was as much important as the PSV value was low.

On the limestone, evolution of the friction with the polishing time was quite in agreement with that of the cotangent (α) and (θ) (Fig. 4). This result proved that the employed geometric parameters are quite suitable for the assessment of the microtexture. However, the evolutions of the friction measured on the diorite and the sandstone were unexpected compared whether with the evolutions of the microtexture parameters or with the evolutions of the friction published in previous studies (1). Indeed, during the first 5 cycles, the friction increased whereas the microtexture harshness decreased (Figs. 5, 6). Observations of the profile aspects and examinations of the individual values of cotangent (α) and (θ) did not reveal any anomaly which could influence the calculated mean values.

In his theory (11), Yandell emphasized the contribution of various texture scales to the hysteresis friction. The same author developed a predictive model (12) in which a texture profile was divided into four scales and the total hysteresis friction was the sum of frictions generated on each texture scale. In order to explain the unexpected results obtained on the diorite and the sandstone, further analyses were performed to investigate the effect of the polishing on other microtexture scales.

Influence of the Microtexture Scales

The motif combination technique divides a texture profile into two scales (10) (Fig. 3) :

- the “roughness” scale which is related to the measured profile ;
- the “undulation” scale which is related to the envelope profile composed of segments connecting the peaks of the measured profile.

The definition of these two scales was motivated by the fact that profiles and their envelope could have distinct functional properties. The separation of texture scales based on the motif theory is simple. It is quite different from the filtering technique employed by Yandell, which is a division of the texture profile into 4 bands by means of a 5th order Bessel filter (12). Since the indenter analysis is based on the motif technique, a microtexture profile was also considered as being composed of the roughness and undulation scales. The appellation used to define the microtexture scales might not be appropriate since the “roughness” term is already

employed to define other road surface irregularities. However, the terms were kept temporarily in this paper to remind that they were derived from the motif theory.

From the above considerations, it could be stated that the analyses presented in the preceding paragraph were related to the roughness scale and the unexpected evolution of the friction on the diorite and the sandstone might be related to the variation of the undulation scale. The indenters analysis was then performed on the envelopes of the measured profiles in order to extract the shape and relief values at the undulation scale. The sampling interval of the envelope profiles was of 50 μm , meaning that the smallest indenter width at the undulation scale is 100 μm .

Values of the microtexture parameters at the undulation scale (Tab. 2) were much less important than those obtained at the roughness scale. This result was somewhat intuitive, for the envelope profiles should be smoother than the measured profiles and there must be less indenters – few hundred microns size – per unit length. The ranking order of the microtexture harshness of the three stones, which was established at the roughness scale, was preserved at the undulation scale. However, the density ranking order was reversed, that means, coarse asperities were present to a less extent on the limestone than on the two other stones. Results from table 2 showed that the polishing action removed the indenters on the three stones, for the densities decreased. It should be noted that higher friction values were related to higher indenters densities, whereas the reverse was true at the roughness scale.

Evolutions of the microtexture at the undulation scale are presented in figures 7, 8 and 9. Variations of the friction were reported also on the graphs. It should be reminded that the same measured friction values were used whatever the texture scales may be. On the limestone, the shape and relief decreased slightly, but the decrease is less important than what could be observed at the roughness scale. On the diorite and the sandstone, it was noted that evolutions of the shape and relief were quite in agreement with that of the friction. The assumption made on the role of the undulation scale in the polishing process seemed then to be verified.

At this time, it could be said that the polishing actions induced variations of the microtexture at two scales : the “roughness” scale related to the asperities of a few tens microns size and the “undulation” scale related to the asperities of a few hundred microns size. Evolutions of the indenters geometry of the aggregates at these two scales depended on the type of stone. On the limestone, indenters at both scales were rounded off and the relief was progressively smoothed by the polishing actions. On the diorite and the sandstone, the small indenters were worn continuously, whereas there was first a roughening effect on the coarse indenters before they were worn by the polishing actions.

It should be noted that the selected sampling interval values for the analyses at the roughness and undulation scales were quite arbitrary. The question is whether any significant feature of the microtexture profiles could have been neglected by this choice. From the above analyses, where friction variations were well related to microtexture variations, it might be stated that the asperities smoothed off by the re-sampling procedure should have negligible influence on the analysis of the polishing process.

Corroboration with Previous Studies

Qualitative comparisons of the above explanations with the SEM observations by Williams and Lees (4) showed similar conclusions on the smoothing of the asperities subjected to the polishing actions. Further comparisons were not investigated for the experimental programs (materials, polishing procedure, polishing states) were not identical.

The evolution of the geometric parameters might be corroborated with the two polishing mechanisms proposed by Tourenq and Fourmaintraux (5). Indeed, since limestone is monomineral, only the “general” polishing occurred, which caused the smoothing of the asperities at all scales. On the diorite and the sandstone, the “differential” polishing occurred during the first 5 polishing cycles. Since the crystal size of these stones was about some hundred microns, the “roughening” effect was seen only at the undulation scale. On and after the 5th cycle, the “general” polishing became predominant and induced the smoothing of the asperities at all scales.

CONCLUSIONS

In this paper, the evolution of the microtexture of three road stones with the polishing time was assessed by means of geometric parameters, which characterize the shape and relief of the microtexture asperities. It was shown that the evolution of the SRT friction, which is commonly employed to measure the degree of polishing of road surface aggregates, could be explained by means of the microtexture parameters. Results showed also that profile analyses should take into account two microtexture scales defined merely from geometric considerations.

These results were obtained on a limited experimental program and must be validated on various road stones using other polishing methods. Refined comparison of the variations of the indenters geometry with the petrography examinations should be performed also. Further investigations should be carried out on road surfaces. However, the results presented in this paper are promising and showed that the geometric parameters could be a useful tool to improve the understanding of the polishing process and by this way contributes to the development of wear prediction models.

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FIGURE CAPTIONS

FIGURE 1 Polishing device.

FIGURE 2 Specimens.

FIGURE 3 Definition of the microtexture parameters.

FIGURE 4 Evolution of the limestone microtexture with the polishing time.

FIGURE 5 Evolution of the diorite microtexture with the polishing time.

FIGURE 6 Evolution of the sandstone microtexture with the polishing time.

FIGURE 7 Evolution of the limestone microtexture with the polishing time (undulation scale).

FIGURE 8 Evolution of the diorite microtexture with the polishing time (undulation scale).

FIGURE 9 Evolution of the sandstone microtexture with the polishing time (undulation scale).

TABLE TITLES

TABLE 1 Values of Friction and Microtexture Parameters

TABLE 2 Values of Friction and Microtexture Parameters (Undulation Scale)

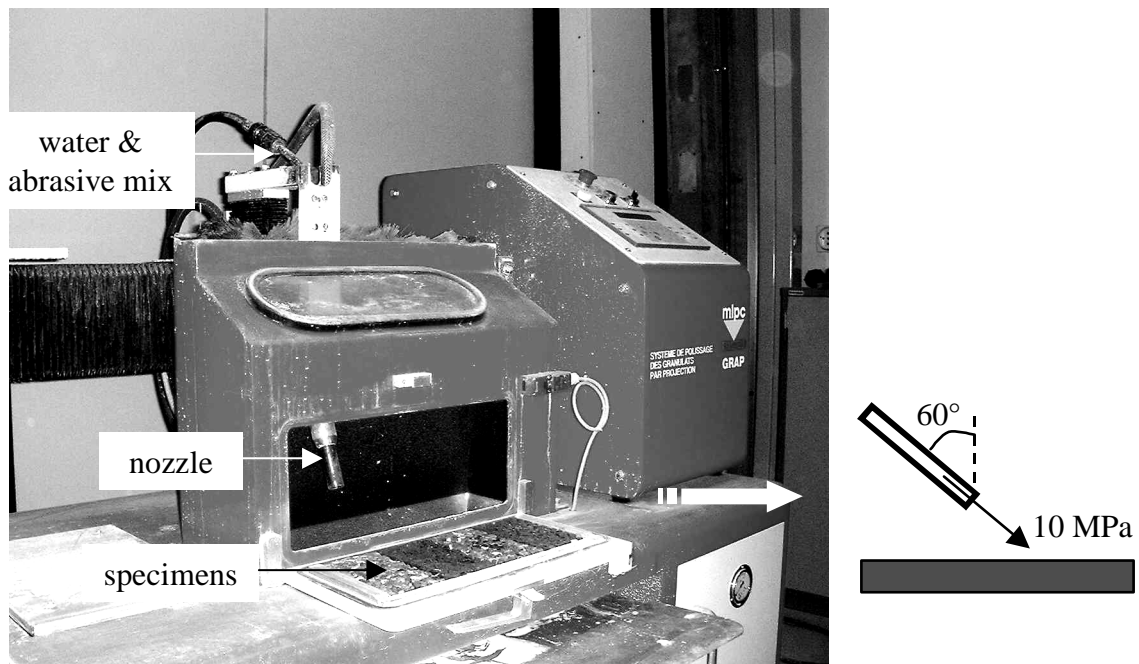


FIGURE 1 Polishing device.



FIGURE 2 Specimens.

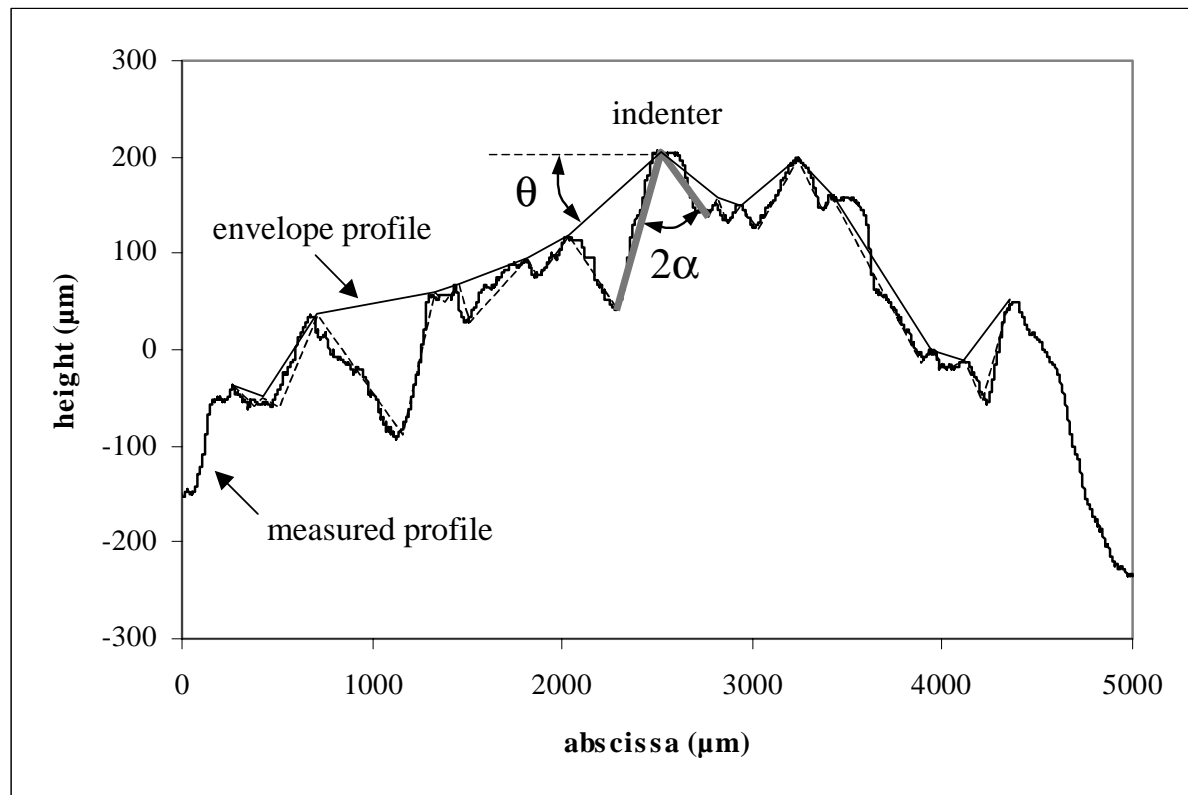


FIGURE 3 Definition of the microtexture parameters.

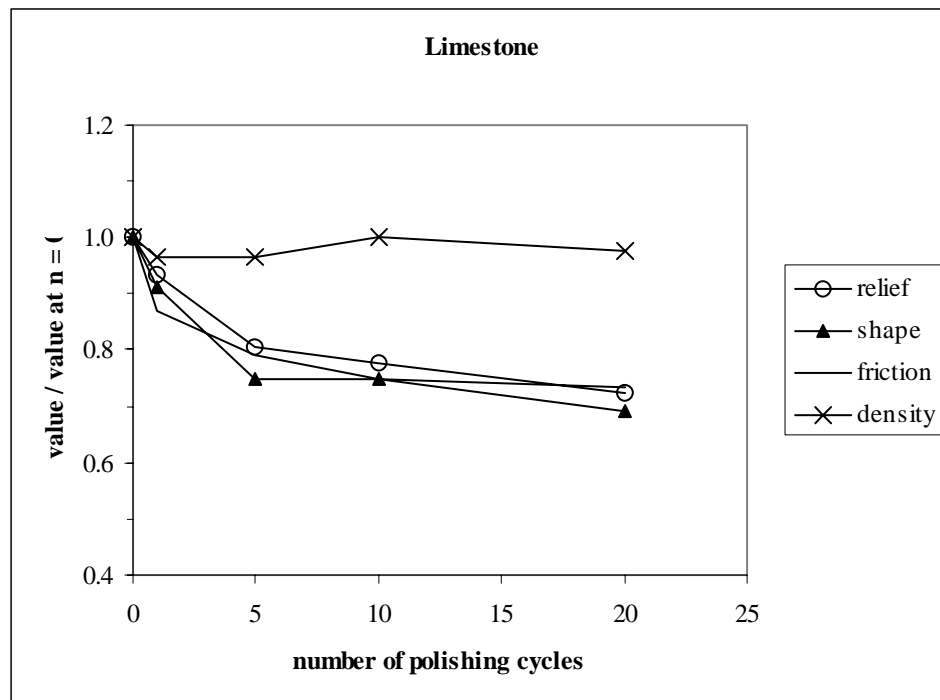


FIGURE 4 Evolution of the limestone microtexture with the polishing time.

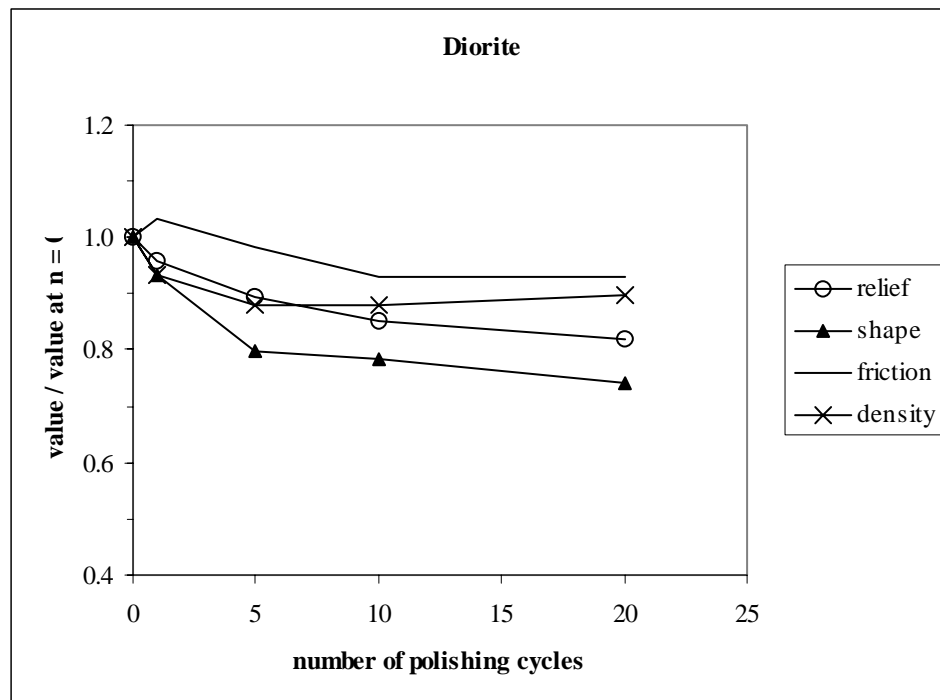


FIGURE 5 Evolution of the diorite microtexture with the polishing time.

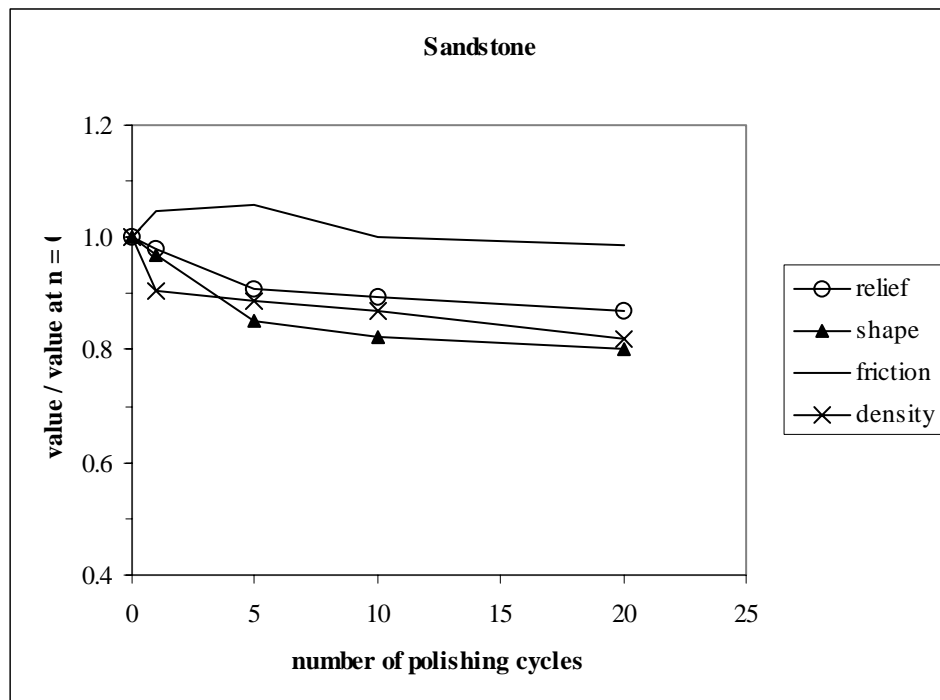


FIGURE 6 Evolution of the sandstone microtexture with the polishing time.

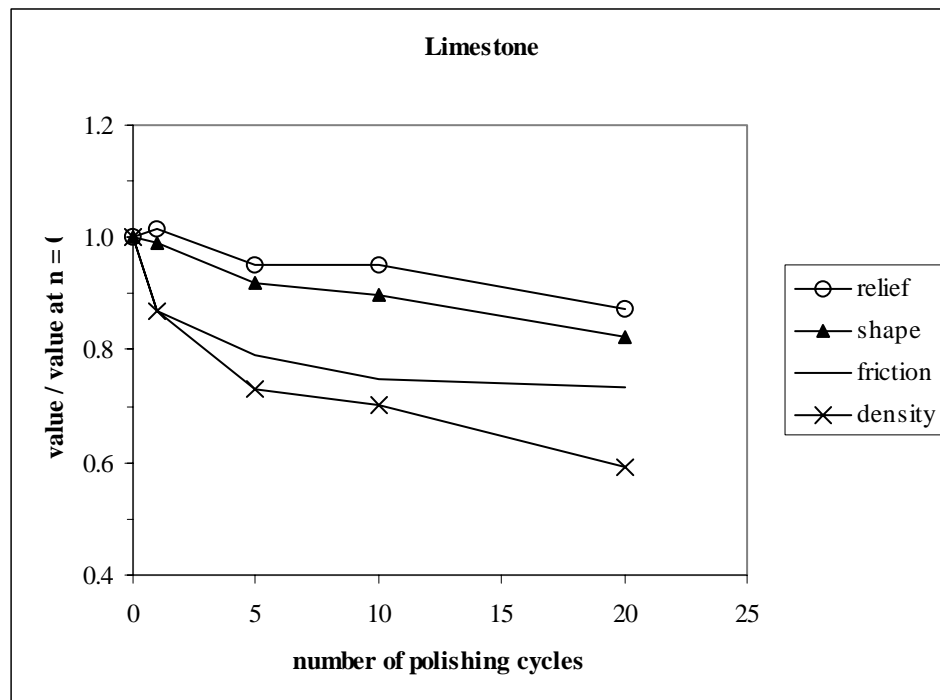


FIGURE 7 Evolution of the limestone microtexture with the polishing time (undulation scale).

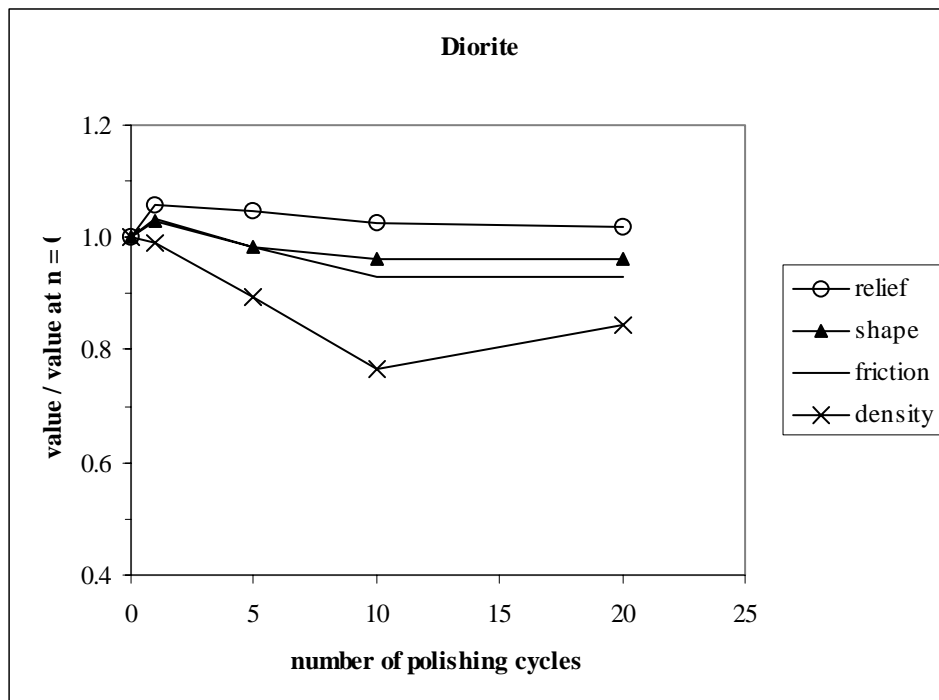


FIGURE 8 Evolution of the diorite microtexture with the polishing time (undulation scale).

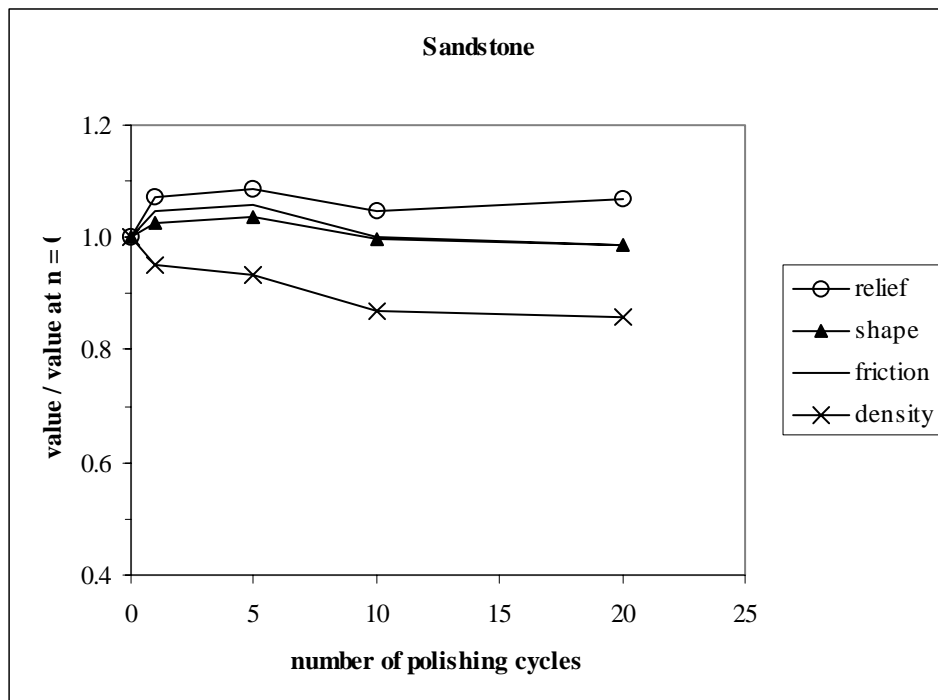


FIGURE 9 Evolution of the sandstone microtexture with the polishing time (undulation scale).

TABLE 1 Values of Friction and Microtexture Parameters

Limestone								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1*	2	1	2	1	2	1	2
0	0.290	0.270	10.8	10.6	31.0	29.0	0.70	0.70
1	0.270	0.240	10.2	9.7	30.0	28.0	0.60	0.61
5	0.220	0.200	8.7	8.5	30.0	28.0	0.55	0.56
10	0.220	0.200	8.3	8.3	31.0	29.0	0.52	0.53
20	0.201	0.187	7.8	7.7	30.8	27.8	0.51	0.52
Diorite								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1	2	1	2	1	2	1	2
0	0.290	0.310	11.1	11.4	29.0	30.0	0.66	0.65
1	0.280	0.280	10.8	10.8	27.0	28.0	0.67	0.68
5	0.230	0.250	9.8	10.3	26.0	26.0	0.64	0.65
10	0.240	0.230	9.7	9.5	25.0	27.0	0.60	0.62
20	0.211	0.235	8.9	9.6	26.3	26.8	0.60	0.61
Sandstone								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1	2	1	2	1	2	1	2
0	0.340	0.340	13.4	13.7	27.0	26.0	0.75	0.77
1	0.330	0.330	13.1	13.5	24.0	24.0	0.79	0.80
5	0.290	0.290	12.2	12.4	24.0	23.0	0.81	0.80
10	0.280	0.280	12.2	12.0	23.0	23.0	0.75	0.77
20	0.279	0.265	12.0	11.6	21.7	21.7	0.74	0.76

*: specimen number.

TABLE 2 Values of Friction and Microtexture Parameters (Undulation Scale)

Limestone								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1*	2	1	2	1	2	1	2
0	0.153	0.149	6.3	6.2	2.4	2.1	0.70	0.70
1	0.149	0.149	6.3	6.3	2.1	1.8	0.60	0.61
5	0.141	0.136	6.1	5.8	1.7	1.6	0.55	0.56
10	0.136	0.134	6.1	5.7	1.8	1.4	0.52	0.53
20	0.123	0.126	5.5	5.3	1.4	1.2	0.51	0.52
Diorite								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1	2	1	2	1	2	1	2
0	0.172	0.162	6.7	6.7	2.0	2.3	0.66	0.65
1	0.175	0.168	6.9	7.3	2.2	2.0	0.67	0.68
5	0.160	0.169	6.8	7.2	2.1	1.8	0.64	0.65
10	0.157	0.164	6.4	7.3	1.7	1.6	0.60	0.62
20	0.153	0.168	6.5	7.1	1.9	1.8	0.60	0.61
Sandstone								
	Cotangent (α)		Theta (degree)		Density (number of indenters / mm)		SRT friction	
Cycle	1	2	1	2	1	2	1	2
0	0.217	0.227	7.5	7.9	2.4	2.7	0.75	0.77
1	0.225	0.230	8.6	7.9	2.3	2.6	0.79	0.80
5	0.229	0.232	8.4	8.3	2.4	2.4	0.81	0.80
10	0.218	0.224	8.6	7.6	2.2	2.2	0.75	0.77
20	0.218	0.220	8.7	7.7	2.1	2.3	0.74	0.76

*: specimen number.