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A surface engineering approach applicable to concrete repair engineering

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Abstract. The objective of the paper is to analyze the effect of substrate roughness and superficial microcraking upon adhesion of repair systems using concrete surface engineering approach. The results presented in this paper have been obtained within the framework of research projects performed to develop a better understanding of the factors affecting the adhesion of repair materials through a surface engineering approach. Based on the results of investigations, the authors showed that the durability and quality of concrete repairs depend to a large degree on the characteristics of the substrate. Mechanical preparation and profiling of the concrete surface to be repaired has to be balanced with potential co-lateral effects such as superficial cracking, too often induced as a result of inappropriate concrete removal method selection, and the loss of benefits due to better mechanical anchorage. The results obtained confirm also that Concrete Surface Engineering, as a scientific concept, will definitely contribute to shed more light on how to optimize repair bond, taking into account interactions between the materials at different observation scales.

Key words: durability of concrete structure, repair, adhesion, surface roughness, microcracking, surface engineering.

1. Introduction

The deterioration of concrete structures is a major problem in many countries throughout the world. Durability of the structures, maintenance and conservation, repairs and modernization are also important research areas for sustainable development in construction [1–3]. To reach a desired durability of new concrete structures as well as existing structures (repair), three main types of surface concrete quality improvement are considered (formalized also in the European Standard EN 1504) [4]:

- improvement of near-to-surface layer quality by hydrophobic treatment or impregnation;
- removal of deteriorated concrete and repair with fresh mortar;
- application of adhesive coating to improve barrier properties.

Therefore mentioned approach emphasises that the properties of the near-surface layer influence barrier properties of concrete and in consequence its durability [5, 6]. Such approach shares characteristics with surface engineering commonly applied to many construction materials like metal alloys, including nanomaterials, eg. [7, 8]. Surface engineering is defined [7] as a scientific and technological approach related to the design, the production and the application of surface layers to improve some properties of the substrate, particularly the resistance to corrosion and abrasion, as well as aesthetic properties. Surface engineering covers all phenomena involving a modification of the near-to-surface layer and/or application of a coating suitable for a given application. In all cases, suitable scientific tools are necessary to characterize properties of layer, quality of substrate and adhesion of coating to substrate.

The surface engineering approach is still rarely applied in civil engineering, especially for concrete-like composites in concrete repair engineering (Fig. 1). However, according to the authors, this scientific approach allows to explain phenomena underlying durability of repair and anticorrosion protection of concrete structures [9, 10], which directly depend on the adhesion quality. Favorable conditions during the phase of creation of the bond between the substrate and the new layer will guarantee the longevity of adhesion and, consequently, of the repair. The high adhesion level creates higher tolerance to some incompatibility between the bonded materials, particularly in the case of concrete-polymer composite repairs on concrete substrate [11, 12].

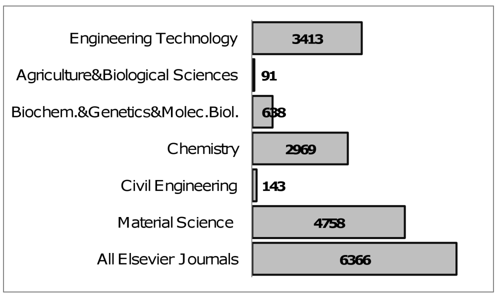

Fig. 1. Number of papers related to "surface engineering" for different categories in the ScienceDirect database of all Elsevier journals

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2. Definitions of adhesion

The ability of two bodies to associate in order to form an assembly or a composite material, is due to the creation of an interface between these two materials [13]: from a thermodynamic point of view, this means that the work of adhesion is greater than the work of cohesion. In order to find the link between cause and effect, one has to define and to measure exactly the electrical, molecular and atomic forces existing between the materials (Fig. 2) and to evaluate the topography of the surface. The measured adhesion, eg. by pull-off test, is a quantitative interpretation of the force or the energy necessary to separate the bodies [13]. This lead Sasse [14] to formulate two interpretations of adhesion definitions:

Definition 1. "Forces in the boundary surface, which result in the mutual adhesion of two materials in contact". This is a qualitative equilibrium problem, which leads to the question: "What is the reason for the attraction between the two materials in contact?" The objective under consideration is the formation of the adhesive bond.

Definition 2. "The fracture stress or another quantified mechanical characteristic for the resistance against separation of two materials in contact". This is a quantitative, not equilibrium-related problem, which leads to the question: "Which magnitude has the resistance against separation?" The objective under consideration is the separation of the adhesive bond.

Most theoretical considerations are based upon definition 1 and most experimental investigations use definition 2. Besides the "mechanical adhesion" theory (interlocking mechanical effects) there are three main "specific adhesion" theories (Fig. 2).

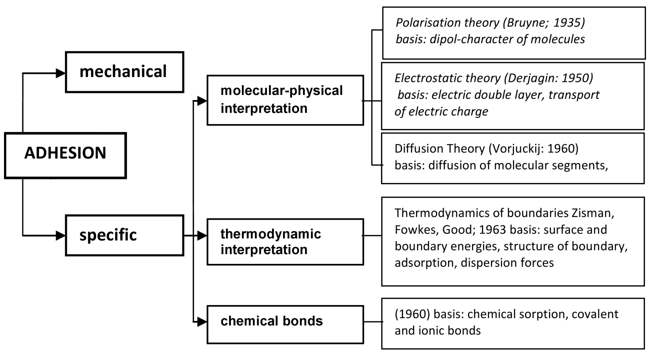


Fig. 2. Principles of adhesion after Ref. 14

In the case of a system created through repair, adhesion depends on many phenomena taking place in the interfacial zone [15, 16]: presence of bond-detrimental layers or inclusions (including bleeding), wettability of the substrate by repair materials, secondary physical attraction forces (van der Waal forces) induced in the system, surface roughness (interlocking mechanism), respective moisture contents in the concrete substrate and repair system (e.g. cement concrete or polymer composite), microcracks left or induced by the surface treatment. This implies that there can be very significant differences between theoretical and experimental strengths evidencing about the limits of the classical theories – if definition 2 is considered (Table 1).

Table 1
Theoretical and experimental adhesion strength values compiled from different authors [14]

van der Waal forces	Adhesion strength (N/mm^2)	
	Theoretical	technical, experimental
permanent dipoles	200–1800	5–20
induced dipoles	40–300	
dispersion forces	60–360	
hydrogen bonds	about 500	

According to Silfwerbrand (Table 2), the creation and durability of bond depend on several factors having different degrees of influence, which can be divided into three main groups [17].

Table 2
Factors affecting bond between concrete substrate and repair material (acc. [17])

Factors	Importance		
	1	2	3
Substrate characteristics			
Substrate properties	X		
Microcracking			X
Laitance			X
Roughness	X		
Cleanliness			X
Overlay characteristics & application technique			
Pre-wetting		X	
Bonding agents	X		
Overlay properties		X	
Placement	X		
Compaction			X
Curing			X
Environmental conditions			
Time		X	
Early traffic	X		
Fatigue	X		
Environment	X		

The objective of this paper is to analyze the effect of substrate roughness and superficial microcraking upon adhesion of repair systems. The results presented in this paper were obtained in the framework of research projects performed at University of Liège in Belgium, Laval University in Canada and Warsaw University of Technology in Poland intending to develop a better understanding of the factors affecting the adhesion of repair materials through a surface engineering approach.

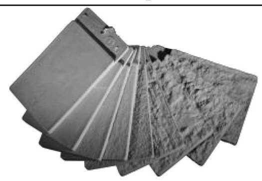
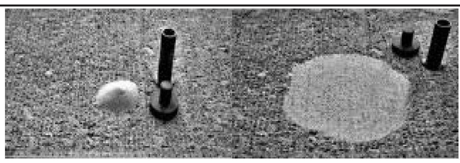
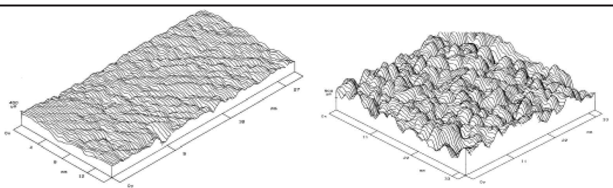
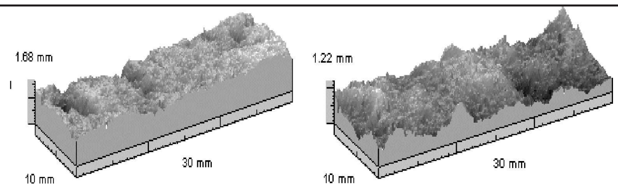
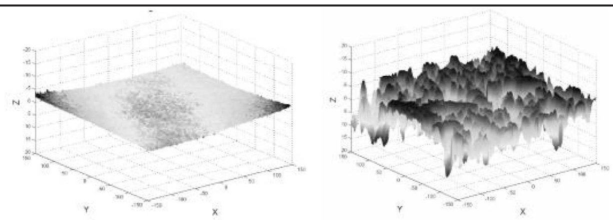
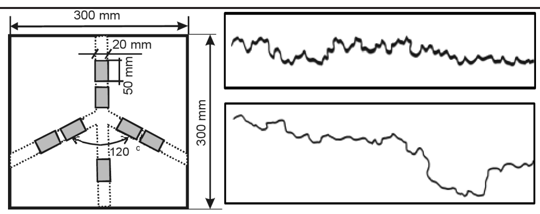
3. Surface roughness

3.1. Roughness characterization. The surface treatment of a concrete substrate is important in order to promote mechanical adhesion [18]. The methods for measuring roughness and surface texture can be classified into three types

[19]: contact methods, non-contact (optical) methods, and the taper sectioning method. Among the contact methods there are mechanical profilometers (extensometer-mounted), tactile tests, kinetic friction measuring device, static friction measurement, rolling-ball measurements, and measurement of the compliance of a metal sphere with a rough surface. Optical (non-contact) methods include optical reflecting instruments, light microscopy, electron microscopy, speckle metrology, opto-morphology (interferometry) and laser profilometry. Taper sectioning is used in metallurgy and basically consists in cutting across a surface at a low angle α to physically amplify the height of asperities (ctg α). In this paper, the effectiveness, accuracy and field applicability of selected techniques [20–32], which are listed in Table 3, are analyzed.

3.2. Profile description. After treatment, concrete surfaces present fractal topography. As for any fractal object, it is possible to break up this surface or profile into a sum of subprofiles [9]. Each sub-profile can be differentiated in terms of wavelengths; there is however no limit or precise criterion to validate the decomposition process (Fig. 3). It is also possible to filter the result mathematically [23]. Using methods with different resolutions, complementary topography scales can be characterized. The mechanical profilometry method, which has high resolution, reaches surface roughness scales referred to as roughness (R) and waviness (W). The opto-morphological method, with a resolution of 0.2 μm, allows characterization of roughness scales referred to as mesowaviness (M) and form (F). In mechanical profilometry a differentiation filtering process based upon the stylus diameter is often used. Then, the vertical and horizontal amplitude decomposition parameters – the most common according to EN ISO 4287 (Table 4) – are calculated. Another useful parameter

Table 3
General characteristics of techniques of roughness evaluation

Technique/reference data	Example	General characteristics
ICRI Concrete Surface Profiles [20–22]		Visual evaluation of concrete surface morphology with concrete surface profiles (CSP plaques 03732)
Sand patch test EN 13036-1 (ASTM E965) EN 1766		Calculation of surface roughness ratio using diameter of sand circle spreading on the surface: $SRI = \frac{V_{SRI}}{d^2_{SRI}} \cdot 1272$ [mm]
Mechanical profilometry [22–24]		A high-precision extensometer is moved all over the surface to obtain a 3-D mapping (x, y, z coordinates); morphological parameters are computed for selected profiles in accordance with EN ISO 4287
Laser profilometry [25–27]		The elevation (distance from the laser beam source) of each sampling point is calculated on the basis of the laser beam transit time; morphological parameters are computed for selected profiles in accordance with EN ISO 4287
Opto-morphometry technique [28–30]		The observation and analysis of the shadow produced by the superficial roughness of the surface (*Moiré*'s fringe pattern principle); morphological parameters are computed for selected profiles in accordance with EN ISO 4287
Microscopic metod [29-32]		The profile parameters are determined with vertical sectioning methods for the profile images registered with a light microscope at given magnification

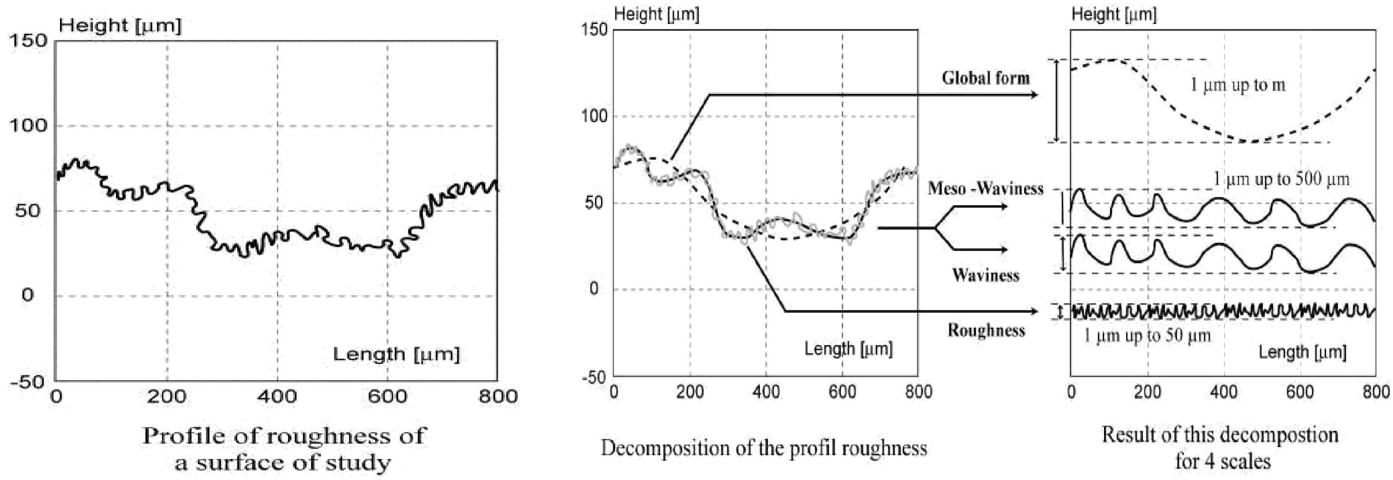


Fig. 3. Scale effect on profile decomposition after Ref. 22

from surface analysis is the bearing ratio (Fig. 4a), defined as the percentage of profile intercepted by a reference line with a given length. If the bearing ratio is determined on the total height of the profile in a number of interception planes as large as possible, and represented on a graph, the Abbott's curve is obtained (Fig. 4b). The shape of Abbott's curve is characterized by three parameters: relative height of the peaks (C_r), depth of the profile (C_f), excluding high peaks and holes, and relative depth of the holes (C_l).

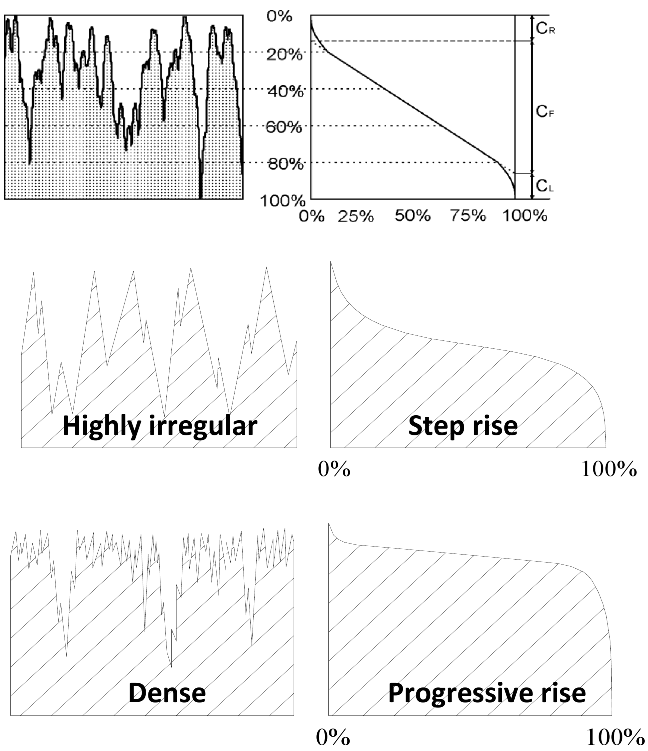


Fig. 4. Illustration of the Abbot's curve parameters after Ref. 9

Table 4
The vertical and horizontal amplitude parameters most often used for characterization of surface profile acc. to EN ISO 4287 (X = P, W, R for total, waviness and roughness profiles, respectively)

Symbol	Parameter	Definition
m_x	mean value and line	line whose height (mean value) is determined by minimal sum square deviation of the profile defined as follows: $X = \min \sum y^2(x)$
X_p	max peak height	distance between the highest point of the profile and the mean line
X_v	max valley depth	distance between the lowest point of the profile and the mean line
X_t	max height	maximum distance between the lowest and the highest point of the profile and it is equal $X_t = \max(X_p + X_v)$
X_a X_a'	arithmetic mean deviation	mean departure of the profile from the reference mean line as follows: $X_a = \frac{1}{l}\int_0^l \lvert y(x)\rvert\, dx$, approximated by $X_a' \approx \frac{1}{n}\sum_{i=1}^{n} \lvert y_i\rvert$
S_m	mean period of profile roughness	mean value of mean line including consecutively a peak and a valley S_{mi}, as follows: $S_m = \frac{1}{n}\sum_{i=1}^{n} S_{mi}$

3.3. Mechanical and laser profilometry. The surfaces of C20/25 concrete slabs were submitted to several surface treatments and evaluated with mechanical (ULg) and laser (WUT) profilometers [33, 34]. The following types of mechanical treatments were used to prepare the concrete test slabs: grinding (GR), sandblasting (SB), shotblasting (SHB35 and SHB45, with treatment time of 35 and 45 s, respectively), hand milling (HMIL) and mechanical (MMIL) milling.

Test slabs without treatment were used as a reference. Surface roughness was characterized with the Sand Patch Test and mechanical profilometry using specimens that were saw cut from the plate (Table 5).

Table 5
Concrete surface geometry parameters determined after surface treatment with mechanical and laser profilometers (acc. to [34]) ("s" suffix is corresponding to laser profilometry and "p" is corresponding to mechanical profilometry)

Method	Parameter	Surface treatment					
		GR	SB	SH35	SH45	HMIL	MMIL
Laser profilometer (parameters related to surface)	W_{ts} [μm]	933	1 130	2 730	3 110	1 300	3 400
	W_{as} [μm]	134	156	444	515	127	384
	W_{vs} [μm]	530	571	1 140	1 680	985	2 340
	C_{RS} [μm]	234	161	509	960	68	341
	C_{FS} [μm]	404	505	1590	3330	409	1460
	C_{LS} [μm]	391	218	175	670	340	1112
	D_s [–]	2.400	2.370	2.420	2.360	2.340	2.380
Mechanical profilometer (parameters related to profile)	W_{tp} [μm]	219	1 036	1 086	2 165	473	867
	W_{ap} [μm]	32	180	215	386	70	179
	W_{vp} [μm]	108	317	516	1009	269	419
	C_{RP} [μm]	57	50	289	698	116	188
	C_{FP} [μm]	55	77	406	619	107	351
	C_{LP} [μm]	69	144	291	669	196	248
Sand Patch	SRI [mm]	0.72	1.40	1.59	1.85	0.79	1.05

The results of surface geometry characterization [33, 34] obtained with the two methods can be summarized as follows:

- the geometrical parameters determined at microscopic level generally indicate that the highest roughness was obtained after shotblasting for 45 s, and the lowest roughness was obtained by grinding;
- the mean microroughness values are close to each other for the treatment types and the both mechanical and laser profilometry methods ($R_{ap} = 17 \pm 2$ μm and $R_{as} = 19 \pm 7$ μm, respectively). However, the total height of the roughness profile determined with laser profilometry was 2.8 to 5.5 times longer than the one obtained with mechanical profilometry with the same filtering process; this indicates that roughness parameters cannot be used alone to appraise surface quality after treatment;
- both the total height and the mean value of the waviness profile measured with the laser profilometer are higher (1.3–4.3 times) than those deduced from the mechanical method. In the case of the Abbott's curve parameters, the ratio even reached a value of 7 times. Nevertheless, values of these ratios do not correspond to the waviness level.

The statistical analysis of the results revealed a high correlation coefficient ($r > 0.94$) of the relationship between the corresponding mean values of waviness profile, W_a (Fig. 5a) as well as the Abbott's parameters C_R and C_F determined with laser and mechanical profilometry (Fig. 5b). A higher scatter in the results for both profilometry methods is observed in the case of other amplitude parameters. Lower statistical significance (Fig. 5c) is obtained for the total heights of the waviness profile (W_{ts} vs. W_{tp}) and the maximum depth of the valleys (W_{vs} vs. W_{vp}) as well as the relative depth of holes, C_L (see Fig. 5b). This could be caused by the fact that different surface areas were scanned with the laser and the mechanical profilometer. However, Figs. 5b and 5c indicate that the low correlation is due to the low values of amplitude parameters obtained with mechanical profilometry for the surface after mechanical milling. This surface has high irregularities and a significant number of deep and wide cracks. It seems that these cracks might be more easily detected by the laser profilometer than by the mechanical profilometer stylus.

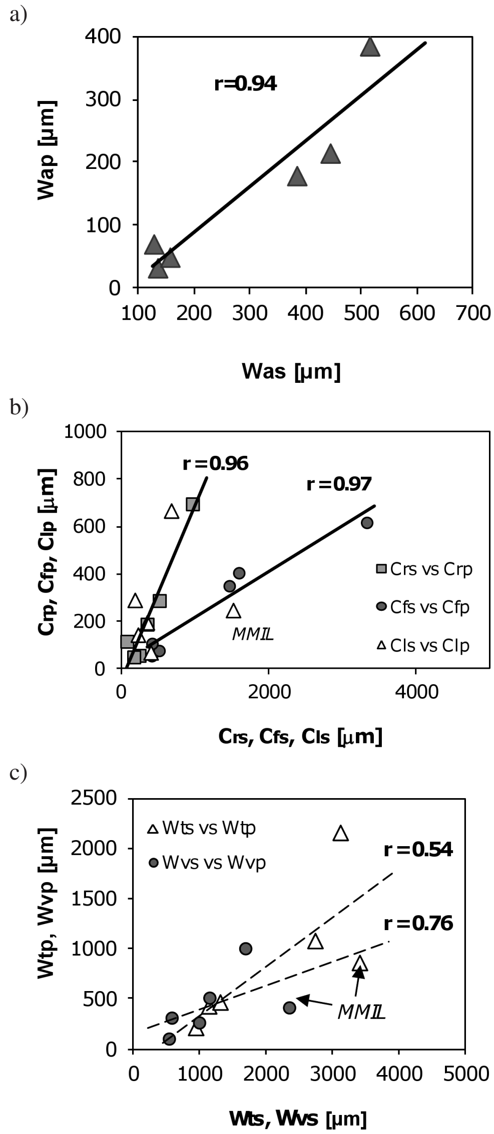


Fig. 5. Relationships between waviness parameters: W_a (a) Abbott's (b) and W_t and W_v (c) determined with laser and mechanical profilometry; suffixes "p" and "s" for mechanical and laser profilometers respectively (acc. to Ref. 34)

3.4. Microscopic method. Concrete surface geometry can be characterized using a scientific approach referred to as quantitative fractography [35, 36]. Although its use is more advanced in the case of metals and ceramics than in cement-based composites, geometrical and stereological parameters are also of significant importance in the latter [37–40]. These parameters can be determined from the image of a concrete sample cross-section (formed or taken on site) obtained with a microscope, usually a light microscope. In addition to the profile parameters determined in accordance with EN ISO 4287, the three following stereological parameters could be considered for characterization of concrete profiles after surface treatment [33, 34]:

- profile (linear) roughness ratio, $R_L = L/L_O$: length of the profile line, L, divided by the projected length of the profile line, L_O;
- surface roughness ratio, $R_S = S/S_O$: true fracture surface area, S, divided by the apparent projected area, S_O;
- fractal dimension, D: a measure of the self-similarity of rough objects. The basic requirement for the fractal boundary is that some structural feature or unit is sequentially repeated at different levels.

The stereological parameters: surface roughness ratio, R_S, and profile roughness ratio, R_L were calculated using a computer program (Profile 1.1) developed at Warsaw University of Technology for automatic profile image analysis [30]. The fractal dimension was calculated with the same program using box-counting method (D_b). The histograms indicate that shotblasting and mechanical milling produced surface with high irregularity (Fig. 6a,b). The values of fractal dimension, D_b determined with the microscopic method were highest for grinding and sandblasting and in general close to values for typical for concrete surfaces: $D = 1.03$–1.25 [30, 37–40]. Range of changes of D_b values is higher in comparison with the surface fractal dimension, D_S, obtained with laser profilometry. The low scattering of D_S value is caused by measurements for surface area with relatively low irregularity. However, the values obtained of D_S are higher than the values that have been determined for fracture surfaces ($D_S = 2.02$–2.3) of various types of concretes [31, 38, 39] and close to those determined for, e.g. steel after surface treatment by grinding [25]. On the basis of the results of fractal measurements with mechanical and laser profilometer, it can be concluded that fractal dimension is not an adequate parameter for appraisal of concrete surface geometry.

Relationship between R_s and W_{as} and W_{ap} had relatively low correlation coefficient – r close to 0.8. This can be explained by the fact that stereological parameter R_s was calculated for longer profile length compared to profile length of sample tested with laser profilometer. The relationship between R_S and R_L for concrete substrates after various treatments can be described by the equation: $R_S \approx 1.46R_L - 0.42$, with a high correlation coefficient ($r > 0.998$). This equation is close to the estimation provided by Wright and Karlsson [40] for non-planar localized surfaces: $R_S \approx 1.57R_L - 0.57$, often used in the fracture analysis of cement concrete (e.g. Brandt and Prokopski [37], Stroeven [41]).

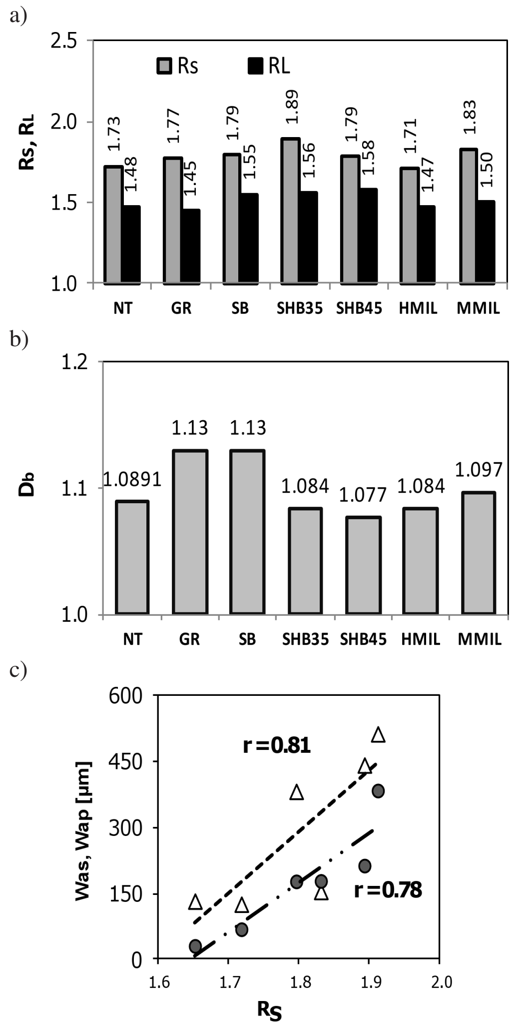


Fig. 6. The stereological parameters of tested concrete substrates: a) R_S and R_L, b) D_b for concrete substrates after various surface treatments and c) the relationships $R_S =$ *vs.* arithmetic mean deviation of waviness profile determined with laser (W_{as}) and mechanical (W_{ap}) profilometer

3.5. Sand patch test. The sand patch tests described in EN 13036-1:2002 (very similar to ASTM E965) is one of the most commonly used method for evaluation of concrete macrotexture surfaces and it is generally used on roadway and airfield pavements. The main advantages of the sand patch method are its speed, non-destructive character, and field applicability. However it is necessarry to provided that the surface is protected from wind and rain. The biggest limitations are the range of validity (from 0,25 to 5,00 mm) and applicability to horizontal surfaces only. Figures 7a and b present a comparison between SRI (*Surface Roughness Index*) values and parameters determined using more sophisticated profilometry techniques: an equivalent correlation exists between the mean waviness obtained by means of the two profilometry techniques and SRI, respectively. Similar conclusions may be given for Abbott's curve parameters (Fig. 7b). The relationship between Rs and SRI exhibits a very high correlation coefficient $r = 0.97$ (Fig. 7c). This confirms that SRI is a good estimation of the mean deviation of a concrete surface profile and that it can be used for practical evaluation of surface roughness.

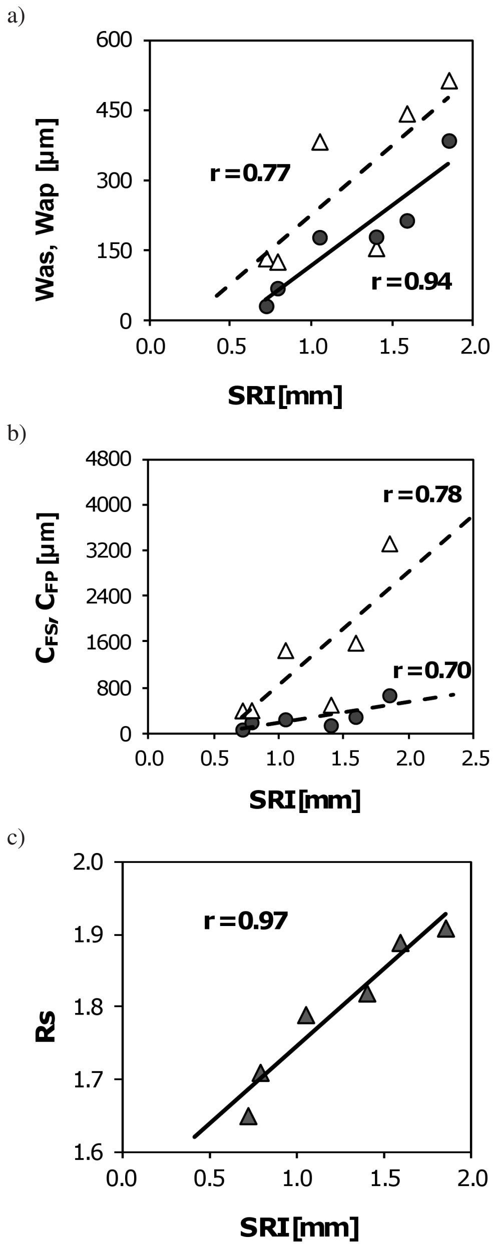


Fig. 7. Surface Rough Index *vs*.: a) arithmetic mean of waviness, b) Abbott's parameters and c) R_S ratio; (p, Δ) and (s, $\bullet$) for mechanical and laser profilometers

3.6. Optical profilometry. Optical profilometry based on Moiré's fringe pattern is an interferometric method used to obtain 3D profile information based on the interference between light and shade stripes [22]. A so-called Moiré pattern occurs when two similar repeating patterns are almost but not quite superimposed. The basic advantage of this method is its non-destructive character and field measurement capabilities. The operating principle of the method is based on the comparison between two images having different Moiré's patterns: the first serves as the reference (image of the pattern with non-deformed parallel fringes), while the second is the projected pattern deformed in accordance with the surface profile. The reference and deformed grids are compared and analyzed using an algorithm that computes the actual 3D surface profile. Research programs were conducted recently to analyze on a comparative basis the profile characteristics yielded with this method together with those obtained with optical profilometry, visual method (with concrete surface profile plates) and mechanical profilometry.

Comparison with a visual method. The nine concrete surface profile rubber templates (CSP), used as a reference for surface preparation before the installation of protective systems, were developed by the International Concrete Repair Institute (ICRI) for rapid on-site visual assessment of roughness [20]. Right now, for most field applications, the CSP templates are likely to be the only accessible tool to evaluate the concrete surface profile after preparation. The surface geometry characteristics of these templates were determined with the optometric method using a 512 × 512-pixel CDD camera. The optical device used in this study could reach a resolution of 200 μm in Z dimension, for a scanning surface area of 350 × 350 mm. The measurement path was equal to 500 μm; the depth of field is 450 μm. Because of the vertical resolution of the device, it is not possible in this case, to separate roughness from waviness. A profile obtained through this approach will consequently give the description of meso-waviness and global form.

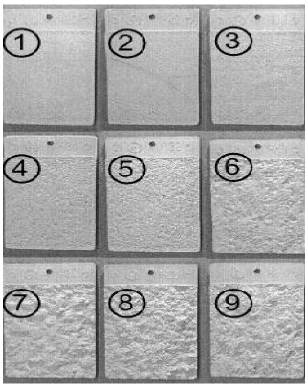
Figure 8 shows that the optometric device is not able to detect any change in terms of roughness level under a threshold CSP (no. 5) value corresponding to the optometric device vertical resolution. Nevertheless, above that value, the optometric method accurately reproduces the surface roughness level in accordance with the CSP scale. Based on the relationship observed in Fig. 8 between the CSP index and the arithmetic deviation of meso-waviness profile, M_a (within the resolution range of the device), it seems possible to significantly improve the CSP replicate system through a real quantitative approach. In addition, the actual CSP templates are rather narrow with regards to the spectrum of concrete surface profiles that can be obtained depending on the surface preparation technique that is used. The identification of *reference* curves similar to that plotted on the graph of Fig. 8, but on a wider scale of surface roughness, help widening the range of application of the method to much coarser profiles such as those obtained eg. with jack hammering and water jetting.

A similar investigation was conducted by Maerz et al. 2001, using this time a laser device [21]. Using laser striping, a rough concrete surface was illuminated with thin slits of red laser light at an angle of 45°, and the surface is observed at angle of 90°. The projected slit of light appears as a straight line if the surface is flat, and then as a progressively more ondulating line as the degree of roughness of the surface increases. Lasers with one, five or eleven stripes were studied and a high-resolution CCD camera with a 7.5-mm lens was used for recording the line images. A bandpass filter was installed over the camera lens to discard both high frequency and low frequency light and to allow only the laser light to get through to the camera. Using a specially developed computer program, they calculated the root mean square of the first derivative of the profile as a single parameter characterizing a profile based on its average slope:

$$Z_a = \sqrt{\frac{1}{n(dx)^2}\sum_{i=1}^{n}(dy)^2}$$

where n – number of evenly spaced sampling points; dx – distance between points along the sampling line; dy – distance between points normal to the sampling line.

a)



b)

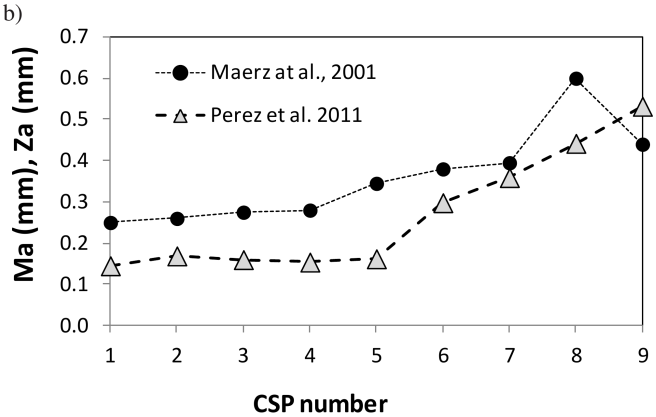


Fig. 8. View of ICRI CSP plaques for evaluation of concrete surface roughness (a) and (b) relationship: arithmetic mean deviation M_a calculated by Perez et al. (Ref. 22) and root mean square of the first derivative of the profile Z_a calculated by Maerz et al. (Ref. 21) for CSP plaques

The results showed the same trend as that found by Perez et al. – i.e. the device could not detect any changes in roughness level under a threshold CSP (in this case no. 4). For the high-range CSP values, the trend was not as clear. However, as CSP number increased the value of Z_a increased too [34–45].

Comparison with a mechanical profilometer. The concrete mixture selected to cast the test specimens (substrate) for the purpose of this study is a 0.40 w/c concrete (10-mm maximum size aggregate) used as a reference material in many on-going research projects conducted at Laval University in relation with repair and rehabilitation [42]. Three types of surface preparation techniques were investigated: scarifying, high pressure water jetting (1240 bar pressure and 23 l/h water flow) and polishing (obtained with two abrasive and rotative wearing plates). There were tested with the device described in p.3.6.1. The sample were also tested at University of Liege with mechanical profilometer using the same device and procedure like in the case of tests presented in p.3.3. On the basis of the results obtained the following conclusions could be drawn:

a) the use of such mechanical technique to evaluate the profiles of concrete has some important limitations:
   - stylus (extensometer tip): because of the lenght of the stylus, it is impossible to make measurements on very rough surfaces eg. prepared by hydro-jetting;
   - air bubbles: some of the entrapped air voids in concrete are so large that the stylus gets stuck into it and the automatic measuring procedure is suddenly interrupted; the selection of the zone to be mapped is very important;
   - dimensions: accurate evaluation of roughness parameters is quite time-consuming and it is the reason why the surface of investigation is limited; moreover, this system is not usable on site.

b) with regards to optical profilometry techniques, it can be stated that:
   - vertical resolution: with the device used in the study reported by Perez et al., it was impossible to evaluate micro-roughness and waviness; nevertheless, recent developments enable to characterize roughness down to that level;
   - air bubbles: future version of algorithm, based on image analysis, will be able to remove air or water bubble in order to obtain real roughness;
   - this method presents a lot of practical advantages. It is very handy: it is not necessary to core the surface, it is possible to perform field measurement with great precision.

It can be pointed out that value of the microroughness R_a after treatment of approximately 15 μm was recorded. This is close to the values determined with the same procedure for previously tested concrete (see Table 5) This tends to confirm that the surface treatment technique has no major influence on micro-roughness (“high frequency waves”) of the profile and that waviness parameters are more effective for appraisal of concrete surface texture.

3.7. Pull-off strength vs. surface roughness. Pull-off strength was determined for specific repair systems placed on substrates with different surface roughness characteristics, with and without a bonding agent. The pull-off test results were analyzed statistically as a function of the surface roughness parameters to identify possible relationships. The relationships between the pull-off strength and SRI (describing surface roughness at the "macroscopic" level), waviness parameter W_{ap}, and surface roughness ratio R_S, describing the surface roughness at "microscopic" level were not statistically significant for both types of overlay systems, i.e. with (Δ) and without (O) bonding agent (Fig. 9). Some trends could however be observed: for systems placed with a bonding agent, the pull-off strength slightly increases as the surface roughness increases. An opposite trend for systems without bonding agent was observed. This can be explained by the fact that the repair mortar that was used had relatively low workability (partially due to fibre content) and could not wet adequately the substrate (Fig. 9). Given its much better workability, the bonding agent could penetrate the surface irregularities and really wet the substrate surface. This indicates that, besides the surface roughness, the ability of the repair material to adequately wet the substrate is a very important factor with regard to adhesion in repair systems.

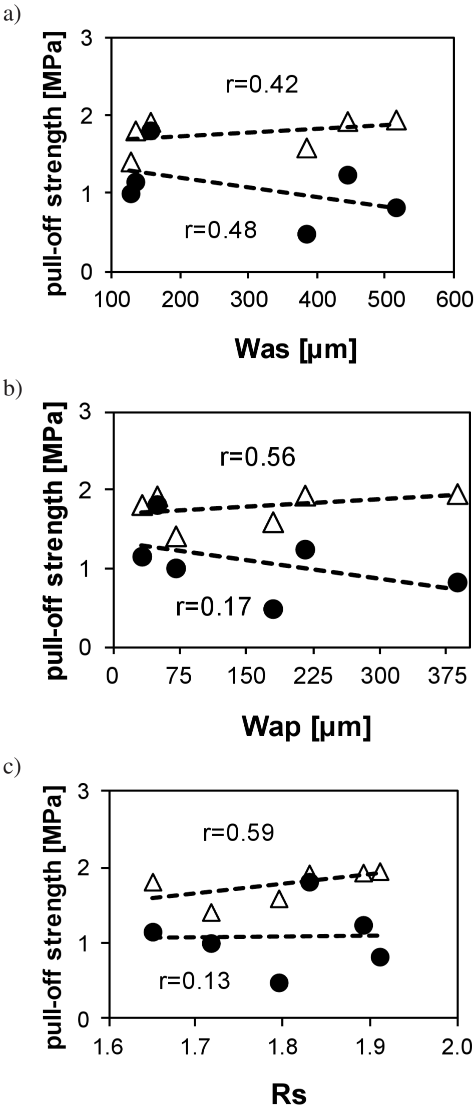


Fig. 9. Relationships between the pull-off strength vs. the mean value of waviness profiles determined with a) laser and b) mechanical profilometry and c) the surface roughness ratio R_s; repair systems with (Δ) and without (•) bond coat

As mechanical interlocking is one of the basic mechanisms of adhesion between hardening mortar and concrete and existing hardened concrete, it is fundamental to be able to characterize the substrate "roughness". Depending on the structure configuration and size, the nature of the work to be performed and the local construction / repair customs, a variety of surface treatments can be used and, as a consequence, a rather wide spectrum of surface roughness can be induced [34]. However, the statistic parameters cannot be univocally related to adhesion of the overlay. It seems that there is a threshold value, over which an increase in roughness of the profile does not necessarily translate into an increase in adhesion [10, 33]. Moreover, an increase in roughness may be obtained with some techniques at the expense of superficial cohesion or integrity (Fig. 10).

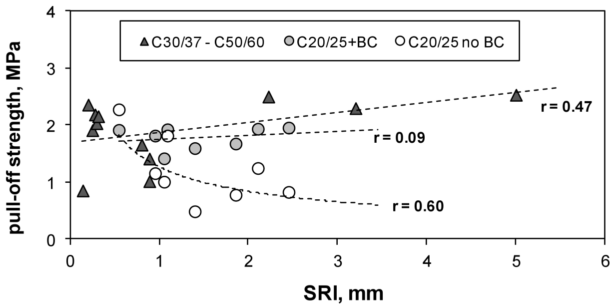


Fig. 10. Pull-off strength versus Surface Roughness Index (SRI) determined with sand patch test for concrete substrate after different surface treatments repaired with polymer-cement mortar after Ref. 10

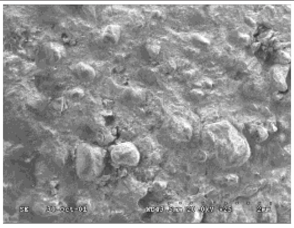
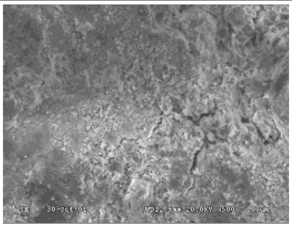
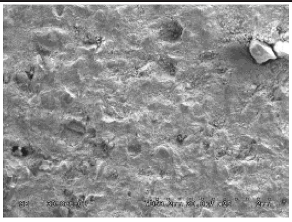
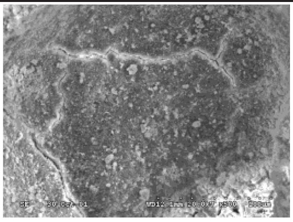
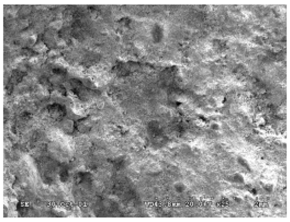
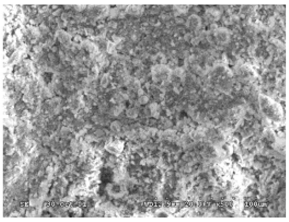
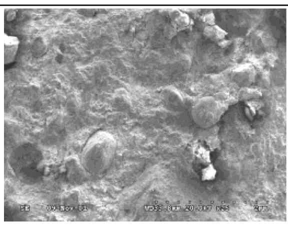
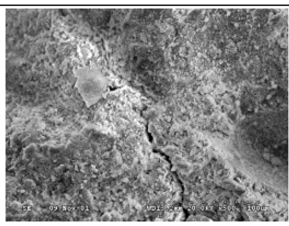
4. Microcracking and adhesion

The main problems arise from *co-lateral effects* of the treatment, especially due to micro-cracks parallel to the surface [43]. Superficial cracking, often referred to as "bruising", is considered as one of the most important parameters influencing adhesion in repair system. The respective influence of the various surface preparation techniques can be evaluated by microscopic observation of the prepared surface (Table 6).

Using light microscope the number and length of microcracks have been systematically recorded for a range of substrate concrete strengths and surface preparation methods. Analysis of the results shows that low pressure water jetting does not generate microcracks. Scabbling may induce a big amount of microcracking in very near-to-surface area. The number of cracks and the total crack length resulting from the preparation with jack-hammer are significantly higher than with any other of the investigated techniques. It is also clear that increasing the jackhammer weight – and thus, its impact energy – causes both the length and the number of cracks to increase significantly (Fig. 11).

Application of polymer primer or polymer modified cement bonding agents usually improve the interface quality due to strengthening of concrete substrate by gluing microcracks and to some degree, loose substrate concrete particles [33, 44, 45]. However, in field conditions, it is not easy to guarantee adequate and reproducible conditions for the placement of repair materials on the coated substrate.

Table 6
SEM observations

Example of surface view SEM: magnification 25x (left) and 500x (right)		Description
Grinding		
		surface without sharp edges with rarely and non-uniformly located valleys at the surface; at higher magnifications, the narrow cracks were observed
Sandblasting		
		surface similar to that after grinding; shallow irregularities of surface - peak-to-valley height did not exceed 1 mm; at higher magnifications, sharp edges of aggregate grains and microcracks, very often forming non-uniform network, were observed
Shotblasting		
		highest surface roughness increasing with the treatment time; high irregularities of surface - the peak-to-valley height increased locally to 7 mm after 45 s treatment; the increase of treatment time caused the forming of a dense network of microcracks and cracks, often along aggregate grains as well as presence of deteriorated or debonded particles
Milling		
		surfaces after milling similar and close to the concrete surface after shotblasting; very high irregularity of the surface, but less than that after shotblasting; at higher magnifications, deep and wide cracks, detached particles and loose concrete fragments were observed

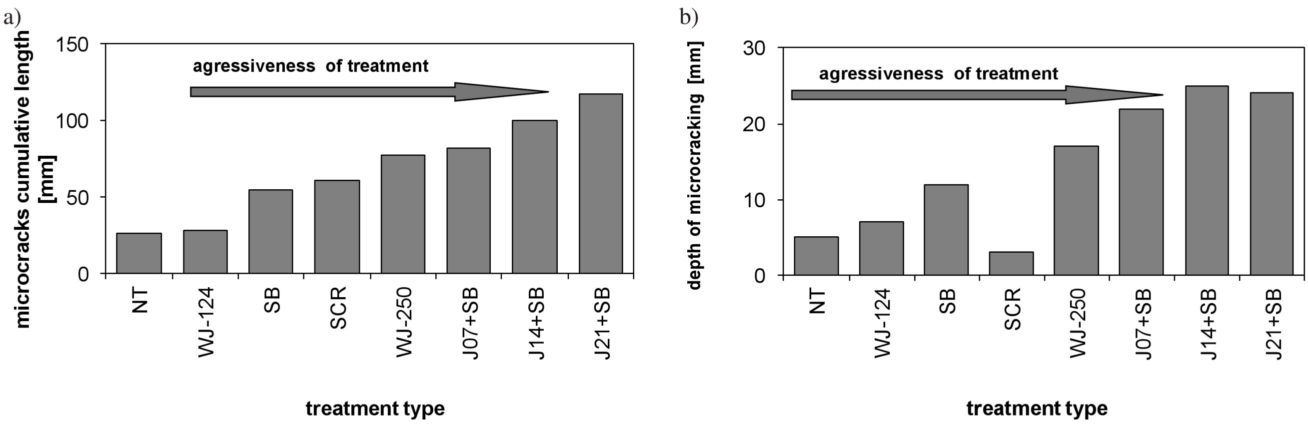


Fig. 11. Length (Li) of the cracks (a) and depth of microcracking (b) vs type of concrete surface treatment: NT – no treatment; WJ – water jetting – pressure 124 psi/250MPa; SB – sandblasting; SCR – scabbling; J+SB – jack hammering of weight 7,14,21 kg + sandblasting after Ref. 10

5. Conclusions

The investigations reported in the recent years, have shown that the durability and quality of concrete repairs depend to a large degree on the characteristics of the substrate. Mechanical preparation and profiling of the concrete surface to be repaired has to be balanced with potential co-lateral effects such as superficial cracking, too often induced as a results of inappropriate concrete removal method selection, and the loss of benefits due to better mechanical anchorage.

Recently, various techniques have become available for the characterization of concrete surface texture. The combination of different methods enable to have a very good description of "roughness" at various scales. Depending on what has to be analysed, mechanical and laser profilometers are more accurate for "micro", while optical method seems to give a better description of the shape of the profile. However, investigations with very precise laboratory laser and mechanical profilometers of concretes surfaces after various treatments in terms of their aggressiveness clearly indicated that the surface treatment technique has no major influence on the micro-roughness ("high frequencies waves"). This allow to conclude that waviness parameters are enough for the assessment of concrete surface prior to repair. This shows the usefulness of recently developed optical method eg. based on Moiré pattern. The main advantages are the rapidity of the procedure and the large area that can be observed in one operation.

Very little is known about the potentially synergetic effects between the various concrete surface parameters (surface roughness, microcracking, wettability) affecting the ability of the surface to be bonded with a repair material. Concrete surface engineering, as a scientific concept including all surface properties of materials and their influence on adhesion, will definitely contribute to shed more light on how to optimize repair bond, taking into account interactions between the materials at different observation scales.

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