CHARACTERIZATION OF CONCRETE SURFACE ROUGHNESS AND ITS RELATION TO ADHESION IN REPAIR SYSTEMS

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Abstract

The aim of this work is the analysis of relationships between parameters of concrete surface geometry determined with various methods as well as their relations to adhesion in repair systems. Several types of concrete preparation techniques were selected to obtain different levels of surface roughness of concrete substrates. Four measurement techniques, corresponding to different levels of observation, have been used to characterize the surface geometry: laser profilometry, mechanical profilometry, a microscopic method and a "sand" (macroscopic) method. The correlations between parameters describing surface geometry are determined. The relationships between bond strength and selected parameters of surface geometry are also discussed.

Keywords: concrete structure, repair, surface treatment, surface geometry, bond strength

1. Introduction

Concrete remains a performing and durable material but the explosion of the quantity of concrete used for constructions and buildings after the Second World War induces an acceleration of maintenance and repair operations [1,2]. The durability of repair depends directly on adhesion quality: good conditions during the phase of creation of the bond between the substrate and the new layer will guarantee the longevity of the adhesion and, consequently, of the repair [3,4]. The adhesion depends on various phenomena taking place in the interfacial zone like [5-7]: the presence of bond-detrimental layers, the wettability of concrete substrate by repair materials, secondary physical attraction forces induced in the system, concrete surface geometry, moisture content in the concrete substrate versus the repair material types (polymeric or cementitious). The recommendation for concrete substrate preparation is given in the new European standard EN 1504-10:2003 [8]. In general, the aim of concrete surface preparation is to obtain surface properties similar to those of the bulk concrete. Superficial concrete must be sound, dry, cohesive and also dust, oil or hydrocarbon exempt. Preparation should attempt two main objectives:

- the shape of the surface should guarantee a good anchorage of the new layer; parallelepiped or "ink-bottle" shapes are greatly preferable,
- preparation must be realised in such a way that sound and homogeneous concrete is reached.

Mechanical treatments (e.g. sandblasting, shotblasting) and water blasting are commonly used for concrete surface preparation. As a result, different types of roughness are obtained. The above mentioned standard EN1504-10 does not define requirements for optimal roughness level. Roughness is a generic word that can give different information versus the level of investigation: in the civil engineering area, the millimetric scale usually permits one to distinguish the main surface treatments. Mechanical interlocking and contact angle modification are two fundamental effects of surface "roughness". The first one is in relation with the "waving" of the surface while the second is more affected by "micro-roughness" [9]: the value of the contact angle made by the liquid on the solid surface is modified by the roughness, according to the Wenzel relation.

The effect of concrete surface roughness on adhesion is not quite clear [10-12]. It is generally assumed that an increase in roughness of the concrete substrate would enhance the adhesion between repair material and concrete substrate. However, some authors [3,12,13] state that surface roughness itself does not always have a significant influence on the adhesion. Instead, the presence of cracks and interface failures will predominantly affect the bond strength between repair material and the concrete substrate.

The effect of a bond coat is also under discussion. According to different opinions [3,14], the bond coat should be avoided because of the creation of an extra plane of weakness and it could limit a good interlocking effect between substrate and repair material in the case of very rough surfaces. However, some authors have shown that the presence of a bond coat can significantly increase the adhesion [9,15,16].

The aim of the work described here is the evaluation of correlation between parameters of concrete surface geometry determined with various methods at different level of observation and their potential relation to adhesion in repair system.

2. Materials and Methods

Concrete substrates (300x300x50mm) of C20/25 class were made from the concrete mix: CEM I 32.5, 2/8 limestone, 0/2 quartz sand. The following types of mechanical treatments were used to prepare the concrete substrates:

- grinding (GR),
- sandblasting (SB),

- shotblasting (SHB35 and SHB45, with treatment time of 35, and 45 s, respectively),
- hand (HMIL) and mechanical (MMIL) milling.

SEM microscope technique was used for qualitative evaluation of the concrete surface at various magnification (20 – 500x), particularly to detect possible cracks resulting from mechanical treatment of concrete surfaces.

Four different methods have been used for the characterization of concrete surface geometry:

a) "sand" (macroscopic) method [11] - the surface roughness described using the so called Surface Roughness Index – SRI. This consists in spreading 50g microsilica sand (50-100 μm) onto the surface, making a circle and measuring its average diameter, which defines the SRI value;

b) microscopic method [17-19] - the stereological parameters are: surface roughness ratio, R_S, profile roughness ratio, R_L and fractal dimension, D_b. They were determined with vertical sectioning methods for the profile images registered with a light microscope at magnification 10x. Samples for microscopic observation of 20x50mm were cut from concrete plate of 300x300 mm (Fig.1a). The total length of examined profile was 350 mm for each substrate type;

c) mechanical profilometry: the commercial profilometer developed for metal surface testing has been adopted for evaluation of a concrete substrate by changing the stylus [20]. In the first step, the roughness of the profile was analyzed. In this case a stylus with a diamond sphere radius of 6 μm was used. The length of measurement was 8 mm and the filter used to separate roughness from the total profile was fixed to 0.8 mm. The measurement of waviness was made with another stylus 79 mm long and a diamond of

1.5 mm radius. The length of the measurement was enlarged to 30 mm or more. The filter to separate waviness from the total profile was classically chosen at 0.8 mm.

d) laser profilometry: the concrete surface was tested with a commercial laser profilometer [21] working in the laser beam triangulation mode with a vertical accuracy of 1 μm and maximum angle of surface measurement of 90°. A correction of the surface image (local lack of height data) was necessary. The value of missing data were approximated using a smooth shape calculated from the neighbours.

In the case of laser profilometry the area of 10x 30mm (Fig.1a,b) was scanned along parallel lines with a distance of 50 μm between subsequent lines. In the case of mechanical profilomtery the surface was scanned along three lines of 30 – 40 mm long (Fig.1a,c). The registered profile was first transformed to remove the effect of the profile orientation ("shape" filtration). The total profile obtained was next filtered and divided into low and high frequencies to separate parameters of waviness and roughness, respectively. The filter used to separate waviness from the total profile was classically chosen at 0.8 mm for both methods (Fig.1b,c). The total height of the profile, Xt, arithmetic mean of the deviations of the profile from the mean line, Xa, and maximum depth of valleys, Xv, were selected for the surface geometry characterization in the case of all levels of filtration [20,21], i.e. for the total (X=P), waviness (X=W) and roughness (X=R) profiles. Additionally, the Abbott's curve parameters were determined. The shape of Abbott's curve is characterized by three parameters [20, 21]:

- Cr - relative height of the peaks;
- Cf - depth of the profile, excluding high peaks and holes;
- Cl - relative depth of the holes.

In the further text indexes "p" and "s" denote parameters measured by mechanical and laser profilometer respectively. Additionally, the fractal dimension, D_S, was estimated by laser profilometry. However, using a standard procedure, it was impossible to calculate a fractal dimension for the entire scanning surface due to the presence of deep holes. The fractal dimension was determined for the surface area with a lower irregularity level.

A commercial polymer-cement repair mortar (max. size of aggregate D_{max} = 2mm) containing glass microfibers was used [13]. The overlay (thickness 10mm) was applied on the concrete substrate with polymer-cement bond (in accordance with the producer's guidelines) and, additionally, without bond coat. The repair mortar had relatively low workability (partially due to the microfiber content) in comparison to the bond coat.

The adhesion between repair material and concrete substrate was characterized with pull-off tests (acc. EN 1542 [22]) after 28 days of hardening. According to this standard a cylindrical disk of 50 mm diameter was glued to the overlay with epoxy glue. The overlay and concrete substrate were drilled to a depth of 10 mm under the overlay. The tensile load was applied to the steel disk until failure occurred. The pull-off bond strength was calculated by dividing the tensile load at failure by the area of the test specimen.

3. Results

3.1. SEM observation

SEM observations (Fig.2a) showed that the surface after grinding has low, uniform roughness without sharp edges with rarely and non-uniformly located valleys at the surface. Narrow cracks are observed at higher magnifications. The sandblasted surface (Fig.2b) is similar to that after grinding (shallow irregularities of surface, peak-to-valley height does not exceed 1mm). However, at higher magnifications sharp edges of aggregate grains and microcraks, very often forming non-uniform networks, are observed. The highest roughness of the surface was obtained after shotblasting (Fig.2c) - peak-to-valley height was locally up to 7mm for 45 s. The increase of treatment time caused the forming of dense network of microcracks and cracks, often along aggregate grains as well as presence of the deteriorated or removed grains. The surfaces after hand and mechanical milling (Fig.2d) are similar to the concrete surface after shotblasting; very high irregularity of the surface but lower than that after shotblasting. At higher magnifications deep and wide cracks, places of grains removal and loose concrete fragments are observed.

3.2. Surface geometry characterization

The results of surface geometry characterization (Tab.1) with the four methods can be summarized as follow:

- the geometrical parameters determined for both macroscopic level (SRI value) and microscopic level (R_S, R_L ratios and waviness parameters) generally indicate that a higher roughness was obtained after shot blasting for 45s and a lower roughness by grinding;
- in the case of the profilometry methods, the waviness parameters are about 5% (mechanical profilometry) and 9% (laser profilometry) smaller than the one corresponding to the total profile. This confirms that the global shape of the profile has been preserved through the waviness filtration;

- the mean roughness values are close to each others for the treatment types and the both profilometry methods (Rap=17±2 and Ras=19±7, respectively). However, the total height of the roughness profile determined with laser profilometry was 2.8 – 5.5 times exceeding the one obtained with mechanical profilometry with the same filtration method.
- both the total height and the mean value of the waviness profile measured with the laser profilometry are 1.3 – 4.3 times higher than the ones deduced from the mechanical method. In the case of the parameters of Abbott's curve this ratio was even 7 times higher. However, values of these ratios do not correspond to the waviness level;
- the values of fractal dimension, Db determined with the microscopic method are close to those obtained for various types of concrete (D = 1.03 – 1.25) [23-25]. Range of Db 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 [25-27] and close to those determined for, e.g. steel after surface treatment by grinding [21].

3.3. Pull-off strength

The roughness and cracks of concrete substrate surface after treatment have an influence on the bond strength in repair systems (Tab.2). The results of pull-off strength measurements for overlays prepared with bond coat were relatively close to each other: 1.4 – 2.0 MPa. The application of the overlay without the bond coat caused a decrease of the pull-off strength. The lowest value (0.5 MPa) was obtained for concrete after mechanical milling. Application of the bond coat caused a significant decrease of the variation coefficient of the pull-off strength. The bond coat increases significantly the pull-off strength in the case of concrete surfaces with high roughness (e.g. after shotblasting) while for the surfaces with low roughness (e.g. after sandblasting) this effect is less significant.

The surface roughness and presence of the bond coat had an effect on the type of failure observed during the pull-off test. In the case of the overlays with a bond coat cohesive failures in concrete substrate were observed Interfacial failures dominated for overlays applied without the bond coat. The percentage of interfacial failure ranged from 50% for shotblasting to 80 % for concrete after grinding.

4. Discussion

The average level of surface roughness can be characterized (at different observation levels) by the surface roughness index, SRI, the mean values of the waviness profile, Was, Wap, and the surface roughness ratio, Rs. The relationships between these parameters are statistically significant (Fig.3) with high correlation coefficients ($r > 0.90$) despite the different way of surface scanning. This indicates that the surface geometry of the substrates tested is discriminated in a similar way using different methods (and simultaneously different observation levels). This observation is confirmed by the high correlation coefficient ($r > 0.94$) of the relationship between the corresponding mean values of waviness profile, Wa (Fig. 4a) and the Abbott's parameters C_R and C_F (Fig.4b) determined with laser and mechanical profilometry. A higher scatter in the results for both profilometry methods is observed in the case of other amplitude parameters. Lower statistical significance (Fig,4c) is obtained for the total heights of the waviness profile (Wts vs. Wtp) and the maximum depth of the valleys (Wvs vs.Wvp) as well as the relative depth of holes, C_L (Fig.4b). This could be caused by different regions of surface scanned with laser and mechanical profilometry. However, Fig.4b and Fig.4c 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 (see Fig.2d). It seems that these cracks might be more easily detected by laser profilometer than by a profilometer with stylus.

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 [28] for non-planar localized surfaces: $R_S \approx 1.57R_L - 0.57$. Formulae given by Underwood [29]: $R_S \approx 1.27R_L - 0.27$ or Chermant and Coster [30]: $R_S \approx 1.75R_L - 0.75$ often used in the fracture analysis of cement concrete (e.g. Brandt and Prokopski [23], Stroeven [31]) are not valid for the description of concrete surface geometry after surface treatment.

The surface roughness and presence of the bond coat had an effect on the type of failure observed during the pull-off test. The relationships between the pull-off strength and SRI (describing surface roughness at a "macroscopic" level), the waviness parameter, Wap, and surface roughness ratio, R_S, describing the surface roughness at a “microscopic” level are not statistically significant for both types of overlay systems, i.e. with and without bond coat (Fig. 5). Some trends could however be observed: for systems with a bond coat, the pull-off strength slightly increases when the surface roughness increases. For a system without the bond coat as the roughness decreases the pull-off strength decreases. This can be explained by a difference in the workability of the repair mortar and bond coating. The repair mortar used in this study had a relatively low workability (partially due to fiber content) and consequently did not completely fill the irregularities and voids at the interface. The workability of the bond coat was higher. Hence, it was able to penetrate irregularities of surface and to bond the loose pieces of concrete. This indicates that, beside the surface roughness, the presence of cracks and loose concrete pieces are important factors that affect the adhesion in repair systems. This is important, especially in the case of relatively poor concretes similar to the tested in this work, because of large effect of surface treatment on the poor quality of the near-to-surface layer (cracking).

5. Conclusions

1. The geometrical parameters determined for both the macroscopic level (SRI value) and the microscopic level (R_S, R_L ratios and waviness parameters) generally indicate that the highest roughness was obtained after shot blasting for 45s and the lower roughness by grinding.

2. Laser profilometry produced a more detailed image of surface profile in comparison with the mechanical method. The values of the descriptive parameters of laser profilometry are ranged from 1 up to 7 times higher than the ones by mechanical approach; only the mean values of the roughness profile were quite similar for both methods and treatment types.

3. The highest correlation between corresponding waviness parameters determined with laser and by mechanical profilometry methods are obtained for the mean values, Wa, as

well as the parameters of Abbott's curve: relative height of the peaks, C_R, and relative depth of the profile, C_F. A lower statistical significance was obtained for other amplitude parameters: the total heights, Wt, maximum height of peaks, Wp, maximum depth of holes, Wv and Abbott's parameter – the relative depth of the holes C_L. A low statistical significance is involved with low values of parameters determined with mechanical profilometry for rough surfaces with deep and wide cracks, e.g. after milling.

4. The number and the size of cracks are dependent on the surface treatment: shotblasting and milling produce more cracks. An increase in duration of the treatment time also induces a greater deterioration of the near-surface layer.

5. Relationships between the pull-off strength and parameters describing surface geometry at different levels were not statistically significant for all types of overlay systems. The results obtained indicate that, beside the surface roughness, the presence of cracks and loose concrete pieces are important factors that affect the adhesion in repair system, especially in the case of a poor concrete substrate.

6. The bond coat increases significantly the pull-off strength in the case of concrete surfaces with high roughness (e.g. after shotblasting) while for the surfaces with low roughness (e.g. after sandblasting) this effect is less significant.

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References

1. Czarnecki L, Vaysburd AM, Mailvaganam NP, Emmons PH, McDonald JE. Repair and rehabilitation of structures – Some random thoughts. Indian Concrete Journal 2000; 74:13-20.
2. Courard L. Adhesion of repair systems to concrete: influence of interfacial topography and transport phenomena. Mag. Conc Res 2005; 57:15-24
3. Silfwerbrand J, Paulsson J. Better bonding of bridge deck overlays. Concrete International 1998;10:56-61.
4. Czarnecki L, Emmons PH. Repair and protection of concrete structures (in Polish). Kraków: Polski Cement; 2000, p.193-202
5. Fiebrich MH. Scientific aspects of adhesion phenomena in the interface mineral substrate-polymers. In Wittman FH,editor. Proc. 2nd Bolomey Workshop, Adherence of young and old concrete. Aedificato Verlag, 1994, p.25-58
   Courard L. Parametric Study for the Creation of the Interface between Concrete and Repairs Products. Mater Struct 2000; 33: 65-72.
6. Czarnecki L, Chmielewska B. Factors affecting adhesion in building joints. Cement-Lime-Concrete, 2005; 2:74-85
7. EN-1504-10:2003, Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity – Part 10: Site application of products and systems and quality control of the works, CEN, Brussels, 2003
8. Courard L. Evaluation of the thermodynamic properties of concrete substrates and cement slurries modified with admixtures. Mater Struct 2002; 35:149-155
9. Czarnecki L, Garbacz A, Kostana K. The Effect of Concrete Surface Roughness on Adhesion in Industrial Floor Systems. 5th Int Colloq - Industrial Floors, Esslingen, Germany, January 21-23; 2003: 168-174.
10. Fukuzawa K, Mitsui M, Numao T. Surface roughness indexes for evaluation of bond strengths between CRFP sheet and concrete. Proc Xth Int Cong on Polymers in Concrete – ICPIC 2001, Honolulu, HI, May 21-24; 2001: pap.12 (CD)
11. Mackowski R. The effect of concrete surface treatment on the quality of the concrete struture repair (in Polish)., 10th Conf on Corrosion and Durability of structures -Kontra 2000. Zakopane, May 23-26; 2000: 221-226
12. Courard L. Contribution à l'analyse des paramètres influençant la création de l'interface entre un béton et un système de réparation. Appétence et adhérence: cause et effet d'une liaison". PhD thesis, Université de Liège, Collection des Publications de la Faculté des Sciences Appliquées, 1999, N° 192, 213 p. (in French)

13. Garbacz A, Górka M, Courard L. On the effect of concrete surface treatment on adhesion in repair systems. Mag Conc Res 2005; 57: 49-60.
14. Silfwerbrand J. Improving concrete bond in repaired bridge decks. Concrete International 1990; 12: 61-66.
15. Austin S, Robins P, Pan Y. Tensile bond testing of concrete repairs, Mater Struct 1995; 28: 249 – 259
16. Pretorius J, Kruger D. The influence of surface roughness on the bond strength of concrete repairs. Proc Xth Int Cong on Polymers in Concrete – ICPIC 2001, Honolulu, HI, May 21-24; 2001: pap 13 (CD)
17. Kurzydłowski KJ, Ralph B (1996). Quantitative description of microstructure. New York: CSC
18. Wojnar L (1995). Image Analysis: Applications in Materials Engineering. New York; CSC
19. Czarnecki L, Garbacz A, Kurach J . On the characterization of polymer concrete fracture surface. Cement & Concrete Composites 2001; 32:399-409
20. Courard L, Nélis M. Surface analysis of mineral substrates for repair works: roughness evaluation by profilometry and surfometry analysis. Mag Conc Res 2003; 55: 355-366
21. Liubimov V, Oczoś K. Geometrical structure of surface (in Polish). Rzeszów, Politechnika Rzeszowska. 2003:pp;.352
22. EN 1542:1999, Product and systems for the protection and repair of concrete structures: Measurement of bond strength by pull-off
23. Brandt AM, Prokopski G. On the fractal dimension of fracture surfaces of concrete elements. J Mat Sci 1993; 28:4762-4766
24. Saouma VE, Barton CC. Fractals, fractures, and size effects in concrete. J Eng Mech 1994; 120: 835-854
25. Wang Y, Diamond S. A fractal study of the fracture surfaces of cement pastes and mortars using a stereoscopic SEM method. Cem Concr Res 2001; 31: 1385-1392
26. Issa MA, Issa MA, Islam MD, Chudnovsky A. Fractal dimension – a measure of fracture roughness and toughness
27. Yan A, Wu K-R, Zhang D, Yao W. Influence of concrete composition on the characterization of fracture surface. Cem Concr Comp 2003; 25:153-157
28. Wright K, Karlsson B. Topographic quantification of non-planar localized surfaces. J.Micros 183; 1:37-51
29. Underwood EE. Stereological analysis of fracture roughness parameters. Acta Stereol 1987; 6:170-178
30. Coster M, Chermant JL. Recent developments in quantitative fractography. Int Metals Rev 1983; 28: 228-250
31. Stroeven P. A stereological approach to roughness of fracture surface and tortuosity of transport paths in concrete. Cem Concr Comp 2000; 22: 331-341

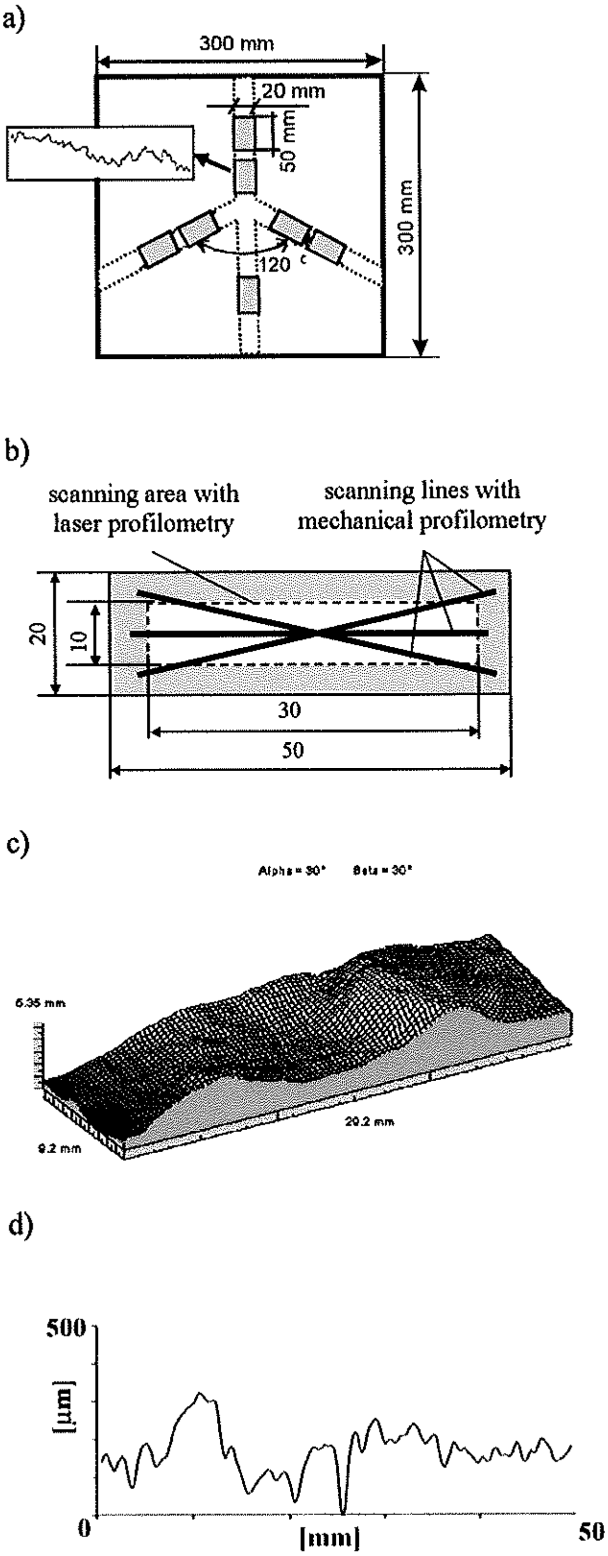
Table 1. Selected parameters of concrete surface geometry after surface treatment determined with various methods

Methods	Parameters	Surface treatment					
		GR	SB	SHB 35	SHB45	HMIL	MMIL
„Sand" method	SRI [mm]	183	171	123	114	174	151
		Profile and surface roughness parameters					
Microscopic Method	Rl [-]	1.41	1.54	1.57	1.59	1.46	1.51
	Rs [-]	1.65	1.83	1.89	1.91	1.72	1.79
	Fractal dimension						
	Db [-]	1.133	1.127	1.084	1.077	1.084	1.097
Laser profilomerty	Waviness profile						
	Wts [µm]	933	1 130	2 730	3 110	1 300	3 400
	Was [µm]	134	156	444	515	127	384
	Wvs [µm]	530	571	1 140	1 680	985	2 340
	Wps [µm]	430	562	1 580	1 430	312	1 060
	Roughness profile						
	Rts [µm]	289	501	634	530	530	504
	Ras [µm]	12	13	23	26	17	21
	Rps [µm]	146	290	218	253	247	258
	Abbott's curve						
	Crs [µm]	234	161	509	960	68	341
	Cfs [µm]	404	505	1590	3330	409	1460
	Cls [µm]	391	218	175	670	340	1512
	Fractal dimension						
	Ds [-]	2.400	2.370	2.420	2.360	2.340	2.380
Mechanical Profilometry	Waviness profile						
	Wtp [µm]	219	434	1 086	2 165	473	867
	Wap [µm]	32	49	215	386	70	179
	Wvp [µm]	108	317	516	1009	269	419
	Wpp [µm]	111	117	570	1157	188	448
	Roughness profile						
	Rtp [µm]	105	95	116	113	113	123
	Rap [µm]	15	15	18	17	16	19
	Rpp [µm]	32	35	34	34	33	37
	Abbott's curve						
	Crp [µm]	57	50	289	698	116	188
	Cfp [µm]	55	77	406	619	107	351
	Clp [µm]	69	144	291	669	196	248

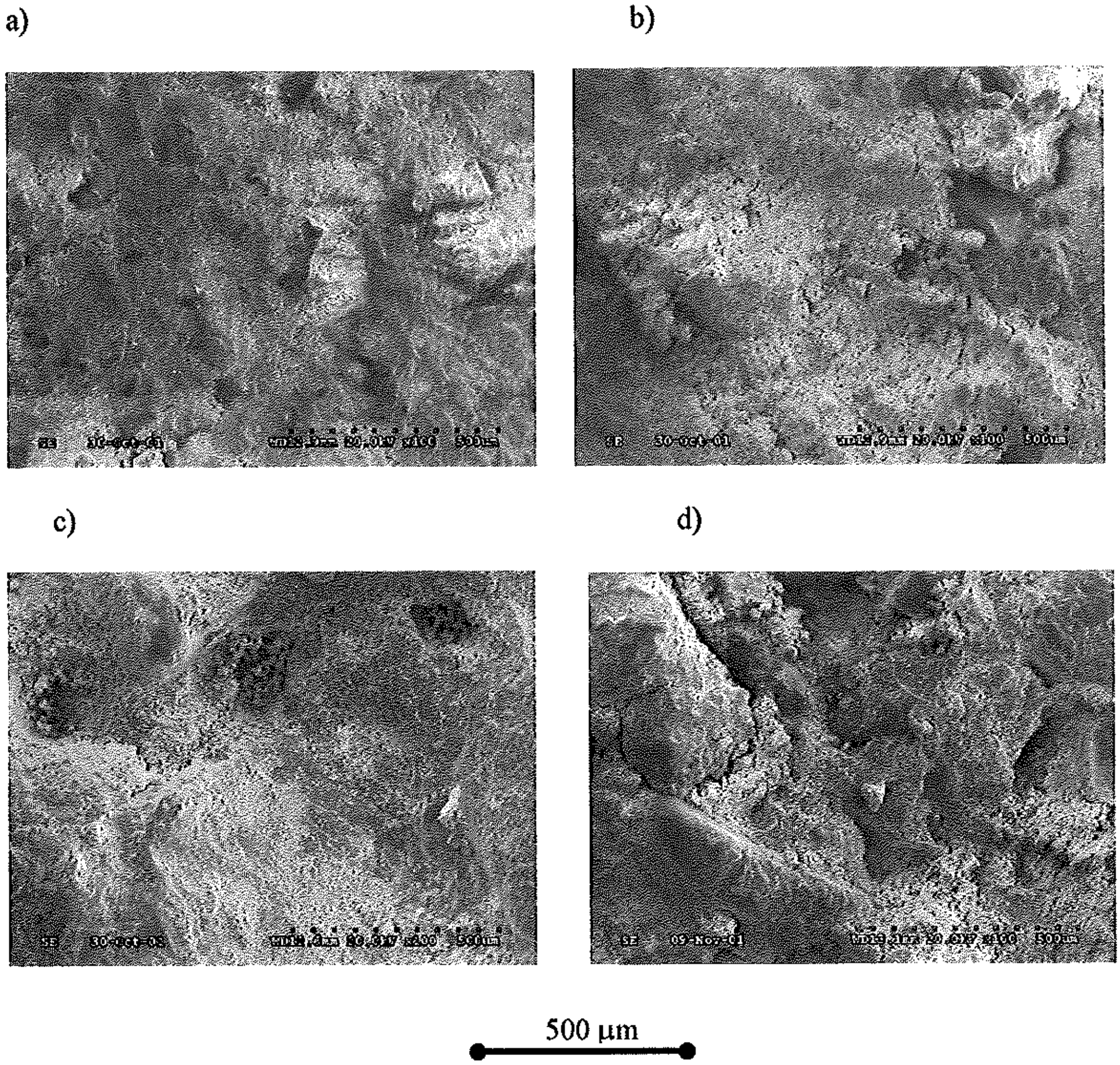
Table 2. Results of pull-off strength tests

Treatment type	Mean value [MPa]	Coefficient of variation [%]	Failure type *) [%]
Overlays without bond coat			
GR	1.16	50.9	21C+79C/R
SB	1.82	32.4	42C+58C/R
SHB35	1.25	28.8	46C+54C/R
SHB45	0.83	25.3	50C+50C/R
HMIL	1.01	40.6	29C+71C/R
MMIL	0.49	57.1	31C+69C/R
Overlays with bond coat			
GR	1.82	15.9	100 C
SB	1.93	11.4	100 C
SHB35	1.94	11.3	100 C
SHB45	1.96	32.7	100 C
HMIL	1.42	12.7	100 C
MMIL	1.60	24.4	100 C

*) C - cohesive failure in concrete substrate.
C/R - interfacial failure between overlay and concrete

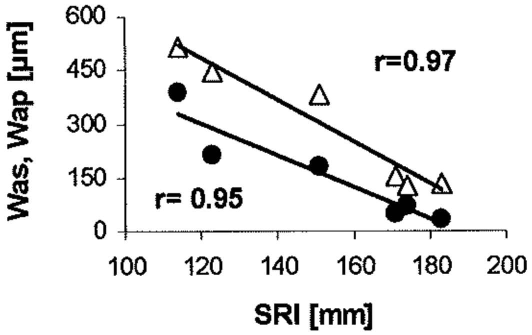


Garbacz et al. - Fig.1



Garbacz et al. - Fig.2

a)



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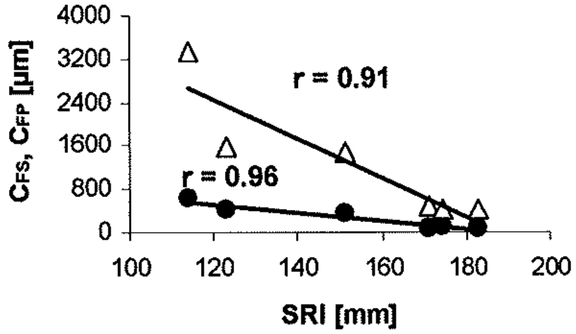

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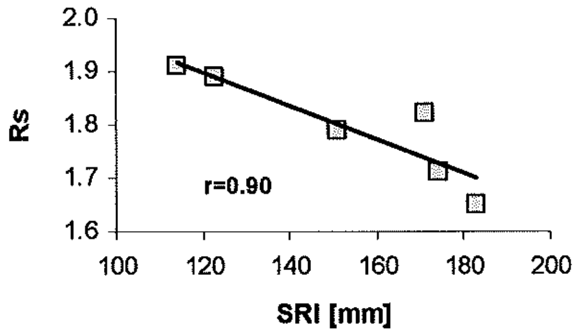

Garbacz et al. - Fig.3

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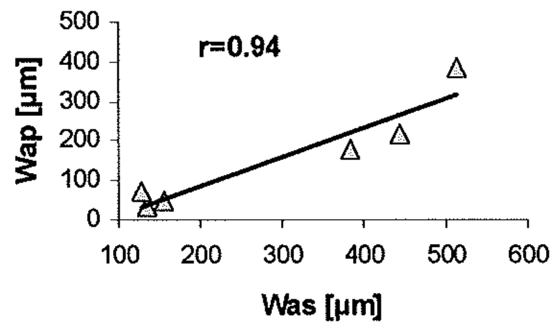

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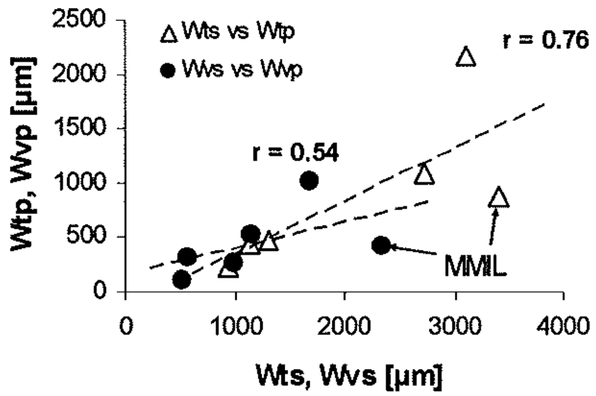

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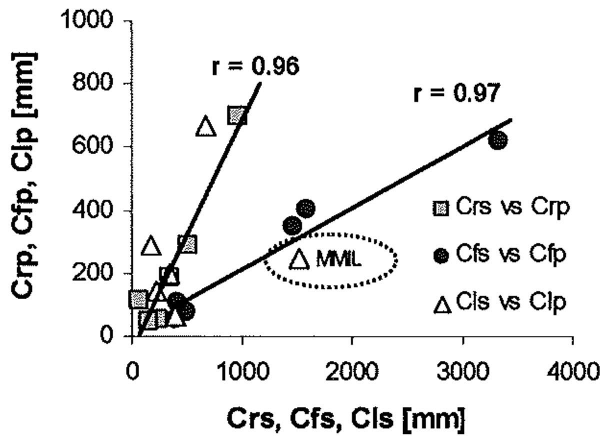
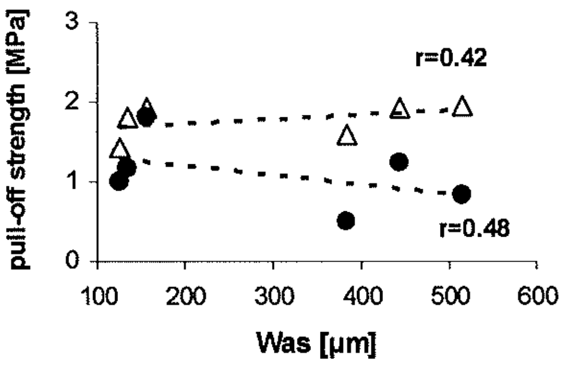


Garbacz et al. - Fig.4

a)



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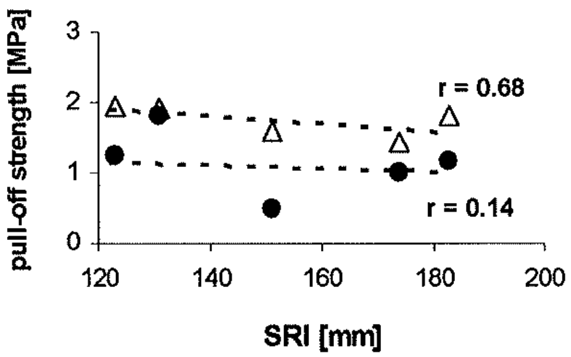

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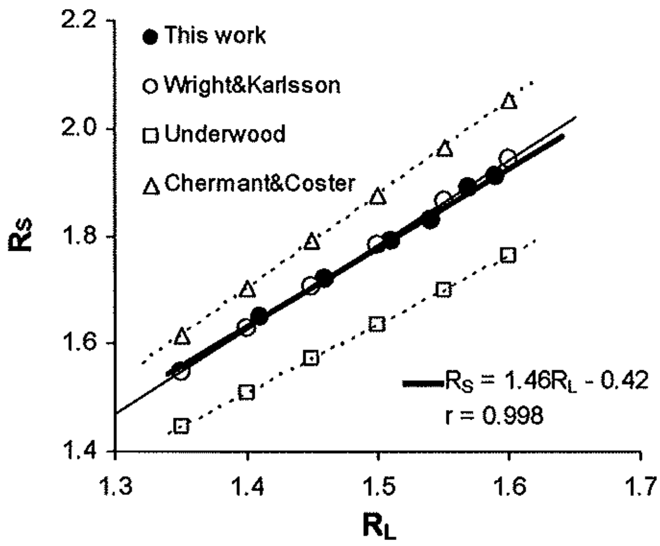

Garbacz et al. - Fig.6.