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Influence of construction technology on the adhesion of remedial concrete

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Original scientific paper

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Influence of construction technology on the adhesion of remedial concrete

An experimental study aimed at determining influence of individual parameters on the quality of remedial work is undertaken by varying the following factors: quality of damaged concrete, technology for preparing surface for remedial work, and types of remedial concrete. The results obtained are analyzed using the newly introduced criterion for the adhesion of concrete re-profiling materials. Advantages gained by the use of the concrete surface hydro-demolition and sanding procedure, latex-modified remedial concrete with bonding layer, and siliceous concrete without the bonding layer, are presented.

Key words:
hydro-demolition, sanding, pneumatic treatment, concrete surface preparation, remedial concretes/mortars

Izvorni znanstveni rad

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Utjecaj tehnologije izvođenja na prionljivost sanacijskih betona

Radi utvrđivanja utjecaja pojedinih parametara na kvalitetu sanacije, proveden je eksperimentalni rad u kojem je varirana kvaliteta oštećenog betona, tehnologija pripreme podloge za sanaciju i vrsta sanacijskog betona. Dobiveni rezultati su analizirani s obzirom na novouvedeni kriterij prionljivosti reprofilacijskih sanacijskih materijala. Utvrđena je prednost postupka hidrodemoliranja i pjeskarenja betona podloge, zatim primjene sanacijskih betona s dodatkom lateksa i veznim slojem te betona sa silicijskom prašinom bez veznog sloja.

Ključne riječi:
hidrodemoliranje, pjeskarenje, pneumatska obrada, priprema betona podloge, reprofilacija, sanacijski betoni/mortovi

Wissenschaftlicher Originalbeitrag

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Einfluss der Ausführungstechnologie auf die Adhäsion von Reparaturbeton

Zur Feststellung des Einflusses einzelner Parameter auf die Qualität der Reparatur wurde eine experimentelle Forschung durchgeführt, in welchem die Qualität des beschädigten Betons, die Technologie der Vorbereitung des Sanierungsuntergrundes sowie die Art des Reparaturbetons variiert wurden. Die erhaltenen Resultate wurden hinsichtlich des neu eingeführten Kriteriums der Adhäsion der Sanierungsmaterialien für die Reprofilierung analysiert. Es wurde der Vorteil des Verfahrens der Hydrodemolierung und der Sandstrahlung des Untergrundbetons, die Anwendung von Reparaturbeton mit einem Zusatz von Latex und einer Bindeschicht sowie von Beton mit einem Siliziumpulver ohne Bindeschicht festgestellt.

Schlüsselwörter:
Hydrodemolierung, Sandstrahlung, pneumatische Bearbeitung, Vorbereitung des Untergrundbetons, Reparaturbeton / Reparaturmörtel

1. Introduction

The issue of durability in aggressive environment is widely considered as one of major problems affecting concrete structures. Concrete structures rapidly deteriorate under such conditions due to inadequate design requirements, mistakes during realization of work, and lack of structural maintenance. That is why rehabilitation is both necessary and unavoidable in order to preserve the bearing capacity and usability of concrete structures.
One of most common forms of concrete structure repair is the procedure involving removal of damaged or contaminated concrete, and concrete reshaping or re-profiling with repair mortars or concretes. The reshaping procedure is usually conducted in the zone of the protective layer, and it consists of a number of stages:

- surface preparation (using well-known technologies for removing concrete layers and preparing for application of new layers),
- application of binder, and
- application of repair material in accordance with requirements for construction of new reshaped layers by placing repair mortars and concretes.

The reshaping procedure is often used when horizontal layers have to be replaced in the course of rehabilitation work for deck slabs on bridges, pavement slabs at car parks, and concrete pavements (to improve drainage, surface driving conditions, bearing capacity, etc.) (cf. Figure 1). The materials used for replacement of horizontal layers are the Portland cement concrete with low water to cement ratio, and the polymer-cement concrete (superplasticized) with latex or silica fume. In such cases, additional reinforcement is often unnecessary. Special attention should however be paid to problems such as the plastic shrinkage, poor compactness, segregation, or poor binding with the existing concrete [1-11].

Figure 1. Replacement of existing layers during deck slab repair on bridges

Main technical and legal regulations relating to implementation of activities for the repair and protection of reinforced-concrete structures using reshaping procedures are given in a series of standards HRN EN 1504 and in Appendix H, Technical Regulations for Concrete Structures.
These standards and regulations provide stricter criteria for the bond between the surface concrete and repair concrete or mortar (2.0 N/mm^2), as compared to previous criteria contained in relevant codes of practice (1.5 N/mm^2). The adhesion of repair material to surface is considered as the most significant quality parameter which practically defines success of a rehabilitation procedure. For this reason, an investigation was conducted to determine which damaged concrete preparation technology, and which type of concrete repair, will be capable of meeting these new adhesion/bonding criteria.

2. Definition of testing

2.1. Testing objective and testing programme

The aim of the testing is to determine an optimum concrete surface preparation technology, and the type of repair concrete that would meet the new adhesion criteria ($f_a \geq 2.0$ N/mm^2), which have replaced the former criteria for tensile adhesion strength ($f_a \geq 1.5$ N/mm^2).
The testing programme was designed to show performance of rehabilitation work on horizontal surfaces, such as on bridge concrete slabs with surface damage, where the contaminated surface layer needs to be removed and the pavement slab reshaped by applying an appropriate repair procedure.
The following parameters were varied during the testing:

- quality of concrete surface (concretes with compressive strength classes C35/45 and C25/30)
- concrete surface treatment technology (hydro-demolition, sandblasting, manual pneumatic removal of concrete)
- type of rehabilitation material (concrete without additives and binder, concrete with silica fume without binder, concrete with latex without binder, and concrete with latex with binder).

The following tests were included in the testing programme:

- testing repair concrete components
- testing properties of repair concretes, in fresh and hardened state
- testing concrete surface in hardened state
- testing concrete surface after surface preparation
- testing quality of rehabilitation work by applying repair concretes onto the prepared concrete surface.

2.2. Test methods

The following methods were used for testing repair concretes and concrete surfaces in fresh and hardened states:

- consistency through settlement in compliance with HRN EN 12350-2
- specific gravity of fresh concrete in compliance with HRN EN 12350-6
- quantity of pores in fresh concrete in compliance with HRN EN 12350-7
- temperature of fresh concrete in compliance with HRN U.M1.032
- compressive strength of concrete in compliance with HRN EN 12390-3
- specific gravity of hardened concrete in compliance with HRN EN 12390-7
- static modulus of elasticity in compliance with HRN U.M1.025
- shrinkage in compliance with HRN EN 12617-4
- tensile strength in compliance with HRN EN 1542

The following test methods were applied to evaluate the concrete surface preparation quality and the quality of rehabilitation work by reshaping with repair concretes:

- testing adhesion of concrete in compliance with HRN EN 1542 at 7, 28 and 90 days
- determining roughness by measuring with calliper.

2.3. Test implementation technology

The test campaign was conducted on the total of 6 blocks of slab shaped concrete, measuring 120x80x15 cm. Blocks were differentiated by concrete quality at slab surface (2 types of concrete), type of concrete surface treatment (3 types) , and re-profiling systems (4 types). Each system was tested at three reference ages, counting from the concrete placing date. Concrete blocks were prepared at a batching plant, and two different concrete qualities were set: 3 concrete slabs were made of concrete class C 35/45 (mark A), and 3 concrete slabs were made of concrete class C25/30 (mark B).
Two concrete types were used for the surface with different compressive strength class because prior tests conducted on existing infrastructural facilities in Croatia have revealed that these two types are the most common concrete quality classes. [10]
Some basic data about the surface concretes are: quantity of cement: 420 kg/m^3 and 250 kg/m^3, CEM II/B-M(S-V)42,5N; natural and crushed aggregate T_{max}= 16 mm; concrete type A is superplasticized and aerated; concrete strength: concrete A f_{cm}^{28}=67,3 MPa; concrete B f_{cm}^{28}=37,9 MPa).
The surface layer was removed from concrete slab models aged 28 days. Three different technologies were used for concrete removal, i.e. for concrete surface preparation:

- Concrete surface treatment with water under high pressure by hydro-demolition (mark HD), as shown in Figure 2;
- Concrete surface treatment with pneumatic removal of concrete by pick-hammering (mark PH), as shown in Figure 3;

Figure 2. Treatment of top concrete surfaces of blocks A and B with water under high pressure (hydro-demolition)

Figure 3. Pneumatic treatment (pick-hammering) of top concrete surfaces of blocks A and B

Figure 4. Top concrete surfaces of blocks A and B subjected to water jet treatment with sand (sandblasting)

- Concrete surface treatment by wet sandblasting (mark PJ), as shown in Figure 4.

This concrete treatment procedure enabled us to apply different concrete removal and surface preparation technologies (HD, PH, PJ) for each concrete (A and B), which resulted in the total of six different systems that were marked as follows: AHD, BHD, APH, BPH, APJ, BPJ.
The adhesion and roughness testing was performed at the previously prepared concrete surfaces. After that, four different repair concretes were placed onto the prepared surfaces, and adhesion of repair concretes onto the concrete surface was tested at the specified concrete ages. Repair concretes were applied on all concrete slab models.
Repair systems used for pavement surface reshaping (cf. Table 1):

- concrete without additives and without binder (mark OC)
- concrete with silica fume without binder (mark SFC)
- concrete with latex without binder (mark LMC)
- concrete with latex and binder (mark LMC+)

The following components were used in the preparation of repair concretes: cement CEM I 42.5R, river aggregate fractions 0-4 and 4-8 mm, superplasticizer based on polycarboxylate ether, polymer additive to concrete containing latex, silica fume, and water.
The binder used with the mixture marked LMC+ was made of a latex/water/cement/sand mixture (mix ratio: 1:2:2:2).

Table 1 Composition of repair concrete (per 1 m^3) used during reshaping

Sanation system / Concrete structure	OC	SFC	LMC
Cement	400	370	400
Water	160	148	160
Superplasticizer	4	3,7	-
Silica fume	-	30	-
Latex	-	-	80
Aggregate	1822,3	1851,2	1658,2
Water/cement ratio	0,40	0,40	0,40

Concrete for the overlaying course was prepared by mixing in laboratory, and was then placed onto the previously prepared concrete surface. Four squares were placed on each block of concrete (divided into four quarters). All repair concretes were placed onto the concrete surface previously wetted with water mist. The placement of repair concrete onto the treated concrete block surface is presented in Figures 5, 6 and 7.

Concrete types marked OC and SFC were cured by wetting over a seven-day period. Repair concrete types marked LMC and LMC+ were cured by wetting during the first two days only. This difference in concrete curing time is due to addition of latex as polymer additive.

Figure 5. Placement of repair concrete: vibrating with internal vibrator, manual floating

Figure 6. Preparation of binder: proportioning and manual mixing of mortar with latex marked LMC+, and rubbing into the surface of blinding concrete

Figure 7. Reshaping concrete freshly placed onto the surface of all 6 blocks

3. Test results

3.1. Repair concrete properties

Properties of repair concrete, in fresh and hardened state, are shown in Tables 2 and 3. It is evident from Table 3 that the addition of silica fume brings about an increase in compressive strength, modulus of elasticity and tensile strength, while addition of latex lowers these values, in relation to the regular repair concrete. Concrete containing latex exhibits greater shrinkage than the concrete containing silica fume.

Table 2. Repair concrete properties in fresh state

Property	OC	SFC	LMC	LMC+
Temperature [°C]	28,0	27,2	25,2	25,2
Settlement [mm]	52	46	38	70
Specific gravity [kg/m³]	2325	2309	2148	2212
Air quantity [%]	4,2	5,2	6,4	6,8

Table 3. Repair concrete properties in hardened state

Property	OC	SFC	LMC
Compressive strength at 7 days [N/mm²]	53,1	56,6	36,8
Compressive strength at 28 days [N/mm²]	59,7	63,8	44,9
Compressive strength at 90 days [N/mm²]	67,4	68,4	56,1
Static modulus of elasticity [GPa]	33,9	36,2	20,2
Shrinkage of concrete at 28 days [mm/m]	-	0,211	0,237
Tensile strength [N/mm²]	4,50	4,68	3,68

3.2. Measuring roughness of treated top surfaces of blinding concrete blocks

The roughness was measured for all six blocks, following the surface preparation procedure involving hydro-demolition, sandblasting and manual pneumatic treatment. The surface roughness was tested on surfaces prepared in that way, using an appropriate template, while calliper was used to measure concrete depth.

The concrete surface roughness measurements are given in Figure 8 and Table 4.

The macro-roughness measurements of concrete surface, expressed through statistical values of a regular distribution of measured points over the concrete surface, can be expressed and compared based on statistical parameters [12-16]:

- standard deviations of all values (σ)
- measured values in the range between -2σ and $+2\sigma$, with 95.4 % accuracy of all results.

Values obtained by analysis of all 6 concrete surfaces are presented in Table 4.

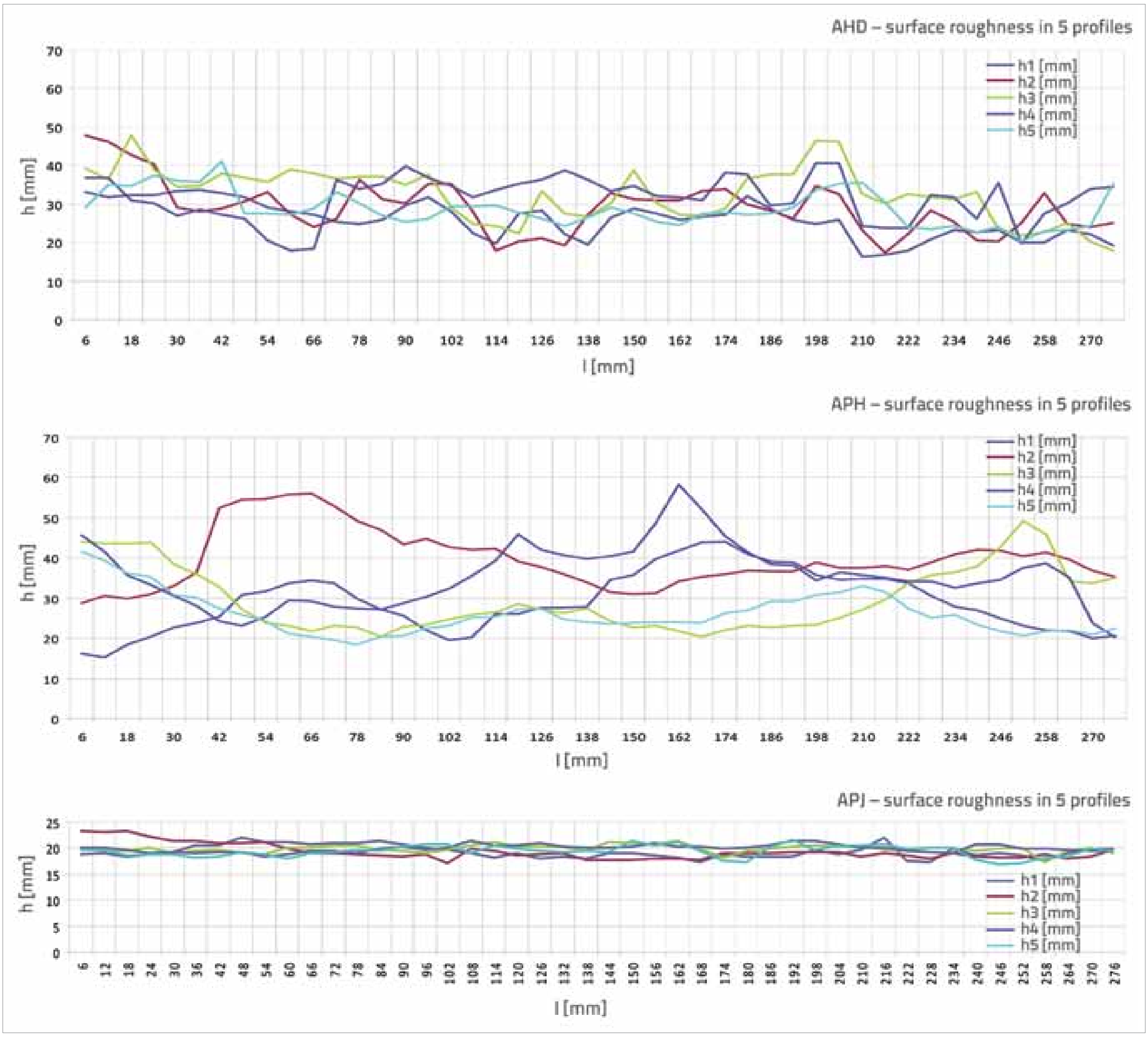

Figure 8. Logged roughness profiles for all three types of surface treatment (on series A concrete blocks)

Table 4. Statistical analysis of roughness measured on all 6 concrete surfaces

Type of surface / Hrapavost podloge	AHD	BHD	APH	BPH	APJ	BPJ
Standard deviation σ_{hr} [mm]	6,29	8,00	8,72	8,28	1,13	0,85
Range between - 2σ do +2σ (95,4 % of all values) [mm]	25,14	32,00	34,90	33,13	4,53	3,40

It can be seen from test results that minimum roughness was obtained by sandblasting, while maximum roughness was acquired by pick hammer.

3.3. Adhesion properties of repair concretes

The main criterion for effectiveness of repair systems was determined according to the repair concrete adhesion testing procedure on concrete blocks, using the so called pull off testing method. During implementation of this test, the fracture occurs along the weakest point in the reshaping system, which is made of the surface concrete, binder (not always present), repair concrete for reshaping, glue, and breadboard. This testing method is most often used for the on-site and laboratory control of adhesion of layers placed on damaged and worn-down concrete.

The testing was performed on the total of 24 test surfaces (6 blocks for 4 different repair concretes), aged 7, 28 and 90 days, all in a series of 3+3+2 test points. The total of 192 adhesion (pull off) tests was performed. The adhesion testing procedure is shown in Figure 9. Average test values are given in Table 5.

Figure 9. Reshaping system adhesion determined by *pull off test*

An overview of adhesion values obtained in the course of all 192 tests is presented in Table 5. The values are grouped into 6 repair systems and 3 age categories. Values for all 4 reshaping systems are presented together. It can be seen from Table 5 that the adhesive strength increases with time for all repair systems. The adhesive strength values for surfaces treated with hydro-demolition and sandblasting are higher than those for pick-hammered surfaces, regardless of their age at the time of testing.

Table 5. Overview of average adhesion values for all 4 reshaping systems, on surface concretes type A and B, at three different time intervals

Block mark	Average values of adhesion [N/mm²]		
	7 days	28 days	90 days
AHD	2,16	2,53	3,28
BHD	1,93	2,28	3,19
APH	0,70	1,12	0,98
BPH	0,11	0,38	0,69
APJ	2,22	3,09	3,55
BPJ	2,30	2,66	2,85

4. Analysis of test results

All repair system test results were analyzed and compared on the basis of the type of surface, technological procedure for concrete surface preparation, and types of materials used for reshaping. All adhesion test results were analyzed using the system efficiency evaluation, and this based on two criteria:

- correlation of individual adhesion results
- relation to the criterion of $f_a \geq 2,0$ N/mm².

4.1. Impact of concrete surface roughness

The relationship between adhesion and roughness values is given in Figure 10 for each type of concrete surface treatment, and for all three ages of the repair system.

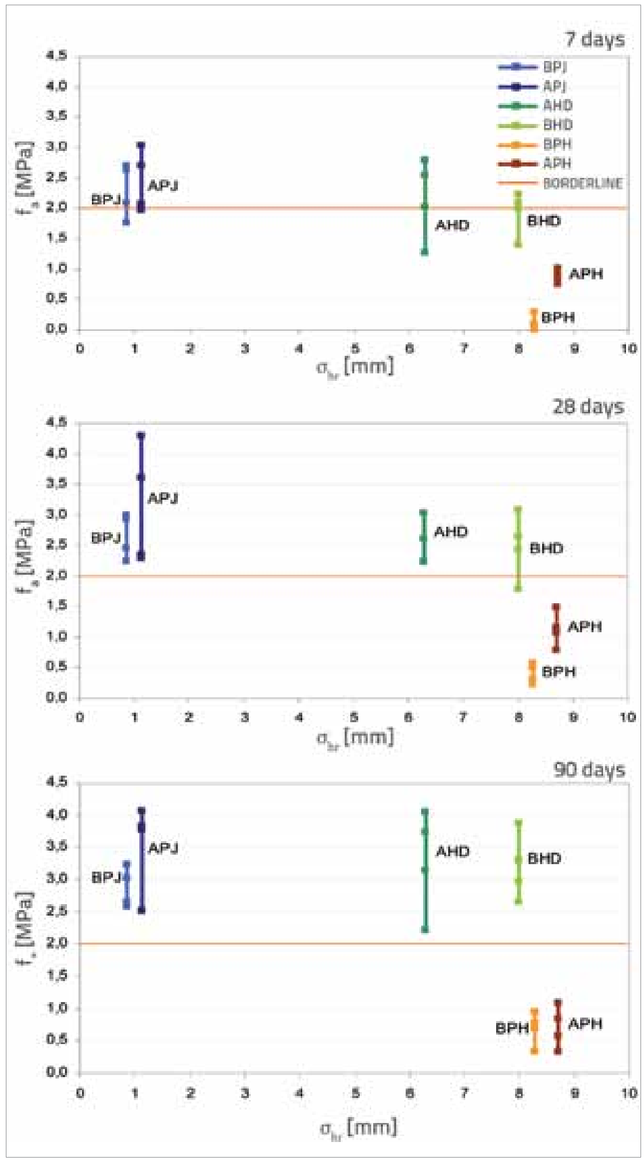

Figure 10. A range of repair concrete adhesion values for each block, in relation to the measured standard deviation of roughness (σ_{hr}) for the overlying course aged 7, 28 and 90 days

It is evident from Figure 10 that high adhesion values are achieved with surface treatment by hydro-demolition (HD) and sandblasting (PJ), regardless of the type of repair system, even though the actual roughness of sandblasted surfaces is significantly lower. With pick-hammered surfaces (PH), the roughness values are high, but the achieved adhesion is significantly lower, which indicates that the roughness test results are also influenced by some other factors.

4.2. Influence of repair concrete and its age

Figures 11, 12 and 13 show adhesion values obtained on the type A concrete surface, for all 4 types of treatment, with development of adhesive strength over time.

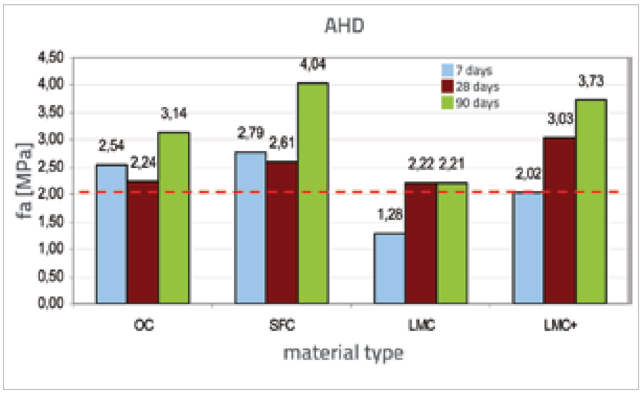

Figure 11 Adhesion on concrete block AHD over time

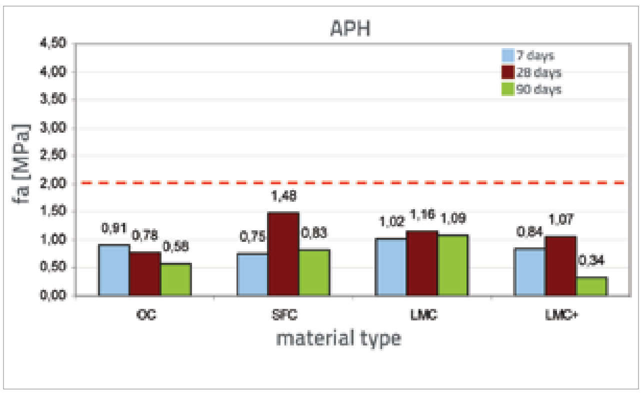

Figure 12. Adhesion on concrete block APH over time

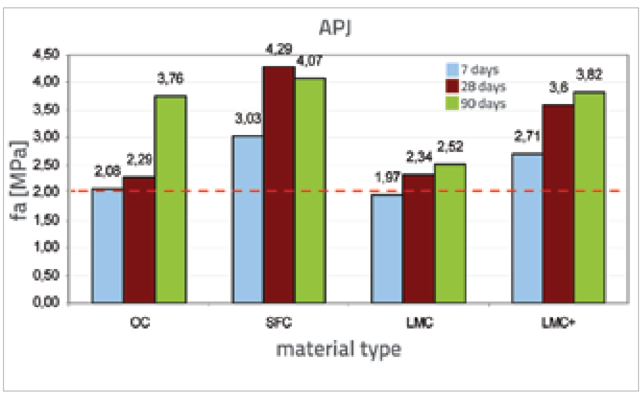

Figure 13 Adhesion on concrete block APJ over time

The diagram presented in Figure 14 shows correlations between different reshaping systems with two surface treatments which meet the required adhesion criteria. Based on this diagram, conclusions may be drawn as to the efficiency of individual repair systems (composition and repair material placing procedure), and their behaviour over time.

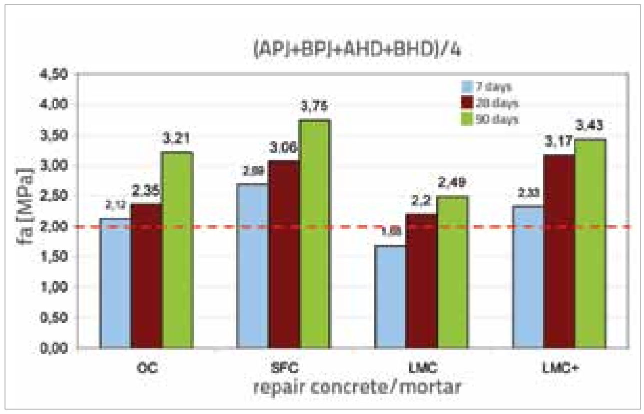

Figure 14 Average adhesions of systems on blocks AHD, BHD, APJ and BPJ, at 7, 28 and 90 days

It is evident from Figures 11 through 13 that adhesions on pick-hammered (PH) concrete surfaces are not compliant with the criterion of $f_a \geq 2.0$ N/mm². It can be noted that the existing concrete suffers damage (microcracks) during surface preparation by pick-hammering, which greatly influences adhesion results. When surface is prepared by hydro-demolition and sandblasting, all repair concretes meet the adhesion criteria at 28 days. However, the best adhesion properties with the abovementioned damaged concrete removal technologies are achieved by the application of repair concretes marked SFC (concrete with silica fume, without the binder) and LMC+ (concrete with latex and binder).
It can be seen in Figure 14 that the adhesion criterion of $f_a \geq 2.0$ N/mm² is already met at 7 days if repair concretes marked SFC and LMC+ are used. Here it should be noted that significantly thicker layers of concrete can be removed by hydro-demolition than by sandblasting.

5. Conclusion

The following conclusions can be made after the testing campaign in which the concrete quality, surface preparation technology, and repair material types have been varied:

- The concrete surface quality does not significantly influence the adhesiveness of the repair system.
- The influence of quality of concrete surface is greater in case of mechanical treatment by pneumatic tools (pick hammers), which results in formation of microcracks in the surface layer. The concrete surface of lower quality is more damaged by pick hammering, which results in much lower adhesion strength of the overlying course.
- Roughness of the surface does not directly affect system adhesion at the level of macro-roughness. The influence of the concrete surface microstructure is obviously more important (microcracks and micro-roughness).
- Adhesion of repair concretes onto horizontal concrete surfaces depends on the surface preparation method:

- Surface preparation procedure using mechanical (pneumatic) tools is unacceptable because the criterion of $f_a \geq 2.0\ N/mm^2$ can not be met at any reshaping age used in the testing.
- Concrete surface preparation procedures by hydro-demolition and sandblasting give similar adhesion results, but hydro-demolition is more favourable as it enables removal of thicker layers of concrete.
- By increasing the age of the system, the adhesion bond is also increased.
- Systems commonly used as repair systems for reshaping the concrete surface, at 28 days or more, meet the abovementioned criterion of $f_a \geq 2.0\ N/mm^2$. These systems are:
- concrete with silica fume, without binder, and
- concrete with latex and binder.

These systems roughly meet the above-mentioned criterion as early as at 7 days.

Results obtained during this testing campaign may be of great practical significance for the performance of rehabilitation work on bridge deck slabs, concrete pavements, and similar structural elements.

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