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Skazlić, Marijan; Borovina, Berislav; Gabrijel, Ivan

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Marijan Skazlić*, Berislav Borovina, Ivan Gabrijel

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Abstract: A large number of concrete bridges need to be repaired due to durability problems. This research focuses on evaluating the bond quality of the repair material, which has the highest influence on the durability of the repair. Onsite experimental research is performed on the vertical surfaces of the column of the Klara Jug bridge, which is located in the southern part of the Zagreb. Since the experimental research is carried out in parallel with the ongoing repair works on other bridge elements, the experimental conditions correspond to the real construction site conditions. Simulation of the actual site rehabilitation process was carried out on the test fields, which included removal of the damaged concrete by hydrodemolition at a depth of 1.5–2 cm, washing of the concrete by roto nozzle and wet spraying of the repair mortar. The results of the pull-off tensile bond strength show that there is an optimum period for spraying of repair mortar after washing the concrete surface. Optimal time for application of mortar is 90 min after completion of washing of the vertical concrete surface by the roto nozzle. In other weather conditions, the application time depends on the expected evaporation of water from the surface. The tensile strength of the bond between concrete and the repair mortar is 62% lower if the concrete is not washed by the roto nozzle prior to the application of the repair mortar. This investigation can serve as a practical guide for the repair of vertical surface of concrete elements of bridges, overpasses and viaducts.

Keywords: bridge, concrete repair, durability, hydrodemolition, pull-off tensile strength, repair mortar

***Corresponding author: Marijan Skazlic,** University of Zagreb Faculty of Civil Engineeering, Department for Materials, Zagreb, Croatia, E-mail: marijan.skazlic@grad.unizg.hr
Berislav Borovina, and Ivan Gabrijel, University of Zagreb Faculty of Civil Engineeering, Department for Materials, Zagreb, Croatia

1 Introduction

A large number of concrete structures, especially bridges, need to be repaired due to durability problems. Damage to concrete structures is mainly caused by aggressive environmental conditions, improper design, construction errors and lack of maintenance (Mavar 2010). Repairing damaged concrete structures is a complex process because it requires knowledge of structural design, material properties and construction and repair techniques. This diversity of knowledge that engineers are confronted with during repair often results in new damage occurring shortly after the repair work. There are a number of cases where the durability of concrete structures is only a few years or much shorter than expected when the repair was planned. In analysing the evaluation data collected at these failed repair sites, it was found that in many cases the bond between the existing concrete and the repair material is the most important parameter determining the durability of the repair (Radić 2010; Borovina 2011). If the bond between the existing concrete and the repair material layer is poor, the quality of the repair material becomes irrelevant to achieving the designed service life (Mehta 1991; Emmons 1993; American Concrete Institute 2014).

One of the most-used methods of concrete repair is reprofiling of concrete elements with repair mortar. The main steps in reprofiling are removal of the damaged concrete, preparation of the concrete surface and application of the repair mortar. Repair mortar must be compatible with existing concrete, which means that it has lower modulus of elasticity and greater or equal values of compressive and flexural strengths. The dynamics of the reprofiling work depend on the degree of damage of the existing concrete, the type of element and the time period between the end of the preparation of the concrete surface and the application of the repair mortar (Emmons 1993; Bjegović et al. 2003; Radić 2010).

Previous research has shown that the optimal procedure for removing damaged concrete and preparing the surface is hydrodemolition under a pressure of up to

2,600 bar. This method of concrete removal has proven to be better in terms of quality of repair compared to impact methods or sandblasting, as it creates fewer microcracks in the concrete (Mavar 2010; Mavar and Skazlić 2012). In hydrodemolition, contaminated or damaged concrete detaches in scaly or lenticular pieces of size 0.5 cm to 5.0 cm mainly through the cement matrix and larger aggregate grains, leaving the interface between the cement matrix and aggregate largely intact. In this way, no porous layer is formed on the surface of the concrete that could affect its strength. Hydrodemolition technology of damaged concrete removal has been shown not to affect the mechanical properties of the concrete (Garbacz et al. 2006; Skazlić and Mavar 2013; Skazlić et al. 2015).

After hydrodemolition and before spraying the repair mortar, the concrete surface must be washed with a lower intensity water jet. This is an important step, not only to remove loose particles and contaminants from the concrete surface, but also to saturate the surface before applying the repair material (Water Jet Technology Association 1987; Borovina 2011; Momber 2011). Surface moisture has a major effect on the mechanical properties of the bond between the repair material and the substrate. The optimum situation is when the pores near the surface are completely saturated and there is no free water on the surface. This ensures that the strength of the repair mortar in the contact layer is not affected by an increase in the water–cement ratio if free water is present on the surface of the contact layer. If the surface is too dry, some of the water from the mortar could be absorbed into the concrete resulting in insufficient water for normal hydration (Garbacz et al. 2005). The variation in surface moisture is governed by the environmental conditions after washing. The evaporation rate depends on air temperature, wind speed and relative humidity. Nomograms for determining the water evaporation rate of fresh concrete have been proposed but are not available for concrete surfaces treated with hydrodemolition. It is possible that this could be determined experimentally, but this would require long-term measurements covering a wide range of environmental conditions. Another important issue is the lack of a rapid and reliable method for evaluating the moisture content of concrete (Borovina 2011; Courard et al. 2011).

The durability of the repair depends on the type, thickness and properties of the repair mortar, but all this becomes irrelevant if the quality of the substrate layer and the surface preparation are not adequate. The quality of the preparation of the concrete substrate for repair is verified by testing the bond strength using the pull-off method. The minimum tensile strength of adhesion on the concrete substrate should be at least 1.5 N/mm^2 (Bonaldo et al. 2005; Momayez et al. 2005; Naderi 2005; Albers et al. 2006; Bissonnette et al. 2014; Courard et al. 2014).

This paper presents the results of an experimental field research investigating the influence of the surface preparation technology after hydrodemolition on the adhesion of repair mortar to concrete. The experimental work is performed on the vertical surfaces of the column of the Klara Jug bridge, which is located in the southern part of the Zagreb Road bypass that overpasses three railway lines and two local roads (Figure 1). The experimental works are carried out in parallel with the ongoing repair works on other structural elements of the bridge, so that the experimental conditions correspond to the real construction site conditions. The results of this investigation can serve as a practical guide for the repair of vertical concrete elements of bridges, overpasses and viaducts.

Fig. 1: View of Klara jug bridge (left); column used for experimental work (right).

2 Experimental work

2.1 Design of experimental work

The experimental work was designed to represent a typical case of repairing damaged concrete with the repair mortar by reprofiling the concrete surface layer, while for hydrodemolition, the technique was used for the removal of damaged and/or contaminated concrete and for surface preparation. In order to avoid extreme ambient temperatures, all experimental activities were scheduled in spring, when ambient temperatures and general atmospheric conditions are moderate. The research focussed on evaluating the bond quality of the repair material, which has the highest influence on the durability of the repair.

The column surface was divided into 24 vertical segments, each with an area of 1 m^2. The existing concrete was removed by hydrodemolition to an average depth of 1.5–2 cm. At this depth, large aggregates were broken, which is a visual indicator of strongly bonded constituents in the concrete substrate. Hydrodemolition was performed using a Hammelmann HDP 114 high-pressure pump at a pressure of 2,100 bar.

After hydrodemolition, the surface preparation was performed with the same type of machine but with a so-called rotary nozzle. The rotary nozzle was operated at a pressure of 1,720 bar, which gives an optimal surface roughness and removes fine particles and concrete residues left behind by hydrodemolition. Moving the nozzle closer to the surface removes loose concrete particles, while a greater distance is more efficient to remove smaller particles. Lower water pressure with higher flow would be more effective in washing off the fine particles, but would not be able to remove loose concrete particles after hydrodemolition. Each 1 m^2 test segment was treated with water for 2 min (Figure 2). This amount of time was sufficient to create a well-prepared surface for mortar application. After water demolition and surface washing, the concrete surface was free of loose parts and cracks, and about 50% of the surface contained visible aggregate particles.

After surface preparation, the repair mortar was applied to the surface using the wet spray method. The repair mortar of class R4, according to the performance requirements of the standard EN 1504-3:2005, was sprayed with spray equipment from the manufacturer Putzmeister. The mortar was delivered in bags and mixed on site. Before delivery, the mortar was stored in a closed warehouse, while after delivery to the construction site, it was protected with a plastic sheet. The mortar was mixed at the construction site by adding water to the mixture. The mortar was mixed in a horizontal mixer positioned directly above the spray pump. When the required homogeneity of the mixture was achieved, the mortar was discharged into the pump and conveyed through a hose. A spray nozzle is attached to the end of the hose. In the nozzle, thorough mixing of compressed air and wet components takes place, forming the final jet.

The reprofiling of the surface layer of the concrete column was planned at a certain time after the surface preparation. First, a thin layer of mortar is sprayed on the surface and then a second layer is applied to achieve full thickness. As the repair mortar is sprayed onto the surface in a stream of air, the mortar hits the surface, forcing the air out of the mixture and compacting the mortar. The method of spraying in two layers minimises the risk of partial coverage of the contact surface with the mortar coming from the jet and ensures a more uniform quality of the repair material on the repaired surface. For each 1 m^2 segment, the spraying process took between 3–4 min. After spraying, the surface was smoothed with hand tools

Fig. 2: Surface preparation by hydrodemolition under high pressure to a depth of 1.5 cm, (left) and spraying of repair mortar (right).

and then additional finishing was applied (Figure 3). The repair mortar was cured by wrapping the surface with geotextile and spraying with water once a day (Figure 3).

Figure 4 shows the surface of the concrete column after hydrodemolition and the test segments.

Figure 5 shows the rotary nozzle used for surface preparation.

During surface preparation and application of the repair mortar, the following parameters were varied:

- Time between the end of the hydrodemolition surface preparation by washing with the roto nozzle and the start of spraying the repair mortar of 0 min, 10 min, 20 min, 30 min, 40 min, 50 min, 60 min, 70 min, 80 min, 90 min, 100 min, 110 min, 120 min, 180 min, 240 min, 6 h, 8 h, 24 h, 48 h and 96 h.
- Time between the end of the hydrodemolition and the start of spraying the repair mortar (without washing the concrete surface with the roto nozzle before spraying) of 0 min, 30 min, 60 min and 90 min.

All repair works were carried out by professionals specialised in the repair of concrete structures. During the entire period of the experimental works, the bridge was open to traffic, as well as the roads and the railroad line below the bridge, so that the presented works correspond to the real site conditions.

During the execution of the repair works, the ambient temperature, relative humidity, air pressure, wind direction and speed were monitored. The average air temperature ranged from 19°C to 27°C, and the relative humidity ranged from 37% to 62%. The air pressure was between 1,019 hPa and 1,022 hPa and the wind was blowing from the east and northeast at a speed between 0.3 m/s and 3 m/s.

2.2 Testing methods

The following test methods were used in the research experiment:

Fig. 3: Finishing of repair mortar surface (left) and curing of repair mortar (right).

Fig. 4: Appearance of concrete surface after surface preparation by hydrodemolition under high pressure (left) and test fields before pull off testing (right).

– assessment of bridge column and testing of concrete quality before experimental work,
– laboratory tests of physical, mechanical, deformation and durability properties of repair mortar, and
– tensile bond strength testing of the repair mortar by the pull-off method.

3 Test results

3.1 Condition assessment and testing of concrete column prior to repair

Before starting the repair work, assessment of the damage and concrete quality of the bridge column included:

– Visual inspection,
– Taking 100 mm cores according to EN 12504-1 and testing of compressive strength according to EN 12390-3 on specimens with a length to diameter ratio of 1:1,
– Taking 100 mm cores and testing of Young's elastic modulus in compression according to the Croatian standard HRN U.M1.025,
– Sampling of concrete powder from the structure and testing of chloride concentration with the RCT test (Germann Instruments),
– Testing of the pull-off tensile strength according to the standard EN 1542.

No damage to the concrete column was found during the visual inspection. Table 1 shows the results of testing the mechanical properties of the concrete specimens. The results show that the concrete has a compressive strength that meets the requirements for the concrete compressive strength class C30/37 according to the standard EN 206. The average Young's modulus of elasticity of the concrete is 32.7 ± 1.7 GPa, which is within the range characteristic of the strength class C30/37. The tensile strength of the concrete determined in the pull-off test is 2.24 ± 0.24 MPa (Figure 6).

The chloride concentration was measured at four test locations. The results are presented in Table 2. The critical concentration of chlorides per mass of concrete is 0.05%. The results in Table 2 show that the chloride concentration within the concrete column is below the critical concentration that could cause corrosion of the reinforcement.

The results of the tests on the concrete of the existing bridge column show that concrete has adequate compressive strength. The surface tensile strength determined by the pull-off method is above 1.5 MPa, which is usually considered the limit value for repair by re-profiling. Considering the low chloride content, it was decided to remove the surface layer of the concrete to a depth of 1.5–2 cm.

3.2 Repair mortar properties

The mortar samples were mixed onsite in a mortar mixer and were compacted according to the standard EN 196-1 in

Fig. 5: Roto nozzle for washing of concrete surface.

moulds for prisms with dimensions 40 mm x 40 mm x 160 mm and in cylinders with diameter 100 mm and height 200 mm. The samples were cured in the laboratory under water at 20 ± 2°C until testing. Figure 7 shows the mortar compacted in moulds for strength testing and the performance of the bending strength test.

The tests of the repair mortar included compressive and bending strength test (according to EN 12190), static Young's modulus (according to HRN U.M1.025), chloride diffusion (according to NT build 492), capillary absorption test (according to EN 13057) and drying shrinkage test (according to EN 12617-4).

The results of the tested mechanical and durability tests on the repair mortar at the age of 28 days are shown in Table 3. Shrinkage properties results of the tested repair mortar are shown in Table 4.

Tab. 1: Mechanical properties of concrete from the bridge column.

Property	Unit	Individual test results		Average value
Compressive strength	N/mm²	54.6		39.0
		38.6		
		31.4		
		31.3		
		39.3		
Pull-off tensile strength	N/mm²	2.20	2.04	2.24
		2.68	1.90	
		2.45	2.05	
		2.27	2.44	
		2.03	2.35	
Static modulus of elasticity	kN/mm²	34.337		32.679
		31.206		
		32.493		

All test results of the repair mortar at 28 days of age showed that the mortar meets the requirements of class R4. Results of laboratory testing of the repair mortar confirmed compatibility of the repair mortar and the existing concrete due to greater values of compressive and flexural strength and the lower value of static modulus of elasticity of the repair mortar compared to existing concrete.

3.3 Pull-off tensile strength testing

Table 5 shows the results of the pull-off test of the repair mortar after 28 days, when the surface was prepared by hydrodemolition and washing before the mortar was sprayed on. Table 6 shows the results of the pull-off tests for the case where surface preparation by hydrodemolition is omitted.

Tables 5 and 6 show the type and description of the braking surface. Mark A represents failure in concrete, mark B represents failure in the repair mortar and mark A/B represents failure at the contact surface of existing concrete and the repair mortar. In Table 5, the results of the pull-off strength equal to zero are not taken into account in the calculation of the average strength and represent cases of irregular failure of the specimen or breakage during the coring process.

4 Analysis and interpretation of results

The graph in Figure 8 shows the pull-off tensile strength tests as a function of the time elapsed between the end of the surface preparation and the application of the repair mortar. The results show that the highest pull-off strength

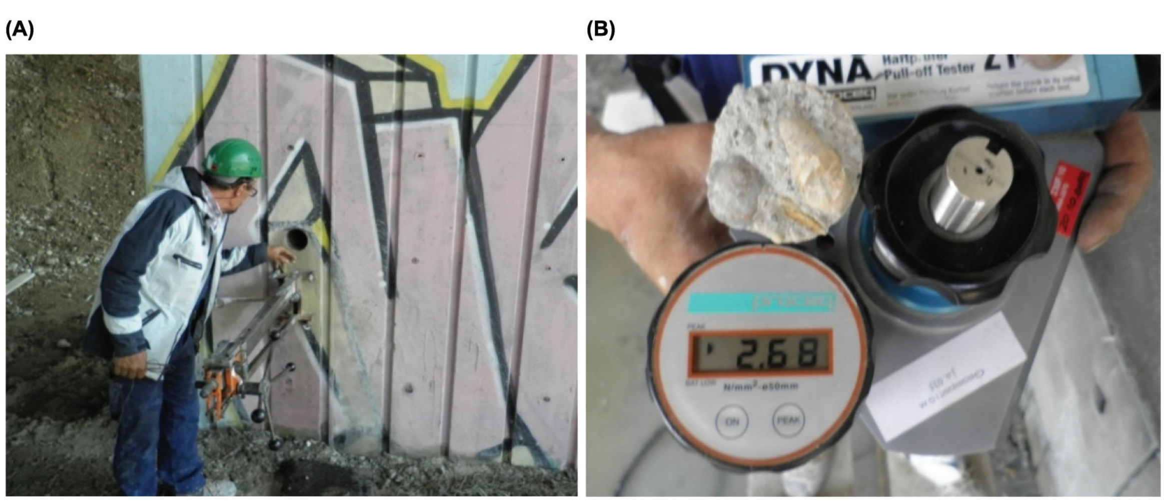

Fig. 6: Testing of concrete before repair: (A) coring of concrete; (B) pull-off test.

is achieved when the repair mortar was applied 90 min after surface preparation. The results also show that application of the repair mortar immediately after surface washing should be avoided. For mortar applied later than 30 min after surface washing, acceptable pull-off strength was obtained (≥1.5 MPa). In this context, it should be emphasised that already after 15 min, the visual appearance of the concrete surface appeared to be suitable for the application of the mortar, i.e. the concrete substrate was water saturated and there was no free water on the surface, which is a criterion mentioned by the manufacturer of the repair mortar, but this resulted in an unsatisfactory pull-off strength. The bond strength curve in Figure 8 shows a continuous increase until reaching the maximum and a steeper decrease after 100–110 min. This is due to the fact that the substrate not only dries out but also becomes contaminated by dust from road and site traffic. After the 3-h period, the pull-off tensile strength drops below the minimum required strength. As the surface becomes increasingly contaminated and the moisture content decreased over a period longer than 3 h, the bond strength decreases continuously.

Figure 9 compares the pull-off strength results of the repair mortar with and without surface preparation. The pull-off tensile strength of the repair mortar applied without surface preparation is on average 62% lower than

Tab. 2: Chloride concentration in concrete at different depths determined by the RCT method.

Test location	Depth (mm)	Chloride content (% of concrete mass)
1	0–10	0.012
	10–20	0.016
2	0–10	0.034
	10–20	0.021
3	0–10	0.018
	10–20	0.019
4	0–10	0.006
	10–20	0.005

Fig. 7: Mortar samples for compressive and bending strength testing (left) and testing of bending strength (right).

Tab. 3: Results of the mechanical and durability tests on the repair mortar.

Property	Unit	Individual test results						Average value
Compressive strength	N/mm^2	71.7	70.7	75.2	71.3	70.2	74.3	72.2
Flexural strength	N/mm^2	8.0		8.4		8.9		8.4
Static modulus of elasticity	kN/mm^2	28.451		26.941		29.334		28.242
Capillary absorption coefficient	kg/m^2/h$^{0.5}$	0.11		0.10		0.11		0.11
Chloride diffusion coefficient	10^{-12} m^2/s	1.24		2.76		1.81		1.94

Tab. 4: Shrinkage of repair mortar.

Age (day)	1	3	6	8	17	28
Shrinkage (mm/m)	0.000	0.238	0.331	0.445	0.642	0.756

Tab. 5: Results of the pull-off tensile strength tests for the case when concrete surface is prepared by hydrodemolition and washed with a roto nozzle prior to application of the repair mortar.

Time	Individual pull-off tensile strength results (N/mm²)			Average pull-off tensile strength result (N/mm²)
0 min	1.10 (50% A, 50% A/B)	1.32 (50% A, 50% A/B)	0.00	1.21
10 min	1.53 (20% A, 80% A/B)	1.54 (50% A/B, 50% B)	1.42 (100% A/B)	1.50
20 min	1.52 (100% A/B)	0.00	0.00	1.52
30 min	1.66 (50% A/B, 50% B)	2.18 (10% A, 90% A/B)	1.46 (20% A, 80% A/B)	1.77
40 min	1.60 (50% A/B, 50% B)	1.97 (50% A, 50% A/B)	0.00	1.79
50 min	1.69 (50% A/B, 50% A)	1.83 (10% A, 90% A/B)	0.00	1.76
60 min	1.48 (100% A/B)	2.35 (50% A/B, 50% B)	0.00	1.92
70 min	1.83 (100% A/B)	2.05 (50% A, 50% A/B)	1.90 (20% A, 80% A/B)	1.93
80 min	2.32 (100% A/B)	2.02 (60% A, 40% A/B)	2.10 (50% A, 50% A/B)	2.15
90 min	2.21 (50% A, 50% A/B)	2.59 (80% A, 20% A/B)	2.50 (80% A, 20% A/B)	2.43
100 min	1.99 (10% A, 90% A/B)	2.08 (60% A, 40% A/B)	2.17 (80% A, 20% A/B)	2.08
110 min	1.75 (50% A/B, 50% B)	1.69 (10% A, 90% A/B)	1.81 (10% A, 90% A/B)	1.75
120 min	1.51 (20% A, 80% A/B)	1.62 (50% A/B, 50% B)	1.63 (20% A, 80% A/B)	1.59
180 min	1.46 (30% A, 70% A/B)	1.70 (50% A/B, 50% B)	1.11 (20% A, 80% A/B)	1.42
240 min	1.11 (20% A/B, 80% B)	1.21 (20% A, 80% A/B)	1.87 (50% A/B, 50% B)	1.40
6 h	1.07 (100% A/B)	1.04 (100% A/B)	0.85 (100% A/B)	0.99
8 h	1.02 (20% A, 80% A/B)	0.95 (10% A, 90% A/B)	0.71 (20% A, 80% A/B)	0.89
24 h	0.82 (10% A, 90% A/B)	0.97 (20% A, 80% A/B)	0.61 (20% A, 80% A/B)	0.80
48 h	0.75 (20% A, 80% A/B)	0.55 (100% A/B)	0.80 (50% A/B, 50% B)	0.70
96 h	0.49 (100% A/B)	0.60 (50% A/B, 50% B)	0.71 (50% A/B, 50% B)	0.60

Tab. 6: Results of the pull-off tensile strength tests for the case when the concrete surface is treated by hydrodemolition but without washing with a roto nozzle prior to application of the repair mortar.

Time	Individual pull-off tensile strength results (N/mm²)			Average pull-off tensile strength results (N/mm²)
0 min	0.19 (100% A/B)	0.16 (100% A/B)	0.83 (80% A/B, 20% B)	0.39
30 min	0.34 (80% A/B, 20% B)	1.11 (50% A/B, 50% B)	0.53 (10% A, 90% A/B)	0.66
60 min	0.45 (10% A, 90% A/B)	0.66 (80% A/B, 20% B)	0.91 (50% B, 50% A/B)	0.67
90 min	1.17 (20% A, 80% A/B)	1.39 (30% A, 70% A/B)	0.83 (20% A, 80% A/B)	1.13

the repair mortar applied on washed surface. This is due to the presence of fine, unbound particles that can be recognised by running the palm over the surface. These particles are mostly chemically inert and contain some amount of unhydrated cement from the existing concrete. This weakens the bond between the substrate and the repair mortar, and failure during the pull-off test occurs predominantly at the contact between these two layers. In addition, surface cracking was observed on the surface of the repair mortar applied without surface preparation, regardless of the same curing method used on the other test fields. This shows that it is essential to wash the surface before applying the repair mortar.

Considering the weather conditions during the study, which were rather uniform and typical for spring, it can be said that the optimal time for applying the repair mortar after washing the concrete surface must be corrected for different weather conditions. In practical application, warmer weather, which leads to greater heating of the concrete surface, will require the repair mortar to be applied more quickly. This case is particularly pronounced when the relative humidity is low and the wind is blowing. In the opposite case, the application should be delayed until the concrete surface has lost excess water after washing. Nomograms showing the evaporation of water from fresh concrete can be a guide in finding the optimum time to

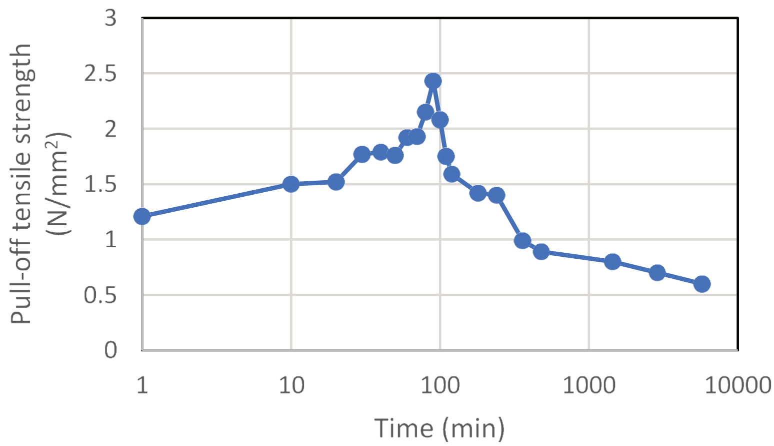

Fig. 8: Influence of time period between the end of surface preparation and application of the repair mortar on pull-off tensile strength.

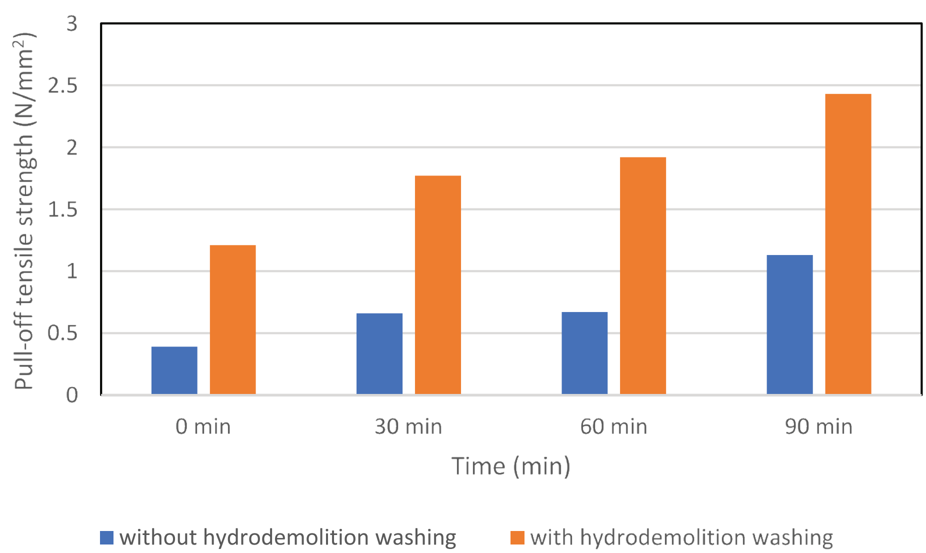

Fig. 9: Comparison of the pull-off tensile strength test results for two cases: with and without surface preparation by washing with a roto nozzle.

start reprofiling. However, it should be noted that different concretes have different water-absorption capacities, and this factor should also be considered, keeping in mind that concretes with lower compressive strengths are generally more porous and absorb more water. It goes without saying that in extreme conditions, the reprofiling work must be suspended or a solution found to reduce the impact of weather conditions on the surface to be rehabilitated.

5 Conclusions

The paper presents the experimental research work carried out on the column of the Klara Jug bridge during its rehabilitation. The research work was carried out in a laboratory and on test fields for each of the 24 samples with an area of 1 m^2. A simulation of the actual site rehabilitation process was carried out on the test fields, which included removal of the damaged concrete by hydrodemolition at a depth of 1.5–2 cm, washing (or not) of the concrete by a roto nozzle and wet spraying of the repair mortar.

The following main conclusions can be drawn:

- The results of the pull-off tensile bond strength show that there is an optimum period for the installation of repair mortar after washing the concrete surface with hydrodemolition. At an average temperature of 23°C, relative humidity of 50% and wind speed of 0.5 m/s to 1.0 m/s, the most suitable time for application of the mortar is 90 min after completion of washing of the vertical concrete surface by a roto nozzle. In other weather conditions, the application time must be postponed depending on the expected evaporation of water from the surface of the concrete substrate.

- The tensile strength of the bond between concrete and repair mortar is 62% lower if the concrete was not washed by a roto nozzle prior to application of the repair mortar.
- In addition to testing the bond tensile strength using the pull-off method, cleaning of the concrete surface prior to application of the repair mortar can be easily verified by running the palm of the hand over the surface and noting the presence of small particles that affect the adhesion of the repair mortar.

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