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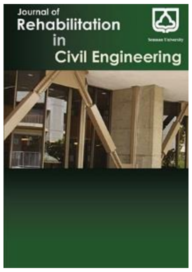

Study of Effect of Paste Volume, Water to Cementitious Materials and Fiber Dosages on Rheological Properties and In-Situ Strength of Self-Compacting Concrete

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ABSTRACT

As a vibration- free concrete, self- compacting concrete (SCC) can be easily used in the absence of consolidation, therefore; it is a good option for repairing and retrofitting concrete structures. The quality of repair layer is highly effective on a successful repair. Accordingly, in this study, factors affecting the quality of fiber-reinforced self-compacting concrete repair layer, including paste volume, the ratio of water to cementitious materials and the amount of fiber, are discussed. For this purpose, the in-situ strength of repair layers and cube samples with and without core are determined using pull- off method. Also comparisons between in-situ strengths in different methods (with and without core, on cubes or on repair layer) with compressive and tensile strength of specimens have been done. Results show that, considering the great influence of shrinkage and tensile strength, with reduced paste volume, cementitious material and increased fiber, in-situ strength of repair layer increases. Moreover, we found that even in the best condition of concrete substrate layer (i.e. saturated surface dry) a repair layer has a lower strength than a cube specimen. Also, presence of fibers has the huge effect on results of pull-off test depends on the method of the test (with or without core).

1. Introduction

SCC (self- compacting concrete) is a new promising innovation in concrete industry in the last 20 years. Compared with traditional concrete, SCC is vibration- free. This results in reduced number of workers, increased profit and improved working environment

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[1]. Fibers are widely used in concrete industry, to prevent cracks. Polypropylene fibers prevent concrete cracking and shrinkage, especially in the early ages. The tendency to shrinkage causes tensile stress and cracking will occur. In some cases, cracks may spread to overtake the entire thickness of concrete members and reduce its quality and durability [2]. High amount of fibers and its highly tensile strength prevent these cracks.

Destruction of highways and concrete bridges under heavy use and environmental attacks over time are significant problems of these structures. Cracked deck of bridges during winter can cause concrete reinforcement corrosion and internal damage. To protect the decks against salt, applying a concrete repair layer is the most considerable effort. The best way to reduce destruction rate is to apply a concrete repair layer on decks of bridges which creates a water proof barrier on decks to protect them against corrosion, water and chemical materials penetration [3]. Early-age shrinkage in repair layer is the most important reason for reducing durability of repair layers. Great attention has been always paid to SCC cracking, because, compared with ordinary concrete, SCC is designed with higher paste volume. Paste volume is usually defined as total volume of cement, water, minerals and chemical additives. Increase in paste will improve flow ability; however, it may cause adverse effects on mechanical properties and time- dependent concrete deformations. Amongst solutions proposed to control cracking which caused by shrinkage, one promising way is to use randomly-distributed steel, carbon, polypropylene and other fibers in concrete that prevents the growth of cracks and creating bridge actions on crack's width. Fibers affect both width and length of shrinkage and reduce damage in concrete layer and substrate concrete interface. Additionally, fibers improve mechanical properties, durability, toughness, impact strength and fatigue strength of repair layer that is highly desirable for a repair layer [4]. Granju [5] states that fibers increase cohesion through crack growth control. Cracking results from non-uniform shrinkage in repair layer [6, 7 and 8]. It is also claimed that fibers have good effects on reducing cracking spread in repair layer [9, 10, 11, 12 and 13]. In France, according to a study on the correlation between shrinkage and debonding of repair layer from substrate concrete, positive effect of reinforced repair layer on fibers was confirmed [9, 14, 15, 16, 17 and 18]. It was also reported that the fibrous cement repair layer, compared with fibreless cement repair layer, is less affected by fatigue [19 and 20]. Compressive strength of repair materials does not affect their bonding significantly. However, tensile strength has serious and positive effects on bonding.

Curing is an important factor to reduce shrinkage of repair layer and tensile stress on the interface with substrate. It prevents moisture drop and reduces early age shrinkage, as a result. It has other advantages as well, namely, reduce of plastic cracking risk, higher strength, improved durability and better wearing strength. Paulson et al [21] recommended a minimum 5-day curing. It was also found out that direct sunshine has negative effects on bonding [22]. Proper substrate, appropriate materials and good curing result in long term appropriate interface properties. Findings show that repaired concrete beams and columns act like single layer [23,24]. Pull- off method has been applied by many studies to determine in-situ strength and bonding. For instance, Mikami et al discussed the effect of heat on bonding of FRP sheets to concrete, using pull- off test [25]. Ghavidel et al studied the effect of disc size and on steel fiber-reinforced SCC through pull- off test [26]. Sun et al analyzed three-dimensional finite element model of failure modes by pull- off test [27]. Also, some researchers have worked on prediction of pull-off test and bonding between repair layer and concrete substrate using fuzzy logic, neural network analysis and other mathematical and heuristic methods [28- 31].

2. Laboratory Experiments

In this study, three important parameters affecting rheological and mechanical properties of fibrous SCC, including the ratio of paste volume to total volume of concrete, the ratio of water to summation of cement and pozzolan and the amount of polypropylene fibers are discussed. The impact of any changes in these parameters on rheological properties of concrete is evaluated through slump flow test, V funnel test, L box test and T50 test. Afterwards, 15-cm cube samples for compressive strength test, standard cylindrical samples for Brazilian test and modulus of elasticity measurement and prismatic samples for shrinkage test were prepared. In order to determine in-situ strength of the repair layer, first, ordinary concretes with high strength (over 50 MPa) were made as cube samples which were divided into three equal 5-cm portions cut by saw. After six months (in order to the samples undergo all shrinkage in this long time and avoid shrinkage and possible errors after applying repair layer), 2-cm self-compacting repair layers were poured on the substrates. After 28 days of curing the samples in water, using pull- off, the in-situ strength of samples was determined. Pull-off was also used to examine the in-situ strength of the SCC poured on cube samples with and without coring, separately. Round gravels of maximum 12.5mm size, 2.64 g/cm^3 bulk density and 1.5% water absorption were used. The bulk density of round sand used for this purpose was 2.6 g/cm^3 with 2.5% water absorption. In this study, 1-425 Portland cement was used, chemical composition of the cement is displayed in table 1.

Table 1. Properties of the cement.

Composition	SiO2 %	Al2O3 %	Fe2O3 %	CaO %	MgO %	SO3 %	CL %	K2O %	Na2O %	LOI %
Dosage	21.19	5.09	3.94	63.04	1.47	2.35	0.029	0.72	0.51	2.17

Micro silica with specific weight of 2200 Kg/m^3 was added to the concrete mix as a portion of cement. Polypropylene fibers were 6 mm long. FARCO PLAST P10-3R super plasticizer was used which is based on modified polycarboxylate. Mix designs of the repair layers are listed in table 2.

Table 2. Mix designs of the repair layers.

Mix designs	Cement (Kg/m^3)	Gravel (Kg/m^3)	Sand (Kg/m^3)	Limestone (Kg/m^3)	Micro silica (Kg/m^3)	Water (Kg/m^3)	PP %	S.P. %	W/(C+MS)	V_{paste}
V1W1P0	405	740	850	229.5	45	144	0	1.5	0.32	0.4
V1W2P0	405	740	850	250	45	162	0	1.3	0.36	0.44
V1W3P0	405	740	850	200.5	45	180	0	۱	0.40	0.48
V2W1P0	442	691	793	332.5	49.2	157	0	1.5	0.32	0.4
V2W2P0	442	691	793	277.5	49.2	177	0	1.2	0.36	0.44
V2W3P0	442	691	793	223.87	49.2	196.5	0	0.9	0.4	0.48

Table 2. Mix designs of the repair layers (continuaded).

Mix designs	Cement (Kg/m^3)	Gravel (Kg/m^3)	Sand (Kg/m^3)	Limestone (Kg/m^3)	Micro silica (Kg/m^3)	Water (Kg/m^3)	PP %	S.P. %	W/(C+MS)	V_{paste}
V3W1P0	486	636	729	357.7	54	173	0	1.1	0.32	0.4
V3W2P0	486	636	729	300	54	194	0	0.8	0.36	0.44
V3W3P0	486	636	729	239.5	54	216	0	0.6	0.40	0.48
V1W1P1	405	740	850	299.5	45	144	0.1	1.5	0.32	0.4
V1W2P1	405	740	850	250	45	162	0.1	1.3	0.36	0.44
V1W3P1	405	740	850	200.5	45	180	0.1	1	0.4	0.48
V2W1P1	442	691	793	332.5	49.2	157	0.1	1.5	0.32	0.4
V2W2P1	442	691	793	277.5	49.2	177	0.1	1.2	0.36	0.44
V2W3P1	442	691	793	223.87	49.2	196.5	0.1	0.9	0.40	0.48
V3W1P1	486	636	729	357.7	54	173	0.1	1.1	0.32	0.4
V3W2P1	486	636	729	300	54	194	0.1	0.8	0.36	0.44
V3W3P1	486	636	729	239.5	54	216	0.1	0.6	0.4	0.48
V1W1P2	405	740	850	229.5	45	144	0.2	1.5	0.32	0.4
V1W2P2	405	740	850	250	45	162	0.2	1.3	0.36	0.44
V1W3P2	405	740	850	200.5	45	180	0.2	1	0.40	0.48
V2W1P2	442	691	793	332.5	49.2	157	0.2	1.5	0.32	0.4
V2W2P2	442	691	793	277.5	49.2	177	0.2	1.2	0.36	0.44
V2W3P2	442	691	793	223.87	49.2	196.5	0.2	0.9	0.4	0.48
V3W1P2	486	636	729	357.7	54	173	0.2	1.1	0.32	0.4
V3W2P2	486	636	729	300	54	194	0.2	0.8	0.36	0.44
V3W3P2	486	636	729	239.5	54	216	0.2	0.6	0.40	0.48

Figure 1 shows the slump-flow test based on EFNARC [28].

Fig. 1. Slump Flow test.

In order to determine in-situ strength of concrete, pull-off test with and without coring can be used. To assess the real quality of repair layer on substrate concrete, pull- off test without coring is used to find in-situ strength of the layer. Images of this process are illustrated in figure 2.

Fig. 2. determination of in-situ strength of repair layer using Pull-Off (without coring).

The in-situ strengths of repair concrete for sample cubes with and without coring were determined. Both tests with and without core were carried out to compare results and examine how much the tests without coring are reliable. The process has been shown in figure 3.

Fig. 3. Failure surfaces in Pull-off test on 15cm cubes (left: without coring, right: with coring).

3 Results

Rheological and mechanical properties of the mix designs have been listed in table 3. Modulus of elasticity and shrinkage have been determined using ASTM C469 and ASTM C157 respectively.

Table 3. Rheological and hardened properties of the mix designs.

Mix design	Slump flow (mm)	T50 (sec)	L – box (mm/mm)	V - funnel (sec)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	shrinkage (×10^6)	In- situ strength of non-core cubic specimen (MPa)	In- situ strength of core cubic specimen (MPa)	In- situ strength of repair layer (MPa)
V1W1P0	670	5.30	1	12.22	56.1	4.86	34.3	470	6.58	3.75	4.33
V1W2P0	630	3.85	1	11.20	55.2	4.77	33.1	600	5.63	3.67	4.08
V1W3P0	600	3.67	1	7.89	53.4	4.42	31.8	690	5.38	3.54	3.79
V2W1P0	730	3.50	1	8.05	53.5	4.67	33.4	520	5.50	3.50	4.08
V2W2P0	680	3.24	1	6.54	52	4.53	32.6	620	5.17	3.42	3.71
V2W3P0	650	2.86	1	4.65	47.3	4.02	30.7	760	4.63	3.33	3.29
V3W1P0	670	3.03	1	5.31	49.1	4.15	32.7	590	5.21	3.25	3.71
V3W2P0	550	2.67	1	3.87	46.2	3.93	31.4	740	4.75	2.92	3.04
V3W3P0	520	4.99	1	2.98	38.9	3.38	29.9	850	4.04	2.79	2.54
V1W1P1	650	5.80	1	13.40	57.9	5.47	37.7	450	6.67	4.17	5.75
V1W2P1	600	4.20	1	12.10	56.4	5.30	36.3	570	5.92	4.13	5.42
V1W3P1	560	4	1	8.66	52.8	5.04	34.8	660	5.04	4.04	4.83
V2W1P1	710	4.10	0.95	9	54.7	5.33	36.8	500	5.71	3.83	5.38
V2W2P1	660	4	0.90	7.63	51.4	5.11	35.5	595	4.83	3.75	5.17
V2W3P1	620	2.99	0.90	5.78	48.7	4.60	33.9	735	4.33	3.88	4.83
V3W1P1	660	3.60	0.85	6	49.5	4.76	35.6	560	5.67	3.08	5.25
V3W2P1	540	2.98	0.85	4.20	45.4	4.43	34.8	700	4.58	3.38	3.92
V3W3P1	500	8	0.70	3.30	37.2	4.20	31.9	790	4.21	3.08	3.58
V1W1P2	640	6	0.95	15	56	5.11	37.8	455	6.83	3.92	4.67
V1W2P2	570	4.5	0.95	14.10	54.8	5.04	35.4	580	5.79	3.79	4.54
V1W3P2	540	4.30	0.90	10.20	53	4.87	34.3	675	5.29	3.96	4.13
V2W1P2	680	4.60	0.85	10.60	52.8	5.14	36.3	515	5.33	3.71	4.58
V2W2P2	640	4.40	0.80	9.8	52.3	4.94	34.7	615	4.58	3.63	5.17
V2W3P2	600	3.26	0.80	6.90	46.6	4.32	33.1	750	4.83	3.42	4.63
V3W1P2	630	4.10	0.70	7.23	49.5	4.42	34.9	570	5.04	3.21	4.29
V3W2P2	530	3.5	0.70	5.10	45.7	4.13	33.4	710	4.96	3	3.58
V3W3P2	480	8.32	0.65	3.98	38.3	3.58	30.7	820	4.33	2.83	2.92

Tensile strength increases by adding 0.1% fibers, however; it drops if this amount rises to 0.2% but it is still higher, compared with fibreless samples. Changes in tensile strength which result from changes in paste volume and the amount of water, are similar to compressive strength so that increase in amounts of paste and mixing water lead to reduce in tensile strength. Adding fibers causes decrease in shrinkage which is due to positive effect of fibers on cracking control and tensile stress. In spite of controlling effect of fibers in samples with 0.2% fibers, compared with samples with 0.1% fiber, less shrinkage occurs i.e. for samples with 0.1% polypropylene fibers, it is -4.70% and for samples with 0.2% polypropylene fibers, it is -2.53%.

Results of in-situ strength of sample cubes without coring are similar to that of Brazilian test, i.e. decline in results occurs with increase in paste volume and water amount. However, in samples with fiber, results are not similar to Brazilian test. Considering that coring was not carried out for this test and only metal cylinder of pull-off test was fixed on the sample, the positive effect of fibers in tensile strength should not be neglected. Results confirm this point as well. Therefore, adding fibers to samples does not make any change in test results and they are almost similar to fibreless tests. Hence, it can be claimed that proper and reliable results are obtained from this test, once fibreless samples are evaluated. However, for samples with fiber, the test cannot represent tensile strength of concrete (when we don't core). While, regarding low or no impact of fibers on compressive strength, even in samples with fiber, the test can be an indicator of compressive strength and in-situ quality of samples.

The in-situ strength test for sample cube with coring indicates tensile strength and concrete quality, the process of which is similar to that of Brazilian test, i.e. reduce in in-situ strength occurs with increase in paste volume and water amounts. However, unlike non-core pull- off test, in fiber ones, results are similar to tensile strength of the concrete. The reason is quite clear. Considering coring and core failure at a depth of 2.5 cm, fibers will be effective and due to tensile nature of pull-off test, results improve, compared with fibreless ones. Additionally, despite better results compared with fibreless samples6, samples with 0.2% polypropylene fibers show weaker results compared with specimens with 0.1% polypropylene fibers, which is an indicator of optimal 0.1% polypropylene fibers amount.

The in-situ strength test for repair layer evaluates the quality of the layer on concrete substrate. Due to considerable impact of polypropylene fibers on reducing of shrinkage and also huge impact of shrinkage on the quality of repair layer, the quality of this layer improves via adding 0.1% polypropylene fibers. This is while the same test on sample cube did not indicate any change in results. This issue shows considerable effect of shrinkage on declined quality of repair layer and also positive impact of fibers on control of shrinkage and increase in quality of repair concrete. With an increase of fibers from 0.1% to 0.2%, results drop again, but they are still better than fibreless specimens. In-situ strength, as expected, depends on the amount of water to cementitious materials and paste volume, so that an increase in either of them causes a decline in the quality of repair layer. To determine in-situ strength of concrete, pull-off test is the best choice, with partial destruction in core and no destruction in non-core specimens. Considering that both tests were carried out in this paper, a comparison between two methods has been done.

It is obvious that results have high dispersion, therefore; there is no reasonable correlation between the two methods for fibrous concrete samples (R^2= 0.3068), because failure occurs on sample surface and fibers do not have any impact on non-core pull- off results.

For pull-off test with core, we obtained R^2=0.9032 for fibreless specimens. So it is quite clear that there is a significant correlation between compressive strength and in-situ strength of core pull-off which proves the reliability and validity of the method to evaluate concrete quality. Also we obtained R^2=0.7126 for fibrous ones. A comparison between that and the former one shows that the accuracy of correlation between the two methods has decreased because fibrous samples were evaluated. Fibers do not have significant impact on compressive strength, while core pull-off results are highly affected by fibers. Hence, the method accuracy declines.

Figures 4 and 5 shows the relationship between pull-off test results for both core and non-core in-situ strength and sample cube compressive strength for both fibrous and fibreless samples. Although fibers do not have any significant impact on non-core pull-off test results, the diagram shows low accuracy of the method ($R^2 < 0.7$). For fibreless samples, core pull-off test is the best option, however; for fiber samples, non-core pull-off test is better for estimation of compressive strength. Results from in-situ strength of repair layer and cube samples are displayed in figure 6. As it is observed, in-situ strength of the repair layers, in most cases, is lower than cube samples which is an indicator of the impact of shrinkage on the quality of repair layer.

4. Predicting the In-Situ Strength of Repair Layer

As was mentioned before, the in-situ strength of repair layer is highly affected by shrinkage, therefore; fibers play the main role in the amount of this strength, unlike the non-core in-situ strength of cube samples with no considerable effect of fibers on results. Using linear regression, a correlation was obtained to estimate the in-situ strength of repair layer. Parameters related to the in-situ strength include: paste volume, ratio of water to cementitious material, fiber dosages, shrinkage, compressive strength and tensile strength. Suitable accuracy of the obtained equation (R^2=0.870 and the average error of about 5%), approves the impact of the parameters on the in-situ strength. It is noteworthy that the effect of parameters was proved earlier in laboratory and test results. Following equation was obtained:

$$INSITU = -15.007 + 16.294(PV) + 16.878 (WTOC) 0.623 + (F) - 0.004(SH) + 0.035 (CS) + 1.510 (TS) \quad (1)$$

Where: INSITU is the in-situ strength of repair layer by non-core pull- off test after 28 days in MPa. PV is the ratio of paste volume to total volume of the concrete, WTOC is the ratio of water to cementitious materials, F is fiber dosages (by volume of the concrete), SH is the amount of shrinkage × 10^6, CS is 28- day compressive strength of 15-cm cube sample in MPa and TS is results from Brazilian test on standard cylinder after 28 days in MPa.

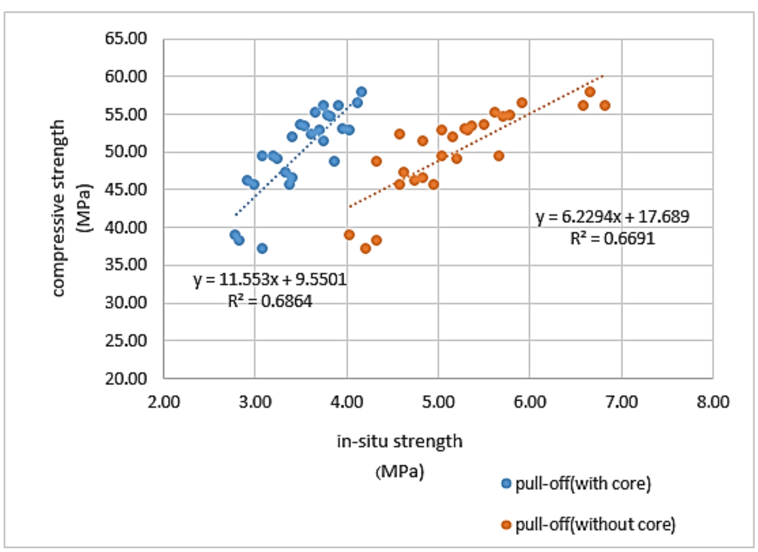

Fig. 4. correlation between compressive strength and pull-off method with and without coring for fibreless and fibrous specimens.

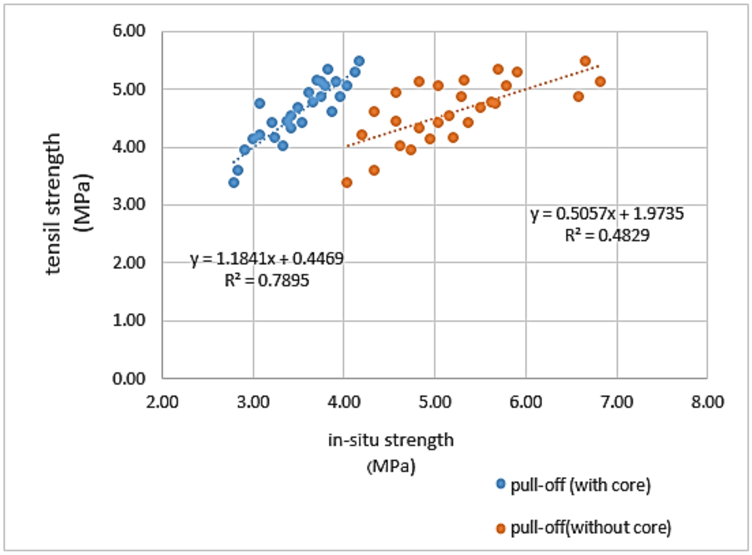

Fig. 5. correlation between tensile strength and pull-off method with and without coring for fibreless and fibrous specimens.

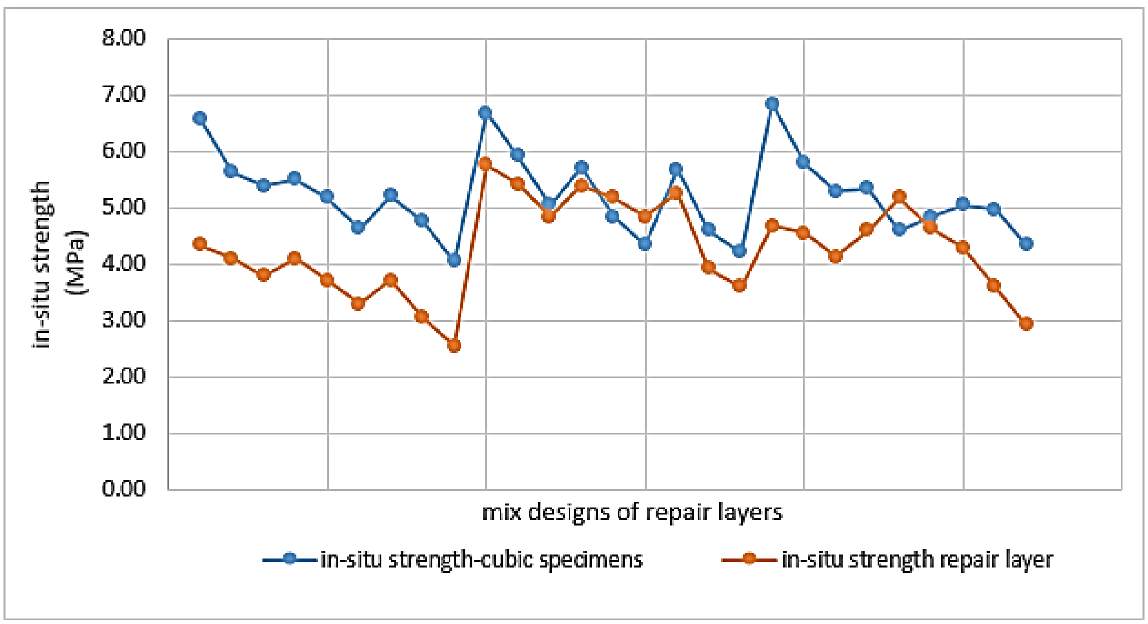

Fig. 6. comparison between in-situ strength of cube specimens and repair layers.

5. Conclusion

In this research, we determined the effect of paste volume, water to cementitious ratio and fiber dosages on in-situ strength of repair layer. Also, we showed that in repair concrete without fiber, pull-off test without coring which it is more simple and absolutely non-destructive, could be used instead of pull-off test with coring. But with usage of fiber in repair layer, the results of these two method showed different character of the concrete repair layer.

1. Adding fibers results in reduce of slump flow and flow ability of concrete which is reflected in T50 test. Additionally, with the change of fiber amount from 0.1% to 0.2%,

discharge rate of V funnel increases 2.77 times and the blocking in L box test reduces 2.01 times.

2. Adding polypropylene fibers results in the increased tensile strength of concrete. On average, 0.1% fibers cause 14.53% and 0.2% fibers cause 7.24% more tensile strength.

3. Adding fibers results in increasing of modulus of elasticity, which is 9.43% for 0.1% and 7.65% for 0.2% fibers. As is seen, samples with 0.1% fibers show better results.

4. Adding fibers results in reduce of shrinkage. On average, adding 0.1% fibers causes 4.70% and adding 0.2% fibers causes 2.53% reduction in shrinkage.

5. Increase in ratio of water to cementitious materials and paste volume, caused reduction in results of pull- off tests.

6. In fibreless conditions, there is a reasonable correlation between the results of pull- off test for cube samples with and without coring.

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