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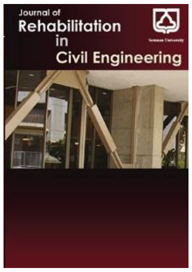

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An Investigation on In-situ Strength and Bonding Strength of Polymer Modified Concretes (PMC) as Repair Overlays on Conventional Concrete Substrate

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ABSTRACT

Polymer modified concrete (PMC) consists of Portland cement concrete with a polymer modifier. Its advantages are proper bonding strength to substrate concrete, high tensile and flexural strength and low amount of shrinkage and permeability. Using PMC overlays can be considered as a method for preservation of damaged concrete structures due to their suitable performance and durability. In this research, 24 mix designs of polymer modified concrete as the repair overlay containing two different types of modifier polymers (Styrene butadiene rubber (SBR)-based and Acrylic-based polymers) with different replacement percentages and various amounts of silica fume was considered to investigate the effect of type and amount of polymers and also presence of silica fume. The in-situ strengths are obtained by the Pull-off Method in different conditions of presence of cores and without cores on cubic samples and without cores on repair overlays. The bonding strength of repair overlays to the substrate is also assessed and a formula is presented for prediction of bonding strength and in-situ strength by consideration mechanical properties.In both polymer modifiers, maximum bonding occurred in the presence of polymer with 20% of cement weight. SBR-based PMC showed stronger bonding compared to the Acrylic-based PMC.

1. Introduction

Polymer modified concretes (PMC) with latexes have been used since the 1950s. Polymer modified concrete consists of Portland cement concrete with a polymer modifier such as acrylic, styrene Butadiene rubber (SBR), polyvinyl acetate and ethylene vinyl acetate. [1, 2]. Some advantages of these concretes are good bonding strength to the substrate concrete, high flexural and tensile strength and low permeability [3-5]. The desirable characteristic of the polymer modified concrete is that it is very similar to conventional cement concrete technology. Only a small number of polymers are suitable to be added to concrete and most of other polymers produce low quality polymer modified concretes. The cost of Polymer modified concrete (PMC) is less than Polymer concretes (PC) which is only consists of polymer and aggregates because less amount of polymer is required in the latter one[1].

The durability of polymer modified concrete against aggressive and corrosive environments is considerable compared to unmodified concretes [6-8]. Dogan et al. [9] have studied high performance concretes containing Styrene Butadiene resin. Styrene Butadiene has been used as a replacement for the cement in different percentages of 1, 3, 5 and 8. Test results of water absorption, compressive strength, tensile strength and ultrasonic pulse velocity are investigated. The results show that addition of SBR decreased the water absorption ratio about 45 percent. Also a slight increase in compressive strength and a significant increase in tensile strength are observed.

Bonding strength between overlay and substrate significantly depends on the test method. According to the method which has been used, bonding strength that is declared may be much greater than its actual value. Bonding between two surfaces generally depends on surface bonding characteristics, friction, involvement of aggregate and specifications that vary over time[10-18]. The bonding of polymer modified concretes to conventional concrete substrate is stronger compared to the bonding between two conventional concretes on each other. In the research of Momayez et al. [19] bonding of polymer concretes modified with SBR and a polymer adhesive named K100 is compared to the conventional concretes and concretes containing silica fume and the superiority of polymer modified concretes has been confirmed. Polymers can also improve the properties of high performance concretes**.** Pull-off test for assessment of bonding strength and in-situ strength is an accepted method. In the research of Ghavidel et al. [20] the applicability of pull-off test for assessing the in-situ quality of steel fiber reinforced self-compacting concrete and effects of different parameters on the test was investigated. Sun et al. [21] studied on the three-dimensional finite element analysis of fracture modes for the pull-off test.

In this study, the effect of type and amount of polymers and also presence of silica fume on in-situ strength and bonding strength of polymer modified concrete as the repair overlay on the conventional concrete substrate is investigated. 24 mix designs of polymer modified concretes as the repair overlays containing two different types of modifier polymers with different replacement percentages and various amounts of silica fume is considered. The in-situ strengths are obtained by Pull-off method in different conditions of: presence of cores and without cores on cubic samples and without cores on repair overlays. The bonding strength of repair overlays to substrate is also assessed and a formula is presented for prediction of bonding strength by consideration of in-situ strength and mechanical properties.

2. Materials and Methods

2.1. Materials

River gravel was used with a maximum grain size of 12.5 mm, density of 2.64 gr/cm^3 and water absorption of 1.5 percent. Gradation was done based on the standard ASTM C33[22]. River sand with rounded corners, density of 2.6 gr/cm^3 and water absorption of 2.5 percent was used. Based on the size of the aggregates, 80% of the consumed sand was between 0 to 3 millimeters and 20% is between 3 to 6 millimeters. In this study, type I Portland cement was used. In this study, two types of polymers were used. PAYA L-310, that is a single-component resin based on SBR produced by Payazhik Co. in Iran and the other polymer is SureAdd 320, that is a single component resin based on Acrylic produced by SureLevel Co. in Iran. Both of these polymers can be used as the modifier polymer in the polymer modified concretes and mortars. Both of the polymers were in the milky white liquid physical state. The value of PH for both of the polymers is 8 ± 1. The densities of PAYA L-310 and SureAdd 320 were 1.01 gr/cm^3 and 1.06 gr/cm^3, respectively. For both polymers, run-time and allowable temperatures were 10^o to 40^{o}C and -10^o to 70^{o}C, respectively. The consumed Silica fume was manufactured by Ferrosilice Co. in Iran which had a density of 2200 Kg/m^3. The consumed superplasticizer with the commercial name of FARCO PLAST P103R was based on the modified Polycarboxylates and had been produced by Shimi Sakhteman Co. in Iran.

2.2. Specimen Preparation

To prevent substrate concrete fracture and the effect of its relative error in various stages of the experiment, concretes with compressive strength of 50 MPa were built to assure that during the bonding tests, fracture does not happen from the substrate concrete. After construction of the concretes and curing them for 28 days in water, 150 mm cubes were saw cut in order to produce 150*150*50 mm concrete slabs to be used as substrate concrete. Considering that the concrete was cut with a special blade, it had a perfectly smooth surface and this smoothness minimized the error due to different possible unevenness in the bonding strength tests results. Then the concretes were remained in the air for about 6 months in order to complete the process of shrinkage. Completion of shrinkage caused the bonding tests of repair overlay to this concrete as the substrate, have less errors.

The mix designs used as overlay materials are shown in Table 1. According to manufacturer's suggestion, the polymer modified concretes has been made with three weight ratios of 1:3, 1:1 and 3:1 replacement of water. Also Silica fume with three percentages of 5, 10 and 15 was used as the replacement of cement. In all of polymer modified concrete mix designs, in order to achieve a better comparison, the amount of superplasticizer was kept constant with the value of 0.3 percent of cement weight. In the naming of the mix designs, “P1” indicates the polymer containing SBR and “P2” indicates the polymer containing acrylic. The number that comes after that, indicates the percentage of water that is replaced with polymer. The presence of ”S” indicates the replacement of cement with Silica fume and the number after that indicates the replacement percentage. 24 hours after applying the overlays, and filling the moulds, specimens were removed. All of polymer modified concrete specimens were moist cured for 5 days, followed by dry curing at ambient temperature for 23 days and then tests were performed. This method of curing was chosen in order to minimize the amount of shrinkage and also permit the latex film to form[23, 24].

2.3. Tests Procedure

For in-situ tests on considered mix designs, the tests were applied in conditions of cored and without core cubic samples and without core repaired samples. Also bonding strength was assessed by Pull-off method with core on repaired samples. For Pull-off test method the thickness of the overlay was 20mm on the substrate concrete and partial cores with height of 2.5 cm were cut on them so that the whole depth of the repair overlay and 0.5 cm of the substrate layer was present in this partial core (Fig.1 and Fig.2).

Table 1 The parameters of mix designs used as the overlays

Mix No.	Name	Gravel (Kg)	Sand (Kg)	Polymer Type	Polymer (kg)	Cement (Kg)	Water (Kg)	P/W[1]	SF[2]	(W+P)/(C+SF)[3]
1	R0	1090	762	-	-	450	180	-	0	0.4
2	P125	1090	762	Paya L-310	45	450	135	0.25	0	0.4
3	P150	1090	762	Paya L-310	90	450	90	0.5	0	0.4
4	P175	1090	762	Paya L-310	135	450	45	0.75	0	0.4
5	P225	1090	762	SureAdd 320	45	450	135	0.25	0	0.4
6	P250	1090	762	SureAdd 320	90	450	90	0.5	0	0.4
7	P275	1090	762	SureAdd 320	135	450	45	0.75	0	0.4
8	S5P125	1090	762	Paya L-310	45	422.5	135	0.25	22.5	0.4
9	S5P150	1090	762	Paya L-310	90	422.5	90	0.5	22.5	0.4
10	S5P175	1090	762	Paya L-310	135	422.5	45	0.75	22.5	0.4
11	S5P225	1090	762	SureAdd 320	45	422.5	135	0.25	22.5	0.4
12	S5P250	1090	762	SureAdd 320	90	422.5	90	0.5	22.5	0.4
13	S5P275	1090	762	SureAdd 320	135	422.5	45	0.75	22.5	0.4
14	S10P125	1090	762	Paya L-310	45	405	135	0.25	45	0.4
15	S10P150	1090	762	Paya L-310	90	405	90	0.5	45	0.4
16	S10P175	1090	762	Paya L-310	135	405	45	0.75	45	0.4
17	S10P225	1090	762	SureAdd 320	45	405	135	0.25	45	0.4
18	S10P250	1090	762	SureAdd 320	90	405	90	0.5	45	0.4
19	S10P275	1090	762	SureAdd 320	135	405	45	0.75	45	0.4
20	S15P125	1090	762	Paya L-310	45	382.5	135	0.25	67.5	0.4
21	S15P150	1090	762	Paya L-310	90	382.5	90	0.5	67.5	0.4
22	S15P175	1090	762	Paya L-310	135	382.5	45	0.75	67.5	0.4
23	S15P225	1090	762	SureAdd 320	45	382.5	135	0.25	67.5	0.4
24	S15P250	1090	762	SureAdd 320	90	382.5	90	0.5	67.5	0.4
25	S15P275	1090	762	SureAdd 320	135	382.5	45	0.75	67.5	0.4

[1]Polymer to water ratio
[2]Silica Fume replacement
[3]Total water and polymer to cement and Silica Fume ratio

The tests for determining the mechanical characteristics including compressive strength, flexural strength, modulus of elasticity and the amount of shrinkage were performed on all mix designs prepared for repair overlay. For determination of bonding strength between repair overlays and the substrate layer and also the in-situ strength of prepared samples with the aid of Pull-off test, steel discs with diameter of 5 cm and height of 2.5 cm according to standard ASTM D7234 [25] was used. In order to perform test, a steel disc was attached by adhesive to the concrete surface. When the adhesive is dried, this steel disc is pulled to the threshold of failure by specific Pull-off test equipment. The tensile force that is required to be applied to steel disc so that the disc with the concrete layer both detach, is assessed.

Fig. 1 Partial core drilled samples and the equipment for In-situ and Pull-off test

Fig. 2 In-situ test with core and without core drilling

3. Results and discussion

The results tests are shown in Table 2. The highest value of 28-day compressive strength of polymer modified concretes containing SBR-based polymer belonged to mix design P150 with the value of 46.22 MPa. The highest value of 28-day compressive strength of polymer modified concretes containing Acrylic-based polymer belonged to mix design P250 and its value was equal to 41.33 MPa. In general, polymer modified concretes with SBR-based polymer had a higher compressive strength compared to the polymer modified concretes with Acrylic-based polymer but in both cases a slight reduction with respect to control mix design was observable. In both types of polymers, 50% replacement of water with polymer showed the highest values of compressive strength and by increasing the replacement of Silica Fume, the compressive strength was decreased. The highest value of flexural strength was obtained in mix designs containing 75% replacement of water with polymer which was 10.82 MPa in mix P175(about 100% increment with respect to control mix) and 9.63 MPa in mix P275(about 77% increment with respect to control mix). All of polymer modified concretes showed higher flexural strength compared to that of control mix design. In case of tensile strength, there are 50% increment in presence of 75% replacement of water with SBR-based polymer and 36% increment in presence of 75% replacement of water with Acrylic-based polymer. The presence of polymer decreased the modulus of elasticity in all of the polymer modified concretes. The minimum value of modulus of elasticity belonged to mix P175 with value of 15.8 GPa and mix P275 with value of 18.3 GPa. As it can be observed, the minimum values of shrinkage occurred in mix designs containing 75% replacement of water with polymer and also presence of 5% silica fume which was equal to 0.00032 in mix S5P175 and 0.000375 in mix S5P275. By increasing the replacement of silica fume up to 10% and 15%, the results showed a significant increment in shrinkage.By presence of polymer, the value of shrinkage has been reduced about 15% in average (without Silica Fume). The replacement of Silica Fume with cement up to 5% reduced the amount of shrinkage about 17% in average but after increasing the amount of replacement, due to deficiency of water which has been replaced with polymer, shrinkage was increased.

Table 2: Results of tests

Mix Name	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Modulus of Elasticity (GPa)	Shrinkage (*10^6)	In-situ strength without core (MPa)	In-situ strength with core (MPa)	In-situ strength without core on repair overlay (MPa)	Bonding strength of repair overlay (MPa)
R0	47.1	3.96	5.43	32.1	460	4.433	3.669	4.535	3.091
P125	40.4	5.09	8.63	27.5	425	5.809	4.790	5.197	3.508
P150	46.2	5.80	10.3	25.1	385	6.318	5.248	5.656	4.010
P175	25.3	5.95	10.82	15.8	340	6.420	5.452	5.758	3.759
P225	34.2	4.74	8.43	24.9	430	5.299	4.484	4.943	3.508
P250	41.3	5.35	8.93	21.1	400	5.554	4.892	5.401	3.968
P275	30.7	5.41	9.64	18.3	390	5.707	5.045	5.503	3.592
S5P125	35.1	3.44	7.23	28.7	410	4.994	3.720	5.299	3.550
S5P150	41.5	4.44	8.22	27.3	365	5.707	4.178	5.605	3.926
S5P175	20.2	5.09	8.71	17.5	320	5.860	4.331	5.758	3.884
S5P225	27.4	4.01	7.05	25.3	425	4.841	3.516	5.045	3.425
S5P250	28.9	4.13	7.93	22.4	390	5.299	3.771	5.401	3.675
S5P275	23.1	4.63	8.61	20.5	375	5.401	3.975	5.452	3.383
S10P125	31.2	2.72	6.62	28.8	450	4.586	3.363	4.688	3.258
S10P150	37.0	3.58	7.71	26.9	410	5.096	3.465	5.045	3.759
S10P175	17.1	3.98	8.37	18.1	370	5.197	3.771	5.096	3.550
S10P225	22.1	3.05	6.21	25.9	460	4.178	3.312	4.382	3.091
S10P250	25.4	3.27	7.27	22.7	420	4.892	3.669	4.586	3.592
S10P275	20.1	3.79	7.93	20.3	415	5.045	3.822	4.637	3.341
S15P125	23.2	2.04	6.25	29.3	480	3.771	3.108	3.822	2.965
S15P150	26.9	2.65	7.48	27.7	445	4.076	3.465	4.025	3.341
S15P175	16.2	2.99	7.94	19.6	390	4.331	3.618	4.127	3.091
S15P225	19.6	2.24	6.05	26.1	495	3.618	2.904	3.363	2.798
S15P250	23.3	2.41	7.12	23.3	455	3.975	3.210	3.567	3.133
S15P275	18.8	2.74	7.82	22	445	4.076	3.312	3.516	2.882

During the assessment of bonding strength by Pull-off method, four mechanisms of failure are possible: failure of steel plate adhesion, failure of substrate, failure of overlay and failure at the boundary of two layers. Only in the case of failure at the boundary, the results show the bonding strength. So the results of tests in which failure occurred in the places excluding the contact zone were eliminated and the tests were repeated to ensure that the failure occurred at the boundary. Also for this reason, saw cut concrete substrate with 28-day compressive strength of about 50 MPa with 6 months age was used in order to minimize the cohesive failures during testing and to have enough aggregate and cement paste to be in contact with the overlay and to avoid contamination of the results with roughness and substrate surface weakness. The highest value of bonding strength belongs to the repair overlay of PMC with the SBR-based polymer in mixture P150 and its value in Pull-off test method was 4.01 MPa. Also the highest value of repair overlay of PMC with Acrylic-based polymer occurred in mix design P250 and its value in Pull-off test method was 3.97 MPa. In all polymer modified concrete designs, an increase in the bonding strength of repair overlay can be observed compared to the control design. In general, polymer modified concretes with SBR-based polymer has a higher bonding strength compared to the polymer modified concretes containing Acrylic-based polymer. The changes of bonding strength between both kind of PMC overlays and substrate concrete by considering the variable of silica fume percentage in Pull-off test method indicates that in both types of polymers, 50% replacement of water with polymer caused the highest bonding strength and increasing the amount of silica fume replacement more than 5% reduces the bonding strength.

As it is observable in Fig.3 and Fig.4, due to high values of R^2 it can be inferred that there is a relationship to a great extent between the results of in-situ strength without core drilling and splitting tensile and also compressive strength. The relationship between in-situ strength with core drilling and without core drilling is shown in Fig.5. The results of these two methods are very close. By increasing the amount of polymer, the in-situ strength was increased in both types of polymers, but the presence of Silica Fume and increasing the replacement percentage of that caused reduction of in-situ strength.

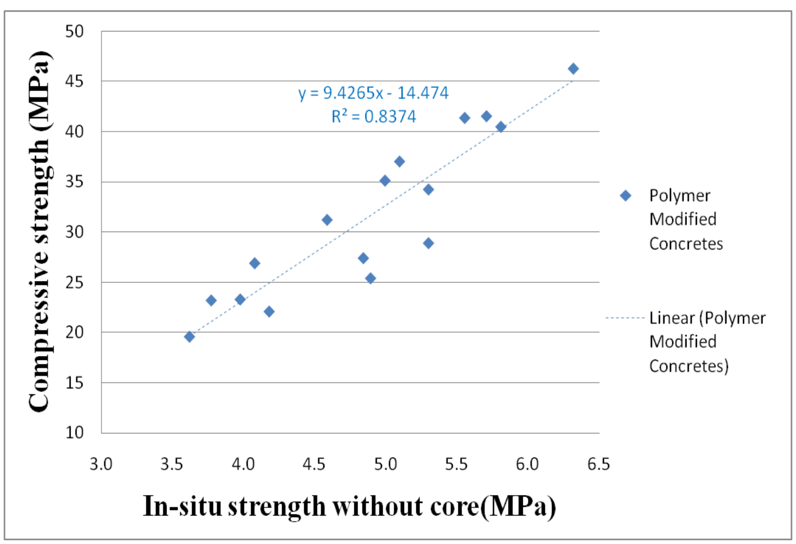

Fig.3 The relationship between in-situ strength without core and compressive strength

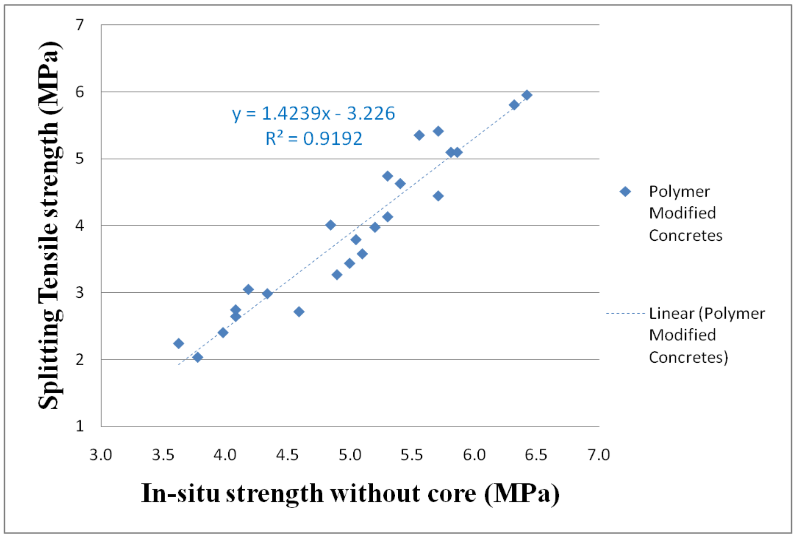

Fig.4 The relationship between in-situ strength without core and tensile strength

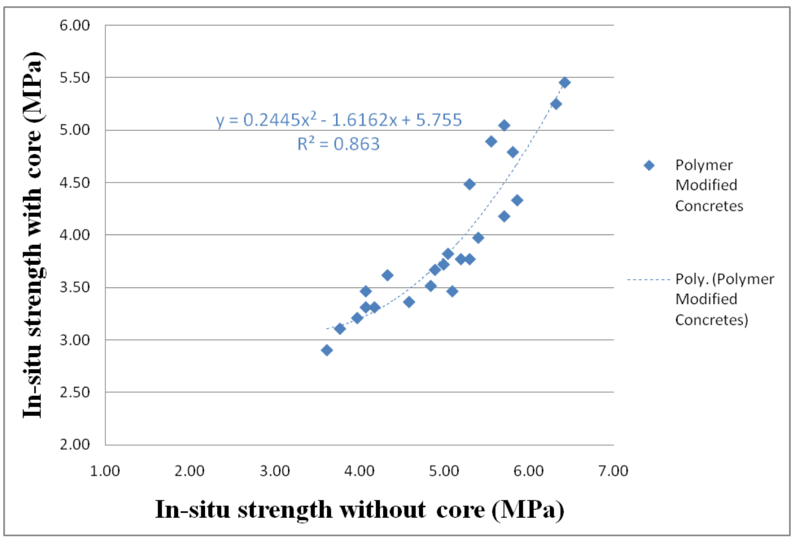

Fig.5 The relationship between in-situ strength with and without core

One of the most important parameters in investigation on properties of repair overlays is shrinkage of new layer. As it shown in Fig.6, by reduction of shrinkage, the results of in-situ strength are increased. Also the Fig.7 indicates the relationship between in-situ strength without core drilling and bonding strength of polymer modified concrete overlays to substrate. Due to high values of R^2 it can be inferred that there is a relationship to a great extent between these tests and by use of in-situ test the quality of bonding of polymer modified concrete repair overlays can be estimated with an acceptable accuracy.

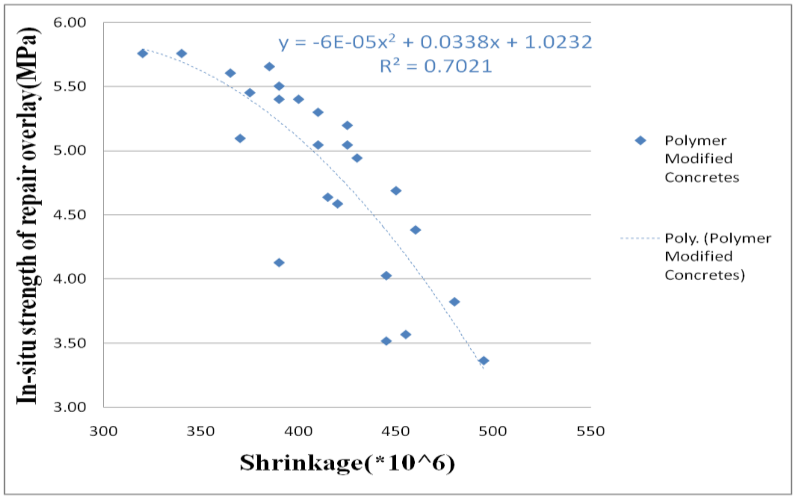

Fig.6 The relationship between in-situ strength without core and shrinkage of repair overlays

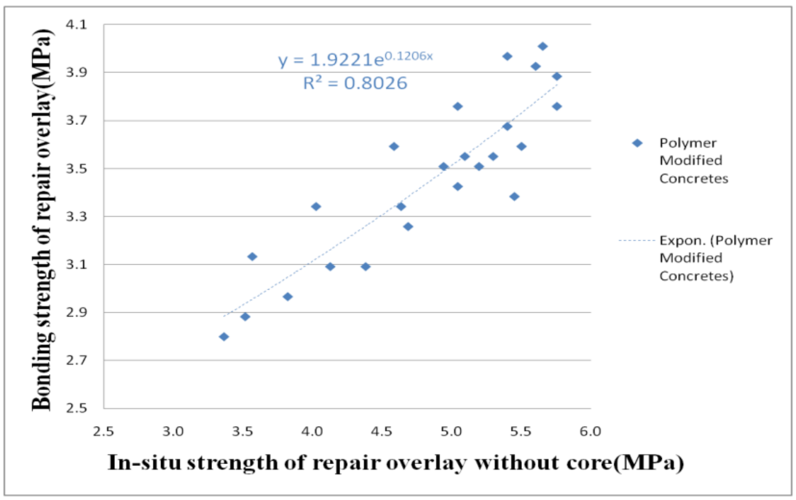

Fig.7 The relationship between in-situ strength without core and bonding strength of repair overlays

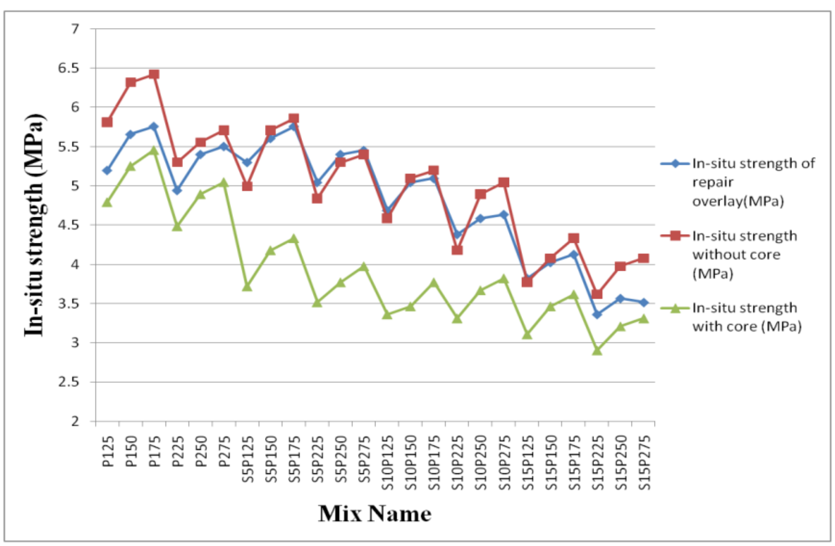

Fig.8 The comparison of three types of in-situ strength tests

In Fig.8 the results of three types of in-situ strength test are compared together. As it can be observed, the results of in-situ strength without core drilling on polymer modified concrete cubic samples and overlay samples are very close but in repair overlay samples because of more shrinkage duo to lower thickness of layer, the strength results are lower. In all tests, the amounts of in-situ strength obtained by using core drilling are decreased.

3.1. Prediction of In-situ Strength by Linear Regression

Using linear regression, relationships to predict in-situ strength of PMC repair overlay are obtained. Parameters associated with the repair overlay are: compressive strength, flexural strength, modulus of elasticity, amount of shrinkage, polymer percentage, silica fume percentage and the type of polymer in polymer modified concretes. The acceptable accuracy of the obtained relationship (average error of less than 3%) indicates the high impact of the mentioned parameters on the bonding strength.

$$insitu = 10.823 + 0.005*f_c - 0.351*flex + 0.077*tensile + 0.035*E - 0.003*Shr + 0.313*pmccnt - 0.581*sf - 0.185*p1orp2 \quad \text{(Eq.1)}$$

Where, *insitu* is predicted in-situ strength of repair overlay (MPa),, f_C is compressive strength (MPa), *flex* is flexural strength (MPa), *E* is modulus of elasticity (GPa), *tensile* is tensile strength (MPa), *Shr* is the amount of shrinkage (*10^6), *pmccnt* is the percentage of polymer in polymer modified concrete, *sf* is the percentage of silica fume and *p1orp2* is the type of polymer in polymer modified concrete (Type1: SBR-based polymer and Type2: Acrylic-based polymer)

In the mentioned equation, parameters '*pmccnt*', '*p1orp2*' and '*sf*' are nominal variables and for '*pmccnt*', the numbers 1, 2, 3 and 4 are placed instead of 0, 25, 50 and 75 respectively and for '*p1orp2*', the numbers 1 and 2 are placed instead of SBR-based and Acrylic-based polymer and also for '*sf*' the numbers 1, 2, 3 and 4 are placed instead of 0, 5, 10 and 15 respectively. The average error for in-situ strengths prediction was 2.06% with respect to test results.

3.2. Prediction of Bonding Strength by In-situ Strength

For prediction of bonding strength by considering the results of in-situ strength, the Eq.2 is proposed. This equation can predict the value of bonding strength to conventional concrete substrate for polymer modified concretes overlays with acceptable accuracy. The average error for prediction of Pull-off method bonding strengths was 3.6% with respect to test results.

$$pulloff = 1.9221*e^{0.1206*insitu} \quad \text{(Eq.2)}$$

Where, *pulloff* is predicted Pull-off method bonding strength of repair overlay (MPa) and *insitu* is in-situ strength of repair overlay (MPa).

4. Conclusion

- In both types of Polymer Modified Concretes (PMC) that had been prepared for repair overlays, the value of compressive strengths have been reduced slightly, but a significant increment was observed in flexural strength (100% increment in presence of 75% replacement of water with SBR-based polymer and 77% increment in presence of 75% replacement of water with Acrylic-based polymer) and tensile strength (50% increment in presence of 75% replacement of water with SBR-based polymer and 36% increment in presence of 75% replacement of water with Acrylic-based polymer)

- By presence of polymer, the value of shrinkage has been reduced about 15% in average (without Silica Fume). The replacement of Silica

Fume with cement up to 5% reduced the value of shrinkage about 17% in average but after increasing the replacement, due to deficiency of water which had been replaced with polymer, shrinkage was increased.

- According to the results, it can be seen that there is an inverse relationship between the shrinkage and bonding strength of repair overlays in both tests. In other words while there is a reduction in shrinkage, an increase in bonding can be observed.

- The results of in-situ strength without core drilling on polymer modified concrete cubic samples and overlay samples are very close but in repair overlay samples because of more shrinkage duo to lower thickness of layer, the strength results are lower. In all tests, the amounts of in-situ strength obtained by using core drilling are decreased.

- Due to high values of R^2 it can be inferred that there is a relationship to a great extent between in-situ test and bonding strength test and by use of in-situ test the quality of bonding of polymer modified concrete repair overlays can be estimated with an acceptable accuracy.

- By linear regression, an equation to predict the in-situ strength considering the mechanical characteristics of polymer modified concrete was proposed. According to the good accuracy (average error for prediction of was 2.06%), this relation can be used in the case of not having the facilities of performing in-situ and bonding strength determination tests. Also for prediction of bonding strength by considering the results of in-situ strength, another equation is proposed. This equation can predict the value of bonding strength to conventional concrete substrate for polymer modified concretes overlays with acceptable accuracy. The average error for prediction of Pull-off method bonding strengths was 3.6% with respect to test results.

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