- Technical Paper -

INVESTIGATION ON MOISTURE BEHAVIOR FOR DIFFERENT FRP-CONCRETE BONDED SYSTEMS

Justin SHRESTHA[*1], Tamon UEDA[*2], Dawei ZHANG[*3]

ABSTRACT

The Fiber Reinforced Polymer (FRP)-concrete bond durability under moist condition for different FRP composites was investigated by the experimental study. From the obtained results up to 12 months, the durability of the composites is found to be highly dependent on the selected materials. Among 6 kinds of different FRP-concrete composites selected for the study, two kinds of the composites showed some reductions in shear bond strength and failures were adhesion failure at the concrete-resin interface, while the remaining composites showed insignificant change. Meanwhile tensile bond strengths were reduced in most of the cases after exposure even though the failures occurred at the concrete region.

Keywords: FRP, bond, water, interface, concrete

1. INTRODUCTION

Strengthening of civil infrastructures by Fiber Reinforced Polymers (FRPs) is one of the most popular methods. However, in long-term, durability of such strengthened structures in various environmental conditions is quite unknown due to limited studies until now. In order to consider these uncertainties in design, ACI committee 440 [1] proposed the environmental-reduction factors which range from 0.85 to 0.95 for the carbon/epoxy system. This reduction factor may not cover all the possible environmental conditions. Therefore, it is necessary to investigate each environmental condition separately, understand the mechanism of deterioration and propose such reduction factors for each condition if necessary. Among several different severe environmental conditions, high humidity is one of the major issues for the marine structures. Continuous exposure to such conditions for long period may result in various adverse effects. In FRP strengthened concrete structure, bond interfaces are of prime importance since they are considered as the weakest layers due to dissimilarity in the material properties. Few of the past studies [2-4] have reported harmful effect of moisture on the epoxy resins and at the interfaces. However, mechanism of deterioration is still unclear. In such circumstances, we need more elaborated studies and confirm the performance of such different materials under different conditions to ensure its long-term durability.

Previously, the authors have conducted some experimental studies for maximum duration of 2 years to investigate the moisture effect on the FRP-concrete bond interface [4]. Some signs of deteriorations were observed in bond strength and failure modes. But there existed some limitations such as having one sample for each exposure condition, limited resin types, and variable testing temperature and humidity conditions. The current experimental study focuses on evaluating bond performance of FRP-concrete composites with various binding and FRP materials after subjecting them to moisture conditions for the maximum period of 18 months overcoming the limitations from previous case. This paper includes some results until 12 months only.

2. TEST PROGRAMS

2.1 Materials

(1) FRP materials and epoxy resins

Altogether six different kinds of commercially available FRPs and epoxy resins in the world were used in the study. This includes plate, strand sheet and continuous fiber sheets along with their suggested epoxy resins. All of the epoxy resins were room temperature curing resin for standard applications. For two of the FRP systems, primer layer was used as recommended by the manufacturers before attaching the FRP sheet onto the concrete surface. Table 1 shows the naming of specimen along with the information on reinforcement type. Detailed chemical information of the resins and their compositions were not disclosed by the manufacturers so some of the general information were extracted from the Material Safety Data Sheet (MSDS) of the resins which is shown in Table 2.

(2) Concrete

The concrete used for the study was a normal

*1 Graduate School of Engineering, Hokkaido University, JCI Student Member
*2 Professor, Department of Civil Engineering, Hokkaido University, Dr.E., JCI Member
*3 Associate Prof., Department of Civil Engineering, Zhejiang University, Dr.E.,

strength with the cylindrical compressive strength of 30 MPa after 28 days of curing. The compressive strengths were tested in every 3 months interval after taking out from the water. Three specimens were tested for each exposure duration.

Table 1 FRP and resin materials with their naming

FRP system	Reinforcement	Primer	Adhesive
BN	Unidirectional sheet	NP	NR
BM	Unidirectional sheet	MP	MR
BF	Unidirectional sheet	x	FR
BP	Unidirectional sheet	x	PR
BY	Strand sheet	x	NY
BS	Plate	x	SR

Table 2 Chemical information of the resins

Type	Base	Hardener
NR	Bisphenol A type epoxy resin	Modified polyamine
NP	Bisphenol A type epoxy resin	Modified polyamine
MR	Bisphenol A type epoxy resin	Modified aliphatic polyamine
MP	Bisphenol A type epoxy resin	Modified aliphatic polyamine
FR	Modified epoxy resin	Polyoxypropylenediamine, Polyetheramine
PR	Bisphenol A type epoxy resin	Blend of cycloaliphatic, isophoronediamine
NY	Bisphenol A type epoxy resin	Aliphatic polyamine
SR	Bisphenol A type epoxy resin	Trimethyl hexamethylene diamine

2.2 Preparation of Specimens

In order to understand the moisture effect on the bond properties, it is necessary to understand behavior of bulk material properties. Therefore, epoxy tensile specimens were prepared in accordance with JIS K 7113 (1995) [5]. Altogether specimens of 8 different epoxy resins including 2 epoxy primers were prepared.

Same concrete block was used to examine the shear and tensile bond strength. As indicated in Fig.1, upper part was used for shear test, whereas the bottom part was used for the direct pull-off test. The concrete blocks were casted and cured for 28 days under moist condition in the laboratory. The bonding surface was grinded by disk sander to remove the thin mortar layer until aggregates became visible. The amount of surface preparation was visually judged and attempt was made to make uniform surface preparation throughout the specimens. After necessary surface preparations, the surface was cleaned by compressed air to remove small dust particles from the surface. Then CFRPs were attached onto the dry concrete surfaces as recommended by the manufacturers. CFRP were attached on three sides of the block in order to take 3 test data for each exposure condition. For the direct pull-off test, steel jig was attached on the FRP with a suitable adhesive then notches were made on the concrete surface around the steel jig. Tensile strength was measured by using direct pull-off testing machine. Dimension for direct pull-off test is shown in Fig. 2. All of the specimens were cured for more than a month before exposing them into any environmental exposures.

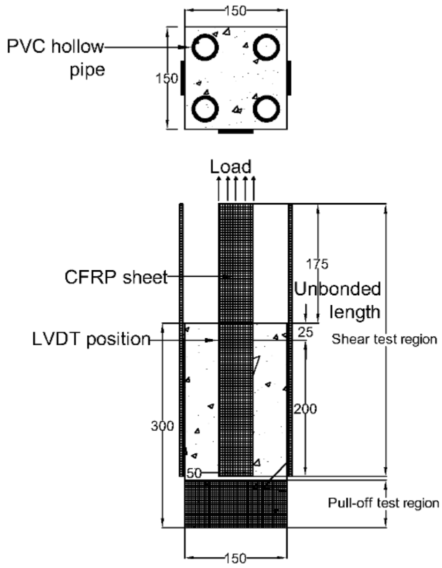


Fig. 1 Details of bond specimen (unit: mm)

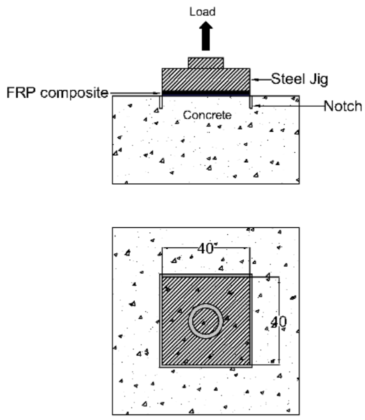


Fig. 2 Details of direct pull-off test specimen (unit: mm)

2.3 Exposure and Testing Conditions

For the environmental exposure, all the specimens were immersed in water pool maintained at a constant temperature of 20 °C. The arrangement of the concrete water pool is shown in Fig. 3. The specimens were tested in every 3 months interval. In order to keep the exposure and testing conditions similar, the bond shear test and resin tensile test were conducted inside the temporarily built environmental chamber which could maintain the temperature and humidity. The schematic of the testing arrangement of the shear specimen inside the controlled chamber is shown in Fig. 4. Throughout the test period, the temperature of 20 ˚C and humidity over 85% was maintained in order to prevent the loss of moisture from the bond interface. For the direct pull-off test, no such arrangements were made as the duration of test was very short.

The specimens which were not subjected to any environmental exposures is referred as 0 month. These specimens were put in an ambient condition inside the laboratory until the test.

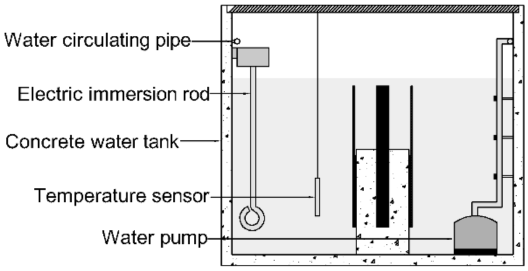


Fig. 3 Schematic of exposure tank

2.4 Testing Procedure

The shear specimen was mounted on the universal testing machine and reaction steel plate was put on top of it. Three long bolts were inserted through the preset plastic pipes inside the concrete specimens which were fixed at the base of the machine. The specimen was adjusted in position to make sure that the FRP-concrete bond line is aligned with the center line of the upper loading grip. The loading speed of the upper grip was set as 0.2 mm/min. Three tests were performed for each exposure condition in order to ensure the reliability of the obtained results.

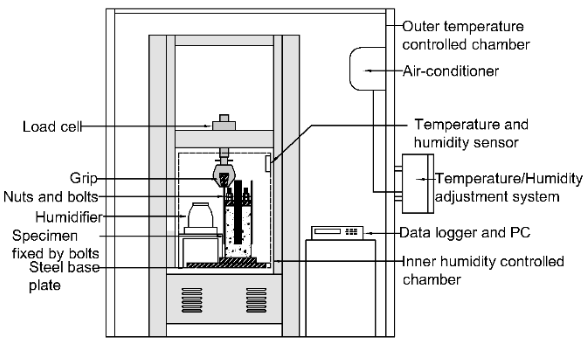


Fig. 4 Test arrangements for the bond specimen

3. RESULTS AND DISCUSSION

3.1 Moisture Effect on Mechanical Properties of Resin

The moisture absorption by different resin specimens is presented in Fig. 5. This includes 6 adhesives/impregnating resins and 2 primers. As expected, the amounts of water absorbed by the resins were different which varied from 0.64 to 2.35% after a year of immersion. Two of the resins, SR and NY showed the lowest absorption compared to the other resins which could be mainly due to higher filler content in the resin composition. In most of the cases, the absorbed moisture is around 2% of the weight. The moisture absorption (%) could be an important characteristic as some of the previous studies have identified this as a key indicator and used this index in order to quantity the damages occurred due to moisture [6]. However, from Fig. 6, it is clear that the relationship between tensile strength and moisture absorption could vary greatly depending on the epoxy resins. The highest reduction in strength occurred in the resin SR type, in which, strength reduction was 33% in average after exposure but the overall moisture absorption is the least compared to the other cases. In contrast, 7 to 22% strength was reduced in average for some of other specimens, while the moisture absorption is greater than 2%. In two of the cases MR and FR types, no reduction were found, however, the moisture absorption was around 2%. Therefore, all the above discussion brings to a point that the moisture durability of the resins is material property dependent and the moisture absorption alone up to 2% cannot be used as an indicator to judge or predict the damages caused by it.

Fig. 7 shows the relationship between tensile strength and the exposure duration. The trends were similar to the relationship between moisture absorption and the tensile strength as the moisture absorption by the resins increased with the exposure duration. Expect MR and FR types, reduction was observed in all cases and the reasons could be due to harmful effect of water on the epoxy resins such as plasticization, hydrolysis, cracking and crazing etc. [7]. In contrast to the tensile strength behavior, the tensile modulus was mostly unaffected as shown in Fig. 8.

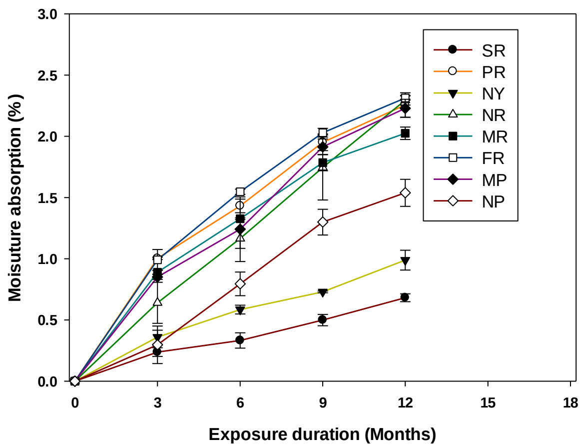


Fig. 5 Moisture absorption by the different resins

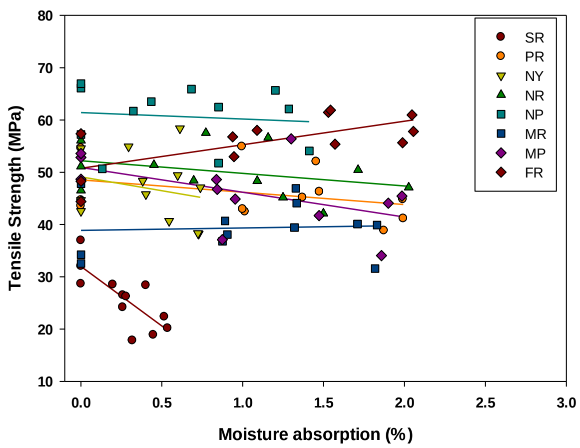


Fig. 6 Relationship between tensile strength and the percentage of moisture absorption

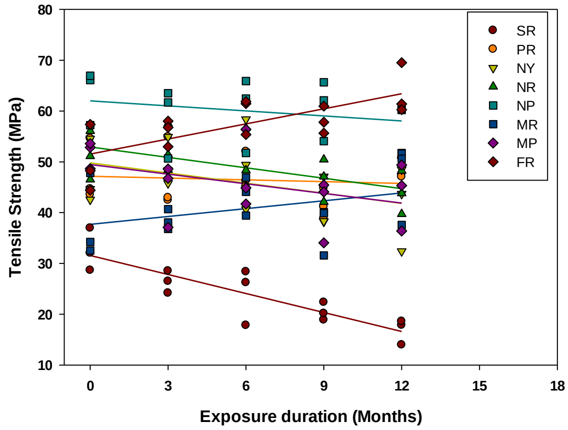


Fig. 7 Relationship between tensile strength and the exposure duration

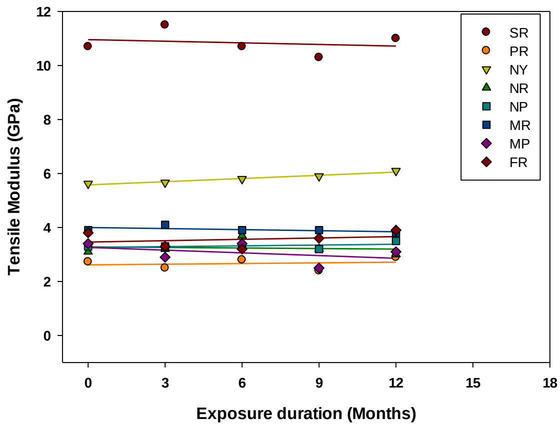


Fig. 8 Relationship between tensile modulus and the exposure duration

3.2 Moisture effect on concrete strength

Fig 9. gives the relation between concrete compressive strength and immersion duration. The strength of the concrete seems to be fairly constant even after a year of immersion. Slight increase in strength was expected after immersion due to the additional curing of concrete as a result of continuous hydration of cement products but no such increase indicates that the strength of concrete would be little lower when tested in presence of water. These two effects may have neutralized each other.

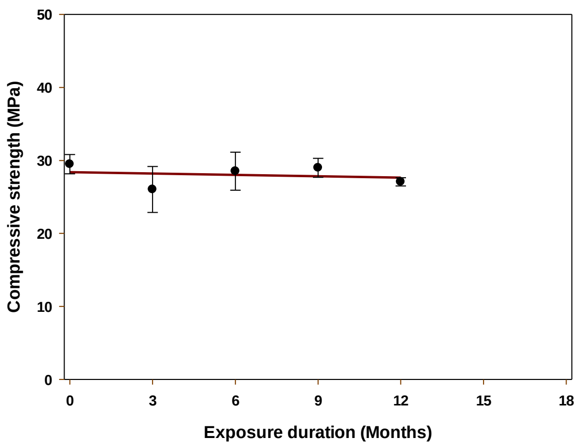


Fig. 9 Relationship between concrete compressive strength and exposure duration

3.3 Moisture effect on FRP-concrete bond

Fig. 10 shows the relationship between shear bond strength and the exposure duration. In response to the given exposure, three different trends were observed which are categorized based on the comparison of average bond strength before and after exposure. The bond strength for specimen BN, BM and BY remain almost constant with a very small scatter within the exposure period. Change in bond strength after the exposure were less than 5% of the unexposed cases. The failure modes for these sets remain almost unchanged as well. The second set of specimens BP and BF showed some significant reduction in bond strength. The average reduction in BP type is about 15% and in the BF type is 24%. Failure modes for both the cases occurred at the interface between concrete and resin layer. Finally, the speicmen type BS showed significant gain in strength after the exposure. The overall bond strength increased by 25% after the exposure. This is indicating some positive effect of moisture on the bond properties but the reason is unclear. Even though the resin properties were significantly deteriorated, this effect was not evident in the shear test results as the failure occurred at the concrete or concrete-resin interface. The resin strength retention was sufficient enough to transfer the stresses from FRP to concrete.

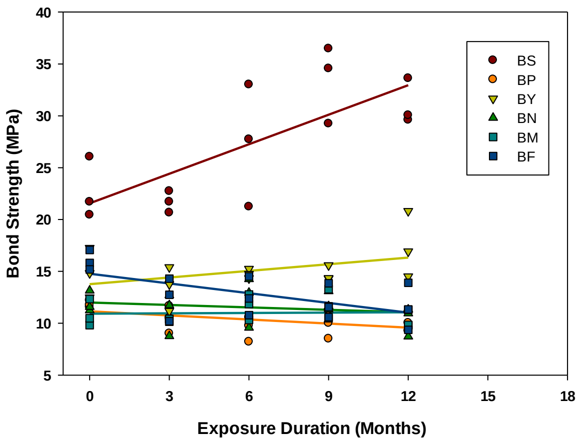


Fig. 10 Relationship between shear strength and the exposure duration

The results of the pull-off test is shown in Fig. 11. Large scatter within the data can be observed despite the best efforts to control the quality of the specimens and the exposure conditions. Such variations could be explained as the extreme localized behavior of the pull-off test. Except specimen types BP and BM, the average reduction in the tensile bond strength varies from 12% to 43% in average after the exposure. In all the cases, irrespective of the exposure condition, failures occurred at the concrete part. Some of the other researchers have also observed such reductions in tensile bond strengths after exposure to continuous immersion or wet-dry cycles but there was a transition of failure surfaces from concrete to mixed or interfacial failures [3, 8, 9]. The reason for reduction was given as the adverse effect of water at the interfacial bond between FRP-concrete interface but it is not the case for the present observed results, as all the failure occurred in the concrete region. This indicates that there is a possibiliy of reduction of tensile strength of concrete due to water but no test were performed to verify it. But, observing almost unchanged behavior of concrete compression strength after a year of exposure, it is hard to believe the above statement however, there is a possiblity that the concrete under compression and tension may behave differently in presence of moisture. This needs to be further investigated. Nevertheless, from Fig. 11, it can be observed that few of the data points after exposure were below the minimum pull-off strength value of 1.4 MPa which is recommended by ACI 440 committee [1].

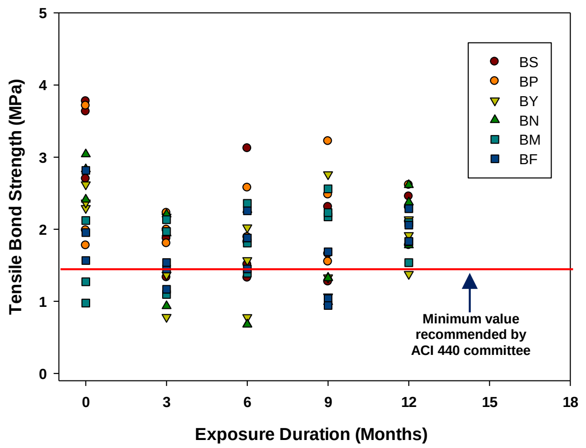


Fig. 11 Relationship between tensile bond strength and the exposure duration

3.4 Failure surfaces

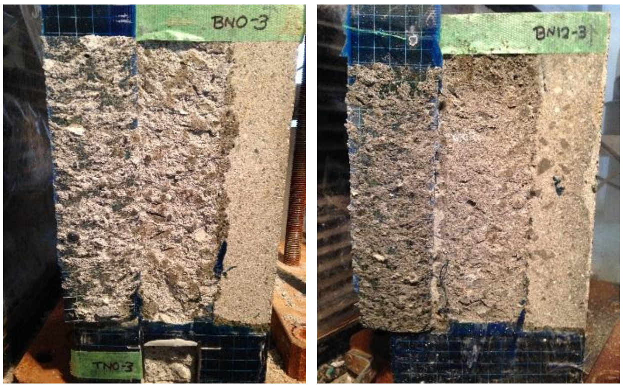
To ensure full effectiveness of the composite system, the desired mode of failure for the shear bond test is the complete shear failure at the concrete layer. In the study, three differennt failure modes were observed which are complete failure at the concrete layer (C) (Fig. 12), partial failure at the concrete and concrete-resin interface (M) (Fig. 13) and finally the complete interface failure between concrete-resin layer (I) (Fig. 14). In case of partial failure mode, the volume of concrete attached on the failed surface of the FRP sheet varies. However, no distinction is made between such cases. Failures in case of specimen types BN and BY occurred mostly at the concrete even after the exposure which means there was no effect of moisture on the failure modes. For specimns BM and BS, transition of failure modes can be observed from concrete to either mixed or interface failures after exposure. Failures for BF and BP type specimens were very similar even before exposure. BF was complete adhesion failure and BP was almost adhesion failure as the concrete volume attached on the FRP sheet was too less. After the exposure, failure remained at the concrete-resin interface but the reduction of bond strength in these two cases suggests that there are some of the adverse effects of moisture. All the failure modes are presented in Tables 3 and 4. In summary, after the moisture exposure, the failure surfaces changed from concrete cohesion to mixed or adhesion failure and from mixed to adhesion failure but no transition of failure from adhesion to mixed or concrete cohesion was observed.

Table 3 Summary of failure modes for BN, BM and BY

Month	BN			BM			BY		
	1	2	3	1	2	3	1	2	3
0	C	C	C	C	M	C	C	C	C
3	C	C	C	M	M	C	C	C	C
6	C	M	C	C	M	C	C	C	C
9	C	C	C	M	I	M	C	C	C
12	M	M	C	C	M	I	C	C	M

Table 4 Summary of failure modes for BP, BF and BS

Month	BP			BF			BS		
	1	2	3	1	2	3	1	2	3
0	M	M	M	I	I	I	C	C	C
3	I	I	I	I	I	I	M	I	C
6	I	I	I	I	I	I	M	M	M
9	I	I	I	I	I	I	C	M	M
12	I	I	I	I	I	I	C	M	M

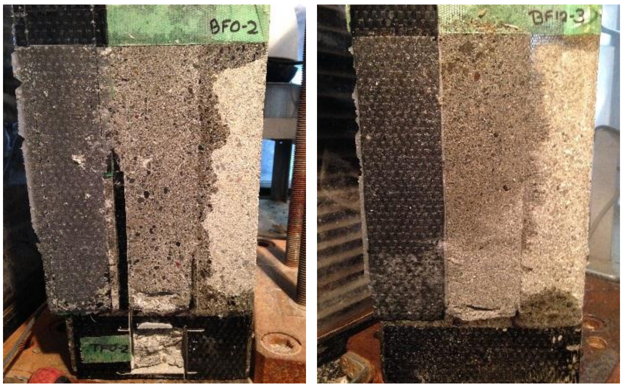


0 month 12 months

Fig. 12 Concrete failure before and after the exposure (Specimen BN type)

0 month 12 months

Fig. 13 Partial concrete-resin interface failure before and after the exposure (Specimen BM type)



0 month 12 months

Fig. 14 Adhesion failure before and after the exposure (Specimen BF type)

0 month 12 months

Fig. 15 Typical failure surfaces before and after exposure from pull-off test

In case of pull-off test, the failure occurred mostly at the mortar layer or the interfacial transition zone (ITZ) whenever big aggregates are present near to the surface. No distinction can be made between failure surfaces before and after exposure as in all the cases the failure occurred at the above-mentioned zone. This suggests that the interface region between the FRP composite and the concrete remained intact even after exposure.

3. CONCLUSIONS

Based on the observed results of FRP-concrete bonded systems until 12 months of exposure in water, following conclusions can be drawn:

1) In overall, tensile strengths of almost all resins are affected by the exposure, however the degree of effect varies.
2) In terms of shear bond behavior, two of 6 tested systems (specimen type “BF” and “BP”) are affected by immersion and for both cases, the failures occurred at the concrete-resin interface. Reduction in average bond strengths after immersion are 24% and 15% respectively.
3) The pull-off strengths were reduced for all cases, and the failure modes were concrete cohesion failure.
4) Comparing all the failure modes, the water seems to affect the shear bond when concrete-resin interface failure (adhesion failure) occurs.

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