Preliminary Investigation of an Approach to Improve Water Impermeability in Concrete with Externally Bonded FRP Systems

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ABSTRACT

Good bond and water impermeability in fiber-reinforced polymer (FRP) bonded/coated systems are essential if the durability of FRP-rehabilitated concrete structures is to be ensured. In addition, water impermeability is required in some special FRP applications, such as the strengthening of underground water pipes. So far, there has been no method in the literature guaranteeing water impermeability in FRP strengthening works. This paper studies the feasibility of using a waterproof coating as the initial primer on cementitious materials before applying externally bonded FRP. In this preliminary investigation, by examining the two most important indicators (i.e., pull-off bond tests and water penetration tests), it was found that the use of an initial waterproof layer in the proposed FRP bonding system did not influence the pull-off bond strength but significantly improved the system's water impermeability. It is therefore suggested that an initial waterproof layer can be included in method statements for externally bonded FRP systems in order to upgrade the effectiveness and durability of FRP systems.

Keywords

FRP; cementitious materials; water impermeability; bond strength; pull-off test; water penetration test

Introduction

In the area of structural rehabilitation using fiber-reinforced polymer (FRP), FRP sheets are normally bonded with resin to the surface of concrete or other types of cementitious materials. It is known that a good bond and water impermeability, which is related to a low chloride ion penetration rate, can lead to high structural durability and inhibit corrosion of the internal steel reinforcement in reinforced concrete (RC) structures (Zhou et al. 2019). The efficiency of FRP systems, in particular in relation to the bond and water impermeability, is affected by many factors such as the materials used and workmanship (Lai et al. 2010; Mabry et al. 2015; Zhou et al. 2017; Wan et al. 2018). The behavior of the bond between the FRP and concrete substrate is a critical parameter that influences the performance of strengthened members. There are two main experimental approaches used to investigate bond-related problems; these being shear-direction pull-out tests to investigate the shear bond at the interface (e.g., Chen and Teng 2001; Wu and

Jiang 2013), and pull-off tests in the normal direction to investigate the normal bond strength (e.g., Winters et al. 2008; Allen and Atadero 2012). Both the shear bond and normal bond reflect the efficiency of the composite system. In practical application, pull-off tests are more commonly used because the damage caused to the composite system is insignificant and can be repaired after testing.

Furthermore, in some special FRP strengthening applications, such as underground water pipes, water impermeability is a critical requirement because water penetration may create a high risk of corrosion and leakage. The cementitious materials (e.g., mortar and concrete) do not themselves have a waterproofing function. Indeed, water can easily penetrate the cementitious surface. For FRP, dry fibers also cannot prevent water penetration due to the large number of voids. The resin performs the waterproofing function in FRP systems. Theoretically speaking, if the resin can achieve 100% coverage of the substrate surface and thereby create a sealed layer separating the interface from the inner parts of the substrate, then the covered surface can be waterproof. But in practice, it is difficult to guarantee even distribution and thickness of resin. Fibers must also be applied to increase the strength of the covering layer. FRP is normally used for reinforcement/strengthening material by taking tension force. When structural strengthening projects using FRP have a requirement of waterproofing, an effective solution for guaranteeing both bond and waterproofing is necessary. However, existing studies on the water impermeability of FRP bonded/coated systems are very few in number. El Maaddawy et al. (2006) found that corrosion of internal steel reinforcement in FRP-wrapped concrete columns still existed but its onset was significantly delayed due to the application of FRP. This indicates that moisture can penetrate into concrete through FRP jackets. Recently, Amran et al. (2020) studied this issue for concrete coated with carbon FRP (CFRP) sheets, and they found that the degree of water impermeability was related to the number of layers of applied CFRP sheets. At a water pressure of 0.5 MPa following BS EN-12390-8 (2019), the average water penetration depth values measured by Amran et al. (2020) were 63.0 mm, 10.3 mm, 4.3 mm, and 0.0 mm for 0, 1, 2, and 3 layers of CFRP sheets, respectively.

However, it is not economical and effective to apply additional FRP layers to avoid water permeability because such an approach involves material overuse in structural design. This paper aims to find a more effective method to achieve water impermeability. In this work, a layer of waterproof phenolic epoxy (novolac) coating was used as an initial primer layer before applying the FRP layer. Subsequently, the externally bonded FRP system includes the interfaces between the FRP-initial layer and the cementitious substrate. Therefore, the interfacial bond behavior of this proposed composite structure is also critically important and needs to be investigated.

Experiments

It is believed that when FRP with resin is applied directly on the surface of cementitious materials, the risk of water penetration still remains (El Maaddawy et al. 2006). Hence, the aim of this study is to find and verify an appropriate and effective interfacial treatment approach that can provide good bonding and avoid water penetration. In this work, laboratory pull-off tests and water penetration tests were conducted to investigate the efficiency of FRP coated cementitious materials.

Specimen Design

In this work, FRP was bonded on the surface of cementitious materials using different interfacial treatments. For each of these different treatments, pull-off tests and water penetration tests were carried out on the specimens. Following BS EN-12390-8: 2019 (2019), 150 × 150 × 150 mm^3

cement mortar cubic specimens were cast and used to represent the cementitious substrates for bonding with FRP.

A total of five different specimen types were tested and studied and these are illustrated and listed in Fig. 1. For type A specimens, after surface cleaning, a layer of waterproof phenolic epoxy (novolac) coating (Product Data (HEMPADUR 85671)), was applied as the primer before applying the FRP sheets. It is a two-component, amine adduct cured phenolic epoxy with very good adhesion and high temperature, water and chemical resistance. Different from the epoxy resins adopted in common practice, this epoxy is not used as the matrix and adhesion in FRP but is a kind of primer coat that is liquid (before curing) and thin covering on the concrete surface. This layer of primer is used with the aim of improving water impermeability. To investigate the primer layer independently, type B specimens were prepared with a layer of this primer coating only. Type C specimens omitted the primer coating layer and FRP layers fully impregnated with resin were applied directly to the substrates of type C specimens. This is the commonly used methodology for FRP rehabilitation jobs on concrete surfaces. Type D specimens were prepared to mimic the FRP bonding occurring in situations with imperfect or poor workmanship. FRP sheets with a very small amount of resin (approximately 30% of that for type C specimens) were applied to the type D substrate surfaces. Type M specimens were plain cement mortar without any coating, and they served as reference samples for water permeability into unprotected cementitious substrates.

Water penetration tests were conducted on all the specimens, while pull-off tests were carried out on specimens of types A, B, C, and D. Four identical specimens were tested for each configuration. Therefore, there were 20 water penetration tests and 16 pull-off tests conducted in total in this work.

Materials

Due to its cost-effectiveness, glass FRP (GFRP) is widely used in various industries, especially for water pipeline rehabilitation projects that require a waterproofing function. Therefore, GFRP was studied in this research and a hand-applied GFRP system, with chopped strand mat glass fibers (Product Data (TGFM-600E)), was used. The FRP used in this work is shown in Fig. 2. The fiber length of this chopped GFRP sheet product was 50 mm. Atlac 430 Vinylester Resin (viscosity in a range of 440-500 mPa.s) with 1% HBO-50 accelerator was used as the resin for the FRP system. The initial primer material used for types A and B specimens was a waterproof phenolic epoxy coating (Product Data (HEMPADUR 85671)).

FRPs are usually applied on the surface of the concrete. The concrete surface can be considered as a simplified mortar layer because of the wall effect; whereby smaller aggregates concentrate near the surface of concrete specimens (Neville 1996; Jiang et al. 2017). In cases where structural repairs are required, the concrete surface is usually quite significantly damaged. In such cases, mortar or other cementitious materials without aggregates are applied to the damaged concrete surface for pre-repairing and smoothing purposes before applying the FRP. Therefore, mortar specimens, representing the behavior of FRP bonded concrete and other cementitious materials, were used in this work. The cement mortar was mixed with a water-cement ratio of 0.55. The weight ratio of cement to sand was 1:2. The average compressive cubic strength of three specimens ($150 \times 150 \times 150$ mm^3) was 48.0 MPa, with a standard deviation of 2.9 MPa. As the purpose of this work was to investigate the pull-off bond strength and water impermeability, the mechanical properties of FRP, resin, and initial coating were not tested.

Specimen preparation

Cement mortar cubes were cast and cured for more than 28 days in the Concrete Technology Laboratory at The Hong Kong Polytechnic University (approximately 25°C and 50% relative humidity), before applying coatings. Before applying the coating materials, the surfaces of the cement mortar substrates were washed with water and high-pressure air to ensure the surfaces were solid and clean. For type A specimens, the initial primer coating (a layer of phenolic epoxy (novolac) coating (Product Data (HEMPADUR 85671))) was applied after surface cleaning. After 3 hours, a layer of resin was applied over the primer. Then, a layer of FRP with fully impregnated resin was applied by wet lay-up process. Finally, another layer of resin was applied as a finishing layer. The procedure for type C specimens was similar to that for type A specimens, but omitted the initial primer. For specimens of types B, and D, which had a single-layer surface treatment, the coating was applied directly to the substrate surface. For FRP bonded specimens, 100 × 100 mm^2 FRP sheets were applied to the top flat surface of the 150 × 150 × 150 mm^3 cement mortar cubes. All the specimens were cured in the laboratory environment (approximately 25°C and 50% relative humidity) for more than five days before testing.

Pull-off tests and water penetration tests

Four pull-off tests were carried out for each coating system (types A-D specimens). The pull-off tests followed ASTM D4541-17 Test Method E (ASTM 2017). Four dollies with a 20 mm-diameter circular cross-section were attached to one coated surface of each coating type, as shown in Fig. 3. A circular hole cutter was used to cut a ring into the substrate (Fig. 3). A PosiTest AT-An automatic adhesion tester was used to conduct the pull-off tests. The bond strength values were measured by the tester and recorded manually.

A separate set of 20 specimens (types A, B, C, D, and M) was prepared for water penetration tests. The tests followed BS EN-12390-8 (2019). The test setup is shown in Fig. 4. The boundary conditions for all the tested specimens are the same. The specimens were placed in the apparatus so that a water pressure of 0.5 MPa could be applied to the underside of each specimen. A 75 mm-diameter circular area was subjected to the water pressure. After sustaining the applied water pressure for 72 hours, the specimens were retrieved from the testing device and the excess water was removed by wiping. Thereafter, the specimens were split cut into two halves, perpendicularly to the specimen surface upon which the water pressure was applied, in order to record the maximum depth of water penetration under the test area. This testing method has been widely adopted to estimate the water impermeability of cementitious materials (e.g., Behfarnia and Rostami 2017).

Test Results

The measured pull-off strength values, as well as failure modes, are listed in Table 1 and Fig. 5. The photos showing the failure modes of pull-off tests are shown in Fig. 6. The water penetration results of the tested specimens are listed in Table 2 and Fig. 7. In addition, photos of the specimens before and after testing are shown in Appendix A.

Discussions and Findings

Bonding

The pull-off bond strength values of type B specimens are the highest among all the tested specimens, because the failure of all the type B specimens occurred in the cement mortar. These pull-off strength values of type B specimens should be related to the tensile strength of the substrate material. The pull-off test results of type B specimens indicate that the interface between the initial coating (phenolic epoxy) and the cementitious substrate has perfect bonding, or at least has a greater bond strength than the substrate's tensile strength.

The failure interfaces of types A, C, and D specimens, as listed in Table 1, showed that the weakest link in the FRP bonded specimens is the interface below the FRP sheets. In this test series, type C specimens (the system with externally bonded FRP and no primer) have the most stable results with the lowest standard deviation, as listed in Table 1. The test scatters of type A and type B specimens are slightly higher, although the average value of type A specimens are very similar to that of type C specimens. The similar standard deviations of type A specimens and type B specimens (= 0.71 MPa and 0.75 MPa, respectively) indicate that the scatter of type A specimens seems to be reasonable. For type D specimens with poor workmanship, the bond strength results showed a high variance because 2 out of 4 results had zero strength. This result is reasonable because type D specimens were simulating poor workmanship using an insufficient amount of resin. Hence, the resin distribution of such specimens is non-uniform, which leads to a high error range (with the highest standard deviation) in the test results. A result of 'zero bond strength' indicates that very little resin was present at the test location. Comparing the bond strength between type A and type C specimens, the bond strength of the FRP-to-initial coating layer is similar to that of the FRP-to-cement mortar interface, with a difference of only 1.4% (3.40 MPa and 3.45 MPa respectively). Hence, compared with type C specimens, the average bond strength of type A specimens is similar, whereas the variability is slightly higher in a reasonable range. Based on the discussions above, it can be argued based on this research that the use of an initial waterproof layer has only a negligible effect in terms of bonding.

Water permeability

The plain mortar specimens (type M specimens without any coating) have the highest penetration results of the water penetration tests, compared with other specimen types. This is to be expected because the plain mortar is cementitious material with high porosity.

When the FRP workmanship or construction quality is poor (type D specimens), the water penetration depth is relatively high (41.0 mm on average). This means that water can penetrate through the FRP sheet when insufficient resin is applied. For the type B specimens with only a single layer of phenolic epoxy coating, although this is a type of waterproof material, the water penetration depth is still high (38.3 mm on average). This phenomenon shows that the use on the cementitious surface of the phenolic epoxy coating alone cannot prevent water penetration. If the phenolic epoxy coating layer is not used (type C specimens), then there are still 50% of cases that have high water penetration depth results even when the FRP is fully impregnated with resin and is applied very carefully. The best performance of water penetration tests occurred in type A specimens. Although a very limited water penetration of 1 mm was measured in two type A specimens, the proposed method showed very good water impermeability performance, with an average result of just 0.5 mm. Hence, the water impermeability performance of type A specimens with the proposed method was greatly improved. For the type C specimens, the standard deviation of type C specimens listed in Table 2 is highest. Although the preparations and wet lay-up process were carried out very carefully, there was nonetheless a 50% risk of water leakage. Hence, the solution involving improvements in the application quality and resin system is in practice difficult to implement. An appropriate approach to prevent water penetration should therefore combine the initial primer layer with the commonly adopted FRP application method.

Although BS EN-12390-8 (2019) does not provide criteria for judging good water impermeability performance in terms of water penetration depth, this is critical to our better understanding of the results of this work. For applications of externally bonded FRP systems on the surfaces of cementitious materials, the main purpose of the waterproof barrier is to prevent water from coming into contact with any ferrous metal objects covered by the cementitious materials. Hence, the water penetration depth must be less than the minimum concrete clear cover thickness required by the design guidelines (e.g., the smallest requirement is 13 mm in ACI 318-11 for shells/folded plate members, and 10 mm in GB 50010-2010 for shells/walls) Therefore, any water penetration depth test results exceeding the minimum concrete cover requirement in the local guideline should be considered inappropriate.

According to ACI 440.2R-17 (ACI 2017), a minimum pull-off bond strength of 1.4 MPa is required for bond-critical FRP applications (e.g., concrete beams externally bonded with FRP). Azzawi et al. (2018) suggested that the actual bond required for load transfer was much lower than 1.4 MPa. For contact-critical FRP applications (e.g., FRP wrapping of columns), the existence of FRP-concrete bonding is less significant (ACI 2017; Jiang et al. 2019). Therefore, the proposed FRP bonding approach using an initial waterproof layer can ensure a sufficient bond strength.

Conclusions

This paper has verified the effectiveness of using a waterproof initial primer before applying FRP sheets to ensure water impermeability. Through pull-off tests and water penetration tests, the following conclusions can be drawn:

1) The initial waterproof layer, phenolic epoxy (novolac) coating (Product Data (HEMPADUR 85671)), may be able to achieve very good bonding with cementitious substrate materials.

2) The critical interface of the bonding system is the FRP and its underlying bonded layer. The bond strength of FRP-to-initial waterproof layer interface is similar to that of the interface between cementitious material and directly bonded FRP. These results seem to indicate that the initial layer does not influence the pull-off bond strength (1.4% difference only), but greatly increases the water impermeability capabilities of the system.

3) Poor workmanship (type D specimens) is a possible root cause of inferior performance in water impermeability and bond behavior.

4) Significant water penetration was found in all specimens, except type A specimens where both initial layer (phenolic epoxy coating) and FRP layer with fully impregnated resin were used. From the test results in this work, without the waterproof phenolic epoxy (novolac) coating as the initial layer, there is still a high possibility of having high water permeability, even if the FRP is fully impregnated with resin and carefully applied.

5) By using the phenolic epoxy (novolac) coating as the initial layer, the FRP bonding system can achieve a good performance in terms of both bond and water impermeability. This FRP bonding system (type A) is effective in applications where waterproofing is a requirement. Therefore, it is suggested that the use of an initial waterproof layer can be included in method statements of FRP bonding in order to upgrade the effectiveness and durability of externally bonded FRP systems.

6) This technical note presents a preliminary study that offers a laboratory-based proof of the concept. In order to widen application of the proposed method, further relevant research will be conducted to gain more conclusive evidence.

Data Availability Statement

All data and models used during the study appear in the submitted article.

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Tables

Table 1 Pull-off test results

Specimen type	Specimen No.	Strength (MPa)	Average (MPa)	Standard deviations (MPa)	Failure mode
Type A: FRP well bonded on the initial layer	1	3.47	3.40	0.71	FRP-to-initial layer interface
	2	4.54			FRP-to-initial layer interface
	3	2.77			FRP-to-initial layer interface
	4	2.82			FRP-to-initial layer interface
Type B: Only initial layer applied on the cement mortar	1	6.48	6.20	0.75	In the cement layer
	2	5.03			In the cement layer
	3	6.19			In the cement layer
	4	7.09			In the cement layer
Type C: Only FRP well bonded without initial layer	1	3.97	3.45	0.44	FRP-to-cement interface
	2	3.79			FRP-to-cement interface
	3	2.99			FRP-to-cement interface
	4	3.04			FRP-to-cement interface
Type D: FRP with very small amount of epoxy and without initial layer	1	4.38	1.63	1.81	Cement layer + FRP-to-cement interface
	2	0			FRP-to-cement interface
	3	2.13			FRP-to-cement interface
	4	0			FRP-to-cement interface

Table 2 Water penetration test results

Specimen type	Specimen No.	Water penetration (mm)	Average (mm)	Standard deviations (MPa)
Type A: FRP well bonded on the initial layer	1	0	0.5	0.5
	2	1		
	3	0		
	4	1		
Type B: Only initial layer applied on the cement mortar	1	36	38.3	5.1
	2	46		
	3	32		
	4	39		
Type C: Only FRP well bonded without initial layer	1	1	14.5	12.9
	2	33		
	3	20		
	4	4		
Type D: FRP with very small amount of epoxy and without initial layer	1	25	41.0	9.8
	2	48		
	3	50		
	4	41		
Type M: Plain mortar	1	50	54.8	4.3
	2	58		
	3	51		
	4	60		

Figures

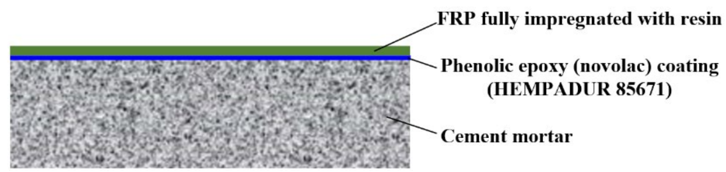
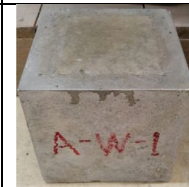
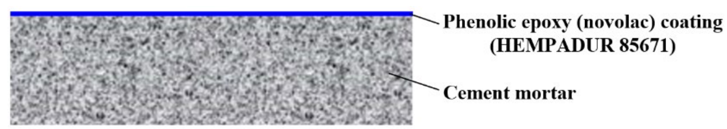
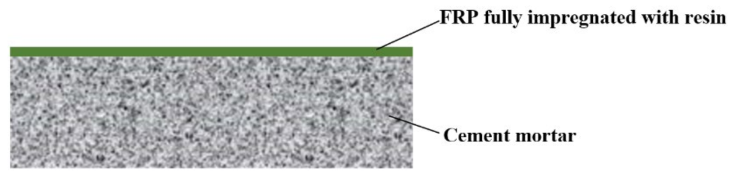
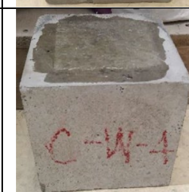
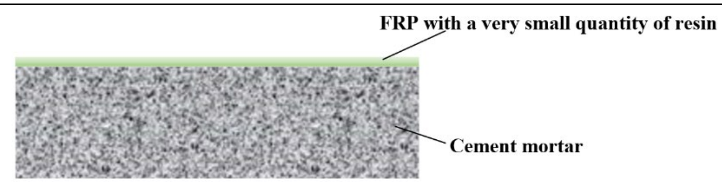
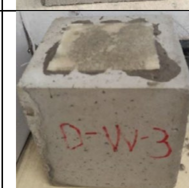
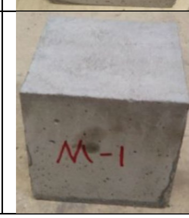
Methods	Illustration	Image	Note
Type A: FRP well bonded on the initial layer			Improved method
Type B: Only initial layer applied on the cement mortar			Waterproof layer only
Type C: Only FRP well bonded without initial layer			Existing method
Type D: FRP with very small amount of epoxy and without initial layer			Substandard method (poor workmanship)
Type M: Plain mortar			Control and reference

Fig. 1. Details of the interfacial treatments of the specimens

Fig. 2. GFRP used in this work

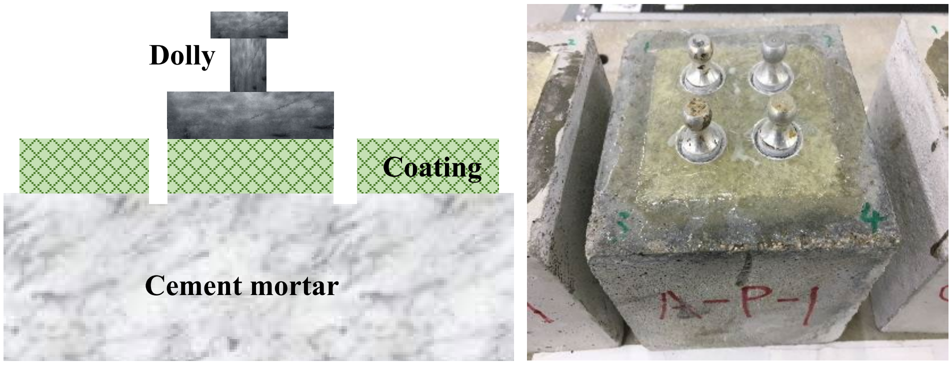


Fig. 3. Pull-off tests

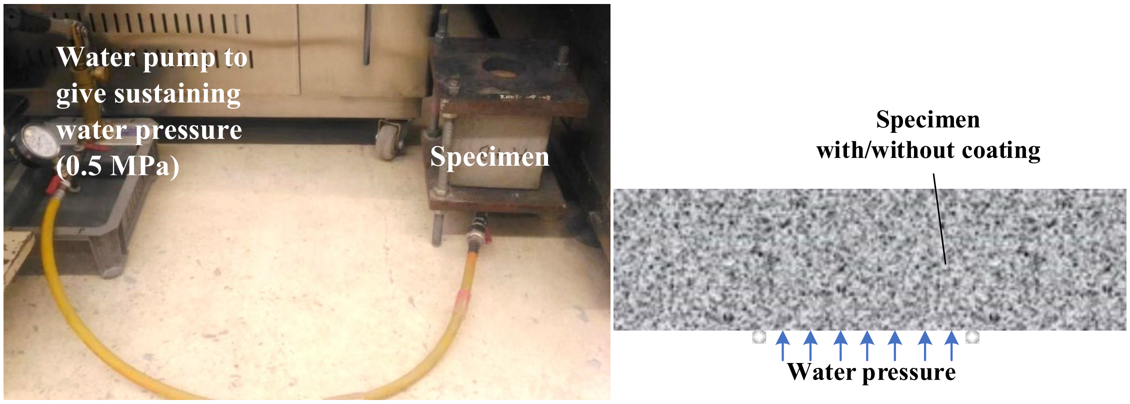


Fig. 4. Setup of the water penetration test

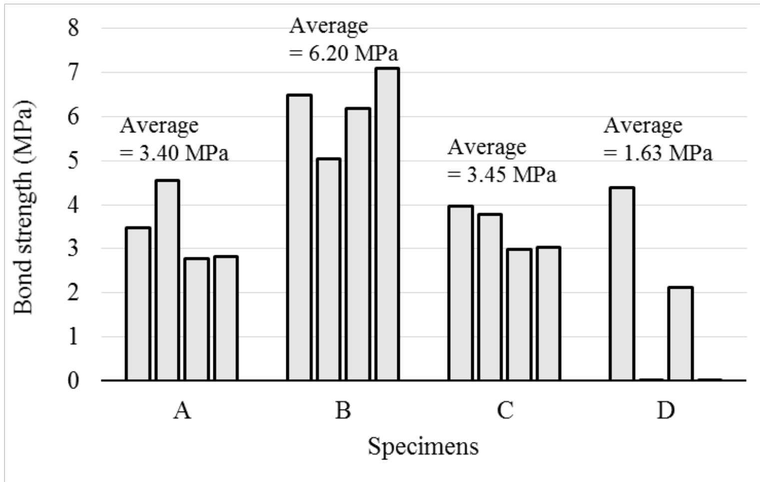
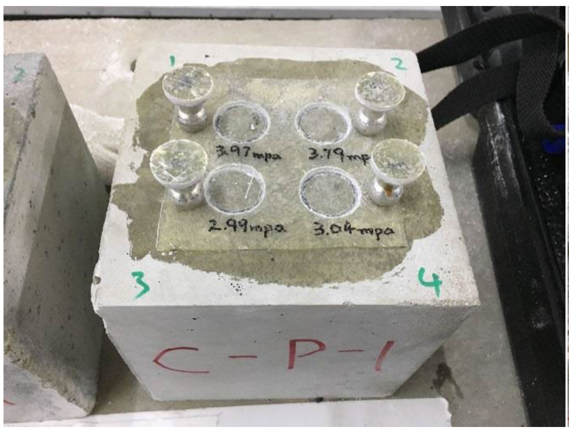


Fig. 5. Results of pull-off tests

(a) Type A (b) Type B



(c) Type C (d) Type D

Fig. 6. Failure modes of pull-off tests

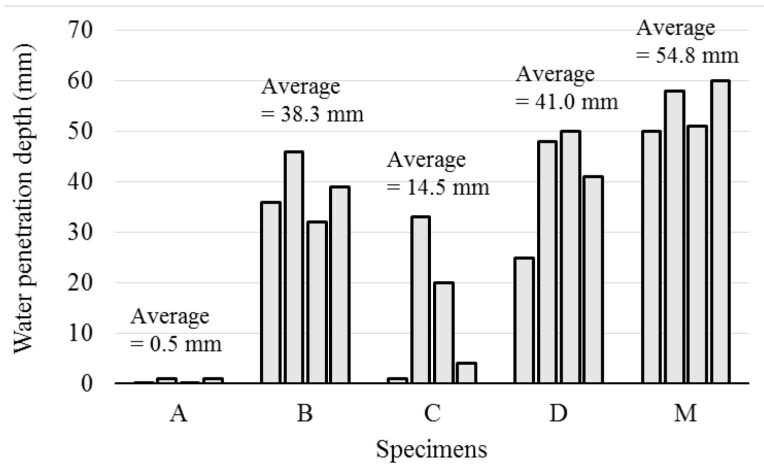
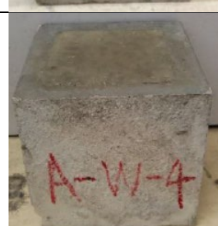
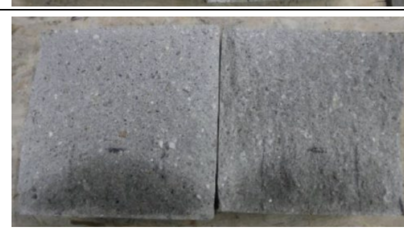
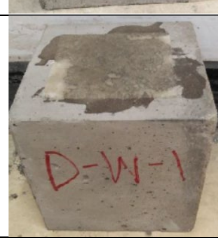
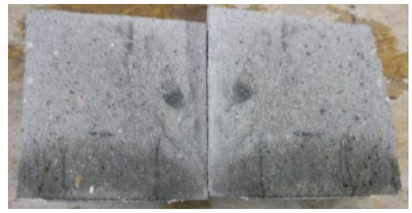


Fig. 7. Results of water penetration tests

Appendix A: Photo record of specimens before and after water penetration tests

Specimen type	Specimen No.	Before testing	After testing
A	1		
	2		
	3		
	4		
B	1		
	2		

	3		
	4		
C	1		
	2		
	3		
	4		
D	1		

	2		
	3		
	4		
M	1		
	2		
	3		
	4