Bond Strength Evaluation of Polymer Modified Cement Mortar Incorporated with Polypropylene Fibers

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Abstract

Bond strength is the adhesion between an overlay and a substrate mortar, it is the key parameter ensuring the durability and having a monolithic system. A proper bond is essential to resist any stresses at the interface associated with volume-changes, freeze-thaw cycles, and vibrations, etc. Polymer-modified cement mortar (PCM) is one of the most well-known adhesive materials, used widely as a binding agent in the engineering construction. Two forms of PCM were investigated in this study. These products are known commercially as Sika MonoTop®-620, which is a form of repair material for concrete structures, and DCP Cemfix 2CS, which is occasionally used as an adhesive to connect the tiles to the concrete base. The effect of polypropylene fiber with volume fractions of 0, 0.5, 0.75, and 1 percent was investigated using three different water-to-binder ratios. A total of 24 distinct mixes were made. The compressive strength, flexural strength and bond strength of the materials were all determined. The bond strength of each mix was assessed using the Slant-Shear and Pull-off test methods. The bond strength values derived by Slant-Shear and Pull-off tests had a high correlation, it was about 85%. Furthermore, bond strength was connected with the material's compressive and flexural strength with a relation of 95% and 86% with Slant-Shear, also 80% and 76% with Pull-off, respectively.

1. Introduction

Nowadays, Polymer-modified cement mortar (PCM) is one of the most used materials in terms of binding in the engineering construction. There are various types of PCM, mostly used to repair concrete structures and set ceramic tiles in buildings, due to provide better bond strength and flexibility as compared to the traditional ones. In the Middle East countries such as Iraq, Iran, and Turkey, the PCM is one of the most desirable construction materials. Numerous local and international companies are available serving different types of PCM such as; Sika, DCP and Kalakiem, Mapei, etc. This paper, based on a laboratory program, examines bond strength of two commercial PCM, through Pull-off and Slant-Shear tests.

Cement-based materials include grout, mortar, or concrete containing Portland cement. It has some disadvantages such as; Low tensile and flexural strength properties. High drying shrinkage, permeability and water absorption, also Low chemical resistance (Ramli and Akhavan Tabassi, 2012).

Bond is the adhesion between overlay and a substrate mortar. The term adhesion describes the connection between two materials with a common interface, while the bond between two materials is the weakest link of the system (Wall and Shrive, 1988), the quality of interfacial adhesion must be controlled. Good bond is one of the main requirements for any successful adhesion (Gorst et al., 2003; Mu et al., 2002). The strength and integrity of the bond depend upon the physical and chemical characteristics (Austin et al., 1995) and the composition (Barroso De Aguiar and Cruz, 1998) of both binding and substrate material. Adhesion to interface depends on various factors such as; type of bonding agent, cleanness and moisture content of surface substrate, roughness of interface surface (Momayez et al., 2005).

The mechanism of Adhesion is basically divided into thermodynamic, mechanical interaction, and chemical bonding mechanism (Beushausen and Alexander, 2008). In the old-to-new concrete or mortar field, the interfacial bonding between the new binding material and the old material substance is related to the mechanical interlocking forces and the Van der Waals forces (Liu et al., 2014).

In recent years, there have been many new materials for binding and repairing of concrete structures, commonly; 1) Cement-based materials (Jung and Chang, 2016), 2) Polymer modified cement-based materials (Ramli and Akhavan Tabassi, 2012), and 3) Polymer or resin materials.

The first patent about using polymer-modified cement system was published in the United Kingdom in 1920s (Ramli and Akhavan Tabassi, 2012). Numerous studies have reported that adding a polymeric compound to cementitious materials can improve the material properties such as strength; flexural, tensile, and interfacial bond between overlay material and the existing substrate (Doğan and Bideci, 2016; Ohama, 1998; Barluenga and Hernández-Olivares, 2004; Medeiros et al., 2009), also improve durability such as; water resistance, chemical resistance, and freeze-thaw resistance (Doğan and Bideci, 2016; Ohama, 1998; Vincke et al., 2002; Ramli and Tabassi, 2012; Jung et al., 2015). That is due to the fact that polymers can help to fill in capillary pores thus reducing permeability resulted in improving the mechanical properties and durability.

For many applications, the Knowledge of the adhesion properties of materials is necessary, for example when covering a wall or a concrete with mortar is needed, the adhesion between the two materials should be checked, otherwise one may have some problems like the delamination of the two materials during service life. Efficiency and durability of the system depends on the bond between binding material and the substrate (Courard et al., 2014). In order to provide durable, high bond strength, and a monolithic system, the two materials should have close properties as much as possible, most likely; elastic modulus, drying shrinkage, and thermal expansion (Momayez et al., 2005).

There are several tests available to evaluate the behavior and/or the strength of overlay-to-substrate interfaces. These tests can be classified into three categories according to the stress resultant at the interface 1) axial, includes; Pull-off (Long and Murray, 1984; Delatte et al., 2000), Direct Tension (Ohama et al., 1986), and Split-Tensile test (Sustersic and Zajc, 1999; Tschegg et al., 2000), 2) bending, includes flexural test (Wall et al., 1986; Abu-Tair et al., 1996; Kunieda et al., 2000; Kamada and Li, 2000), and 3) shear, includes testing by; Direct Shear (Chen et al., 1995; Li et al., 1997), Slant-Shear (Tayeh et al., 2013; Pattnaik, 2015), Bi-surface shear, and Push-off (Hofbeck et al., 1969; Mattock, 1974; Crane, 2010).

Bond strength can be expressed by shear resistance or tensile resistance. Based on failure modes either in tension or in shear, two test methods are applicable; first one is “Pull-off test” which is a tensile test, it can be performed both in situ and in the lab. The second one which has the shear failure mode is “Slant-Shear test” and it can be done only in the lab. The simplicity and accuracy of the tests have made them the most popular test methods.

In the present paper, two commercial adhesive compounds from Sika and DCP company, namely; Sika MonoTop®-620 and Cemfix-2C, respectively were selected to bond mortar substrate and repairing. Polypropylene fibers were also added. Finally, considering bond strength the performance of the adhesives was evaluated.

2. Research Significance

With the rapid development of infrastructure worldwide, various materials have been also developed. One of the most widely applicable is PCM, it can be utilized in terms of binding the construction materials. PCM is produced for various purposes, repairing and binding ceramic tiles are the most available and desirable types. There is a great deal of interest in bond between existing material substrate and the overlay materials. Shear stress is commonly encountered in buildings, but there is no consensus among practitioners for evaluating such strength. This paper reports the results of an experimental investigation on two types of PCM. Since no similar research have found in this area, this investigation provides a wide knowledge about bond strength of PCM materials through the most reliable tests such as Slant-Shear and Pull-off test.

3. Experimental Test Method

Since the overlay materials are mortar, a mortar substrate was prepared to provide a similar materials condition. There are simple tests that can be applied on the mortars. In this study, the following test methods were used to investigate the PCM materials.

3.1 Slant- Shear Test

The Slant-Shear test is one of the most common ways to check bond strength, firstly proposed in form of “Arizona Slant Shear Test” in 1976 (Kreigh, 1976). There are several tests available to evaluate the adhesion between substrate and overlay materials. Among these, Slant-Shear test is the most commonly used to assess the adhesion between mortar layers due to the simplicity of the experimental setup. In this test, the interface is subjected to both shear and compressive stress states, allowing a relatively uniform stress distribution at the interface. The bond strength of the PCM materials is determined using the standard ASTM C882 test procedure. After preparing a mortar substrate with having a minimum compressive strength of 31 MPa at 28 days of age, the PCM is bonded to the substrate mortar specimen on a slant elliptical plane inclined at 30° angle from vertical axis to form a composite cylinder with 75 mm diameter and 150 mm height, Fig. 1.

The bond strength is determined at the diagonal face by determining the compressive load required to fail the composite cylinder then the bond strength is calculated as [Max Load]/ [Area of Slant Surface].

3.2 Pull-off Test

In practice, Pull-off test is the usual way to measure the tensile bond strength or adhesion where one material is bonded to another, especially for cement-based materials (mortar or concrete). It is a good method to evaluate the adhesion strength of renderings or ceramic tiles (Ramos et al., 2012). It has simplicity and the possibility to do the test both in field and in lab (Austin et al., 1995).

According to ASTM C1583-04 test procedure, by using a rotary core cutting drill with diamond bits, a partial core usually 50 mm in diameter is drilled perpendicular to the surface of the overlay with extending beyond the interface into the substrate. Then a circular metal disc (dolly) with a suitable epoxy resin is attached to the surface. When the resin is achieved sufficient strength, almost after 24 hours, a tensile force is applied at a steady rate perpendicular to the disc by means of a device, which in turn reacts against the surrounding area of the overlay, till the failure occurs, Fig. 2. The bond strength can be easily defined as maximum tensile force divided by the interface area.

There are numerous devices exist which can apply the force. In this study a digital pull-off strength tester from MATEST was used, with a 50 mm diameter disc, load capacity of 16 KN and a resolution of 10 N as shown in Fig. 3. Factors such as load rate, load axiality, coring depth, and dolly attachment must be controlled to minimize variability and the influence of stress concentrations (Austin et al., 1995).

Sprinkel and Ozyildirim (2000) have presented a range of bond strength to qualify the test results, Table 1. In this test, failures can occur in substrate, overlay, interface, the epoxy used to bond the caps to the core, and a combination of these locations. The magnitude of the tensile force, type and location of the failure give valuable information about the performance of the binding material. Failure in the substrate indicates that the bond strength is greater than the tensile strength of the substrate, while the failure in the overlay material indicates that the bond strength is greater than the tensile strength of the overlay (Bonaldo et al., 2005). A 100% failure in the bond interface maintains a true indication of bond strength, and the result will be discarded if the failure occurs in the epoxy (Sprinkel and Ozyildirim, 2000).

Table 1
Interfacial bond strength quality
(Sprinkel and Ozyildirim, 2000)

Bond strength (MPa)	Quality
≥ 2.1	Excellent
1.7 to 2.1	Very good
1.4 to 1.7	Good
0.7 to 1.4	Fair
0 to 0.7	Poor

4. Materials And Methods

4.1 Materials

The experimental program included evaluating bond strength of PCM through Slant-Shear and Pull-off test. The Slant-Shear test was provided according to ASTM C882 specifications. Therefore, plastic cylinder molds with 75 mm diameter and height of 150 mm were prepared. For the other test, four square wooden slabs of 60×60×5 cm were created. The cylinder molds and slabs were firstly casted with a mortar substrate. The main raw materials for the substrate were Ordinary Portland cement (OPC), natural river sand as a fine aggregate with Fineness Modulus of 3.0, and Super-plasticizers with trade name of Flocrete SP42 was utilized. For the second stage, the PCM materials were provided. A tile adhesive material from DCP company, namely, Cemfix 2CS consisting of a special blend of cement, well graded aggregate and special additives that mixed with the synthetic polymer modified latex was used. From Sika company, a polymer modified surfacing/ finishing structural repair mortar, namely, Sika MonoTop®-620 was also used as overlay for the prepared substrates. Synthetic fibers such as Polypropylene fiber (PPF) was utilized in the overlay mixes.

4.2 Experimental Procedure

4.2.1 Mortar Substrate

Since the investigation is about checking the bond between two materials in a system, one material acts as a substrate and another as an overlay. In this study, both materials were prepared through casting with regard to the available standards and specifications.

The mortar mixtures were prepared based on the ASTM C109. The cement-to-sand ratio of 1:2.5, and water-to-cement ratio of 0.45 was used. For the purpose of testing by Slant-Shear, half of the cylinders were casted with a slant surface and angle of 30º with the vertical based on the ASTM C882 standard. De-molded those half-cylinders after 24 hours, and cured in water at laboratory temperature. As per the ASTM C109 standard, 50×50×50 mm cubes were also casted for checking the compressive strength at 28 days. The half-cylinders were air dried for 7 days after completing 28 days of water curing.

For testing by Pull-off, the same condition as for the half-cylinders was provided. Therefore, the four slabs were casted by a mortar substrate with the same mix design properties used for the half- cylinders. For each slab, three 100×200 mm cylinders were casted to check the strength in compression at 28 days. The slabs were cured for about 10 days through covering by wet sheets after 24 hours from casting, Fig. 4.

As the area of bonding is a very effective factor, this study tried to take a normal surface condition for the substrates, provided nearly same state for both half-cylinders and the slab substrates. The surface finishing of the slabs was done by mean of wooden float.

4.2.2 Overlay PCM

From PCM materials, various mixtures were prepared with different water-to-binder ratio and volume fraction (Vf) of polypropylene fibers. For Sika MonoTop®-620, water-to-binder ratio of 0.16, 0.18, and 0.20, for Cemfix 2CS material, the ratio of 0.25, 0.30, and 0.35 was used based on their datasheets. PPF used in Vf of (0, 0.5, 0.75, and 1%) for each product, Fig. 5. The overall 24 different mixes were prepared and used as an overlay for bonding the previously prepared substrates, Table 2. The overlay materials were mixed by a handy-mixer until achieving a smooth and a homogenous mixture, Fig. 6. The flowability of each mix was also checked by the flow table test as per ASTM C1437-01.

Table 2
Mix properties of overlay materials.

Sika MonoTop®-620	**Water/Binder**	**PPF Vf%**	**Mix Designation**	**Binder (Kg)**	**Water (Kg)**	**PPF (g)**
Mix 1	0.16	0	SA1	14	2.24	0
Mix 2	0.16	0.5	SA2	15	2.4	35.9
Mix 3	0.16	0.75	SA3	15	2.4	54
Mix 4	0.16	1.0	SA4	15	2.4	72
Mix 5	0.18	0	SB1	15	2.7	0
Mix 6	0.18	0.5	SB2	15	2.7	37
Mix 7	0.18	0.75	SB3	15	2.7	55
Mix 8	0.18	1.0	SB4	15	2.7	73
Mix 9	0.2	0	SC1	10.5	2.1	0
Mix 10	0.2	0.5	SC2	12.5	2.5	31
Mix 11	0.2	0.75	SC3	14	2.8	52
Mix 12	0.2	1.0	SC4	14	2.8	69
Cemfix 2CS						
Mix 1	0.25	0	DA1	12	3	0
Mix 2	0.25	0.5	DA2	12	3	39
Mix 3	0.25	0.75	DA3	12	3	58.5
Mix 4	0.25	1.0	DA4	12	3	78
Mix 5	0.30	0	DB1	12	3.6	0
Mix 6	0.30	0.5	DB2	12	3.6	40
Mix 7	0.30	0.75	DB3	12	3.6	60
Mix 8	0.30	1.0	DB4	11	3.3	74
Mix 9	0.35	0	DC1	12	4.2	0
Mix 10	0.35	0.5	DC2	12	4.2	42
Mix 11	0.35	0.75	DC3	9.88	3.45	51.75
Mix 12	0.35	1.0	DC4	10	3.5	70

As per ASTM C882, after 28 days of water curing and 7 days air drying, the half-cylinder substrates were cleaned properly by means of dry brushing to eliminate any dust and fine materials. Exactly at the day of 35, after taking into their specimens again, the half-cylinder substrates were bonded on a slant elliptical plane inclined at an angle 30 from vertical by the previously explained 24 PCM mixes to create composite cylinders. The compressive strength of the PCM mixes were also determined using 50 mm cube as per the ASTM C 109 standard. The composite cylinders and cubes were de-molded after 24 hours from casting and cured in water for 28 days. Since the curing duration completed, the composite cylinders were capped and prepared for testing by compression, Fig. 7.

The slab substrates were cured for about 10–15 days. After gaining sufficient strength roughly 34 MPa, the slabs were air dried for 24 hours, and cleaned by the same way of cleaning half-cylinders. At the same day and from the same batch for overlaying half-cylinders, the surfaces of the slabs were covered by some amount of the prepared PCM mixes with thickness of 1 cm. The overlay surfaces were leveled and finished by the same previously used wooden float, Fig. 8. After 24 hours from covering, the overlays on the slabs were kept moist through covering by wet sheets for 28 days. The flexural strength of mixes was also determined through casting prisms of 40×40×160 mm as per the ASTM C348-02.

5. Testing

Composite cylinders were prepared for testing after completing curing period, they were capped as per ASTM C882 recommendation. Compressive tests were carried out on the composite cylinders in accordance to ASTM C39. During testing, the substrate part is required to be at the bottom and overlay at the top, Fig. 9.

According to ASTM C1583-04 standard, the Pull-off test was performed on the 28th day after the PCM was applied on the slab surfaces. Partial cores with 50 mm in diameter and depth of 15 mm were drilled perpendicular to the surface of the overlay by means of a rotary core cutting drill with diamond bits, considering 30–60 mm far from the overlay edges to avoid weak areas. A number of cores were taken with a distance of at least 100 mm center-to-center of cores. After cleaning all the cores using air blower, the metal dollies with a suitable epoxy resin were attached to the surfaces. After 24 hours and achieving sufficient strength of the epoxy resins, a tensile force was applied at a steady rate perpendicular to the dollies by means of a Pull-off device, the bond strength was conducted by the maximum tensile force divided by the interface area.

6. Result And Discussion

6.1 Test results

In conducting Slant-Shear bond tests on the composite cylinders, three different modes of failures were observed as shown in Figure 10. Figure (a) shows the failure on the slant surface indicating a failure of the bond between the overlay and substrate material. Figure (b) and (c) show the failure of the composite cylinder in substrate and overlay material, respectively, indicating a weaker material strength than the bond strength at the interface. Table 3 contains cube compressive strength for both mortar substrate and overlay PCM, and bond strength between the two materials determined by testing composite cylinders in compression with their failure modes.

Table 3 Compressive strength and Slant-Shear bond strength with failure modes.

Mixes	Compressive strength (MPa) (ASTM C39)		Slant-Shear Bond strength (MPa) (ASTM C882)	Failure Modes
	Substrate	PCM		
SA1	48.56	38.17	26.06	In the bond
SA2	48.56	33.85	22.65	In the substrate
SA3	52.46	29.6	21.05	In the PCM
SA4	52.46	30.55	20.31	In the bond
SB1	52.46	25.34	13.49	In the bond
SB2	52.46	24.65	16.03	In the substrate
SB3	52.46	26.25	20	In the substrate
SB4	52.46	26.49	20.29	In the bond
SC1	48.56	28.07	20.44	In the bond
SC2	48.56	24.27	14.04	In the bond
SC3	48.56	21.39	18.7	In the bond
SC4	48.56	24.89	18.04	In the bond
DA1	48.49	10.74	5.83	In the PCM
DA2	48.49	13.44	5.35	In the PCM
DA3	48.49	13.09	8.02	In the PCM
DA4	48.49	13.76	7.70	In the PCM
DB1	44.66	7.18	7.49	In the PCM
DB2	44.66	7.15	7.50	In the PCM
DB3	44.66	7.20	7.32	In the bond
DB4	44.66	9.45	9.58	In the bond
DC1	48.49	6.41	4.87	In the PCM
DC2	48.49	6.12	4.83	In the PCM
DC3	44.66	6.02	6.65	In the PCM
DC4	44.66	5.61	6.48	In the PCM

During performing the Pull-off test, two types of failure modes were identified depending on the location of the disintegration surface, Figure 11. Figure (a) shows failure in the PCM, and figure (b) shows failure in the interfacial bonding. No failures neither due to the substrate nor epoxy material was observed. The flexural strength determined by flexural test and results from Pull-off test with the failure modes are shown in the Table 4.

Table 4 Flexural strength and Pull-off bond strength with failures modes.

Mixes	**Flexural Strength (MPa)** (ASTM C348-02)	**Pull-off Bond Strength (MPa)** (ASTM C1583-04)	**Failure Modes**
SA1	9.38	2.68	In the PCM
SA2	11.06	2.86	In the bond
SA3	8.15	1.21	In the bond
SA4	8.56	2.12	In the bond
SB1	8.27	2.06	In the bond
SB2	7.82	1.12	In the PCM
SB3	8.43	1.64	In the PCM
SB4	7.57	1.94	In the PCM
SC1	7.50	1.83	In the bond
SC2	7.76	1.77	In the bond
SC3	7.93	2.4	In the PCM
SC4	7.96	1.98	In the PCM
DA1	6.12	0.70	In the PCM
DA2	5.83	0.88	In the PCM
DA3	7.13	0.69	In the PCM
DA4	6.83	0.52	In the bond
DB1	4.66	1.15	In the PCM
DB2	4.35	0.63	In the PCM
DB3	3.57	1.22	In the PCM
DB4	4.66	1.58	In the PCM
DC1	3.72	0.47	In the PCM
DC2	3.73	0.23	In the PCM
DC3	4.41	0.71	In the PCM
DC4	3.87	1.11	In the PCM

6.2 Effected factors and Correlations

In this experimental study, the main influence factors in the overlay mixes can be determined such as the water-to-binder ratio, fiber content, and the type of PCM.

6.2.1. Effect of water-to-binder ratio

1. Flowability

The main influence factor related to the overlay mix ingredients is water-to-binder ratio, it has significant effect on the workability of PCM materials. Increasing water-to-binder ratio leads to increase in the flowability of the mixes by around 12%. In this study the water-to-binder ratio of 0.16, 0.18, 0.20, 0.25, 0.30, and 0.35 were employed as shown in the Figure 12.

2. Mechanical properties

In this study, the mechanical properties such as compressive strength, flexural strength, Slant-Shear, and Pull-off bond strength were measured. The effect of water-to-binder ratio was observed in each test results.

Increasing water-to-binder ratio influenced decreasing in compressive strength by 33% from 0.16 to 0.18 and 0.25 to 0.30 ratio, and 10% difference from 0.18 to 0.20 and 0.30 to 0.35 was observed, Figure 13. In terms of flexural strength, there was a reduction about 10% between the mixes prepared from MonoTop®-620, and 20% between the Cemfix 2CS mixes, Figure 14.

In the Slant-Shear test results, the effect of water-to-binder ratio was different for each PCM. The Slant-Shear bond strength was decreased beyond 0.16 by 48% for Sika MonoTop®-620. However, 52% increasing was observed in the ratio of 0.20, but still 0.16 remained as the highest. In the Cemfix 2CS, the bond strength increased with increasing water-to-binder ratio from 0.25 to 0.30 ratio by 28%, but 35% decreasing was observed when 0.35 was used, Figure 15. The mixes with having 0.16 and 0.30 water-to-binder ratio showed the optimum Slant-Shear bond strength.

The effect of water-to-binder ratio on the Pull-of bond strength was also evaluated. Generally, the bond decreased with increasing the ratio by around 10% for the MonoTop®-620. Although, the bond increased in the Cemfix 2CS from 0.25 to 0.30 by 23%, but the reduction with 59% was occurred for 0.35 ratio, Figure 16. The effect of water-to-binder ratio on the bond strength is greatly depends upon the type of PCM.

6.2.2. Effect of fiber content

1. Flowability

In this investigation, four different PPF dosages of 0, 0.5, 0.75, and 1.0% were employed. The availability of fibers in the mixes definitely affected the flowability and consistency of PCM materials. Increasing fiber content to the mixes provided lower flowability. The reduction amount was about 11% for fixed water-to-binder ratio. Actually, the reduction amount is small because the polymers provide a little fluidity and consistency, each material has own ranges of the flow decreasing. Figure 17 shows the flow reduction of all the mixes with different water-to-binder ratio.

2. Mechanical properties

Adding fibers to the overlay mixes is a good idea in order to improve some weaknesses such as reducing early cracks through increasing tensile strength. In this study, effects of fibers on the compressive strength, flexural strength, and both Slant-Shear and Pull-off bond strength were evaluated. From the compressive strength results, it was observed that increasing fibers decreased the strength with a reduction amount ranged from 2 to 14%, then a small increasing was occurred, it could either exceed more than that of original high strength as obtained for the mixes having 0.25 and 0.35 water-to-binder ratio by averaged 30% increasing amount, or it could not increase the strength sufficiently, Figure 18.

In the Slant-Shear bond strength, the reduction due to incorporated fibers in most of the mixes was also observed ranged from 1.5 to 31%. However, with adding more fibers, mixes with having 0.18, 0.25 and 0.35 ratio were improved by nearly 33% at 1% fiber dosage, Figure 19. In was concluded that, some reduction in the strength was normally occurred by no more than 15% due to incorporating PPF, but adding more fibers mostly 1% may improve it by more than 33% in most of the mixes. Hence, both the fiber dosage and water-to-binder ratio have great influence on the bond strength.

Influence of the incorporated fibers was clearly expressed in terms of flexural and Pull-off bond strength rather than compressive and Slant-Shear bond strength, both strength type was improved by adding fibers in an optimum point. In the Pull-off bond strength, for 0.16 mix ratio, the 0.5% PPF showed the highest strength value with having about 7% difference with control one. The other mixes such as 0.20 at 0.75%, 0.25 at 0.5%, 0.30 at 1%, and 0.35 at 1% of PPF exhibit the highest strength value with a difference of 30, 26, 37, and137% from control mixes, respectively. Although, fiber addition for the mix with having 0.18 water-to-binder ratio couldn't obtained any increasing, the maximum reduction was at 0.5% PPF with having roughly 46% difference with the control mix, Figure 20.

In the flexural strength also some reduction was observed, but in general the optimum point was found at 0.75% PPF for mixes with having 0.18, 0.25, and 0.35 with increasing by 1.9, 16.5, and 18.5%, respectively. However, the optimum flexural strength was found at 0.5% in the mixes having 0.16 ratio, and 1% PPF in 0.20 by roughly 18% and 6% increasing, respectively. For the mix of 0.20 ratio, the strength was reduced in 0.5 and 0.75% but increasing was achieved at 1% PPF for the same control value, Figure 21.

Generally, Higher flexural and Pull-off bond strength are obtained during incorporating fibers to PCM considering the fiber dosage, water-to-binder ratio and type of PCM.

6.2.3. Correlations

The correlations between the measured compressive strength and bond strength values were analyzed as illustrated in Figures 22 and 23. The higher correlation indicates that there is a stronger relation between the compressive and Slant-Shear bond strength rather than that of Pull-off bond strength, the relation was 95% and 80% respectively. Furthermore, Slant-Shear bond strength has a higher relation with flexural strength though, the relation was about 86%, while there is a relation of 76% between flexural and Pull-off bond strength, Figures 24 and 25. The reason to low relation between flexural and Pull-off strength is sometimes due to the curing time regime, as Kim (2020) concluded 31% higher relation in seven days compared to 28 days. There must be other factors contribute to the Pull-off bond strength such as; surface roughness, moisture, type of used epoxy etc. Furthermore, the type of polymers has more effect on the tensile strength than compressive strength, resulted in higher compressive strength than flexural and pull-off bond strength, similar to previous study by Medeiros et al. (2009).

There is also a strong relation between Slant-Shear and Pull-off bond strength, compressive and flexural strength, the relation was about 85 % and 94% respectively, Figure 26 and 27. The strong relation between compressive and flexural strength was also achieved by Kim (2020).

Conclusions

In this study, experiments were performed on two types of PCM materials producing by two different companies. The conclusions derived from the experimental results are as follows:

1. Based on their datasheet, each PCM material had own water-to-binder ratio. Modification in this ratio, exhibits great influence mostly on the mechanical properties, but poor effect on the flowability due to availability of polymers.

2. The addition of PPF in an appropriate amount exhibits the better performance in terms of flexural and Pull-off bond strength, while reduction was observed in the compressive and Slant-Shear bond strength. In terms of flexural strength, the 0.75% of PPF showed the optimum in almost all the mixes. However, in the Pull-off bond strength, the optimum was found mostly with 0.5 and 1%. The Reductions in flowability was also noted due to incorporated fibers.

3. The bond strength provided by Slant-Shear test had a direct relation with the compressive and flexural strength of overlay materials with 95% and 86%, respectively. Although lower relation was observed with Pull-off bond strength, it has a relation with compressive and flexural strength with 80% and 76%, respectively.

4. There is a strong relation between bond strength values determined by Slant-Shear and Pull-off test, it was about 85%. A strong relation between compressive and flexural strength was also observed, it was nearly 94%.

5. In the Sika MonoTop®-620, the failure modes were mostly either in the bond or in the substrate in both Slant-Shear and Pull-off test, it is a good indicator about the material. Although in the Cemfix 2CS, the failure modes were mostly in the overlay material itself. The effect of water-to-binder ratio and fiber content on the failure modes were complex, clear difference was not observed. Generally, the failure

modes greatly depend upon the type of PCM. Furthermore, the test results of used PCM materials were in different ranges, that is due to the application purposes.

Declarations

Conflicts of Interest

All authors declare that there is no conflict of interest or financial conflicts to disclose.

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Figures

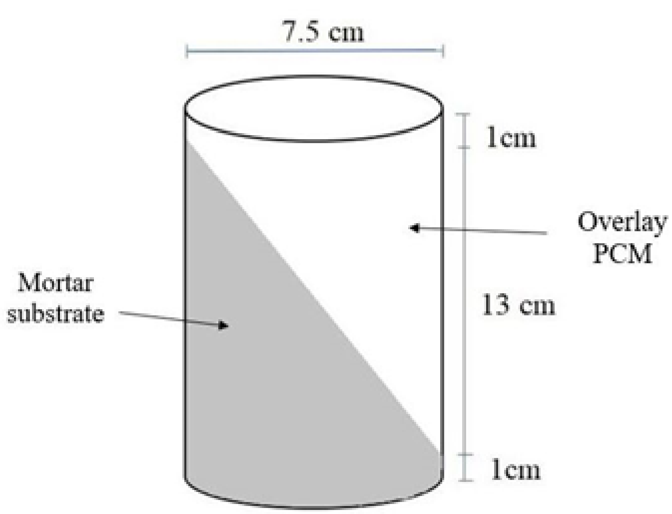

Figure 1

Schematic diagram of composite cylinder for Slant-Shear test.

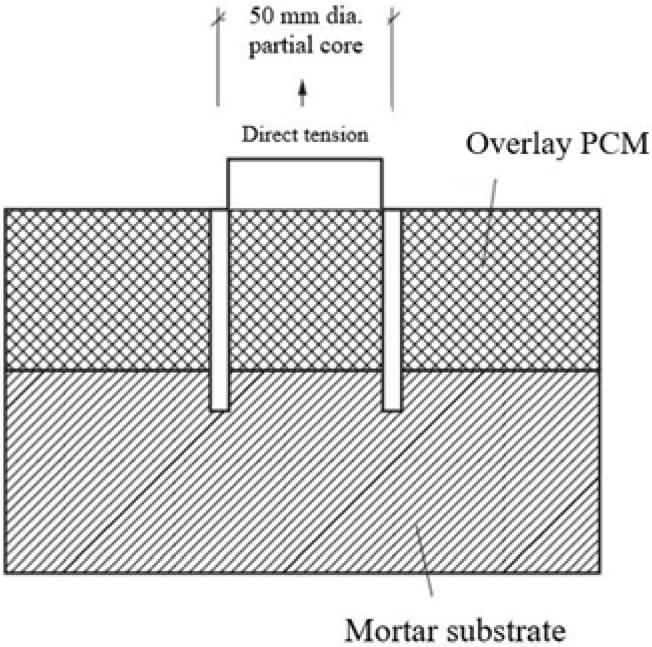

Figure 2

Schematic diagram of Pull-off test.

Figure 3

Pull-off test device apparature.

a) Half-cylinder substrates   b) Slab substrate

Figure 4

Mortar substrate preparation.

a) Sika MonoTop®-620   b) Cemfix 2CS   c) PPF

Figure 5

Materials for overlying the substrates.

Figure 6

Mixing overlay materials by handy-mixer.

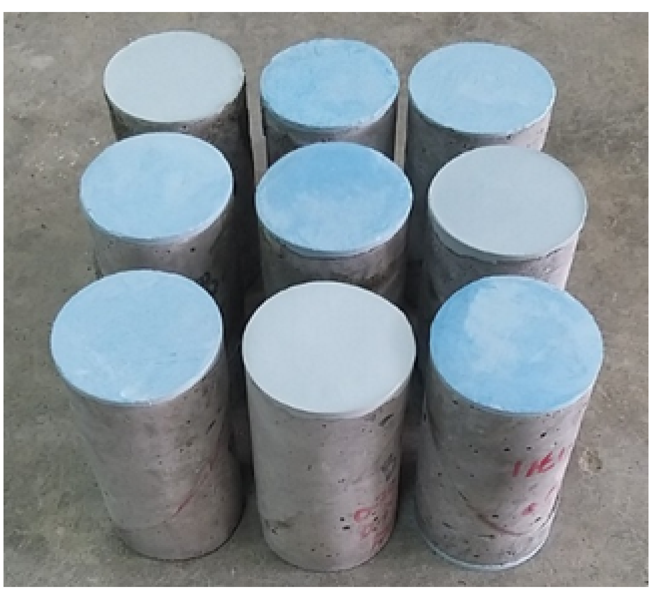

Figure 7

Capping composite cylinders for Slant-Shear test.

Figure 8

Covering slab substrates by PCM mixes.

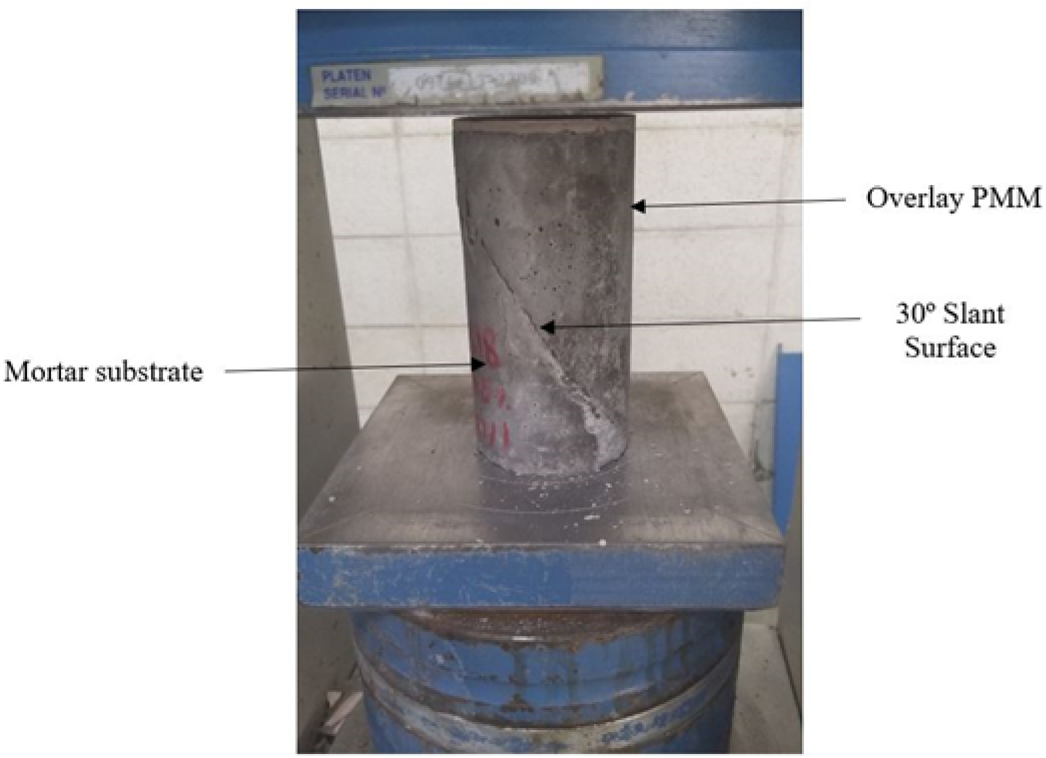

Figure 9

Checking bond strength by Slant-Shear test.

a) Failure on slant surface b) Failure of mortar substrate c) Failure of overlay PCM

Figure 10

Failure modes of composite cylinders.

a) Failure in PMM b) Failure in the interficial bond

Figure 11

Failure modes during testing by Pull-off.

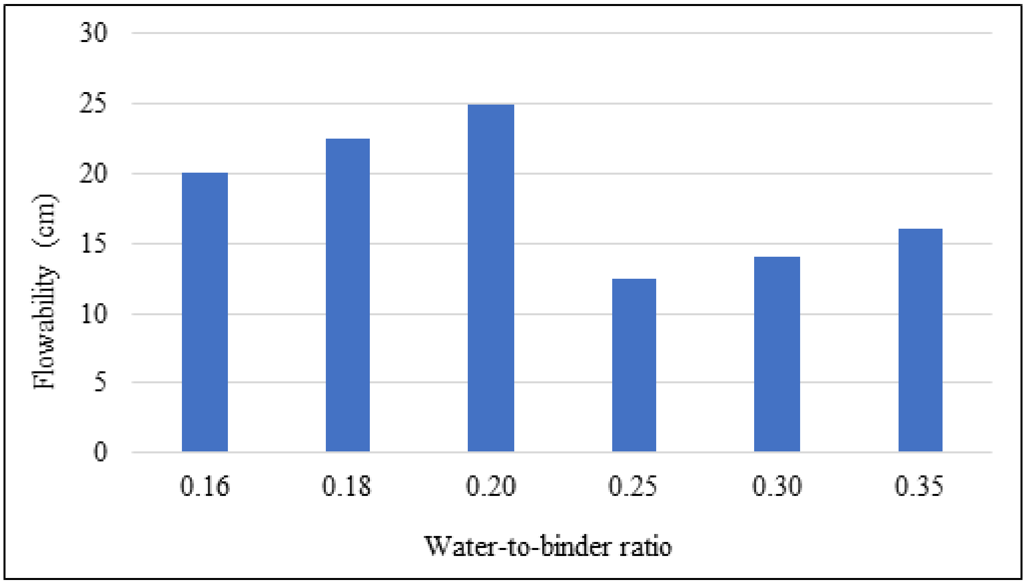

Figure 12

Effect of water-to-binder ratio on the flowability of PMM.

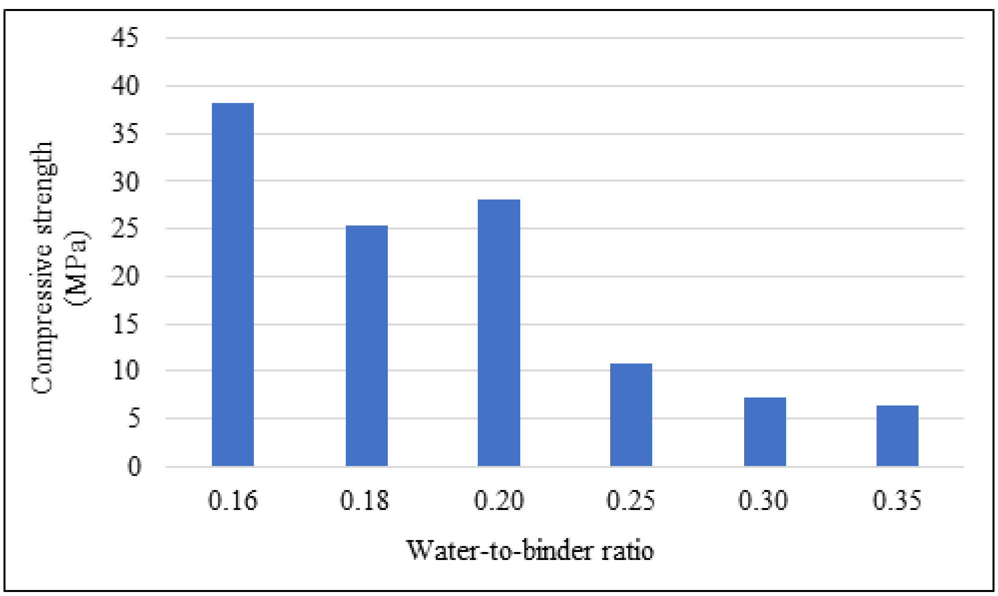

Figure 13

Effect of water-to-binder ratio on the compressive strength.

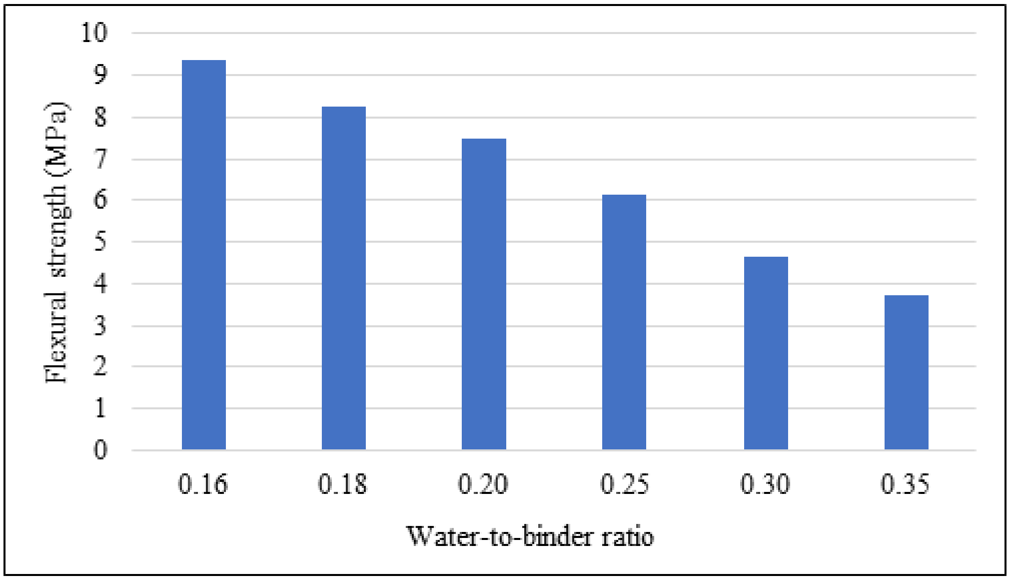

Figure 14

Effect of water-to-binder ratio on the flexural strength.

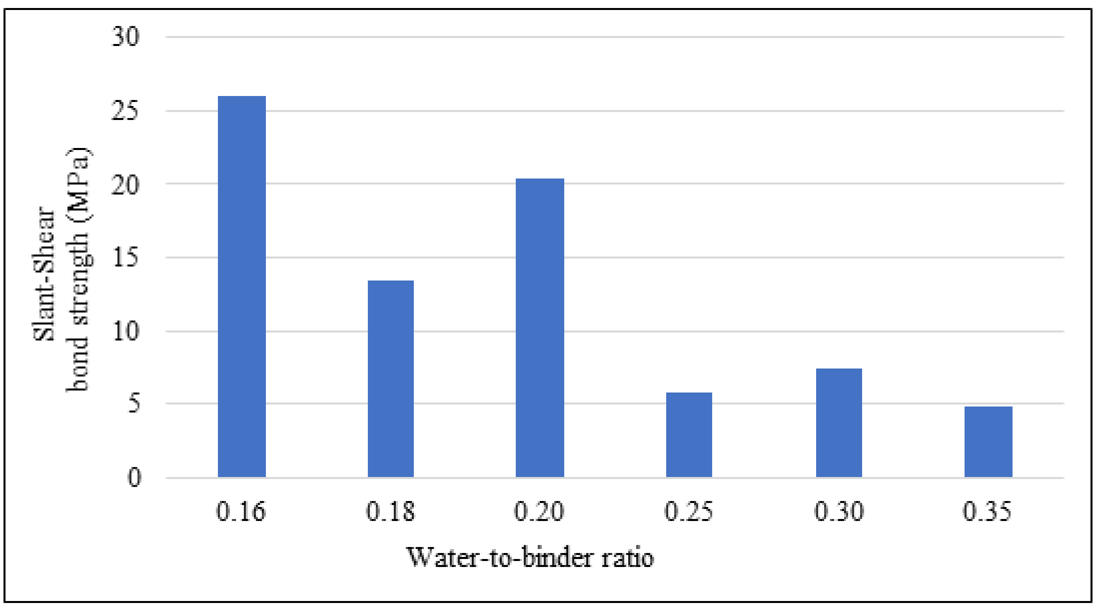

Figure 15

Effect of water-to-binder ratio on the Slant-Shear bond strength.

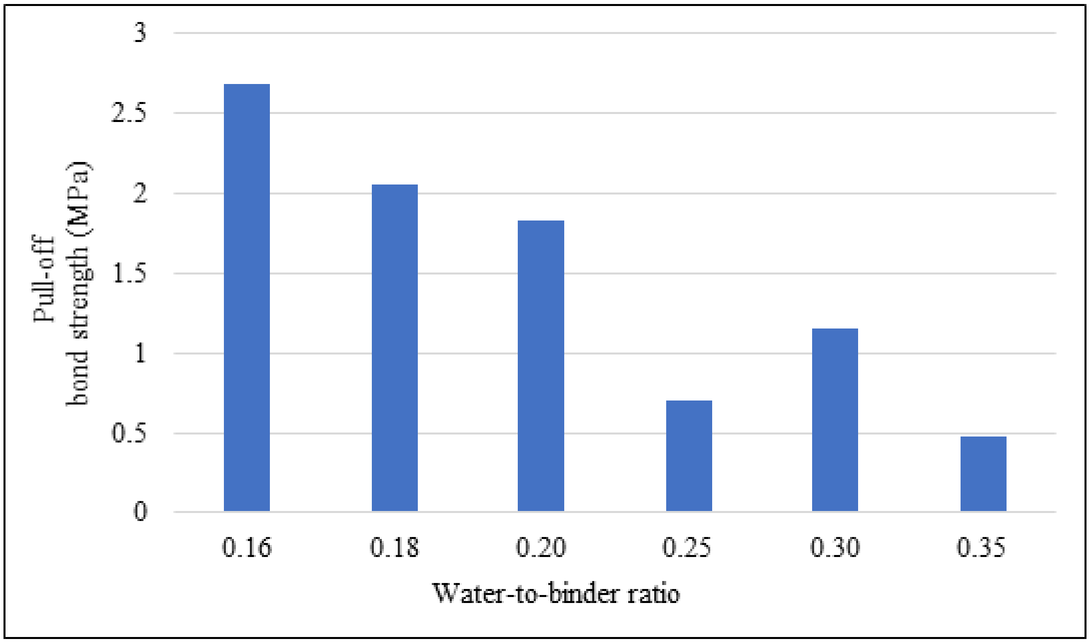

Figure 16

Effect of water-to-binder ratio on the Pull-off bond strength.

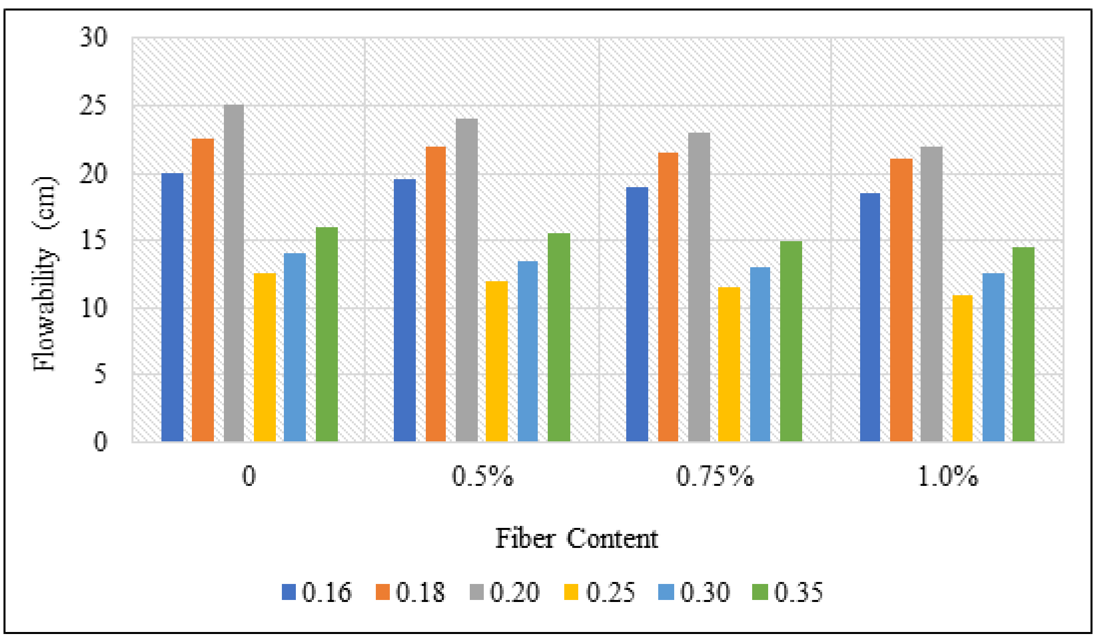

Figure 17

Effect of fiber content on the flowability of PMM with different water-to-binder ratio.

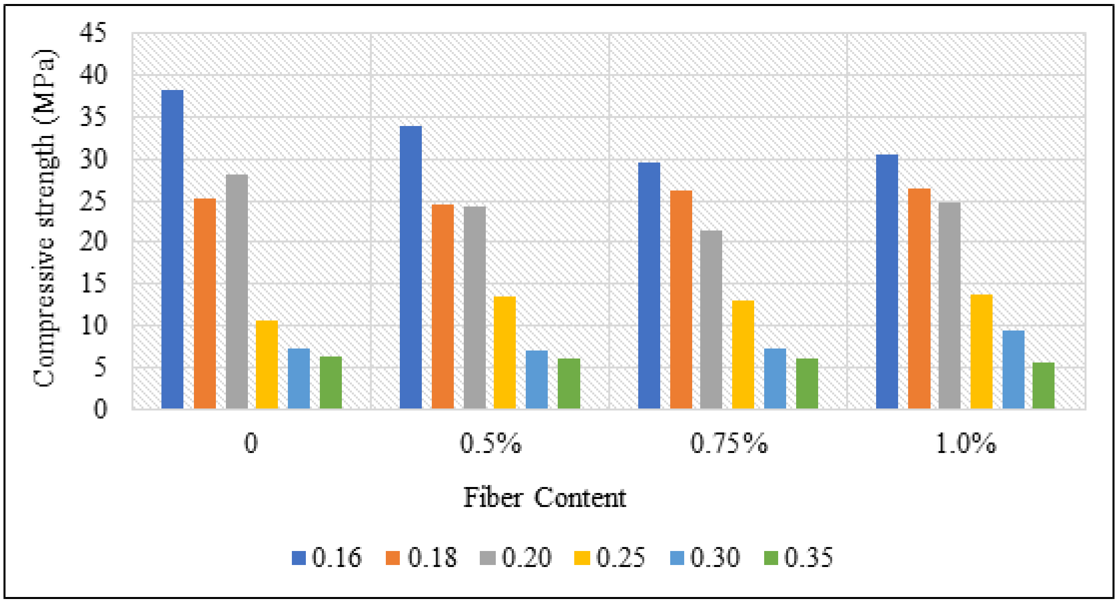

Figure 18

Effect of fiber content on the compressive strength with different water-to-binder ratio.

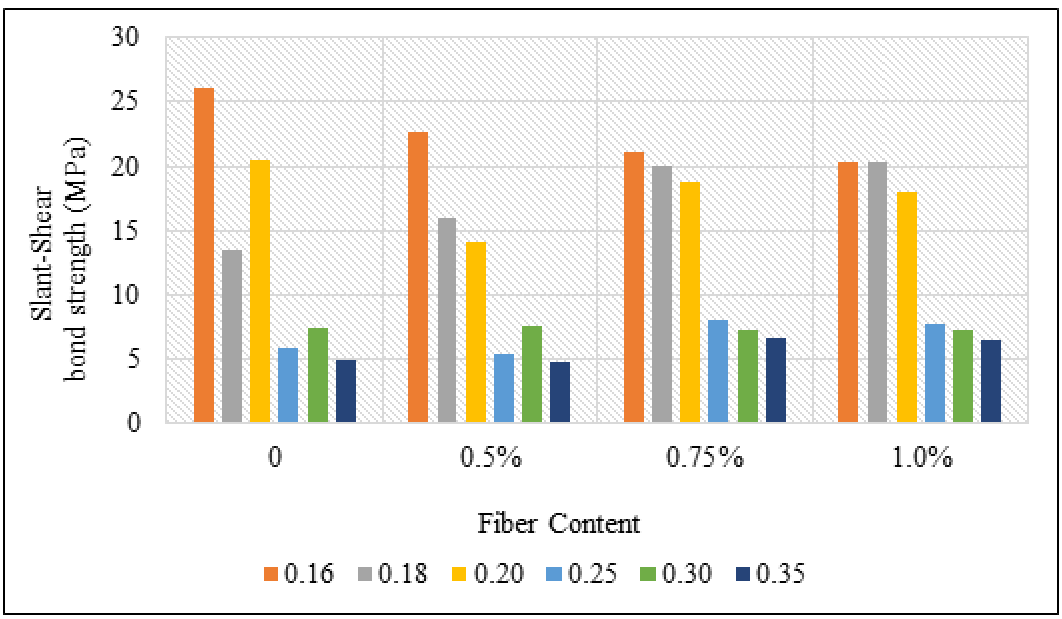

Figure 19

Effect of fiber content on the Slant-Shear bond strength with different water-to-binder ratio.

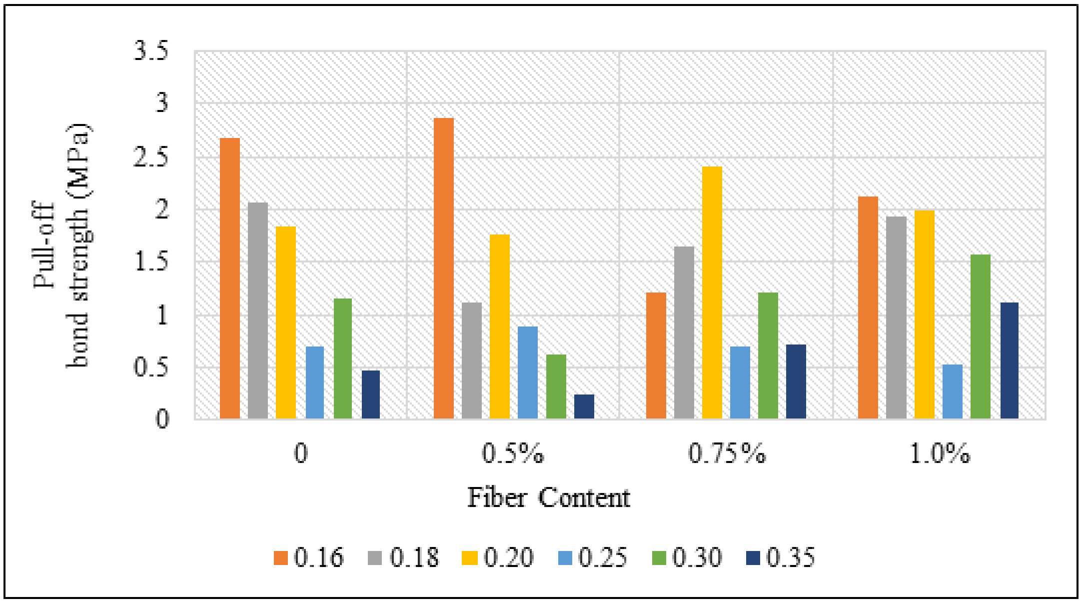

Figure 20

Effect of fiber content on the Pull-off bond strength with different water-to-binder ratio.

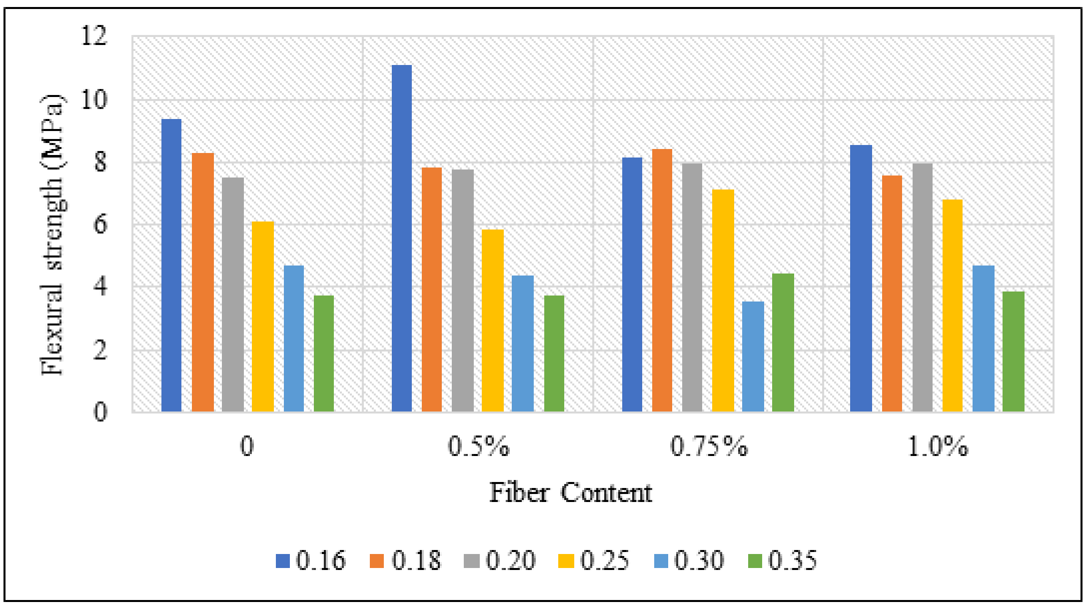

Figure 21

Effect of fiber content on the flexural strength with different water-to-binder ratio.

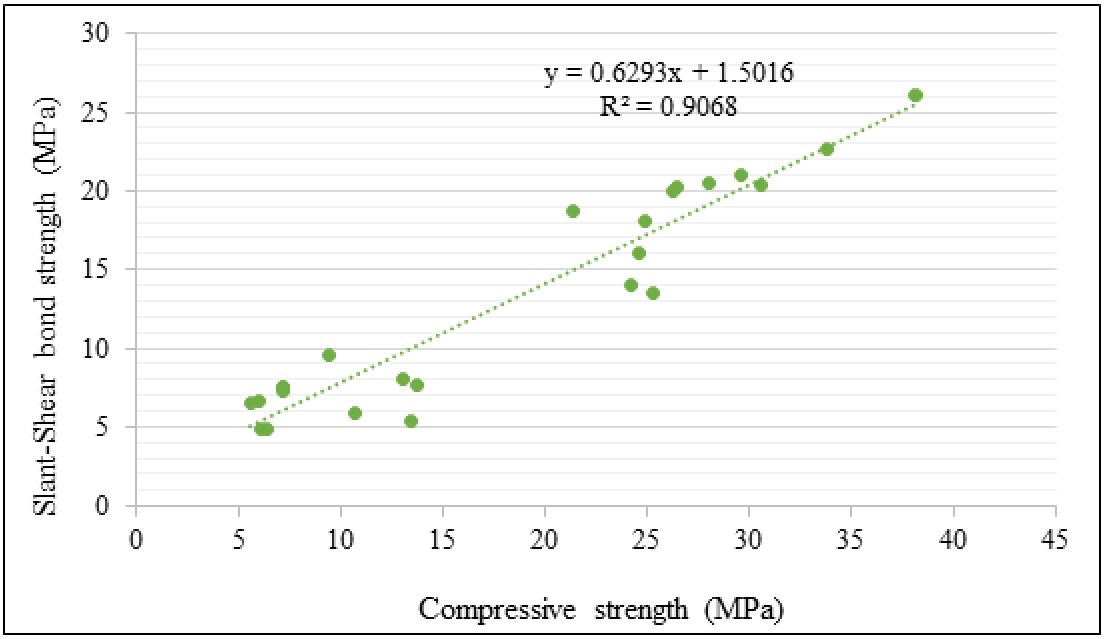

Figure 22

Relationship between compressive and Slant-Shear bond strength.

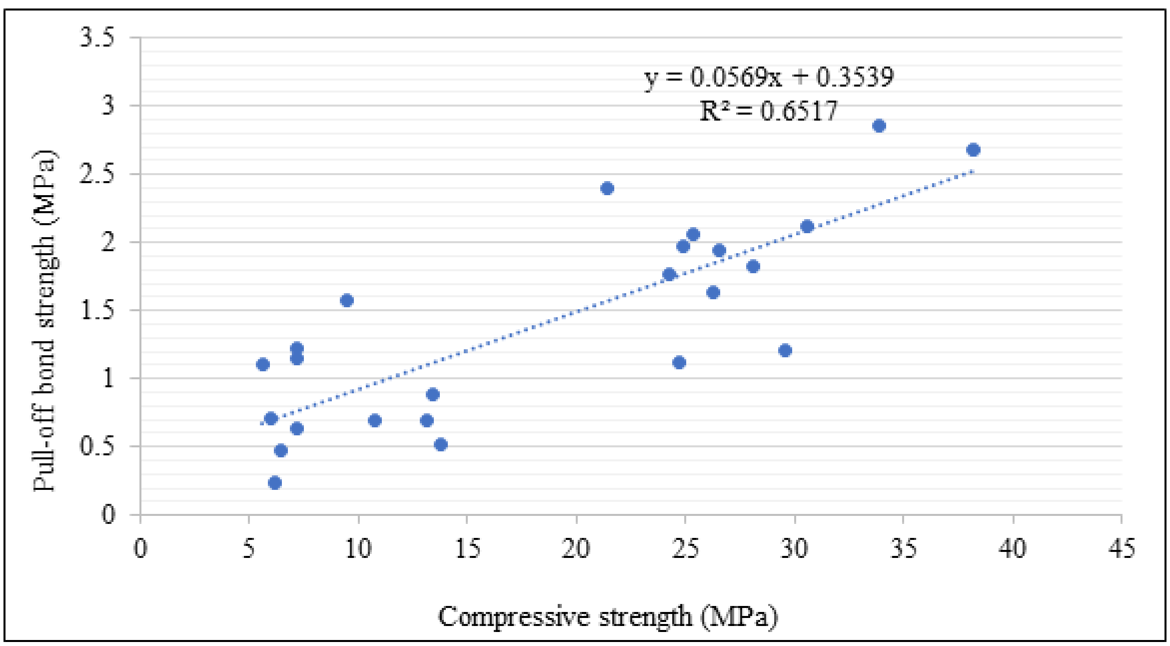

Figure 23

Relationship between compressive and Pull-off bond strength.

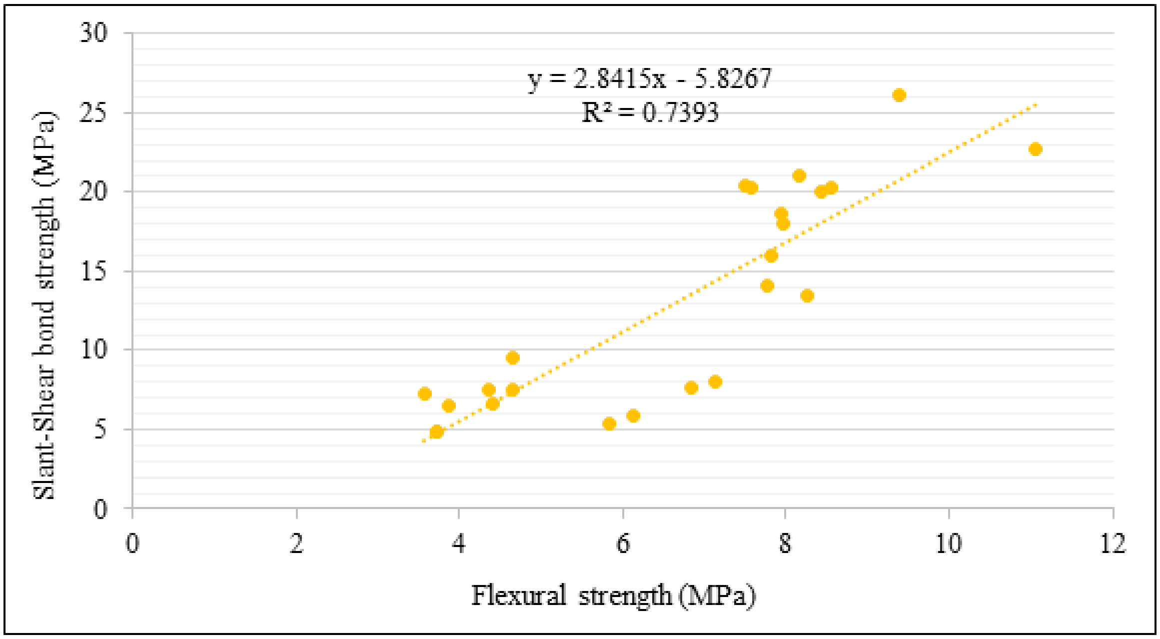

Figure 24

Relationship between flexural and Slant-Shear bond strength.

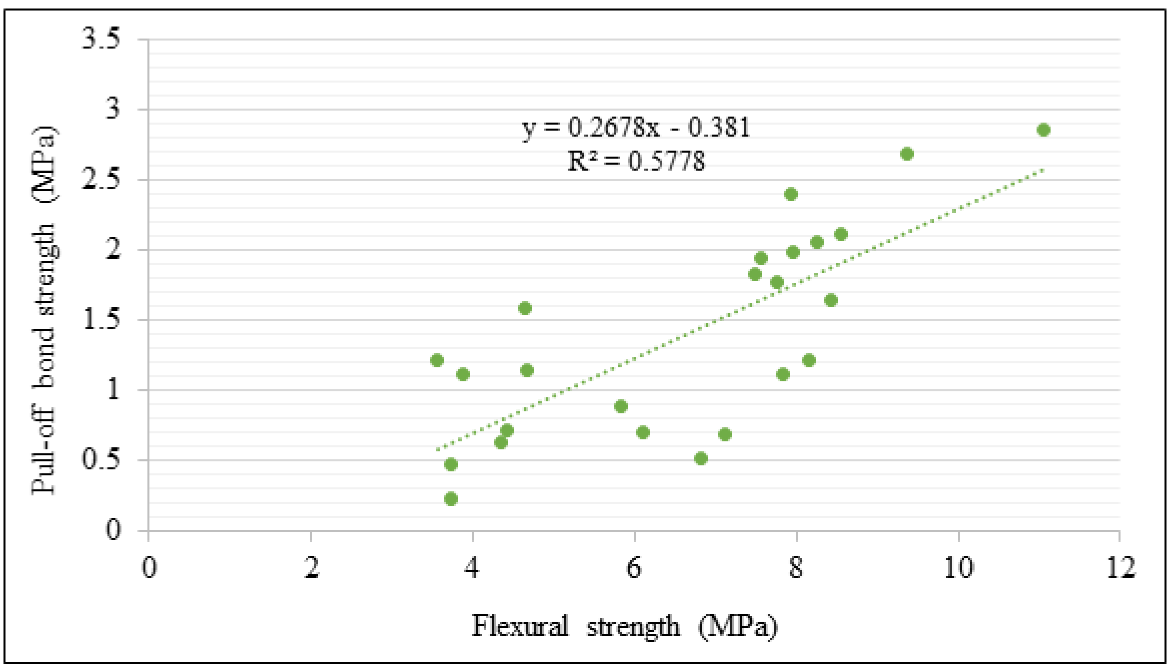

Figure 25

Relationship between Flexural and Pull-off bond strength.

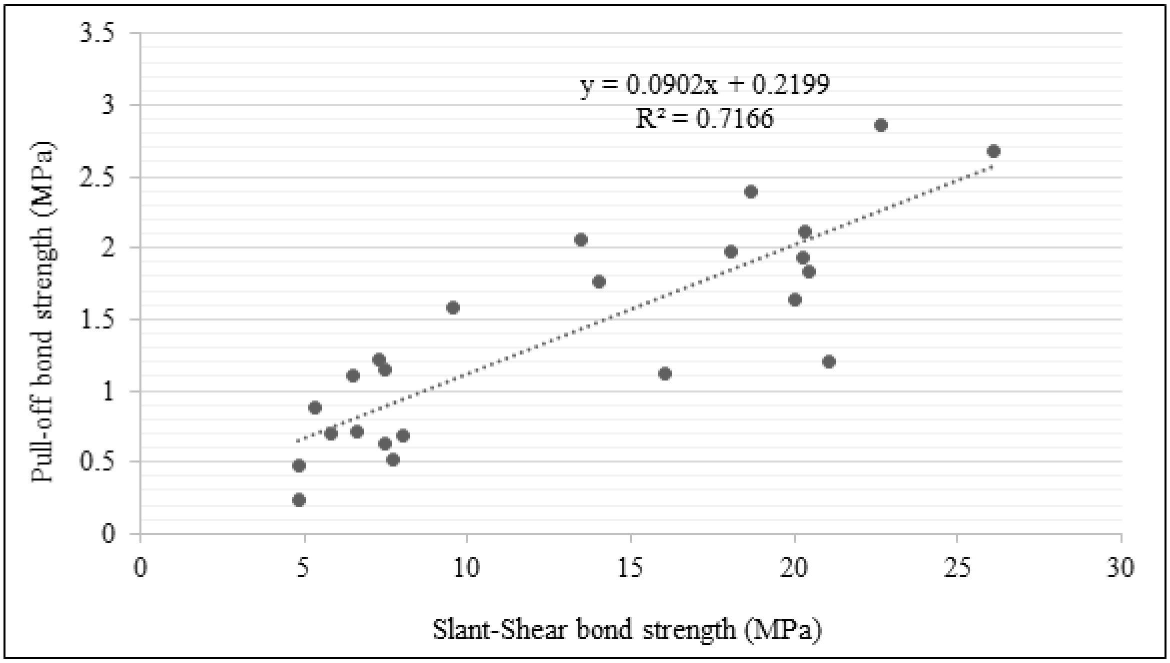

Figure 26

Relationship between Slant-Shear and Pull-off bond strength.

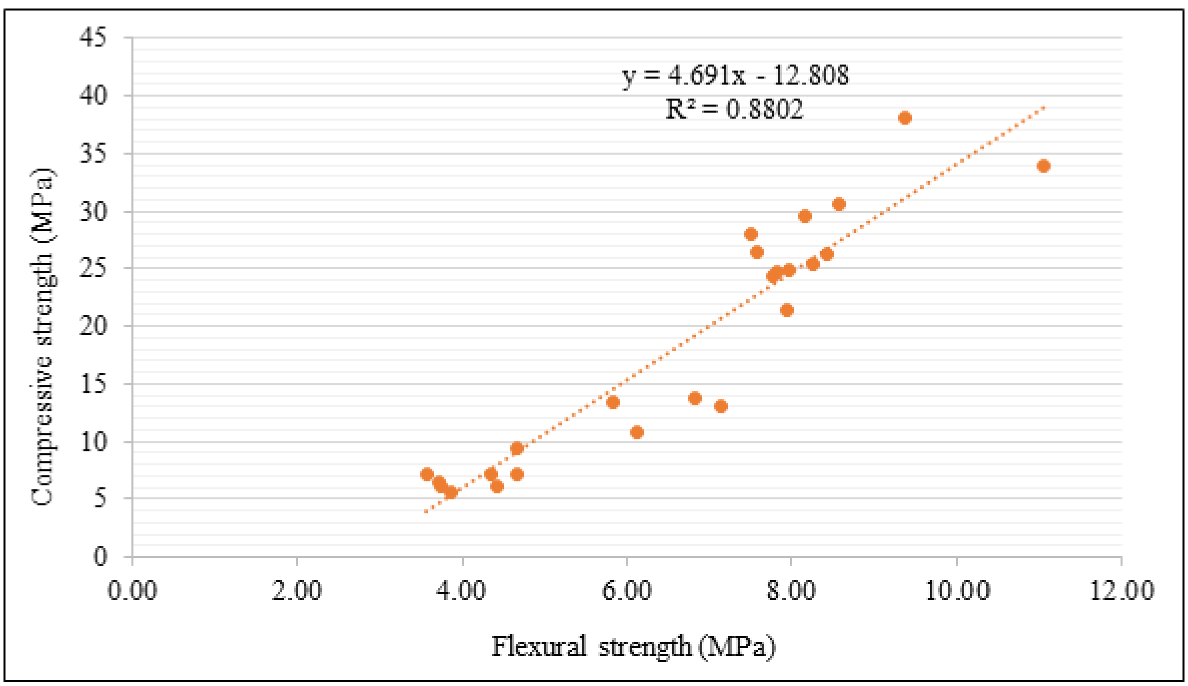

Figure 27

Relationship between flexural and compressive strength.