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*Research Article*

# Effect of Polypropylene and Basalt Fiber on the Behavior of Mortars for Repair Applications

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The fresh, mechanical, and durability properties of the polypropylene fiber-reinforced mortar (PP FRM) and the basalt fiber-reinforced mortar (BFRM) with various fiber contents were tested in this paper. The test results show that the presence of polypropylene (PP) fiber and basalt fiber (BF) in the mortar reduces the initial slump flow and increases the slump flow loss rate. The bond strength and flexural strength of fiber-reinforced mortar (FRM) are improved, whereas no obvious improvement on the compressive strength has been observed. Compared with the control mortar, the bond strength of PP FRM and BFRM reinforced with 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ fiber increases by 16.60%–28.80% and 10.60%–21.40%, respectively. Furthermore, FRM shows lower drying shrinkage, superior abrasion resistance, water impermeability, and freeze-thaw resistance compared with the control mortar. The abrasion resistance strength of PP FRM and BFRM is 77.30% and 38.65% more than the control mortar with 2.6 kg/m$^3$ fiber content. Therefore, PP FRM and BFRM are suitable to be utilized as repair materials, especially in repairing hydraulic structures surfaces with excellent bond strength and abrasion resistance.

## 1. Introduction

Currently, cement-based materials are one of the most widely used construction materials in the off-shore structures and marine structures due to their high compressive strength and low cost. It is noteworthy that cement-based materials are more brittle than other materials and have inherent disadvantages including low tensile strength and weakness in impact resistance. Besides, the cement-based materials are easy to crack because of the shrinkage of the materials and the concentration of stress [1–5]. As a result, the off-shore structures and marine structures begin to suffer degradation after a period of using time. How to use structures safely has become a major concerned issue in the development of sustainable engineering structures. Related studies have pointed out that utilizing cement mortar to repair the deteriorated concrete structures is a cost-effective and easily realized method to prolong their service life [6, 7]. Therefore, the repair materials with high mechanical strength and sufficient durability properties are in great demand.

Over the last three decades, fiber-reinforced mortar (FRM) and fiber-reinforced concrete (FRC) are among the most widely used materials to repair old concrete structures [8, 9]. There are many researches about the properties of FRM and FRC. A number of previous studies have shown that the introduction of fibers increases the mechanical strength of the mortar or concrete, especially in terms of splitting tensile strength and flexural strength [10–12]. Moreover, the use of fibers in the mortar or concrete can significantly enhance the bond strength between old substrate and the repair materials, which is one of the most important requirements for a successful repair [1, 8, 13]. In addition, utilizing fibers in the mortar or concrete also substantially improves the toughness and flexural postcracking behavior of the mixture [7, 14–16]. Likewise, the presence of fibers also lowers the number and the width of cracks in the mortar or concrete due to the bridge action of them [17]. More importantly is that the incorporation of fibers improves the durability properties of mortar or concrete [18, 19], that is, the abrasion resistance and freeze-thaw resistance. From the studies above, it can be seen that some results about the effect of fibers on the properties of the cement-based materials have been established [20–22]. It has been found that FRM and FRC show a marked improvement in toughness and impact resistance and are suitable to be utilized as repair materials, especially in repairing hydraulic structures surfaces. However, the main attention of these researches is paid to the mechanical properties of the repair mortars. There are still some problems existing on the certain specific properties of FRM and FRC. For instance, very few studies focus on the effect of fibers on fresh properties and durability properties of FRM and FRC, such as the abrasion resistance, which is one of the most significant requirements for hydraulic structures. The information about the effect of fibers on the water penetration depth of FRM and FRC is also very limited. Therefore, more studies need to be carried out in these aspects.

In this study, two kinds of FRM were prepared, including polypropylene fiber-reinforced mortar (PP FRM) and basalt fiber-reinforced mortar (BFRM), with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$. The fresh, mechanical properties of the mortars were assessed. Durability properties including drying shrinkage, abrasion resistance, water permeability, and freeze-thaw resistance of the mortars were measured too. A more comprehensive understanding about the effect of PP fiber and BF on the properties of the mortars was presented.

## 2. Experimental

### *2.1. Materials*

*2.1.1. Cement.* The Ordinary Portland Cement (OPC) used was provided by China Cement Plant. The chemical compositions and physical properties of the OPC are given in Table 1.

*2.1.2. Fine Aggregates.* The natural river sand was used as fine aggregates. The particle size distribution and physical properties of fine aggregates are presented in Table 2.

*2.1.3. Superplasticizer.* A sulfonated naphthalene-formaldehyde (SNF) superplasticizer (SP) with 2%–4% sodium sulfate was used in this study. SNF SP is yellow powder and its active ingredients are more than 97%. The pH of SNF SP is 7–9 and the chloride content in the SNF SP is 0.2%.

*2.1.4. Fiber.* Two types of fibers, that is, PP fiber and BF, were used in this study. The physical and mechanical properties of PP fiber and BF are presented in Table 3.

*2.2. Mix Proportions.* In this study, a total of seven mortar mixes were used, including one control mortar and six mortar mixes with PP fiber and BF of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$. The dosage of SNF SP mentioned is the weight percent of cement content. The details of the mix proportions of the mortar are shown in Table 4.

*2.3. Preparation and Curing Conditions of Samples.* First, the components of the mortar mixture were batched by weight and cement and fine aggregates were premixed with the dry mixing for 1 min. Then, the fibers were added into the mixture and mixed for another 1 min. After that, the entire amount of mixing water with SNF SP was added and mixed for 3 min, leading to a total mixing period of 5 min. Before casting, a variety of tests were conducted to determine the fresh properties of the mortar. Finally, the mortar samples were

Table 1: The chemical compositions and physical properties of the OPC.

| Chemical compositions | % |
|---|---|
| $SiO_2$ | 20.58 |
| $Al_2O_3$ | 5.64 |
| $Fe_2O_3$ | 3.95 |
| CaO | 62.25 |
| MgO | 2.48 |
| $TiO_2$ | 0.32 |
| $SO_3$ | 3.18 |
| $Na_2O$ | 0.36 |
| Mineral properties | % |
| CS | 54.7 |
| $C_2S$ | 20.24 |
| $C_3A$ | 6.59 |
| $C_4AF$ | 12.07 |
| Physical properties | |
| Initial setting time (min) | 65 |
| Final setting time (min) | 600 |
| Mechanical properties | |
| Compressive strength (MPa) | |
| 3 days | 17.6 |
| 28 days | 46.2 |
| Flexural strength (MPa) | |
| 3 days | 3.5 |
| 28 days | 7.8 |

Table 2: The particle size distributions and physical properties of fine aggregates.

| Sieve size (mm) | Cumulative pass amount (%) |
|---|---|
| 4.75 | 100 |
| 2.36 | 100 |
| 1.18 | 78.61 |
| 0.6 | 48.24 |
| 0.3 | 33.1 |
| 0.15 | 0.14 |
| 0.075 | 0.00 |
| Fineness modulus | 2.33 |
| Specific gravity | 2.51 |
| Water absorption | 0.80 |
| Properties | |
| Density-OD (kg/m$^3$)[a] | 2580 |
| Density-SSD (kg/m$^3$)[b] | 2620 |

[a]OD-density at absolutely dry condition.
[b]SSD-density at saturated surface dry condition.

Table 3: The physical and mechanical properties of PP fiber and BF.

| Fiber variety | Length (mm) | Density (g/cm$^3$) | Modulus of elastic (GPa) | Diameter ($\mu$m) | Tensile strength (MPa) | Elongation at break (%) | Water absorption |
|---|---|---|---|---|---|---|---|
| PP | 4–19 | 0.91 | 3.5 | 20–50 | 500 | 12.9 | <0.1 |
| BF | 20 | 2.7 | 93–110 | 13 | 624 | 3.1 | <0.5 |

Table 4: Mix proportions of the mortar.

| Mix | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) | PP fiber (kg/m$^3$) | BF (kg/m$^3$) | Superplasticizer (%) |
|---|---|---|---|---|---|---|
| Control | 680.8 | 1361.6 | 367.3 | — | — | 0.2 |
| PP-0.6 | 680.8 | 1361.6 | 367.3 | 0.6 | — | 0.2 |
| PP-1.6 | 680.8 | 1361.6 | 367.3 | 1.6 | — | 0.2 |
| PP-2.6 | 680.8 | 1361.6 | 367.3 | 2.6 | — | 0.2 |
| BF-0.6 | 680.8 | 1361.6 | 367.3 | — | 0.6 | 0.2 |
| BF-1.6 | 680.8 | 1361.6 | 367.3 | — | 1.6 | 0.2 |
| BF-2.6 | 680.8 | 1361.6 | 367.3 | — | 2.6 | 0.2 |

using a mechanical vibrating table for 2-3 min at a frequency of 50 Hz and the vibration amplitude of 0.5 mm. The mortar samples were subsequently cast in the different molds and covered with a polyethylene film in the laboratory at 23°C for 24 hours according to GOST 10180. After 1 day, the mortar samples were removed from the molds and transferred to a humidity room with a temperature of 20°C and a relative humidity of 90 ± 5% until the age of testing.

*2.4. Fresh Properties*

*2.4.1. Workability Test.* The workability of the fresh mortar was indicated by the initial slump flow (by flow table) of the material measured by a slump test according to EN 1015-3. The initial slump flow value was represented by the mean diameter (measured in two perpendicular directions) of the fresh mortar after lifting the standard slump cone.

*2.4.2. Slump Flow Preservation.* The slump flow preservation of the mortar was measured by the slump flow variations of the mortar with elapsed time. The slump flow value of the mortar was checked on the initial slump flow and 2 h after the first test.

*2.4.3. Setting Times of the Mortar.* The setting times of the mortar were tested according to EN 480-2 method.

*2.5. Mechanical Properties*

*2.5.1. Flexural Strength and Equivalent Compressive Strength.* The flexural strength and equivalent compressive strength of the specimens were tested at the ages of 3, 7, 28, 90, and 180 days according to EN 1015-11 test method. The 40 mm × 40 mm × 160 mm prism samples were prepared and the flexural strength test results were the average value of three samples. The equivalent compressive strength test was carried out on the broken pieces (portions of the prisms broken in the flexural strength test).

*2.5.2. Bond Strength with Old Mortar Substrates.* The bond strength test was conducted according to DL/T5150-2001. In the test, first, halves of the specimens, which represent the old mortar, were prepared with the ratio of cement : sand : water (1 : 3 : 0.5) and cured at 20°C and 90 ± 5% relative humidity for 14 days. A total of six halves were cast. Before casting the new mortar onto the old mortar substrates, the grease on the bonding surface of old substrates was wiped off by acetone and brush to clear up the particles on it. After that, halves of specimens were placed into their respective molds prior to filling the remaining halves with the new mortar. The composite specimens were completed as shown in Figure 1. The bond strength between the new mortar and the old mortar was calculated by

$$f_b = \frac{P}{A}, \tag{1}$$

where $f_b$ is the bond strength between the new mortar and the old mortar (MPa); $P$ is the maximum applied load (N); $A$ is the area of bond plane (mm$^2$).

*2.6. Durability Properties*

*2.6.1. Drying Shrinkage.* The drying shrinkage test of mortar was conducted on three 40 mm × 40 mm × 160 mm prismatic specimens according to modified ASTM C1148 method. The initial lengths of the mortar bars were measured after curing in the laboratory for 24 h. Then, the mortar samples were conveyed to a drying chamber with a temperature of 20–25°C and a relative humidity of 50–55% until further measurements at 1, 3, 7, 14, 21, 28, and 56 days.

*2.6.2. Abrasion Resistance.* The abrasion resistance of the mortar specimens was tested according to ASTM C1138/97 (an underwater method). Three $\varphi$300 mm × 100 mm cylinder specimens of the mortar were used for abrasion resistance test. The mortar specimens were abraded by underwater steel balls for a period of 72 hours and the weight of the

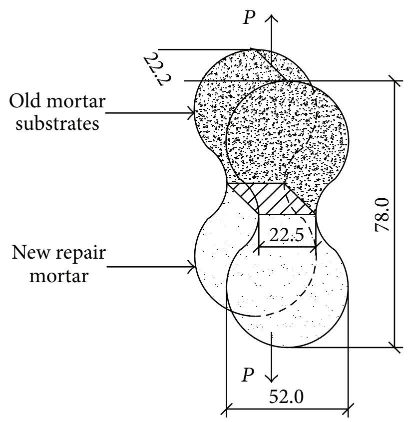


Figure 1: Composite specimens for bond strength test.

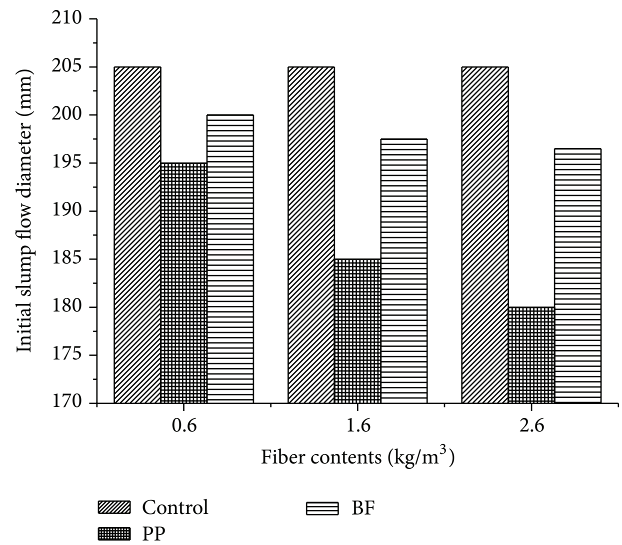


Figure 2: The effect of the contents of PP fiber and BF on the initial slump flow of the mortar.

mortar before and after the test was obtained. Besides, the morphological changes and damage characteristics of the specimens were observed. The weight loss and the abrasion resistance strength of the mortar can be calculated as follows:

$$\Delta M = \frac{m_0 - m_1}{m_0}, \tag{2}$$

where $\Delta M$ is the weight loss after abrasion (%); $m_0$ is the weight of specimens before test (kg); $m_1$ is the weight of specimens after test (kg). One has

$$f_a = \frac{TS}{\Delta M}, \tag{3}$$

where $f_a$ is the abrasion resistance strength of mortar specimens (h/(kg/m$^2$)); $T$ is the total testing time (h); $S$ is the area suffered abrasion (m$^2$); $\Delta M$ is the loss of weight of specimens after abrasion (kg).

*2.6.3. Water Permeability.* The water permeability test of the mortar specimens was performed according to DL/T5150-2001. Six $\varphi$70 mm × $\varphi$80 mm × 30 mm truncated cone specimens were cured for 28 days. In the test, the mortar specimen was dried at 60°C until constant mass and the specimen should be cooled down to room temperature. Then, the four sides of the mortar specimen were sealed by silicon rubber. After that, the specimen was placed into water permeability test equipment for 24 h. An initial water pressure of 0.2 MPa was applied to the bottom of the specimen for 2 h and the water pressure increased at a rate of 0.1 MPa/h until water penetrated through the specimen. Finally, the water pressure was kept for another 6 h. The truncated cone specimen was split into two halves and the water penetration depth was measured.

*2.6.4. Freeze-Thaw Resistance.* The freeze-thaw test was carried out according to ASTM C666 method using the specimens of three 40 mm × 40 mm × 160 mm prismatic specimens. The mortar specimens were cured in a humidity room with a temperature of 20°C and a relative humidity of 90 ± 5% for 28 days. For each freeze-thaw cycle, the mortar specimens were frozen at −18°C for 2 h and then immersed in water at 4°C for 2 h. The freeze-thaw resistance of the mortar specimens was assessed by strength loss and weight loss.

## 3. Results and Discussion

### *3.1. The Effect of the Contents of PP Fiber and BF on the Fresh Properties of the Mortar*

*3.1.1. Initial Slump Flow and Slump Flow Preservation.* From Figure 2, it can be seen that the initial slump flow values of PP FRM and BFRM with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ are 195 mm, 185 mm, and 180 mm and 200 mm, 197.5 mm, and 196.5 mm, a reduction of 4.88%, 9.75%, and 12.20% and 2.44%, 3.66%, and 4.15% in comparison to the initial slump flow of the control mortar. The incorporation of PP fiber and BF into the mortar significantly decreases the initial slump flow of the mortar. The reason for this phenomenon is possible that a network structure may form due to the distributed fibers in the mortar, which retrains mixture from segregation and flow. Fibers can absorb more cement paste to wrap around due to their high contents and large surface area, and the increase of the viscosity of mixture leads to the decrease in the workability of mortar [23].

The slump flow loss rates (after 2 h) of PP FRM and BFRM are presented in Figure 3. When PP fiber, BF of 0.6 kg/m$^3$ and 1.6 kg/m$^3$, is used in the mortar, the slump flow loss rate of the mortar changes from 11.71% in the control mortar, to 15.89% and 17.57% and 12.99% and 13.92% in PP FRM and BFRM, respectively. With the further increase in the contents of PP fiber and BF from 1.6 kg/m$^3$ to 2.6 kg/m$^3$, PP FRM and BFRM have a higher slump flow loss rate of 23.61% and 18.57%.

*3.1.2. Setting Times of the Mortar.* The test results of the setting times of the mortar are shown in Figure 4. As noticed, PP FRM and BFRM with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ have the setting times of 238 min, 230 min,

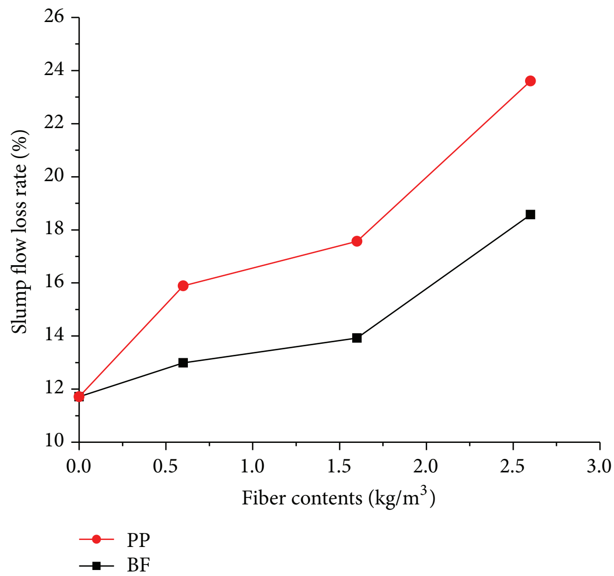


Figure 3: The effect of the contents of PP fiber and BF on the slump flow loss rate (after 2 h) of the mortar.

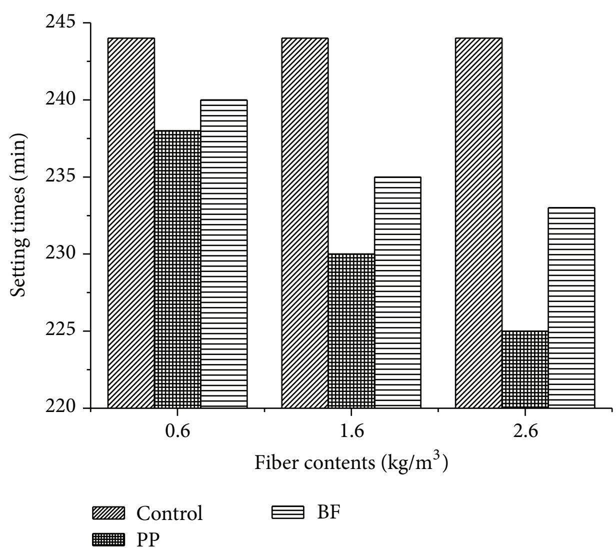


Figure 4: The effect of the replacement level of PP fiber and BF on the setting times of the mortar.

and 225 min and 240 min, 235 min, and 233 min, which are shortened by 6 min, 14 min, and 19 min and 4 min, 9 min, and 11 min, in comparison to the setting times of control mortar. The effect of the contents of fiber on the setting times of mortar is not significant.

### 3.2. The Effect of the Contents of PP Fiber and BF on the Mechanical Properties of the Mortar

*3.2.1. Flexural Strength.* Table 5 gives the flexural strength of the control mortar, PP FRM, and BFRM at the curing periods of 3, 7, 28, 90, and 180 days. The flexural strength of all the mortar mixtures shows an increase with the change of the curing period and PP FRM and BFRM have a higher flexural strength than the control mortar. At the curing period of 28 days, the flexural strength of PP FRM and BFRM has an increase of 18.10%–29.60% and 12.50%–20.80%, respectively, in comparison to the control mortar. Moreover, at the same fiber content, PP FRM has a higher flexural strength than BFRM.

*3.2.2. Compressive Strength.* Table 6 presents the compressive strength of control mortar, PP FRM, and BFRM at the curing periods of 3, 7, 28, 90, and 180 days. It can be seen that the incorporation of fiber does not significantly change the magnitude of the mortar compressive strength. The tendency of the compressive strength of the mortar to increase with PP fiber and BF incorporating can be found within the curing periods of 90 days. With the further increase of curing periods of 180 days, the negative effect of the PP fiber and BF on the compressive strength of the mortar occurs. The test results are consistent with previous study results [2, 3]. Similarly, at the same fiber content, the contribution of PP fiber to the compressive strength of the mortar is higher than that of BF.

*3.2.3. Bond Strength.* Figure 5 depicts the bond strength between the new mortar and the old mortar substrates after curing specimens for 28 days. Since the bond property between the deteriorated concrete structures and the new repair materials is one of the most important factors for structural integrity and functionality, many researchers have examined the bond characteristics between the fiber-reinforced repair mortars and substrates through different methods. The most widely accepted test methods include the slant shear test, the splitting tensile test, and the flexural bond test [1, 8, 13, 24]. All tests results reveal that addition of fibers to the mortar can significantly enhance the interfacial bonding between the repair mortar and substrates, no matter by means of direct test or indirect test. Similarly, results in this direct test show that the increase in bond strength of all FRM specimens is significant.

The bond strength of PP FRM and BFRM with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ is 2.81 MPa, 3.00 MPa, and 3.10 MPa and 2.67 MPa, 2.86 MPa, and 2.93 MPa, respectively. It is 116.60%, 124.60%, and 128.80% and 110.60%, 118.50%, and 121.40% bond strength of the control mortar. The increase in the bond strength can be attributed to this fact that, on one hand, the use of PP fiber and BF in the mortar reduces shrinkage cracking in the interfacial transition zone and bleeding at the interface [1, 25]. On the other hand, utilizing PP fiber and BF into the mortar can also improve the interfacial transition zone between the old mortar and new repair materials.

Besides, the failure modes of mortar specimens in bond strength test can generally be categorized into two types, namely, (1) pure interface failure; (2) interfacial failure combined with old mortar substrate fracture. Results show that the contents of PP fiber and BF in the mortar has a large effect on the bond strength since most interfacial failure of the specimens containing more than 1.6 kg/m$^3$ fiber contents occurs after the old mortar substrate suffering some degree of damage. The rest of the specimens, including the control

Table 5: Flexural strength test results of the mortar.

| Repair mortar | Flexural strength 3 d Measured (MPa) | 3 d SE (%) | 7 d Measured (MPa) | 7 d SE (%) | 28 d Measured (MPa) | 28 d SE (%) | 90 d Measured (MPa) | 90 d SE (%) | 180 d Measured (MPa) | 180 d SE (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | 5.40 | — | 6.40 | — | 7.20 | — | 8.10 | — | 8.70 | — |
| PP-0.6 | 6.59 | 22.10 | 7.71 | 20.40 | 8.50 | 18.10 | 9.53 | 17.60 | 10.19 | 17.10 |
| PP-1.6 | 6.93 | 28.30 | 8.09 | 26.40 | 9.03 | 25.40 | 10.09 | 24.60 | 10.77 | 23.80 |
| PP-2.6 | 7.03 | 30.20 | 8.23 | 28.60 | 9.33 | 29.60 | 10.35 | 27.80 | 11.04 | 26.90 |
| BF-0.6 | 6.27 | 16.20 | 9.09 | 14.20 | 8.10 | 12.50 | 9.06 | 11.80 | 9.71 | 11.60 |
| BF-1.6 | 6.58 | 21.80 | 7.65 | 19.60 | 8.48 | 17.80 | 9.45 | 16.70 | 10.11 | 16.20 |
| BF-2.6 | 6.70 | 24.10 | 7.85 | 22.70 | 8.70 | 20.80 | 9.74 | 20.30 | 10.37 | 19.20 |

Notes: SE (%) = [(strength of FRM − strength of the control mortar)/strength of the control mortar] × 100%.

Table 6: Compressive strength test results of the mortar.

| Repair mortar | Compressive strength 3 d Measured (MPa) | 3 d SE (%) | 7 d Measured (MPa) | 7 d SE (%) | 28 d Measured (MPa) | 28 d SE (%) | 90 d Measured (MPa) | 90 d SE (%) | 180 d Measured (MPa) | 180 d SE (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | 16.50 | — | 30.10 | — | 51.30 | — | 56.60 | — | 58.10 | — |
| PP-0.6 | 17.87 | 8.30 | 32.05 | 6.50 | 53.40 | 4.10 | 57.28 | 1.20 | 57.22 | −1.50 |
| PP-1.6 | 18.34 | 11.20 | 32.98 | 9.60 | 55.09 | 7.40 | 58.58 | 3.50 | 55.48 | −4.50 |
| PP-2.6 | 18.50 | 12.10 | 33.35 | 10.80 | 55.51 | 8.20 | 58.92 | 4.10 | 55.08 | −5.20 |
| BF-0.6 | 17.19 | 4.20 | 31.06 | 3.20 | 52.12 | 1.60 | 57.02 | 0.60 | 57.75 | −0.60 |
| BF-1.6 | 17.60 | 6.70 | 31.78 | 5.60 | 53.24 | 3.80 | 57.73 | 1.20 | 56.76 | −2.30 |
| BF-2.6 | 17.84 | 8.10 | 31.94 | 6.10 | 53.61 | 4.50 | 57.90 | 2.30 | 56.29 | −3.10 |

Notes: SE (%) = [(strength of FRM − strength of the control mortar)/strength of the control mortar] × 100%.

mortar and mortar with smaller contents of fiber, mostly fail at the interface, where no cracking and fracturing can be observed at both the old mortar and the new repair mortar.

### 3.3. The Effect of the Contents of PP Fiber and BF on the Durability Properties of the Mortar

*3.3.1. Drying Shrinkage.* The drying shrinkage values of the mortar specimens measured at the curing periods of 1, 3, 7, 14, 21, 28, and 56 days are shown in Figure 6. On one hand, the drying shrinkage increases with curing time for all specimens, increasing more rapidly at the earlier stages and slowing down in later stages. On the other hand, both PP fiber and BF reduce the drying shrinkage of mortar effectively, compared with the control mortar. The decrease of the drying shrinkage value of the mortar is more obvious with the increase in the contents of fiber. Also, at a given content of fiber, utilizing PP fiber into the mortar can more effectively mitigate the drying shrinkage than BF incorporating into the mortar.

*3.3.2. Abrasion Resistance.* The spalling of the mortar on the surface of hydraulic structures can be observed due to particular conditions, and the abrasion resistance of the mortar is one of the most significant requirements for hydraulic structures. In this work, the underwater method was used to determine the abrasion resistance property of PP FRM and BFRM. After 72 hours of abrasion resistance testing, the weight loss, abrasion resistance strength, and the surface morphology of the mortars are shown in Figures 7 and 8.

It can be observed from Figure 7 that, after 72 hours of abrasion resistance testing, PP FRM and BFRM with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ present a reduction of 19.49%, 34.38%, and 43.75% and 12.05%, 21.88%, and 27.83% in weight loss, compared with the control mortar. Moreover, 24.94%, 53.48%, and 77.30% and 13.71%, 27.87%, and 38.65% higher abrasion resistance strength than the control mortar can be found in the mortars with the fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$, respectively. It shows that the presence of PP fiber and BF in the mortar shows better results with respect to the abrasion resistance than those of the control mortar. Horszczaruk [26] also reported that the concrete reinforced with polymeric fiber had higher abrasion resistance. Grdic et al. [18] have proved that the enhancement of mechanical characteristics could decelerate the abrasive erosion process. As a result of the

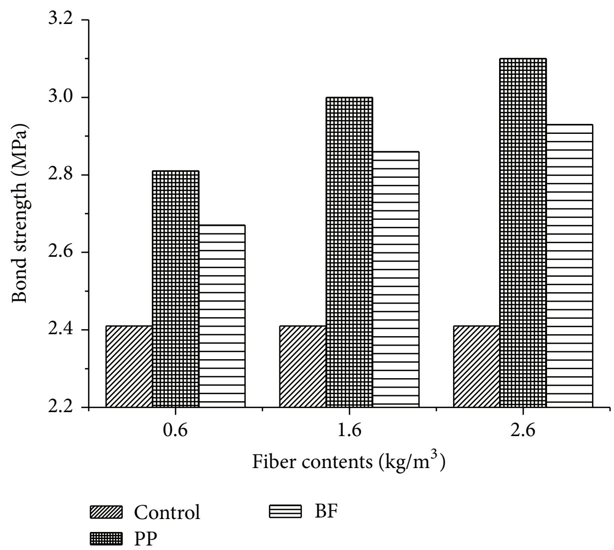


Figure 5: Bond strength between FRM and the old mortar.

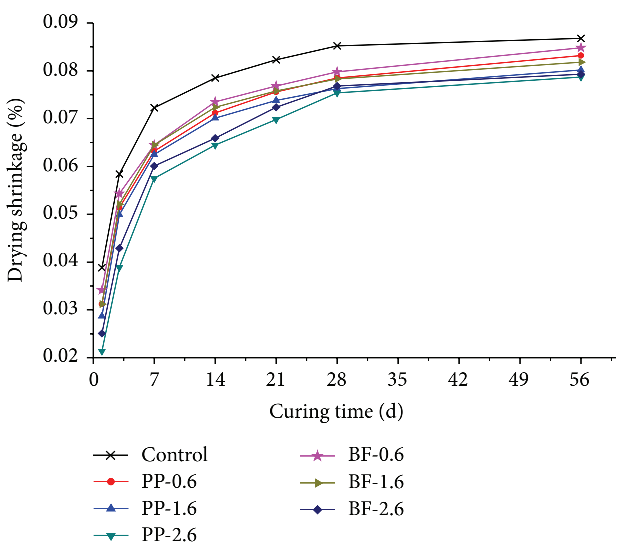


Figure 6: Drying shrinkage curves of FRM at different fiber contents.

significant improvement in mechanical strength, the abrasion resistance strength of FRM is enhanced.

The surface morphology of the control mortar and FRM with a fiber content of 1.6 kg/m$^3$ after abrasion resistance test can be seen in Figure 8. The surface of PP FRM does not have clear evidence of the deterioration (Figure 8(a)), while some gloss begin to recede on the surface of BFRM (Figure 8(b)). For the control mortar, the surface suffers some obvious deterioration (Figure 8(c)). PP FRM and BFRM are more effective than the control mortar on the resistance abrasion damage. Also, the effect of PP fiber on the abrasion resistance of the mortar is more significant than BF.

*3.3.3. Water Permeability.* Figure 9 presents the water penetration depth of the mortar specimens under 1.5 MPa. When contents of PP fibers and BF of 2.6 kg/m$^3$ were used in the mortar, the water penetration depth changes from 13.8 mm for the control mortar to 4.1 mm and 5.6 mm for PP FRM and BFRM, respectively. Since permeability is related to the porous internal structure of the material and to the linkage with the external material surface, relevant studies have been carried out by some researchers. Medina et al. [27] have reported that as the volume fraction of polypropylene fiber is increased from 0% to 0.07% in the Natural Pozzolan Cement concrete, the permeability depth decreases 32%. Water permeability test performed by Ramezanianpour et al. [28] indicates that the water penetration depth is 7.7 mm for the concrete specimen with 0.7 kg/m$^3$ polypropylene fiber content which is 30% lower than that of plain concrete. Such phenomenon can be explained by this fact, the addition of PP fibers and BF into the mortar controls the formation of the crack and effectively reduces the inherent cracking tendency in the mortar. Besides, pore blocking effect of fibers makes the pore structures in the hardened mortar become more disconnected, resulting in less capillary porosity and lower water penetration of the mortar. Superior water permeability property can effectively prevent mortars from corroded by detrimental substances, thus the durability of mortars gets enhanced. In addition, at the same content of fiber, the effect of PP fiber on the water penetration of the mortar is more significant than BF.

Table 7: Weight loss of the mortar specimens after the freeze-thaw cycles.

| Repair mortar | Weight loss (%) | | |
|---|---|---|---|
| | 50 cycles | 100 cycles | 150 cycles |
| Control | 0.25 | 0.56 | 0.92 |
| PP-0.6 | 0.16 | 0.39 | 0.78 |
| PP-1.6 | 0.12 | 0.32 | 0.73 |
| PP-2.6 | 0.09 | 0.27 | 0.68 |
| BF-0.6 | 0.19 | 0.46 | 0.86 |
| BF-1.6 | 0.16 | 0.40 | 0.81 |
| BF-2.6 | 0.14 | 0.36 | 0.76 |

*3.3.4. Freeze-Thaw Resistance.* The damage of the mortar under freeze-thaw cycles was assessed by the weight loss and strength loss of the mortars. The test results are shown in Table 7 and Figure 10.

As shown in Table 7, the process of the freeze-thaw cycles increased the weight loss of the mortar. Moreover, the change trend of the weight loss in the control mortar, PP FRM, and BFRM has no obvious difference. At the same cycles of freezing and thawing, PP FRM and BFRM have a lower weight loss than the control mortar. Also, the weight loss of PP FRM and BFRM reduces with the increase in the content of the fiber.

Figure 10 shows, after 150 cycles of freezing and thawing, the compressive strength losses of PP FRM and BFRM with the fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ are 16.60%, 12,30%, and 10.10% and 17.80%, 14.40%, and 13.50%, respectively. Moreover, after the freeze-thaw cycles, the mortar samples with the PP fibers and BF of different

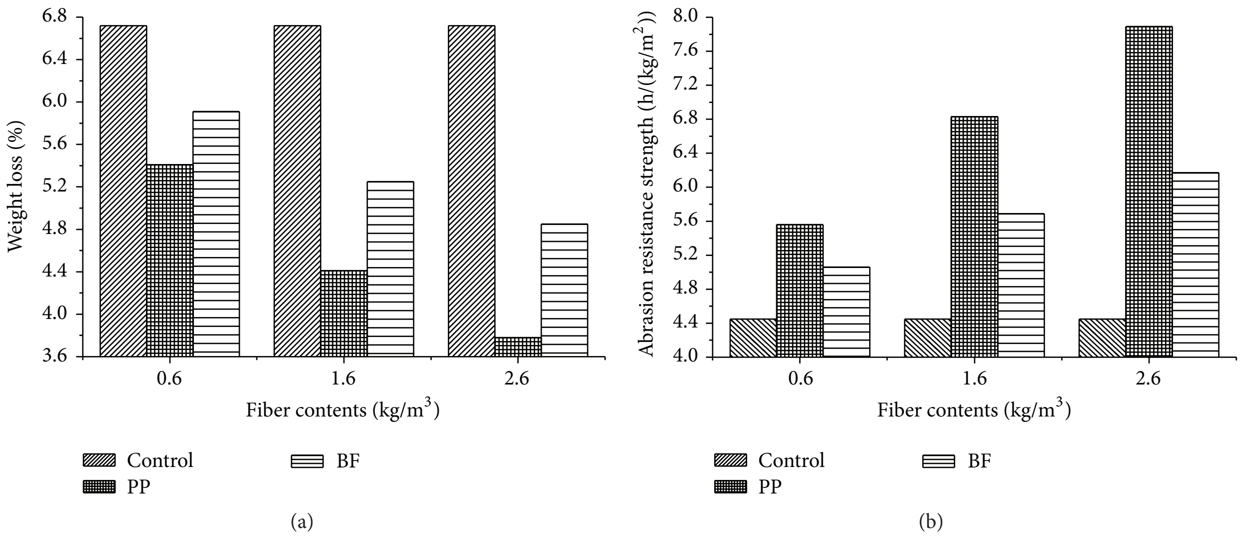


Figure 7: Abrasion resistance test results of FRM: (a) weight loss of FRM; (b) abrasion resistance strength of FRM.

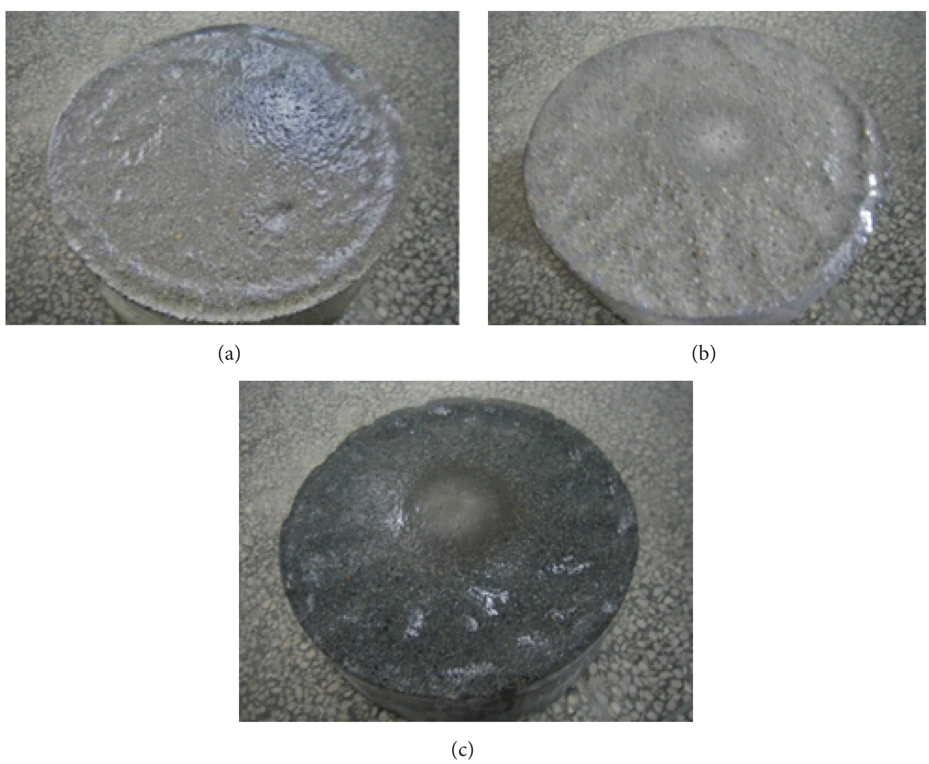


Figure 8: Surface morphology of FRM after 72 hours of abrasion: (a) PP FRM; (b) BFRM; (c) control mortar.

contents have a lower compressive strength loss than the control mortar. It can also be observed from Figure 10 that the tendency of utilizing PP fibers and BF in the mortar to reduce the flexural strength loss of the mortar can also be found after 150 cycles of freezing and thawing. It indicates that PP fibers and BF in the mortar show an excellent resistance against the damage caused by freeze-thaw cycles. This may be due to the fact that the randomly distributed PP fibers and BF in the mortar mixtures retrain the expansion of the mortar caused by volume changes of water in the pores during freeze-thaw cycles and then reduce the damage [2].

## 4. Conclusions

The experimental study on the repair properties of PP FRM and BFRM with fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$, respectively, reveals the following conclusions:

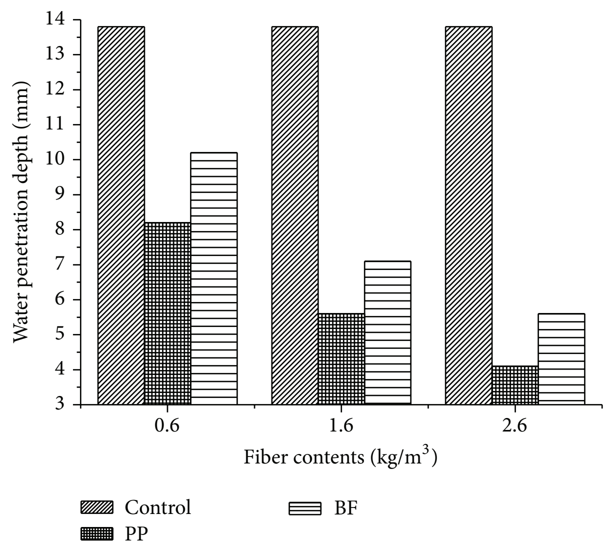


Figure 9: Water penetration depth of FRM at different fiber contents.

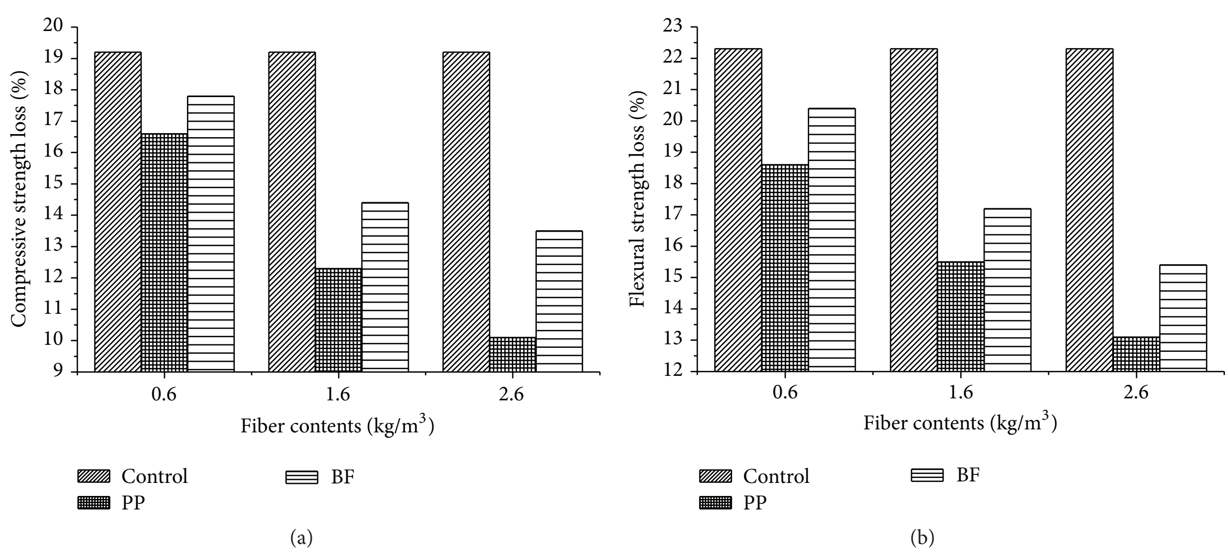


Figure 10: Strength loss of FRM at different fiber contents after 150 cycles of freezing-thawing: (a) compressive strength loss; (b) flexural strength loss.

(1) The presence of the PP fiber and BF in the mortar reduces the initial slump flow and increases the slump flow loss rate; the use of the PP fiber and BF in the mortar does not have obvious negative effect on the setting times of the mortar.

(2) Addition of PP fiber and BF significantly improves the bond strength and flexural strength of repair mortar, whereas the compressive strength shows no obvious increase. Compared with control mortar, the bond strength of FRM reinforced with 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$ PP fiber presents a 16.60%, 24.60%, and 28.80% increase, respectively. And the corresponding bond strength increments of BFRM are 10.60%, 18.50%, and 21.40%.

(3) Addition of both PP fiber and BF to the repair mortar leads to lower drying shrinkage, superior abrasion resistance, impermeability, and freeze-thaw resistance. The abrasion resistance strength of PP FRM presents a 24.94%, 53.48%, and 77.30% increase, respectively, over the control mortar with the fiber contents of 0.6 kg/m$^3$, 1.6 kg/m$^3$, and 2.6 kg/m$^3$. And the corresponding increment is 13.71%, 27.87%, and 38.65% for BFRM. Compared with the 13.80 mm water penetration depth of the control mortar, the water penetration depth of PP FRM and BFRM with 2.6 kg/m$^3$ fiber contents is 4.1 mm and 5.6 mm, respectively.

PP FRM outperforms BFRM slightly in every mechanical and durability property at the same fiber contents. The outperformance arises from its lower density and possibly from the better distribution through the cementitious matrix. However, BF still performs excellently in improving properties of repair mortar, and as an emerging material, BF is attaining more applications in engineering field similar to PP fiber, due to its attractive properties and cheaper price. Therefore, PP FRM and BFRM are suitable to be utilized as repair materials, especially in repairing hydraulic structures surfaces with excellent bond strength and abrasion resistance.

## Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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## References

[1] N. Banthia, C. Zanotti, and M. Sappakittipakorn, "Sustainable fiber reinforced concrete for repair applications," *Construction and Building Materials*, vol. 67, pp. 405–412, 2014.

[2] O. Karahan and C. D. Atiş, "The durability properties of polypropylene fiber reinforced fly ash concrete," *Materials & Design*, vol. 32, no. 2, pp. 1044–1049, 2011.

[3] S. B. Kim, N. H. Yi, H. Y. Kim, J.-H. J. Kim, and Y.-C. Song, "Material and structural performance evaluation of recycled PET fiber reinforced concrete," *Cement and Concrete Composites*, vol. 32, no. 3, pp. 232–240, 2010.

[4] P. S. Song, S. Hwang, and B. C. Sheu, "Strength properties of nylon- and polypropylene-fiber-reinforced concretes," *Cement and Concrete Research*, vol. 35, no. 8, pp. 1546–1550, 2005.

[5] A. Wang, M. Deng, D. Sun, L. Mo, J. Wang, and M. Tang, "Effect of combination of steel fiber and MgO-type expansive agent on properties of concrete," *Journal Wuhan University of Technology, Materials Science Edition*, vol. 26, no. 4, pp. 786–790, 2011.

[6] M. M. Al-Zahrani, M. Maslehuddin, S. U. Al-Dulaijan, and M. Ibrahim, "Mechanical properties and durability characteristics of polymer- and cement-based repair materials," *Cement and Concrete Composites*, vol. 25, no. 4-5, pp. 527–537, 2003.

[7] J. Luo, Q. Li, T. Zhao, S. Gao, and S. Sun, "Bonding and toughness properties of PVA fibre reinforced aqueous epoxy resin cement repair mortar," *Construction and Building Materials*, vol. 49, pp. 766–771, 2013.

[8] A. Mallat and A. Alliche, "Mechanical investigation of two fiber-reinforced repair mortars and the repaired system," *Construction and Building Materials*, vol. 25, no. 4, pp. 1587–1595, 2011.

[9] Y. Wu, Q. Sun, L. Kong, and H. Fang, "Properties and microstructure of polymer emulsions modified fibers reinforced cementitious composites," *Journal Wuhan University of Technology, Materials Science Edition*, vol. 29, no. 4, pp. 795–802, 2014.

[10] E. T. Dawood and M. Ramli, "The effect of using high strength flowable system as repair material," *Composites Part B: Engineering*, vol. 57, pp. 91–95, 2014.

[11] M. Hsie, C. Tu, and P. S. Song, "Mechanical properties of polypropylene hybrid fiber-reinforced concrete," *Materials Science and Engineering A*, vol. 494, no. 1-2, pp. 153–157, 2008.

[12] P. S. Song and S. Hwang, "Mechanical properties of high-strength steel fiber-reinforced concrete," *Construction and Building Materials*, vol. 18, no. 9, pp. 669–673, 2004.

[13] C. Zanotti, N. Banthia, and G. Plizzari, "A study of some factors affecting bond in cementitious fiber reinforced repairs," *Cement and Concrete Research*, vol. 63, pp. 117–126, 2014.

[14] E. T. Dawood and M. Ramli, "High strength characteristics of cement mortar reinforced with hybrid fibres," *Construction and Building Materials*, vol. 25, no. 5, pp. 2240–2247, 2011.

[15] F. Iucolano, B. Liguori, and C. Colella, "Fibre-reinforced lime-based mortars: a possible resource for ancient masonry restoration," *Construction and Building Materials*, vol. 38, pp. 785–789, 2013.

[16] S. Spadea, I. Farina, A. Carrafiello, and F. Fraternali, "Recycled nylon fibers as cement mortar reinforcement," *Construction and Building Materials*, vol. 80, pp. 200–209, 2015.

[17] A. Izaguirre, J. Lanas, and J. I. Alvarez, "Effect of a polypropylene fibre on the behaviour of aerial lime-based mortars," *Construction and Building Materials*, vol. 25, no. 2, pp. 992–1000, 2011.

[18] Z. J. Grdic, G. A. T. Curcic, N. S. Ristic, and I. M. Despotovic, "Abrasion resistance of concrete micro-reinforced with polypropylene fibers," *Construction and Building Materials*, vol. 27, no. 1, pp. 305–312, 2012.

[19] A. Çavdar, "Investigation of freeze-thaw effects on mechanical properties of fiber reinforced cement mortars," *Composites Part B*, vol. 58, pp. 463–472, 2014.

[20] L. A. Pereira-de-Oliveira, J. P. Castro-Gomes, and M. C. S. Nepomuceno, "Effect of acrylic fibres geometry on physical, mechanical and durability properties of cement mortars," *Construction and Building Materials*, vol. 27, no. 1, pp. 189–196, 2012.

[21] C. Jiang, K. Fan, F. Wu, and D. Chen, "Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete," *Materials and Design*, vol. 58, pp. 187–193, 2014.

[22] E. Quagliarini, F. Monni, S. Lenci, and F. Bondioli, "Tensile characterization of basalt fiber rods and ropes: a first contribution," *Construction and Building Materials*, vol. 34, pp. 372–380, 2012.

[23] B. Chen and J. Liu, "Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability," *Cement and Concrete Research*, vol. 35, no. 5, pp. 913–917, 2005.

[24] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Y. L. Voo, "Mechanical and permeability properties of the interface between normal concrete substrate and ultra high performance fiber concrete overlay," *Construction and Building Materials*, vol. 36, pp. 538–548, 2012.

[25] S. Hu, H. Wang, G. Zhang, and Q. Ding, "Bonding and abrasion resistance of geopolymeric repair material made with steel slag," *Cement and Concrete Composites*, vol. 30, no. 3, pp. 239–244, 2008.

[26] E. Horszczaruk, "Abrasion resistance of high-strength concrete in hydraulic structures," *Wear*, vol. 259, no. 1–6, pp. 62–69, 2005.

[27] N. F. Medina, G. Barluenga, and F. Hernández-Olivares, "Enhancement of durability of concrete composites containing natural pozzolans blended cement through the use of Polypropylene fibers," *Composites Part B*, vol. 61, pp. 214–221, 2014.

[28] A. A. Ramezanianpour, M. Esmaeili, S. A. Ghahari, and M. H. Najafi, "Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers," *Construction and Building Materials*, vol. 44, pp. 411–418, 2013.