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Research Article

Performance Evaluation of the Fiber-Reinforced Cement Composites Blended with Wheat Straw Ash

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Increasing demand for cement in the construction industry is posing a serious threat to the environment. This necessitates the utilization of supplementary cementitious materials such as silica fume, fly ash, rice husk ash, and wheat straw ash as a cement replacement material. Additionally, fiber-reinforced cement composites can be efficiently used in repair and rehabilitation works. In this study, we have investigated the performance of fiber-reinforced cement composites blended with wheat straw ash. Wheat straw ash has been proved to be an effective pozzolanic material. Cement was replaced by 20% (weight) wheat straw ash. Polypropylene fibers were added at a dosage of 0%, 0.5%, 1%, and 2% by weight of cement. Mortar specimens were fabricated and investigated for the compressive, flexure, and indirect tensile strengths, ultrasonic pulse velocity, chloride migration resistance, and carbonation resistance. The results demonstrate that the addition of fibers caused a reduction in the compressive strength, pulse velocity, chloride migration resistance, and carbonation resistance; however, flexure and indirect tensile strengths were significantly enhanced. Moreover, the incorporation of fine size wheat straw ash particles compensated the negative effect of fiber inclusion.

1. Introduction

Agricultural residue ashes (ARAs) are posing a serious threat to the environment as most of these end up as a landfill matter. ARAs such as rice husk ash, sugarcane bagasse ash, and corn stover ash contain an enormous amount of silica which makes these ashes an effective pozzolanic material. The silica present in these materials reacts with calcium hydroxide (CH), a hydration product of cement, resulting in the formation of additional hydration products [1]. Among various ARAs, rice husk ash (RHA), due to their high silica content and low cost, is the extensively used pozzolan [2–6]. Several studies were conducted to investigate the pozzolanic activity of RHA [2–4]. The results of these studies exhibit that a high specific surface area [2], rich silica content [4], and porous microstructure [3] of well-burnt RHA are responsible for its enhanced pozzolanic activity. Incorporation of RHA resulted in an increased compressive strength, low permeability, and enhanced resistance to chloride penetration and acid attack [5, 6]. In the same way, the addition of rice straw ash (10%) caused an increase in compressive strength and decreased permeability [7]. In another study, it has been reported that the bagasse ash can be efficiently used as a cement replacement material [8]. Apart from this, palm oil fuel ash, corncob ash, barley straw ash, and wheat straw ash (WSA) has also been proved to reveal pozzolanic properties [9–11]. The efficiency of WSA as a filler and pozzolanic material in the cement-based composites has been investigated by several researchers [12–18]. It has been reported that the addition of WSA enhanced compressive and flexural strengths of cement mortars [12, 13]. The filler effect of WSA resulted in improved mechanical properties [14]. Additionally, the enhancement in the durability properties of WSA-containing cement composites has also been reported in the scientific literature [15–17]. A previous study [19] of the authors investigated the influence of mechanical processing on the hydration characteristics of wheat straw ash.

Reinforcement of cement composites with fibers is a proven technique to enhance toughness, ductility, and tensile strength [20]. The incorporation of fibers detains the progression of cracks [21]. Fiber-reinforced cement composites are mostly used as a shotcreting material in the repair and rehabilitation of concrete structures. Among various fibers, the polypropylene (PP) fiber, due to its low cost, is a popular material in the construction industry. Several researchers studied the performance of cement composites reinforced with PP fibers [22–26]. The results of the study conducted by Karahan and Atis [23] demonstrate that the inclusion of PP fibers caused a reduction in workability and drying shrinkage and increased freeze-thaw resistance and compressive strength. Also, water absorption, porosity, and sorptivity coefficient values amplified as the fiber content increased. In order to combat with the negative effects of fibers, supplementary cementitious materials are used, which densify the microstructure of mortars. Gutierrez et al. [27] studied the influence of pozzolans, i.e., silica fume, fly ash, and metakaolin, on the performance of fiber-reinforced mortars. The results of their study demonstrate that the addition of fibers resulted in a decline in compressive strength and increased capillarity absorption and chloride penetration. However, the addition of pozzolanic materials significantly compensated for these losses. It means that the utilization of fibers along with pozzolanic materials has a beneficial impact on the overall performance of cement composites.

An area that has not been thoroughly investigated is the effect of WSA on the properties of polypropylene fiber-reinforced cement mortars. Therefore, it is imperative to examine the performance of WSA-blended fiber-reinforced cement composites. We have used WSA as a cement replacement material. The hydration characteristics of WSA particles of various sizes have been examined thoroughly by the authors in their previous work [19]. The results of that study demonstrate that the mixes with 20% WSA ground for at least 60 minutes presented an enhanced pozzolanic efficiency. Therefore, in this study, we used WSA at a replacement level of 20% by weight of the binder. In addition, PP fibers were incorporated at a dosage of 0.5%, 1%, and 2% by weight of cement. The effect of WSA and PP fibers was investigated by measuring compressive, flexure, and indirect tensile strengths, ultrasonic pulse velocity tests, carbonation resistance, and chloride penetration resistance.

2. Experimental Design

2.1. Materials. We used ordinary Portland cement (OPC) conforming to ASTM C150 [28]. Wheat straw (chopped) was collected from a local agriculturist in the Tehsil Khaliqabad (Balochistan Province) of Pakistan. Straw was burnt in an open land at the first stage to reduce the volume of ash. The ash obtained was incinerated at a temperature of 670°C for 5 hours in a laboratory-scale oven [18]. Later on, the ash was subjected to sudden cooling in order to obtain a higher pozzolanic material [18]. Then, ash was subsequently processed in a combination of the milling process (ball mill: 60 minutes and disintegrator mill: 3 cycles, each 5 minutes) to reduce its particle size. Chemical and physical properties of WSA (Figure 1) and OPC are summarized in Table 1. The particle-size distribution curve (measured with a particle size analyzer, Malvern Mastersizer 2000) and X-ray diffraction of WSA particles are shown in Figures 2 and 3, respectively. Natural sand was used as a fine aggregate. PP fibers (Figure 4) with a density of 0.92 g/cm^3 was used for this study. A polycarboxylate-based superplasticizer was used to adjust the mortar flow.

2.2. Fabrication of Specimens and Testing Methods. A binder to sand ratio of 1 : 2.75 and a water to cement ratio of 0.40 were used to make mortar mixes. Cement was replaced with WSA at a level of 20% (by weight), and PP fibers were added at a dosage of 0%, 0.5%, 1%, and 2% by weight of cement. The mixes were denoted as WX/PY, where X represents the amount of WSA and Y represents the dosage of the PP fiber. For instance, W20/P0.5 indicates the mortar mix with 20% WSA and 0.5% PP fibers. Superplasticizer was used to maintain the mortar flow at $110 \pm 5\%$. Mortar cubes ($50 \times 50 \times 50$ mm^3) and prisms ($40 \times 40 \times 160$ mm^3) were fabricated following ASTM C109 [29] and ASTM C348 [30], respectively. Cylindrical specimens of dimensions (Ø100×200 mm) were also prepared for chloride migration, indirect tensile strength, and carbonation tests. After casting, the specimens were kept at room temperature for 24 hours. The specimens were subsequently demolded and placed in water for curing till the designed testing was reached.

The compressive, flexure, and indirect tensile strength (IDT) tests were conducted at the ages of 7, 28, and 90 days following ASTM standards [29–31]. For each test, three replicates were used, and the average value was reported. Additionally, ultrasonic pulse velocity (UPV) test was also conducted after 7, 28, and 90 days of curing in water in accordance with ASTM C597 [32]. Rapid chloride migration test (RMT) was carried out on the mortar specimens after 28 days of water curing by following NT BUILD 492 [33]. The specimens measuring Ø100×50 mm for the carbonation test were obtained from the cylindrical specimens. All the sides of the specimen were sealed except for the one allowing the ingress of CO_2. The specimens were subjected to a simulated carbonation environment in a chamber with 5% of CO_2 concentration, 20°C, and 60% relative humidity. After 28 days, the specimens were removed from the chamber and split into half using a universal testing machine. The surfaces of the split sections were sprayed with phenolphthalein in order to measure carbonation depth. A minimum of ten measurements was made for each specimen, and average values are reported.

3. Results and Discussion

3.1. Compressive Strength. Figure 5 portrays the results of the compressive strength test conducted on the mortar specimens at 7, 28, and 90 days of water curing. As expected, compressive strength decreased with the addition of fibers. For example, W0/P0.5 presented a decrease of 4.2%, 3.3%, and 3.7% at 7, 28, and 90 days, respectively, in comparison

Figure 1: Wheat straw ash.

Table 1: Chemical and physical properties of OPC and WSA.

Composition	Weight (%) OPC	Weight (%) WSA
SiO_2	20.8	65.7
Al_2O_3	6.3	3.7
Fe_2O_3	3.2	2.6
CaO	62	7.8
MgO	3.3	2.7
SO_3	2.2	2.3
Na_2O	—	2.5
K_2O	—	3.3
P_2O_5	—	1.7
TiO_2	—	0.2
Loss on ignition	1.3	7.3
Specific surface area (cm^2/g)	3200	18021

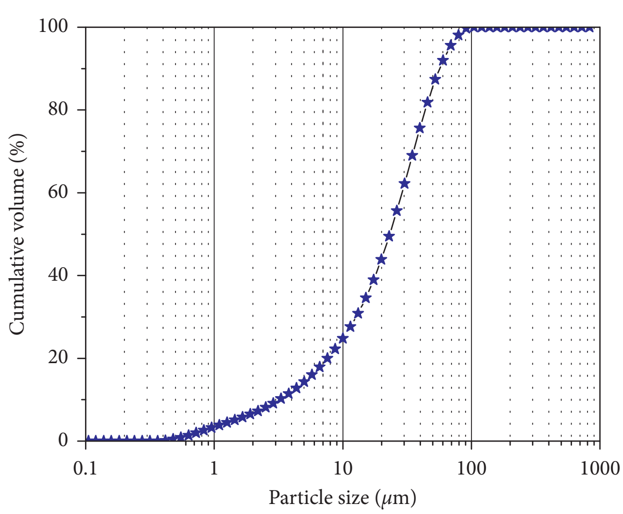

Figure 2: Particle-size distribution curve of WSA.

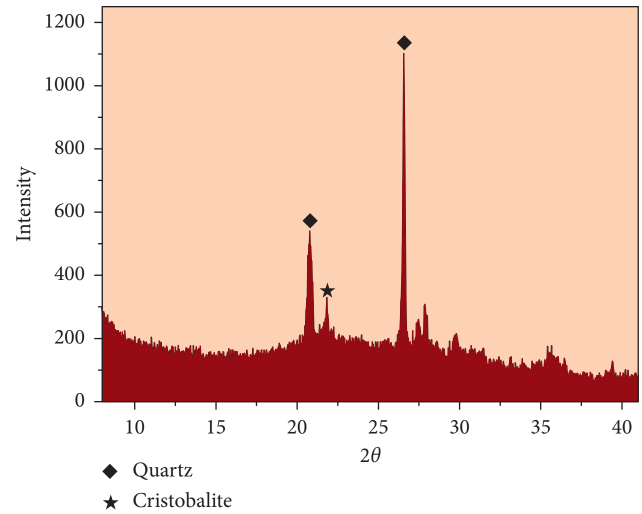

Figure 3: X-ray diffraction of WSA particles.

Figure 4: Polypropylene fibers.

with W0/P0. The decline in the compressive strength was higher as the fiber content is increased. W0 specimens with 1% and 2% PP fibers depicted a decrement of 13.7% and 22.1% at 7 days, 12.8% and 21.6% at 28 days, and 13.4% and 23.6% at 90 days, respectively. The addition of WSA amplified the compressive strength at all the ages. For instance, the replacement of cement with 20% WSA (W20/P0) increased compressive strength by 1.8%, 5.9%, and 8.6% at 7, 28, and 90 days, respectively, as compared to the W0/P0 mortar specimen. Also, the compressive strength for the WSA-containing specimens with 0.5% PP fibers (W20/P0.5) was slightly decreased than that of the W20/P0 specimen. The dosage of 1% and 2% PP fibers to the WSA specimens caused a decline in the compressive strength; however, the decrement was lower than the respective mortar specimens without WSA. For example, W20/P1 and W20/P2 showed a decrease of 6.2% and 19.1% at 7 days, 5.6% and 18% at 28 days, and 5.2% and 17.8% at 90 days, respectively, compared to the W0/P0 specimens. Importantly, the WSA-containing specimens presented an enhanced compressive strength in comparison to their respective mortar specimens without WSA. For instance, at the age of 7 days, W20/P0, W20/P0.5, W20/P1, and W20/P2 showed an increment of 1.8%, 5.4%, 8.8%, and 3.8%, respectively. The compressive strength increased by 5.9%, 4.7%, 8.3%, and 4.6% at 28 days and 8.6%,

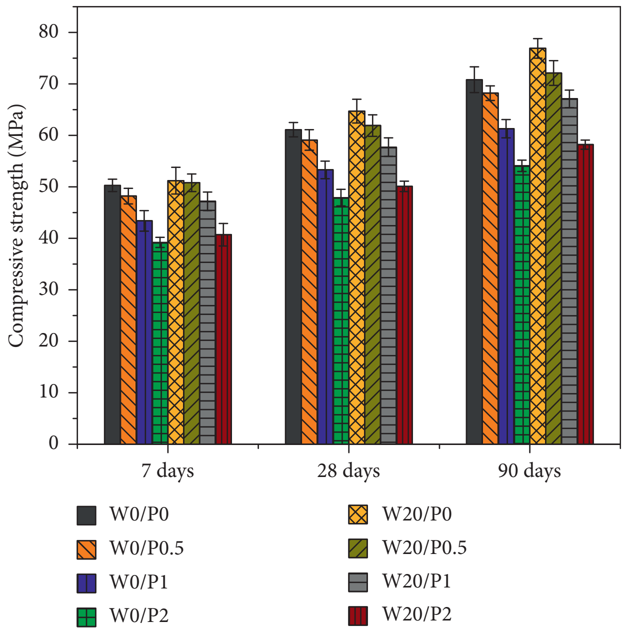

Figure 5: Compressive strength of the mortar specimens.

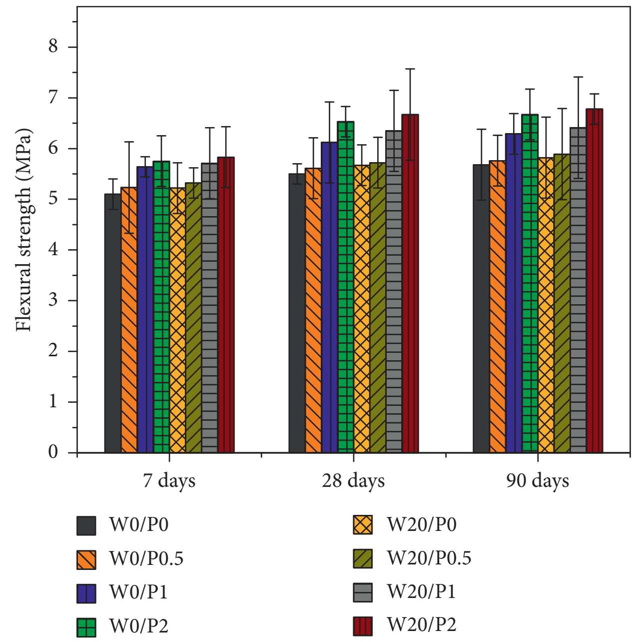

Figure 6: Flexure strength of the mortar specimens.

5.7%, 9.5%, and 7.6% at 90 days for W20/P0, W20/P0.5, W20/P1, and W20/P2 specimens, respectively.

The reduction in the compressive strength due to the addition of PP fibers has been reported in the previous studies. Cavdar [22] reported that an addition of 1.2% PP fibers caused a reduction of 18.4% in the compressive strength of the mortar specimens. Similarly, Gutierrez et al. [27] observed that a reduction of up to 30% in the compressive strength was observed for the specimens with PP fibers. This decrease in the compressive strength is attributed to the discontinuity in the cement matrix imparted by the fibers [34]. Apart from this, the addition of WSA particles resulted in lesser strength loss. It is mainly due to the filler and pozzolanic effects of the fine WSA particles [19]. The compensation in the strength loss of the fiber-reinforced composites due to the addition of pozzolanic materials has also been discussed in a previous study [27].

3.2. Flexure Strength. Figure 6 depicts the results of the flexure strength test carried out on the mortar specimens at various ages. Contrary to the results of the compressive strength test, the addition of fibers caused an increase in the flexure strength. The flexure strength for all the mortar specimens varied within a range of 5–7 MPa at various curing ages. For example, the dosage of 0.5%, 1%, and 2% PP fibers in the W0 mortar specimens raised the flexure strength by 2.5%, 10.6%, and 12.7% at 7 days; 2%, 11.3%, and 18.7% at 28 days; and 1.4%, 10.7%, and 17.4% at 90 days, respectively, in comparison to the W0 specimen containing 0% PP fibers. The replacement of cement by WSA (20%) further amplified the flexure strength. For instance, W20/P0, W20/P0.5, W20/P1, and W20/P2 depicted an increment of 2.4%, 4.3%, 12%, and 14.3% at 7 days; 3.1%, 4%, 15.5%, and 21.3% at 28 days; and 2.5%, 3.7%, 12.9%, and 19.4% at 90 days, respectively, compared to the W0/P0 specimens. In the same way, the mortar specimens containing WSA presented higher flexure strength compared to their respective mortar specimens with 0% WSA. At the age of 7, 28, and 90 days, an enhancement of 2.4%, 3.1%, and 2.5% for W20/P0; 1.7%, 2%, and 2.3% for W20/P0.5; 1.2%, 3.8%, and 1.9% for W20/P1; and 1.4%, 2.1%, and 1.6% for W20/P2 specimens was observed in comparison to their respective mortar specimens.

The addition of PP fibers resulted in an increased flexure strength. Similar results were obtained and reported in previous studies [35–37] in which flexure strength of the mortar specimens increased with the inclusion of fibers. Daneti et al. [35] have reported in their study that an increment of 25% in the flexure tensile strength of the foamed concrete specimens was observed for 2% fiber addition.

3.3. Indirect Tensile Strength. The results of the indirect tensile (IDT) strength test performed on the mortar specimens at various ages are displayed in Figure 7. Similar to the results of the flexure strength test, the addition of PP fibers caused an enhancement in the IDT strength. All the mortar specimens depicted IDT strength in the range of 2–4 MPa at various ages. The addition of 0.5%, 1%, and 2% PP fibers in the W0 specimens resulted in an increment of 2.8%, 10.6%, and 12.2% at the age of 7 days; 3%, 11.2%, and 15.4% at the age of 28 days; and 3.2%, 11.7%, and 14.2% at the age of 90 days, respectively. A significant amplification in the IDT strength was observed when the cement was replaced with 20% WSA. For instance, at the age of 7 days, an increment of 3.5%, 4.3%, 12.2%, and 14.2% in the IDT strength was observed for W20/P0, W20/P0.5, W20/P1, and W20/P2 mortar specimens, respectively, compared to that of the W0/P0 specimen. At the curing age of 28 and 90 days, an increase of 3% and 3.2% for W20/P0; 4.1% and 3.9% for W20/P0.5; 13.5% and 13.8% for W20/P1; and 18.7% and

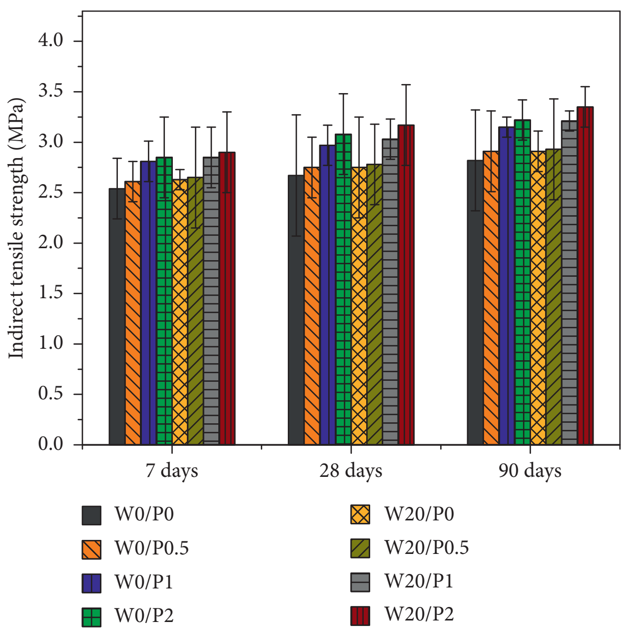

Figure 7: Indirect tensile strength of the mortar specimens.

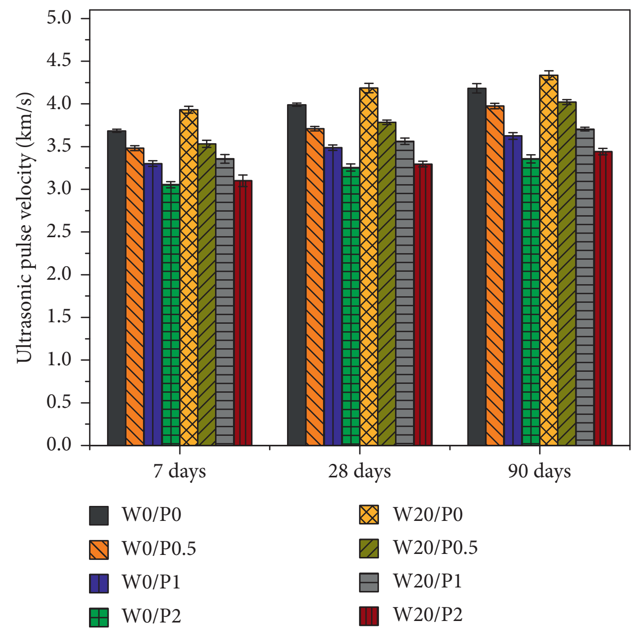

Figure 8: Ultrasonic pulse velocity of the mortar specimens.

18.8% for W20/P2 specimens, respectively, was observed. Additionally, W20 specimens showed an enhanced IDT strength in comparison with the respective W0 mortar specimens. For example, W20/P0, W20/P0.5, W20/P1, and W20/P2 specimens displayed an increment of 3.5%, 1.5%, 1.4%, and 1.8% at the age of 7 days; 3%, 1.1%, 2%, and 2.9% at the age of 28 days; and 3.2%, 0.7%, 1.9%, and 4% at the age of 90 days, respectively, was observed compared to the respective W0 mortar specimens.

The increase in the tensile strength due to the addition of PP fibers has been previously reported. For example, the results of the study conducted by Wu et al. [37] reveal that the splitting tensile strength of the specimens increased by 10–37% for PP fiber addition of 0.25–0.75% (volume fraction). The tensile stress transferred to the fibers precludes the propagation of microcracks, thus, amplify the splitting tensile strength [38].

3.4. Ultrasonic Pulse Velocity. The ultrasonic pulse velocity (UPV) test was conducted on the mortar specimens at different ages. From the results shown in Figure 8, it is obvious that the addition of PP fibers caused a reduction in the UPV of the mortar specimens. For example, W0/P0.5, W0/P1, and W0/P2 mortar specimens reduced the pulse velocity by 5.5%, 10.4%, and 17.1% at 7 days; 7%, 12.6%, and 18.4% at 28 days; and 4.9%, 13.3%, and 19.7% at 90 days, respectively, compared to the W0/P0 specimen. The addition of WSA resulted in an amplified pulse velocity in comparison with the specimens containing 0% WSA. For instance, the UPV for the W20/P0 mortar specimen increased by 6.7%, 4.9%, and 3.7% at 7, 28, and 90 days, respectively, compared to the W0/P0 specimen. Also, the reduction in UPV in WSA-containing specimens due to the addition of PP fibers was lower than the respective specimens without WSA. From the UPV results, it is evident that W20/P0.5, W20/P1, and W20/P2 caused a reduction of 4.2%, 8.9%, and 15.9% at 7 days; 5.2%, 10.7%, and 17.4% at 28 days; and 3.8%, 11.4%, and 17.7% at 90 days, respectively, in comparison with the W0/P0 specimen. The addition of WSA compensated for the loss in the pulse velocities due to the incorporation of fibers. For example, W20/P0, W20/P0.5, W20/P1, and W20/P2 mortar specimens increased the UPV by 6.7%, 1.4%, 1.7%, and 1.5% at 7 days; 4.9%, 2%, 2.1%, and 1.2% at 28 days; and 3.7%, 1.2%, 2.2%, and 2.5% at 90 days, respectively, compared to their respective mortar specimens without WSA. Similar findings from previous studies can also be found [39, 40]. The results of their studies demonstrate that fiber inclusion caused a reduction in UPV values. This reduction is mainly attributed to the improvement in the inner conductivity of pores due to the addition of PP fibers [41]. However, the filling and pozzolanic effects of WSA densified the microstructure of cement composites resulting in comparably increased UPV values [19].

Figure 9 exhibits the relationship between the compressive strength and UPV values of the mortar specimens at various curing ages. From the figure, it is obvious that there is a direct relationship between compressive strength and pulse velocities. The specimens with 0% PP fibers (W0/P0 and W20/P0) depicted slightly different behaviors than the other specimens. It means the relationship between compressive strength and UPV is dependent on the constituents of the cement composites. Pulse velocity values increase as the microstructure becomes dense which results in an enhanced compressive strength.

3.5. Chloride Migration. The rapid chloride migration test was conducted on the mortar specimens after 28 days of curing in water. The specimens were split into half (shown schematically in Figure 10) afterward sprayed with an

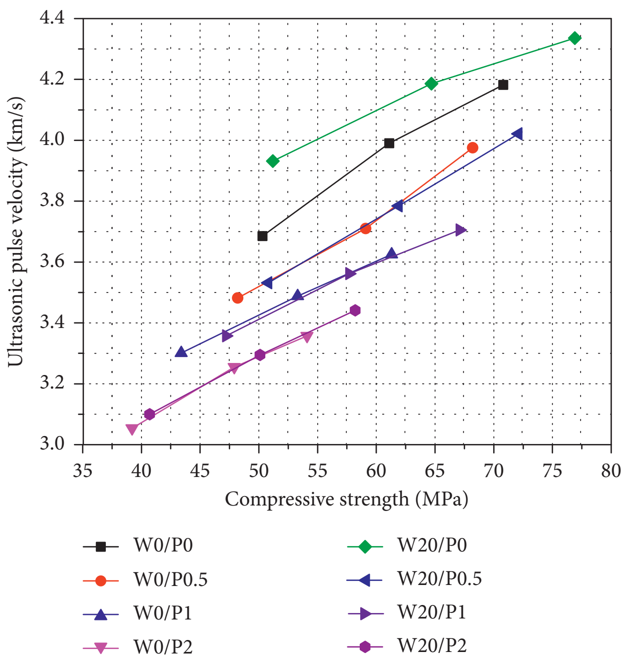

Figure 9: Ultrasonic pulse velocity-compressive strength relationship.

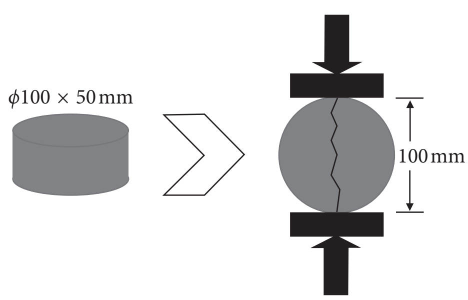

Figure 10: Procedure for the splitting of the specimen.

$AgNO_3$ solution to measure the chloride penetration depth. Silver ions react with chloride ions resulting in white silver chloride precipitation, which is easily distinguished. Figure 11 exhibits the values of nonsteady state migration coefficient (D_{nssm}) for mortar specimens at various ages. It can be seen that the addition of fibers increased chloride penetration. The W0 specimens with a fiber dosage of 0.5%, 1%, and 2% presented an increase of 1.2%, 2.3%, and 7.9%, in the penetration, respectively, in comparison with the W0/P0 specimen. The addition of WSA resulted in a lower penetration of chloride ions. A reduction of 7.9%, 4.2%, 1.9%, and 1.8% in the chloride penetration depth was observed for W20/P0, W20/P0.5, W20/P1, and W20/P2 mortar specimens, respectively, compared to the W0/P0 specimen. Comparing the penetration depths of the mortar specimens, W20 specimens with PP fibers (W20/P0, W20/P0.5, W20/P1, and W20/P2) depicted a decrease of 7.9%, 5.4%, 4.1%, and 5.7%, respectively in comparison with the respective W0 specimens. The results of a previous study [27] demonstrate that the addition of fibers negatively affected in terms of

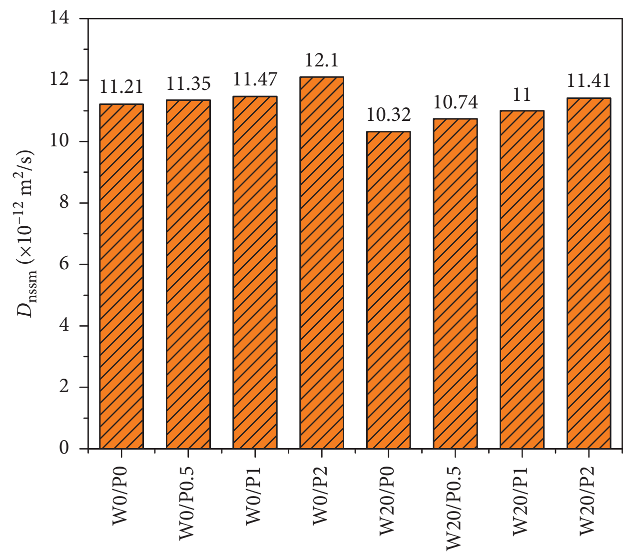

Figure 11: Nonsteady state migration coefficient of mortar specimens.

chloride penetration. This effect was due to the increased capillary porosity of the composite. However, the addition of pozzolanic material compensated the negative impact of fibers. Similar behavior was observed in this study as well.

3.6. Carbonation. The mortar specimens in the carbonation chamber were removed after 28 days and were split into half and sprayed with phenolphthalein to measure the depth of carbonation. Figure 12 shows the average depths of carbonation in each specimen. Similar to the chloride penetration results, the depth of carbonation increased with the inclusion of PP fibers. Carbonation depths of 13.4, 13.57, 13.85, and 14.12 mm were measured for W0 specimens with 0%, 0.5%, 1%, and 2% fibers. On the other hand, the specimens with WSA caused a reduced depth of carbonation. For example, W20/P0, W20/P0.5, W20/P1, and W20/P2 specimens presented carbonation depths of 12.29, 12.55, 12.92, and 13.11 mm, respectively. These specimens exhibited a decrease of 8.3%, 7.5%, 6.7%, and 7.2% in the carbonation depths in comparison with their respective W0 specimens. From the results of the UPV test, it is evident that the addition of PP fibers reduced the pulse velocity due to the improved inner connectivity of the pores. It may be the reason for higher carbonation depths in the fiber-reinforced specimens.

The addition of WSA in the fiber-reinforced cement composites resulted in an amplified performance. It is mainly attributed to the pozzolanic and filler effects of WSA; former consuming calcium hydroxide and later causing a densification of the microstructure. Also, the fine size WSA particles provided nucleation sites for the formation of additional hydration products, which also contributed to the improvement in the microstructure of the composites. These effects are discussed in detail in the previous study by the authors [19].

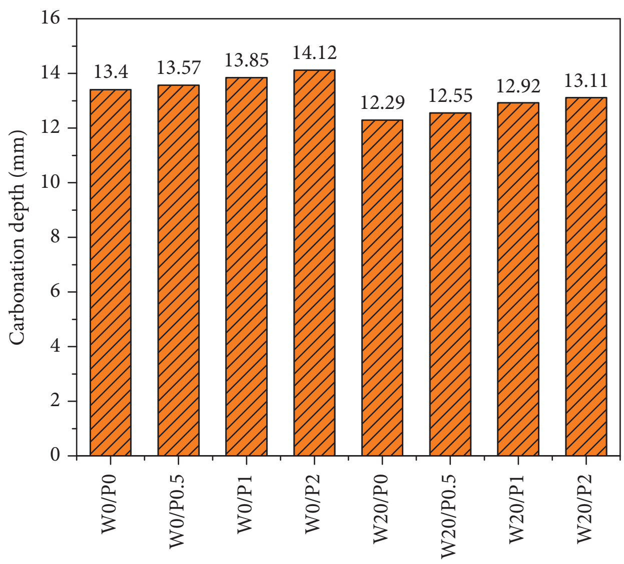

Figure 12: Carbonation depths of the mortar specimens.

4. Conclusions

Fiber-reinforced WSA blended cement mortars were used to investigate the performance of fibers on various mechanical and durability properties. The addition of PP fibers resulted in significant enhancement in the flexure and indirect tensile strengths of the mortars specimens. The compressive strength, pulse velocity, chloride migration, and carbonation resistance of the cement mortars decreased. However, the addition of WSA particles compensated the negative impact of PP fibers. The fine size particles of the WSA imparted pozzolanic and filler effects which resulted in a densified microstructure of the cement composites. Thus, it can be concluded that the incorporation of PP fibers along with WSA can enhance the performance of the cement composites. In addition, the utilization of WSA as a cement replacement material contributes to a clean and healthy environment.

Data Availability

The tabulated data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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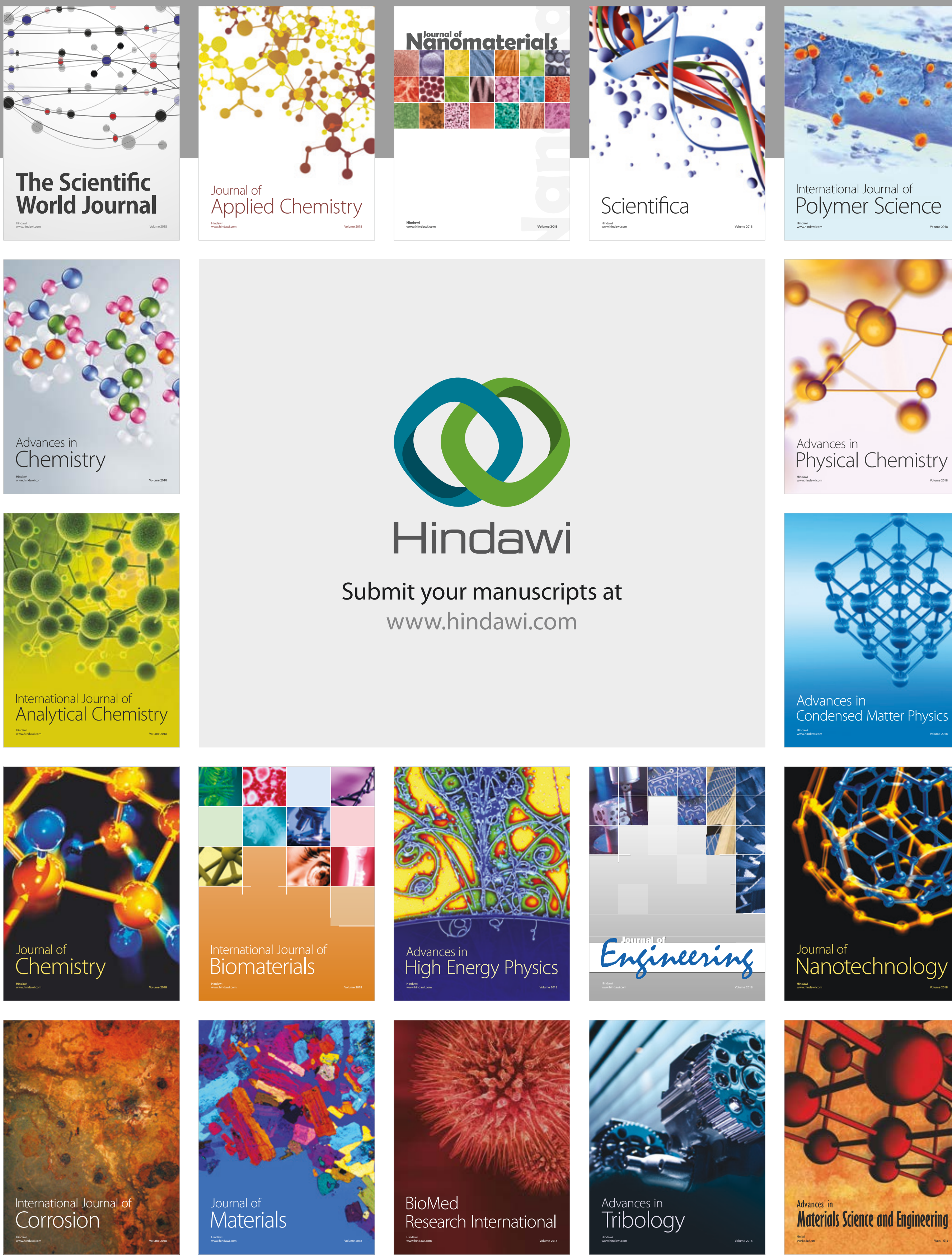
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