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Research Article

Strength and Durability Assessment of Portland Cement Mortars Formulated from Hydrogen-Rich Water

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We investigated the effects of hydrogen-rich water (HRW) on the strength and durability of Portland cement mortars. We comparatively assessed the performances of HRW-based mortars (HWMs) with respect to cement mortars fabricated from control water (CWM). The results indicate that the use of HRW significantly improves the compressive, flexural, and splitting tensile strength of mortars at both the early and later ages of curing. Durability was assessed in terms of capillary absorption, ultrasonic pulse velocity (UPV), dynamic elastic modulus (DEM), and electrical resistivity (ER). We attribute the generally improved mechanical and durability properties of HWMs to the formation of more cement hydrates with fewer voids in the hydrogen-rich environment. Based on X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscope (SEM) analyses, we deduce that the use of HRW in Portland cement mortars produces a more compact, dense, and durable microstructure with fewer voids due to a higher degree of hydration.

1. Introduction

Portland cement-based concrete is the most widely used construction material. This has led researchers to invent new cement production technologies and investigate the use of various materials and additives. Concrete structures are subjected to harsh environments that affect their long-term serviceability and durability [1]. The durability of concrete is defined as its ability to maintain its structural integrity, protective capacity, and aesthetic characteristics for a prolonged period of time. Researchers are always working to develop stronger, more durable concrete. Additionally, the quest for shorter setting times and high early strength has led researchers to modify Portland cement using innovative chemical and mineral admixtures to meet those demands. The need to produce more sustainable concrete has led researchers to formulate complex mixes that use secondary mineral additions and a wide variety of chemical admixtures to improve concrete performance [2].

The most important consideration taken into account when using different products in concrete is their eventual effects on the end structure's sustainability. Generally, cement is partially replaced by mineral admixtures (fly ash, slag, rice husk ash, silica fume, etc.) to improve the long-term durability of concrete materials by producing dense and compact microstructures [3–6]. Additionally, mineral admixtures improve the interface between cement paste and aggregates by increasing the density of cement paste, which contributes to enhanced mechanical performance. Although mineral admixtures are low-cost materials that result in decreased permeability, low heat of hydration, and increased chemical resistance in the resulting concrete materials, they are often associated with some disadvantages, such as reduced strength at an early age and longer curing times [7]. In addition to mineral admixtures, engineers also use various chemical admixtures in concrete to enhance its performance. Conventionally, set accelerators (both chloride and nonchloride) are used to reduce the setting time and increase the early strength of concrete materials. However, chloride-based set accelerators have the disadvantage of depassivation of steel reinforcements. Latex and calcium stearate are permeability reducers, which increase the impermeability of concrete materials to improve durability. Certain hydrophobic materials (water repellents) also tend to increase absorption

Table 1: Chemical composition of Portland cement.

	Chemical composition (%)						
Binder type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
Portland cement	21.95	6.59	2.81	60.12	3.32	2.11	2.58

resistance and thereby the durability of concrete [8]. Water reducers and superplasticizers such as lignosulfonate and polycarboxylate also tend to improve the mechanical performance and durability of concrete by reducing the w/c ratio without affecting flowability [9]. The use of epoxy resins [10], expanded polystyrene [11], and subabsorbent polymers [12] has also led to improved strength and durability in cement mortars. Certain self-curing chemicals also enhance the durability of concrete by decreasing the water transport properties through a higher degree of hydration [13].

A review of the literature shows that mineral and chemical admixtures control the strength and durability properties of concrete. From a chemical standpoint, it is important to accelerate the hydration rate of tricalcium silicate (C_3S), which is responsible for the production of calcium silicate hydrate (CSH)—the main hydration product responsible for enhanced strength and durability. However, sometimes this increased hydration reaction has a negative effect on strength and durability. Based on an extensive literature study, it is ascertained that the effect of hydrogen-rich water (HRW) on the durability of cement system is yet to be investigated adequately. Therefore, we have investigated the effects of using hydrogen-rich water as a chemical admixture on the strength and durability of cement mortars. We compared our results with those from mortars fabricated from normal (control) water. In our previous work, we demonstrated that HRW accelerates the hydration mechanism of cement by causing plain cement pastes to set at a faster rate [14]. HRW is a type of water with the high amount of molecular hydrogen species (H_2). HRW possesses a unique potential to suppress several human diseases [15, 16]. In this study, HRW was produced using a chemical mixture containing glycerol, magnesium hydride, and silicon hydride. During the HRW production, the system produces magnesium hydroxide as well as silicon hydroxide, which in turn increases the pH of the system. It indicates that OH^- (hydroxyl) concentration increases in HRW system. The results obtained from this study suggest that HRW has a positive effect on the strength and durability properties of Portland cement mortars. According to Glavind [17], the goals of sustainable concrete should be achieved by utilizing the inherently environmentally beneficial properties of concrete, for example, the high strength and good durability. For civil infrastructures, the key sustainability issues are strength and durability, as if durability is worse, the service life of structure will be reduced and environmental footprint of the final concrete might not be beneficial. Additionally, the primary sustainability aspect of chemical admixtures is the working environment; the admixture (chemical or mineral) should not pose any hazard to workers and structure health. The set accelerating tendency of HRW favors its use instead of calcium chloride which is related to serious durability problems in reinforced and prestressed concrete. HRW on the other hand is believed to be sustainable development in the field of chemical admixtures, which not only shortens the setting time but also improves the strength and durability of cement mortars.

2. Experimental

2.1. Materials. Portland cement conforming to ASTM C150 having a specific gravity of 3.09 provided by Sayeong Inc., Korea, was used as the primary binding material in this study. Its chemical composition is given in Table 1. River sand with an average particle size of 2.34 mm and specific gravity of 2.72 conforming to the grading requirements of ASTM C33 was used. HRW was produced using a chemical mixture provided by H_2 Vision Inc., Korea (http://www.h2vision.co.kr). This chemical produces hydrogen in normal water. The chemical composition of the mixture consisted of 95% glycerol, 4% MgH_2, and 1% SiH_4.

$$MgH_2 + 2H_2O \longrightarrow Mg(OH)_2 + 2H_2 \quad (1)$$

$$SiH_4 + 2H_2O \longrightarrow Si(OH)_4 + 2H_2 \quad (2)$$

2.2. Mix Proportions and Fabrication of Mortars. Total of 5 mix proportions were produced of normal water and HRW. The water-to-cement ratio and sand-to-cement ratio were kept constant for each mix formulation at 0.485 and 2.75, respectively. CWMs were produced using normal water, and HWMs were produced using HRW. The HRW concentrations were 0.2, 0.3, 0.4, and 0.5 ppm. The hydrogen concentration in water was monitored using a hydrogen water needle sensor provided by Japan. The mortars were labeled as follows: normal water (control) was CWM0, and the mortars fabricated from 0.2, 0.3, 0.4, and 0.5 ppm of concentrated HRW were HWM0.2, HWM0.3, HWM0.4, and HWM0.5, respectively. The formulation summary for the mortar mixes is in Table 2.

Cement and sand were first dry mixed in the mixer with a rotating speed of 80 rpm for one minute. Then water (HRW for the HWM mortars) was added, and it was further mixed for one minute. The prepared mortars were cast into molds in three layers, with each layer tamped 32 times. The specimens were removed from the molds after 1 day and placed in normal water for curing at 23 ± 2°C at 100% RH for 7, 28, 56, and 90 days.

2.3. Testing Methods. Initial and final setting times of cement mortars were determined using an ELE penetration resistance instrument conforming to ASTM C403/403M [18]. This method determines the force required to push a 5 mm

Table 2: Mix proportions of mortar mixtures for 1 m^3.

Mixture code	Cement (kg)	Sand (kg)	Water (kg)	Hydrogen conc. (ppm)
CWM0	542	1490.5	262.87^a	0
HWM0.2	542	1490.5	262.87^b	0.2
HWM0.3	542	1490.5	262.87^b	0.3
HWM0.4	542	1490.5	262.87^b	0.4
HWM0.5	542	1490.5	262.87^b	0.5

a = normal (control) water; b = hydrogen-rich water (HRW).

diameter needle into 25 mm of freshly prepared mortar placed in a 100 mm cube mold. The penetration resistance offered by the mortars was plotted versus time. The initial and final setting times were calculated from the same plot when penetration resistance values reached 3.5 MPa and 27.6 MPa, respectively. Apparent porosity for 28-day hardened (50 mm side) mortar specimens was determined in accordance with ASTM C642 [19].

Compressive and flexural strength tests were performed on 50 mm side cubes and 40 × 40 × 160 mm^3 prismatic specimens, respectively. The compressive and flexural strength of the mortar mixtures were in accordance with ASTM C109 [20] and ASTM C348 [21], respectively, at 7, 28, 56, and 90 days. The splitting tensile strength test was performed on 70 × 70 × 70 mm^3 cubical specimens in accordance with BS EN 12390-6 [22] at 7, 28, 56, and 90 days. 50 mm side cube specimens were used for capillary absorption, ultrasonic pulse velocity (UPV), dynamic elastic modulus (DEM), and electrical resistivity (ER) evaluation of the mortar mixtures. 7-, 28-, 56-, and 90-day UPV of the mortar mixtures were determined in accordance with ASTM C597 [23]. The DEM (E_d) of the mortar mixtures was determined from the corresponding UPV values at different curing ages using the formula

$$E_d = \frac{\rho c^2 (1 + \upsilon)(1 - 2\upsilon)}{(1 - \upsilon)}, \quad (3)$$

where c is the ultrasonic pulse velocity in m/s, ρ is the dry density of hardened mortar in kg/m^3, and υ is Poisson's ratio. Poisson's ratio for all mixes was taken as 0.20.

Capillary absorption test on the cubic specimens was performed after 28 days of curing in accordance with UNI EN 1580:2010 [24]. This test measures the amount of water absorbed through capillary absorption by a dried specimen. The specimens were dried at 60 ± 2°C until the mass became constant. The side surfaces of the specimens were sealed with a sealant for contact with water up to a depth of 5 mm. The ER test on mortars was performed at 7, 28, 56, and 90 days using an ER measuring device with two electrodes. The electrodes were attached to two sides of the specimens; the ER was calculated using the formula

$$\mathrm{ER} = \frac{RA}{L}, \quad (4)$$

where R is the resistance, A is the area of the cross section, and L is the sample length.

For the Fourier transform infrared spectroscopic (FTIR) and X-ray diffraction (XRD) analyses, the 28-day hydrated mortar samples (CWM0 and HWM0.5) taken from fractured mortar specimens after compressive strength testing were used. The samples were ground and treated with acetone to remove water and thereby mitigate the hydration reaction. FTIR was performed using a spectrometer (Nexus 870, Thermo Nicolet Corp., USA). Exactly 1 mg of sample was mixed with 100 mg KBr to make a pallet. We collected 32 scans per sample at 4000 to 400 cm^{-1}. The structural characteristics of the hydrated cement mortar samples were evaluated using an XRD diffractometer (Ultima III, Rigaku Inc., Japan) operated with a Cu-Kα radiation (40 kV, 30 mA) element to record the XRD of the hydrated cement sample in the 2θ range of 8 to 90 degrees at a rate of 1 degree per min. To observe the morphology and the extent to which hydration products formed at the microlevel, scanning electron microscope (SEM) analysis (backscattered mode) was performed on 7- and 28-day hydrated samples (CWM0 and HWM0.5) using a field emission scanning electron microscope (Nova Nano SEM 450, Field Electron and Ion Co., USA). The samples were coated with platinum to prevent charging and analyzed at 15 kv at 12kx magnification.

3. Results and Discussion

3.1. Setting Time and Apparent Porosity. Figure 1 represents the initial and setting times of all the fresh mortar mixtures used in this experimental program. As shown in the figure, increased HRW concentrations decreased the setting time of the mortars. The initial setting times for CWM0, HWM0.2, HWM0.3, HWM0.4, and HWM0.5 were 350, 302, 248, 196, and 44 minutes, respectively. The final setting times for the same mixes were 462, 377, 297, 254, and 62 minutes. This decrease in setting time (both initial and final setting times) with the increase in HRW concentration indicates the set accelerating effect of HRW in mortar mixtures. The fast early and final setting times are attributed to the rapid hydration of an HRW environment. It is known that a set accelerator reduces the duration of the induction period required for the growth of cement hydrates, which leads to a higher degree of hydration at an early age [25, 26]. The 28-day apparent porosity exhibited by all mortar mixtures is also shown in Figure 1. The results indicate that increasing HRW concentrations lead to lower porosity in the mortars. The 28-day apparent porosity of HWM0.5 was 13%, whereas it was 17% for CWM0. The reduced porosity indicates the

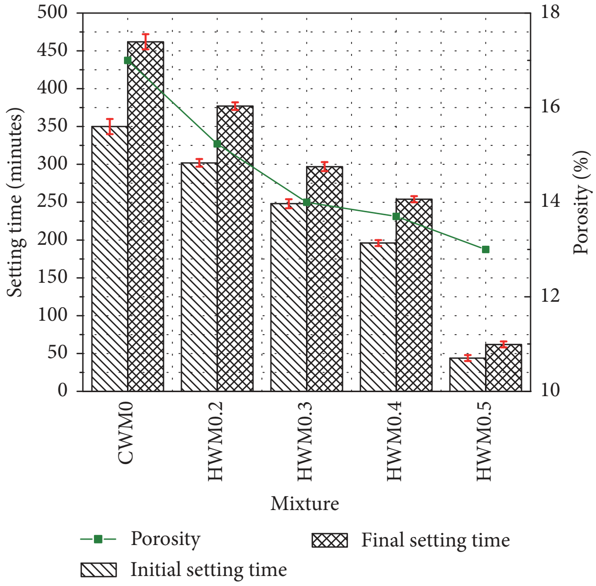


Figure 1: Setting time and 28-day apparent porosity of cement mortars.

presence of fewer open pores and voids, which implies a dense microstructure. Additionally, it is presumed that in HWMs better degree of hydration leads to a reduction of capillary pore volume because capillary pores become filled with hydration products, and gel pore volume is increased as more gel is formed. This leads to reduced total porosity in the case of HWMs.

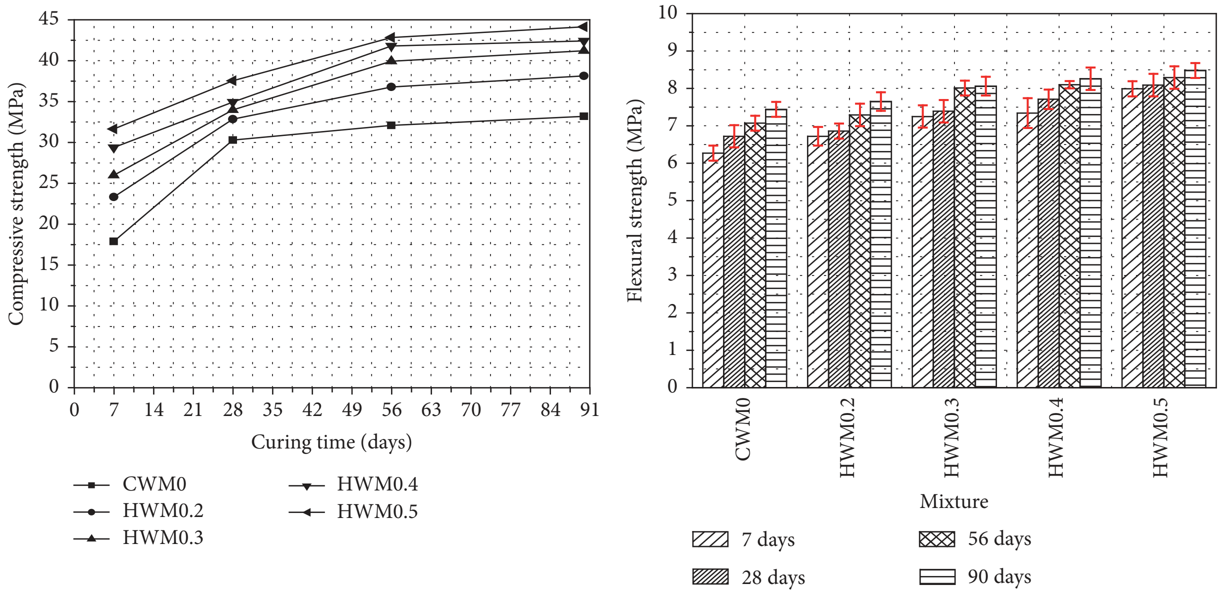
3.2. Compressive, Flexural, and Splitting Tensile Strength. The compressive strength development of all the mortar mixtures during the entire curing period is shown in Figure 2(a). The compressive strength results presented are the average of 6 specimens for each mortar mix. As shown in the figure, the compressive strength increased with the curing time irrespective of the mixture. The 28-day compressive strength of all mortar mixtures was in the range of 30.28–37.54 MPa: 30.28, 32.84, 33.98, 34.95, and 37.54 MPa for CWM0, HWM0.2, HWM0.3, HWM0.4, and HWM0.5, respectively. A higher strength gain for HWMs was also observed at later ages (56 and 90 days). The percentage increase in compressive strength for HWM0.5 compared to CWM0 after 7, 28, 56, and 90 days of curing was 76%, 24%, 33.5%, and 33%, respectively. This remarkable increase in compressive strength at an early age indicates the set accelerating effect of HRW. The enhancement in compressive strength in HWMs is attributed to their more compact and dense microstructure caused by precipitation of more hydration products (calcium hydroxide (CH) and CSH) in the hydrogen-rich environment, which leads to reduced apparent porosity and fewer intermittent pores. Those hydrated products contribute to high compressive strength by reducing the porosity and improving the microstructure of the paste matrix and interfacial transition zones in the cement-sand interface of the mortar mixtures. It is a well-established fact that the strength of cement mortars is primarily the result of a three-dimensional network of hydrate phases that offer resistance to external loads without breakdown.

The flexural strength of all mortar mixtures increased systematically with the compressive strength (Figure 2(b)). At all ages (7, 28, 56, and 90 days), an ascending trend was observed for flexural strength in all mixtures. The 28-day flexural strength of all mortar mixtures was in the range of 6.72–8.09 MPa. The highest 28-day flexural strength was in HWM0.5 (8.09 MPa), and the lowest strength was in CWM0 (6.72 MPa). Thus, it is deduced that the HWMs can resist deformation under flexural loads better than the CWM.

The variation in the splitting tensile strength of the mortar specimens with age is shown in Figure 3. The splitting tensile strength did not show a significant increase in mortars fabricated using low concentrations of HRW (0.1, 0.2, and 0.3 ppm), but a significant improvement was observed at the HRW concentrations of 0.4 and 0.5 ppm. The highest splitting tensile strength of 2.5 MPa after 28 days was achieved by HWM0.5, compared to 2 MPa achieved by CWM0. Unlike the compression and flexural strength results, relatively fewer sharp variations in tensile strength were observed. In general, HRW has a positive effect on the splitting tensile strength of mortars, which we attribute to its filling effect caused by the precipitation of more cement hydrates.

The HRW increases the pH of normal water from 7 to 10. It is stated elsewhere [27] that, at a pH value below 8.5, calcium essentially exists as Ca^{+2}, whereas silica species are in their weakly ionized state. However, at an increased pH value, calcium and silicate species exist as hydroxylated species ($Ca(OH)_2$) and silicate anions, respectively. Therefore interstitial CSH forms through a combination of $Ca(OH)_2$ and silicate ions at the grain surface [28]. During the hydration phase, the cement pore solution is rich in species such as Na^+, Ca^+, K^+, SO_4^-, and OH^-. Aluminum, silicate, and iron are also present in lower amounts [29]. The increased concentration of OH^- ions that HRW brings to the pore solution results in increased dissolution of Ca^{+2} ions, causing rapid nucleation and growth of CH and CSH.

3.3. Capillary Absorption. The absorption and transmission of water, *capillary absorption*, indicate the volume of voids in cement mortar systems. A higher capillary absorption value indicates more permeable voids. Water is the carrier of various harmful ions; therefore, capillary absorption is an important test for the durability of construction materials. Generally, higher mechanical strength correlates with a lower capillary absorption coefficient. Figure 4 shows the capillary absorption coefficient for all the mortar mixtures at 28 days. In this figure, it is observed that increase in HRW concentration results in the reduction in capillary absorption. The percent decrease in capillary absorption with respect to CWM0 for HWM0.2, HWM0.3, HWM0.4, and HWM0.5 was observed to be 13.3, 26.3, 40, and 46.6%, respectively. The higher uptake of water in CWM0 is caused by its larger capillary pores, whereas the lower water uptake in the HWMs occurs because they have fewer interconnected flow channels. In the HWMs, the hydration products occupy more space than they do in CWM0; in other words, the formation of hydration products reduces capillary porosity.



(a) (b)

Figure 2: (a) Variation in the compressive strength of mortar mixtures with age. (b) Variation in the flexural strength of mortar mixtures with age.

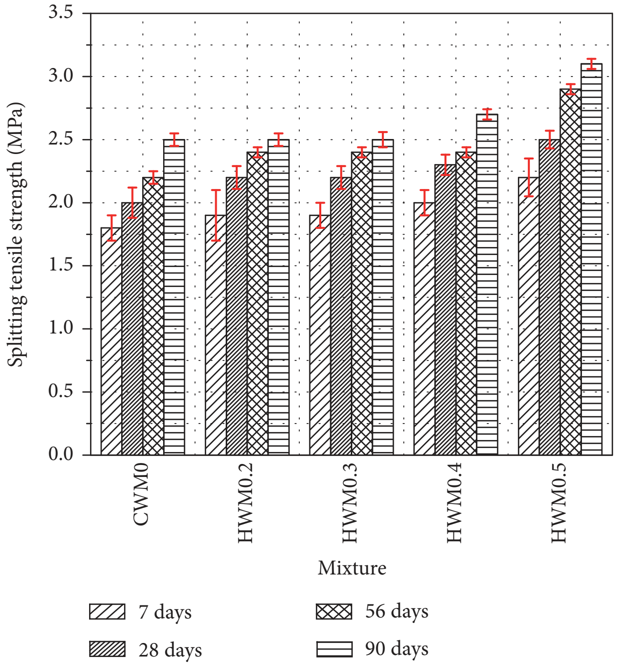


Figure 3: Variation in the splitting tensile strength of mortar mixtures with age.

Thus, the higher degree of hydration leads to decreased capillary porosity [30].

3.4. Ultrasonic Pulse Velocity and Dynamic Elastic Modulus.

The UPV and DEM demonstrated by all mixes at various curing ages are shown in Figures 5(a) and 5(b), respectively.

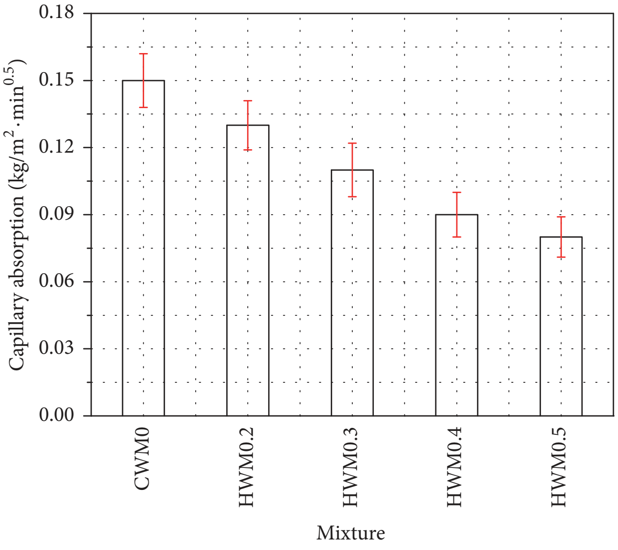
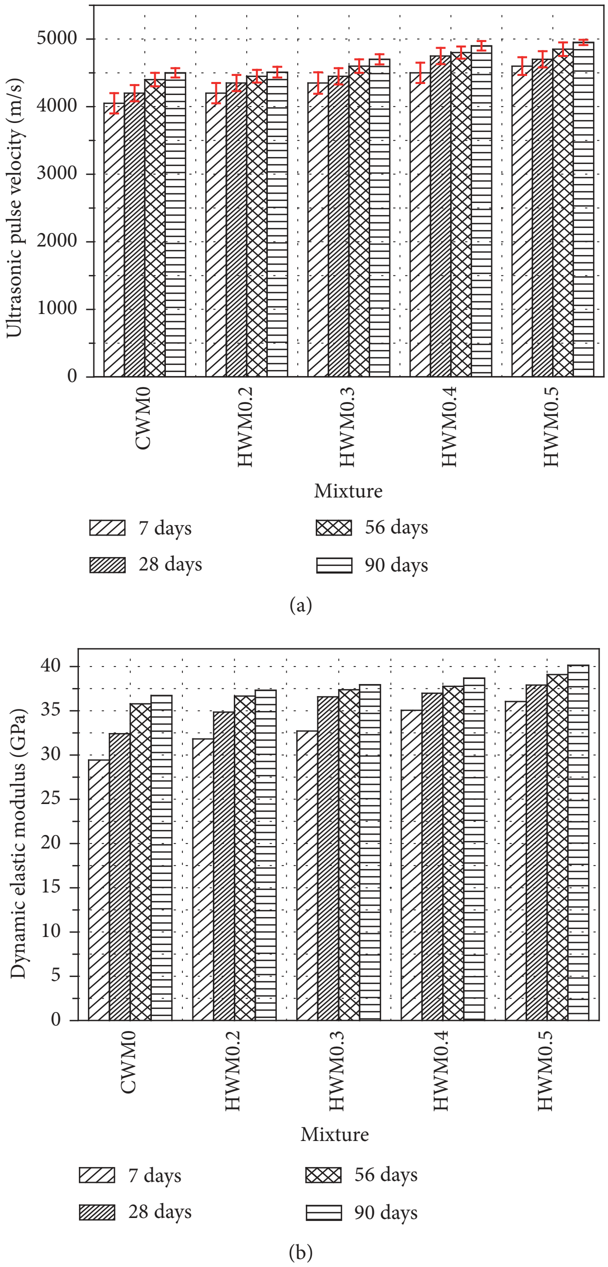


Figure 4: Capillary absorption coefficients of mortar mixtures at the curing age of 28 days.

As shown in the figure, the UPV values increase with curing age irrespective of the mixture. Both CWM0 and HWM0.2 show UPV values lower than the desirable lower limit of 4500 m/s, as specified by Whitehurst [31] for strong concrete, until 56 days. HWM0.3, HWM0.4, and HWM0.5 reached 4500 m/s at the curing ages of 56, 28, and 7 days, respectively. Factors such as pore structure, material properties, mix proportion, and the interfacial zone between aggregates and cement paste all affect UPV values. It is ascertained that HRW induces precipitation of more hydration products

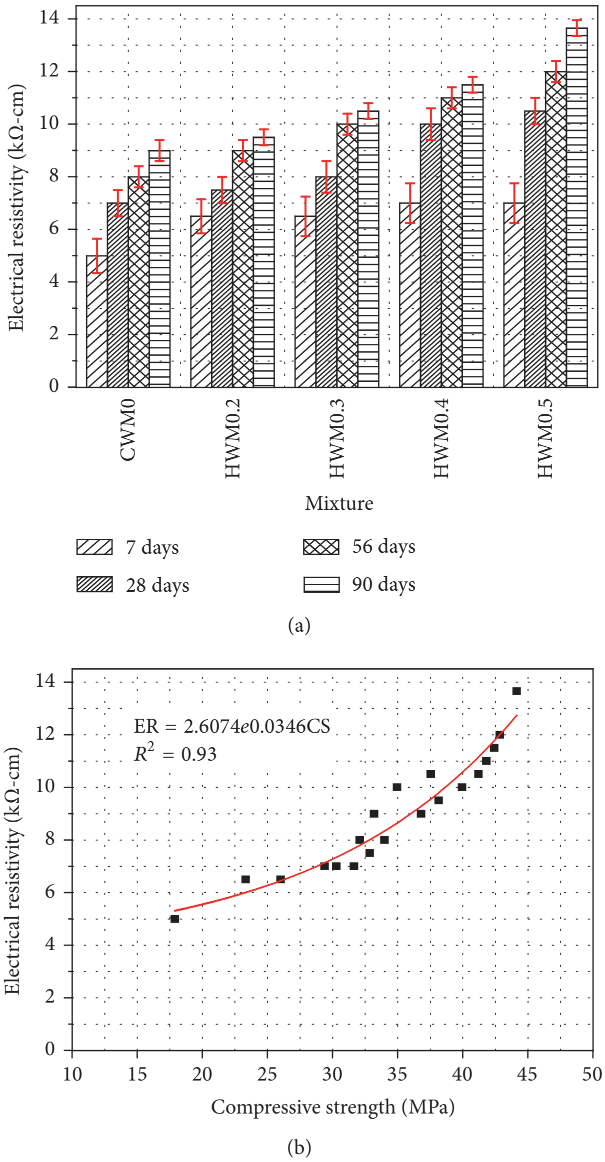


(a)

(b)

Figure 5: (a) Variation in the UPV values of mortar mixtures with age. (b) Variation in the DEM values of mortar mixtures with age.

compared to the CWM, leading to denser, more compact microstructures. As a result, the porosity of the cement matrix was reduced and the continuity of pores diminished. Thus, in the CWM, the increased number of pores and CSH/pore interfaces delayed propagation of the ultrasonic pulse, leading to reduced velocity. The DEM depends on the UPV value and dry density of each mortar. As expected, the use of HRW increased the density of mortar because the higher degree of hydration leads to the formation of more cement hydrates and reduced apparent porosity. Thus, the HWMs demonstrated higher DEM than the CWM0 because of their higher UPV and density values.



(a)

(b)

Figure 6: (a) Electrical resistivity of mortar mixtures at various ages. (b) Relationship between compressive strength and electrical resistivity of different mortar mixtures.

3.5. *Electrical Resistivity.*

The ER demonstrated by all mortar mixtures is shown in Figure 6(a). A significant increase in ER was noticed with age for all mixtures. As shown in the figure, the ER exhibited by all mortar mixtures at the curing age of 28 days was found to be in the range of 7–10.5 kΩ-cm: 7, 7.5, 8, 10, and 10.5 kΩ-cm for CWM0, HWM0.2, HWM0.3, HWM0.4, and HWM0.5, respectively. According to ACI 222 [32], corrosion is less likely to occur when ER is equal to or greater than 10. At 28 days, that criterion was met by only HWM0.4 and HWM0.5. The beneficial effects of HRW on ER were even more pronounced at 56 and 90 days. A percentage increase of 50% and 52% in ER was observed for HRW0.5 with respect to CWM0 at 56 and 90 days, respectively. Moreover, it is ascertained that the increase in HRW concentration enabled mortars to develop a denser, more compact microstructure,

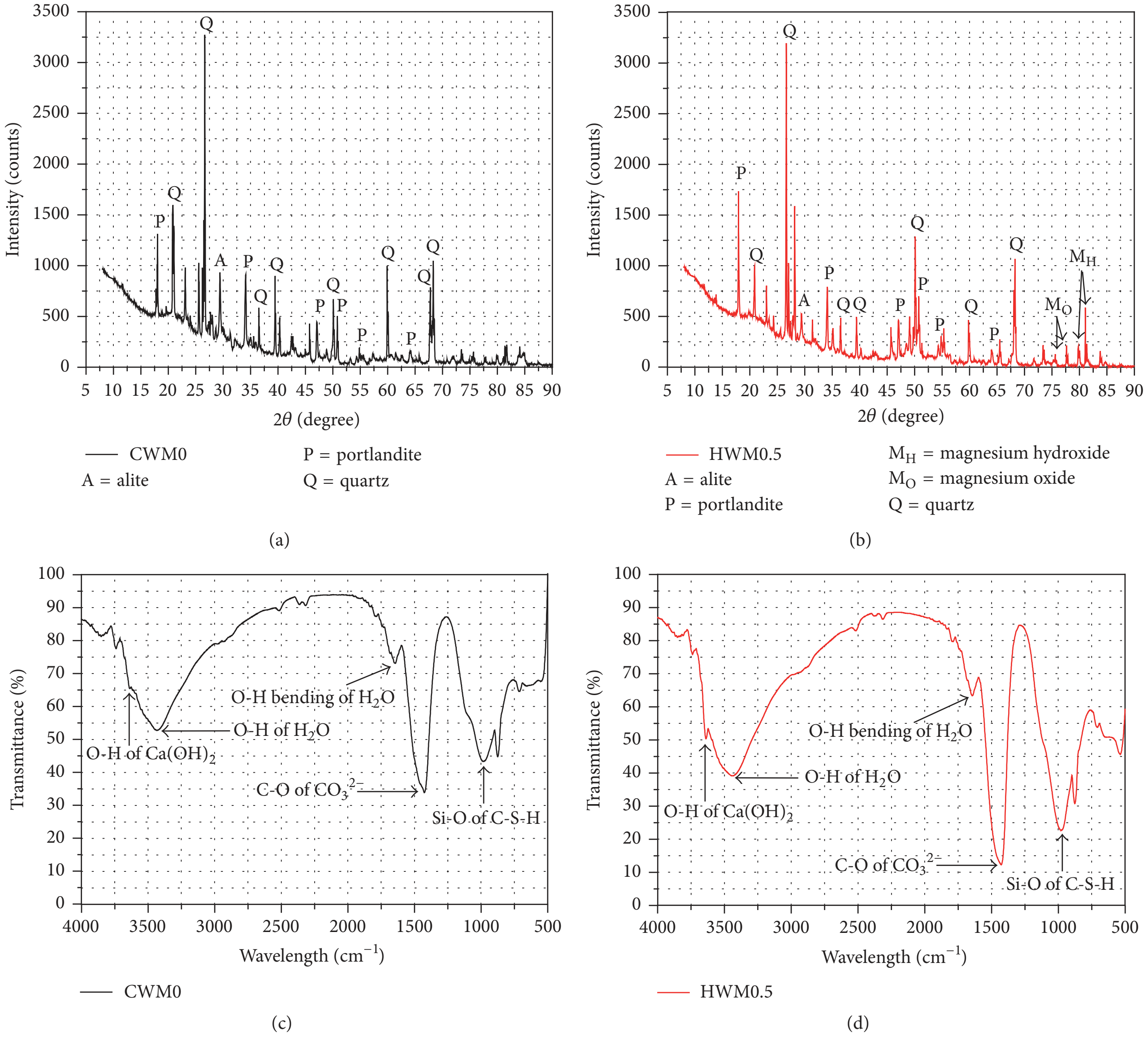


Figure 7: (a) XRD pattern for CWM0 after 28 days of hydration; (b) XRD pattern for HWM0.5 after 28 days of hydration; (c) FTIR transmittance spectrum for CWM0 after 28 days of hydration; (d) FTIR transmittance spectrum for HWM0.5 after 28 days of hydration.

which reduced the interconnectivity between pores and thus resulted in higher ER. That is, it is presumed that the denser microstructure, less-continuous pore system, and reduced porosity allow the HWMs to demonstrate better resistivity. ER is an important parameter that governs the corrosion of reinforcement in concrete. The densification of microstructures increases both ER and the compressive strength of mortars [33]. It is known that as the compressive strength increases, the ER also increases. Some researchers have found a significant correlation between the two parameters, which led them to formulate logarithmic, exponential, and linear relationships [34]. In this investigation, we observed an exponential relationship between compressive strength and ER at all curing ages, with a regression coefficient (R^2) of 0.93, as shown in Figure 6(b). It is presumed that alkaline environment in the pore solution HWMs would provide an appropriate environment for the steel bars embedded so that they can passivate and remain passivated against corrosion. The increased alkalinity leads to a denser pore structure, which apparently is overweighing the increased ionic concentration in pore water. Increased electrical resistivity of concrete was observed by Pruckner and Gjørv [35] in the alkaline environment provided by NaOH.

3.6. XRD and FTIR Analyses. Figures 7(a) and 7(b) present the XRD patterns obtained for CWM0 and HWM0.5 samples after 28 days of hydration in the 2θ range 8–90°, respectively. The XRD patterns of both the CWM0 and HWM0.5 mortar samples mostly contain peaks at the same positions but with different intensities. The prominent peaks at 2θ values of 18.09°, 34.09°, 47.12°, 50.77°, 54.34°, and 64.23° appear to be due to portlandite phase (P) [36, 37]. The intense

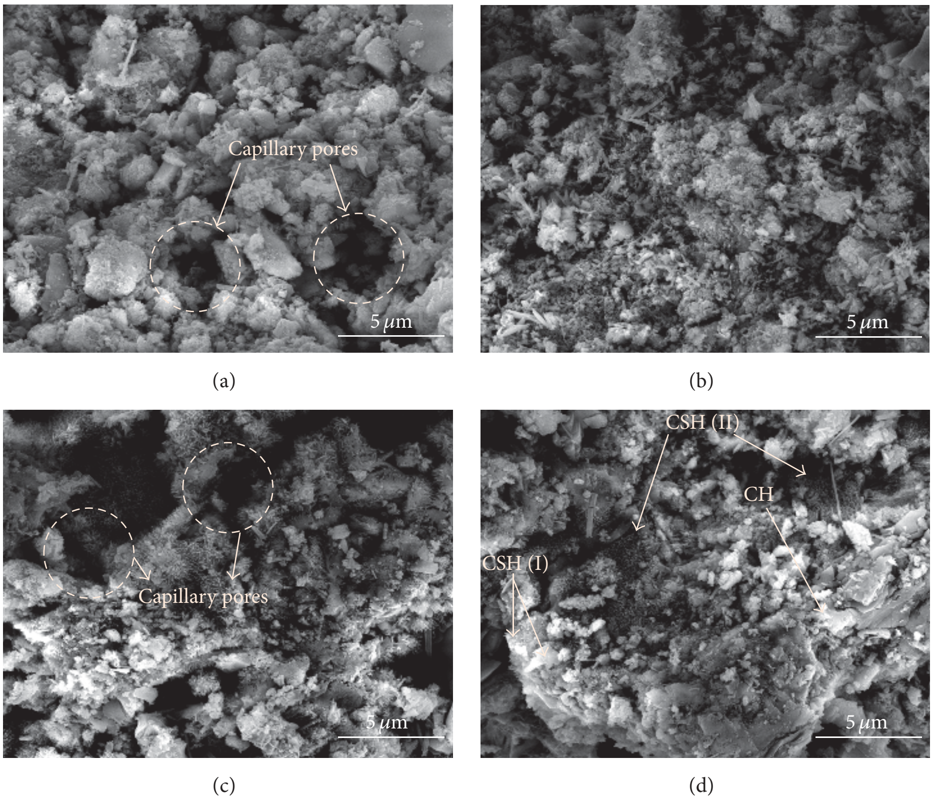


Figure 8: (a) SEM for CWM0 after 7 days of hydration; (b) SEM for HWM0.5 after 7 days of hydration; (c) SEM for CWM0 after 28 days of hydration; (d) SEM for HWM0.5 after 28 days of hydration.

peaks at 2θ values of 20.85°, 26.65°, 36.54°, 39.46°, 50.14°, 59.95°, 68.13°, and 67.75° are due to the presence of quartz (Q) [36]. In the XRD pattern of HWM0.5, some other peaks appear due to magnesium oxide (75.6° and 77.75°) and magnesium hydroxide (79.88° and 81.35°). The kinetics of the hydration process can be studied by measuring the amount of unreacted C_3S (alite) in the XRD pattern as a function of hydration time [38]. The less intense alite (A) peak at a 2θ value of 29.4° in the XRD pattern thus indicates the greater degree of hydration in HWM0.5. Additionally, due to lesser crystalline nature of calcium silicate hydrate, it is difficult to identify it. It is stated elsewhere [39] that the peak of the calcium silicate hydrate (CSH) phase is mostly situated behind the several alite phase reflections (especially at the $2\theta = 29.2°$). Therefore, the amount of calcium hydroxide (portlandite) content in the hydrated cement paste would be an indication of the formation of the hydrated product. According to Neville [40] the progress of cement hydration can be determined predicting the calcium hydroxide content. It can be observed from the XRD patterns that HWM0.5 shows more intense peaks for portlandite (CH) than the CWM0, indicating a higher degree of hydration from the hydrogen-rich environment.

Figures 7(c) and 7(d) show the FTIR transmittance spectra of CWM0 and HWM0.5 cured for 28 days, respectively. The IR bands at 713, 873, 930–1020, 1420, 1640, 2890, 3100–3400, and 3638 cm^{-1} appeared due to ν_4 stretching of carbonate, ν_2 stretching of carbonate, CSH vibrations, ν_3 stretching of carbonate, ν_2 bending of water molecules, H-C stretching of methyl, ν_1 and ν_2 stretching of water molecules, and O-H stretching of $Ca(OH)_2$, respectively [41]. In the high zone, a more acute peak appears at 3638 cm^{-1} due to O-H stretching of $Ca(OH)_2$ in HWM0.5 than in CWM0, indicating a greater degree of CH formation. Comparing the bands of the two samples from silicate at 930–1020 cm^{-1}, it is clear that HRW accelerates the formation of CSH, as the band is quite reinforced in HWM0.5 compared to CWM0. The degree of hydration is a fundamental parameter for cementitious materials because the evolution of mechanical properties greatly depends on it [42]. The FTIR analysis thus helps confirm the formation of more hydrated products (CH and CSH) in HWM0.5 compared to CWM0.

3.7. Microstructure Investigations. Our study of the microstructure of the mortars presents an internal structure that includes CH, CSH, and micropores. The mechanical and durability performances of mortars are greatly influenced by their microstructures, which can be shown in SEM micrographs. Figure 8 shows SEM microstructure images of CWM0 and HWM0.5. It is evident that the HWM0.5 (Figures 8(b) and 8(d)) has a denser, more compact, and overall improved microstructure containing CSH, crystalline CH, and fewer voids than the CWM0 (Figures 8(a) and 8(c)). The increased amount of cement hydrates such as CH and CSH in the HWM0.5 explains its higher mechanical strength. The SEM image of HWM0.5 at 28 days (Figure 8(d)) shows type II CSH (reticular or honeycombed shape) in conjunction with type I CSH (rod-shaped). According to Ramachandran et al. [43], this phenomenon usually occurs in the presence of chemical admixtures. Regarding durability, it was deduced that the microstructures of mixtures with HRW get denser and more packed, especially at advanced ages. Additionally, the capillary pores get smaller, which produces a compact microstructure that results in high ER, UPV, and DEM values. Concrete durability greatly depends on the microstructure and product uniformity of the cement paste; thus the growth and development of CSH are a decisive factor for concrete performance in terms of durability [44]. Moreover, $Ca(OH)_2$ also plays a vital role in concrete durability; it is the source of high pH in the concrete pore fluid, which holds relevance in terms of chemical attacks such as corrosion and alkali silica reaction [30]. The evolution of strength, durability related, and time-dependent properties of concrete materials are highly dependent upon microstructure of cement paste. Thus, promoting the more homogenous growth of cement hydrates positively affects the durability of concrete, as observed in our HWMs.

4. Conclusions

To evaluate the effects of HRW on the mechanical performance and durability of cement mortar systems, we carried out an experimental investigation. The experimental study led to the following conclusions:

(1) The use of HRW in mortar reduces the initial and final setting times. The effect is greatly pronounced at an HRW concentration of 0.5 ppm. The fast setting time is an indication of accelerated hydration. Use of HRW reduced the apparent porosity of mortars, indicating the formation of the dense microstructure.

(2) When HRW is used in cement, the compressive and flexural strength increases at both earlier and later ages. Significant enhancement in the splitting tensile strength of mortars was observed for mortars fabricated from 0.4 and 0.5 ppm HRW. The enhanced strength is attributed to the promotion of hydration reactions in the presence of HRW.

(3) The results for capillary absorption coefficients of HWMs suggest that its use in mortars improves their durability, because of the compact and dense microstructure. The reduced transport properties lead to better durability.

(4) The UPV, DEM, and ER results demonstrate the better performance of HWMs compared to the CWM through improved microstructure and product uniformity with a less interconnected pore network. Additionally, based on ER results it is deduced that HWMs offer better resistance against corrosion.

(5) Based on XRD, FTIR, and SEM results, it is deduced that HWMs show a greater amount of hydrated product formation due to a higher degree of hydration, which is the reason for their better mechanical and durability performance compared with the CWM. SEM analysis revealed a more compact and denser microstructure in the HWMs with fewer capillary pores compared to CWM.

Conflicts of Interest

The authors declare no conflicts of interest.

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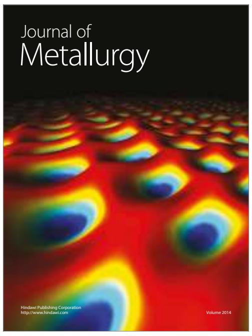
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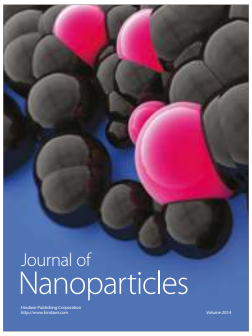
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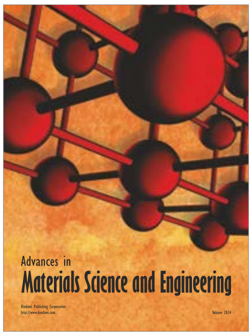
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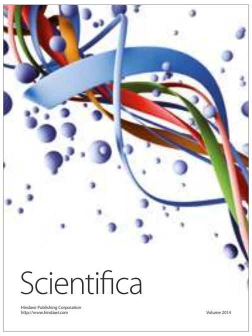
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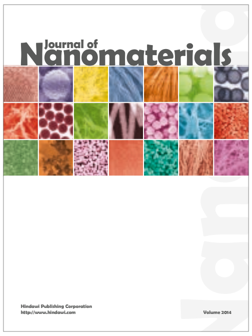
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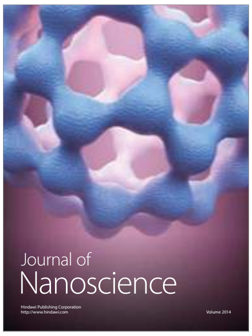
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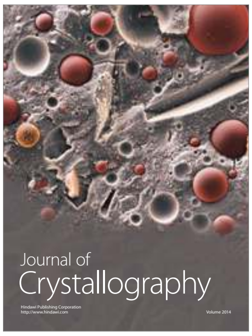
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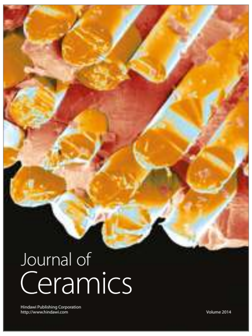
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