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Original Research Article

Mechanical Strength, Durability, and Environmental Properties of Ternary Blended Self-Compacting Cementitious Mortar Containing Class F Fly Ash and Waste Ceramic Powder

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ABSTRACT

In this paper, the mechanical as well as workability and durability properties of Self-Compacting Mortars (SCMs) made of different contents of Waste Ceramic Powder (WCP) and class F Fly Ash (FA) were experimentally assessed. To this end, the fresh properties of the SCM mixtures were evaluated through detailed examination of both mini slump flow and mini V-funnel tests. Ternary SCM mixtures are characterized by more flowability and passing ability than the control mix. The compressive and flexural strength, water absorption, and electrical resistivity tests were also carried out at different curing ages. The obtained results revealed that the compressive and flexural strength of the ternary SCM samples were lower than those of the control mix, especially at the ages of 7 and 28 days. However, there was a strength gain between 28 and 90 days due to the pozzolanic reactivity of both FA and WCP. Water absorption of the ternary SCM specimens containing FA and WCP followed a decreasing trend, thus highlighting the filling effect of the used pozzolans. Ternary SCM samples had considerably higher electrical resistivity (up to 144 % at 90 days) than the binary blends and control mix. Scanning Electron Microscopy (SEM) images confirmed that application of FA and WCP would fill in the pores and micro-cracks. Based on the obtained results, it can be concluded that both FA and WCP act more as a filler rather than a reactive pozzolanic material. Finally, the environmental analysis results revealed that replacement of 50 % of the Portland cement with 30 % FA and 20 % WCP would result in a reduction in the carbon footprint and energy demand by 47 % and 29 %, respectively.

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1. INTRODUCTION

One of the most important concerns in sustainable development of construction industry is to build structures with the lowest possible energy consumption and air pollution [1]. Portland cement plants emit about one ton of carbon dioxide released into the air for every ton of cement powder production [2]. However, concrete

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is the most consumed man-made material all around the world, and its production is inevitable. To solve this problem, efforts have been made to reduce cement consumption by replacing cement with other supplementary materials. Cement consumption could also be reduced by extending the lifetime of structures. Any weakness in the durability properties used in constructions proved to be a more important reason for failure of the concrete structures rather than the strength loss. Using the waste materials in cementitious mixtures as the supplementary materials enjoys two main benefits: (1) efficient reuse of the agricultural, mining, and industrial by-products or even unusable waste materials in cementitious mixtures significantly contributes to having a cleaner environment [3,4], and (2) partial replacement of cement by supplementary materials will improve the mechanical and durability properties of cementitious mixtures [5-11] and reduce the cement consumption through prolonging the structure service life [12].

The main focus in this study is put on the waste materials called Fly Ash (FA) [13-16] and Waste Ceramic Powder (WCP) [17-20]. Characterized by pozzolanic properties, these materials can be utilized as the supplementary materials. A large amount of waste ceramic tiles is annually discarded in the environment. Grinding the ceramic tiles facilitates use of waste ceramic in the cementitious mixtures so that different sizes of waste ceramic can be transformed into pozzolanic powder as well as fine or coarse aggregates [21-23]. WCP mainly plays the filler role in concrete mixtures. Utilizing the fine particles of WCP as the fine aggregates or fillers make the mixtures more flowable [24], less permeable, and more durable than its regular counterparts, when exposed to chloride ion penetration [25]. In addition to the mentioned role of the WCP, its incorporation into the concrete mixtures can affect the long-term compressive strength of the samples [9]. Moreover, Differential Scanning Calorimetry (DSC) and thermogravimetric analyses confirmed the gradual consumption of calcium hydroxide over time [26]. Based on these two facts as well as the XRD analysis results [20], it can be concluded that when used in cementitious mixtures, WCP had pozzolanic activities. The positive effects of the WCP introduction on the durability as well as mechanical properties of cementitious mixtures can be multiplied by preparing a ternary cementitious mixture by adding a highly-active pozzolan such as FA and nano-SiO_2 [20]. FA is one of the most used materials in cementitious mixtures as a supplementary material in the world [13-16]. It is a by-product produced in coal-fired power plants. Huge tons of FA are annually produced in the world, a majority of which are released into the environment. There are two types of FA that are used in concrete: class C FA and class F FA. Class F FA is pozzolanic while class C FA is both self-cementing and pozzolanic [27]. The main difference between the class F and class C FA is related to their chemical composition. According to the ASTM C-618 [28], both class F and C FA must contain the total amount of aluminum, silicon, and iron oxides higher than 70 % and 50 % wt., respectively. Class F FA is a low-calcium FA containing less than 10 % and 1.5 % CaO and Na_2O, respectively. Class F FA has lower density and higher fineness than those of its class C fly counterpart [27]. The introduced FA powders into the concrete must satisfy the fineness requirements to ensure that the retained materials on the 0.045-mm sieve are lower than 40 % [29]. Of note, non-conforming FA has also several reasonable properties [30]. Self-Compacting Concrete (SCC) samples containing class F FA are characterized by higher compressive strength and lower shrinkage [15,31] than those of their counterparts. However, their compressive strength might not significantly increase, compared to that of the ordinary SCC samples. According to the observations, the value of the mentioned criterion decreased in the mixtures containing high-volume class C FA [32]. Incorporation of finer particles of FA into the self-compacting mixtures would slightly lessen their strength while making them more flowable with better passing ability [33]. In addition, introduction of class F FA into the self-compacting mixtures would significantly increase the electrical resistivity and improve the volume stability of the samples [34]. Incorporation of the FA into the SCC would decrease the total charge passing through the samples, hence higher resistance of the produced samples to the penetration of chloride ions than that of the control samples. In addition, the produced samples had lower weight loss when exposed to acid attack [35]. Higher or similar porosity in Interfacial Transition Zone (ITZ) and significantly better durability of the SCC samples with FA than those of the control samples strongly proved the greater impact of the binder type in the cementitious mixtures than that of porosity on the durability of SCC mixtures in the case of deteriorations caused by penetration of harmful ions and liquids [36].

Numerous research studies have investigated the durability and mechanical properties of binary Self-Compacting Mortars (SCMs) made of either WCP or FA. However, to the best of the authors’ knowledge, no research was found in the literature on the properties of ternary blended cementitious mixtures using WCP and FA in the Portland cement. In this regard, the current study selected the FA as a supplementary material to improve the durability and mechanical properties of the self-compacting mixture containing WCP. Then, it evaluated the flowability and passing ability of the SCM mixture using mini slump flow and mini V-funnel tests. In the current research, the compressive and flexural strength, water absorption, and electrical resistivity of the SCC samples were investigated at the age of 7, 28, and 90 days. In addition, the microstructural structure of the hardened samples was evaluated using Scanning Electron

Microscopy (SEM) images. Finally, an environmental assessment was carried out to study the effects of different FA and WCP contents on the carbon dioxide emission and energy consumption of the SCM mixes.

2. EXPERIMENTAL

2.1. Materials

In this paper, the SCM mixtures were prepared using Portland cement, FA, WCP, water, sand, and Super-Plasticizer (SP). The Portland cement used in the mixtures was Type-II cement produced by Sepahan cement Co. Esfahan, Iran, which meets the requirements of ASTM C-150 [37]. Class-F FA was used for constructing the mixture with enough fineness in accordance with the instructions of UNE-EN 933-10 [38]. FA can be appropriately used for blending the pozzolanic cementitious mixtures on condition that the amount of FA powder is about 33 % on the 45 µm sieve. WCP was prepared through some physical processing on the waste ceramic tiles of RAK ceramic company in Isfahan, Iran. Waste ceramic tiles were ground using air jet mill and then, they were passed through a 75 µm (#200) sieve. The materials passing through the 75 µm sieve were used for preparing the paste. Table 1 lists the chemical composition as well as the physical properties of the cement, WCP, and FA.

TABLE 1. Physical and chemical properties of the binders used in this study

	Chemical compound	OPC	WCP	FA
Chemical Composition	SiO_2	21.5	63.29	70.70
	Al_2O_3	6.0	18.29	20.70
	Fe_2O_3	2.5	4.32	3.90
	CaO	66	4.46	1.13
	MgO	2.0	0.72	0.77
	SO_3	0.3	0.10	0.44
	Total Alkali (Na_2O+0.658 K_2O)	0.75	2.18	0.98
	LOI	1.00	1.61	0.70
Physical Properties	Specific Gravity (g/cm^3)	3.18	2.36	2.20
	Specific Surface Area (cm^2/g)	3500	3250	2850

The pozzolanic properties can be attributed to the cementitious raw materials when the total amounts of SiO_2, Fe_2O_3, and Al_2O_3 are higher than 70 %, the volume of SO_3 oxides is lower than 5 %, and their Loss of Ignition (LOI) is lower than 6 % [28]. As observed in Table 1, the total amounts of the WCP and FA are about 85.9 % and 95.3 %, respectively, and their corresponding SO_3 volume and LOI are sufficiently low. Therefore, it can be concluded that both WCP and FA exhibit pozzolanic behavior in a sense that they might contribute in the hydration process along with delay.

Natural river sand was used as fine aggregate. The values of the density, water absorption, and fineness modulus of the used sand were 2460 kg/m^3, 1.8 %, and 3.2, respectively. The specification of the implemented sand meets the ASTM C-778 requirements [39]. Mixing water was supplied from purified drinking municipal water. In order to reduce the required water consumption and make the mixture more flowable, the polycarboxylic-ether-based Superplasticizer (SP) was utilized. The chosen SP type was High-Range Water Reducer (HRWR) with the density of 1.07 g/cm^3 (at 20 °C) and pH of 7.5 ± 1.

2.2. Mix Design and Sample Preparation

This study aims to evaluate the performance of ternary SCM mixes produced from different percentages of FA, WCP, and Portland cement. The primary binder was Portland cement which was then partially substituted by different amounts of FA and WCP. The total replacement ratio of cement with the aforementioned materials was considered to be 50 % to maintain adequate strength development. The replacement ratios of the FA with Portland cement were 10, 20, and 30 %, and those for the WCP were 5, 10, 15, and 20 % (by weight). The WCP and FA were incorporated at the previously mentioned dosages alone and combined with each other to evaluate their sole and combined effects on the properties of the mixtures.

Some preliminary tests were also done to find out the precise amounts of the required contributing materials in the SCM mixtures to obtain a reasonable range of outputs. Different w/c ratios and amounts of the raw materials were examined to obtain the material proportions for different mixes that are listed in Table 2. This table also shows the required weight of materials (kg) used for making one cubic meter of SCM mixtures. In the mix ID letters, W and F stands for WCP and FA, respectively. The total mass of one cubic meter of the blended SCM mixtures for all of the mix IDs was assumed to be 2106 kg. Further, the ratio of water to cementitious materials (w/c) was assumed to be 0.48 for all SCM mixes.

Aggregates and cementitious powders containing cement, FA, and WCP were initially mixed in a dry state. Then, SP and water were mixed to produce a homogenous solution, and the resultant solution was added to the mixture. The mixture was blended until a uniform mortar was created. When the SCM was ready, the fresh properties of the mixture were examined using mini slump flow and mini V-funnel tests according to EFNARC guidelines [40]. The mixture with a larger slump flow diameter is more capable of overcoming friction and the consequent deformation under its weight [6].

The diameter of the fresh mixture must be measured when it was spread on the test plate after removing the standard slump cone.

TABLE 2. Mixture proportions of blended mortars (kg/m^3)

Sample ID	Cement	FA	WCP	Water	Sand	SP
Control	550	-	-	264	1286	6.6
FA10	495	55	-	264	1286	6.6
FA20	440	110	-	264	1286	6.6
FA30	385	165	-	264	1286	6.6
WC5	522.5	-	27.5	264	1286	6.6
WC10	495	-	55	264	1286	6.6
WC15	467.5	-	82.5	264	1286	6.6
WC20	440	-	110	264	1286	6.6
FA10WC5	467.5	55	27.5	264	1286	6.6
FA20WC5	412.5	110	27.5	264	1286	6.6
FA30WC5	357.5	165	27.5	264	1286	6.6
FA10WC10	440	55	55	264	1286	6.6
FA20WC10	385	110	55	264	1286	6.6
FA30WC10	330	165	55	264	1286	6.6
FA10WC15	412.5	55	82.5	264	1286	6.6
FA20WC15	357.5	110	82.5	264	1286	6.6
FA30WC15	302.5	165	82.5	264	1286	6.6
FA10WC20	385	55	110	264	1286	6.6
FA20WC20	330	110	110	264	1286	6.6
FA30WC20	275	165	110	264	1286	6.6

Followed by conducting the tests to evaluate the fresh properties, the whole mixture was blended again before casting. To assess the durability and mechanical properties of different mixes, both prismatic beams and cubic molds are required. Prism mold with dimensions of 40×40×160 mm was used to construct SCM samples and evaluate their flexural strength. The molds with dimensions of 50×50×50 mm were used to cast the cubic samples and assess their compressive strength and water absorption. Followed by 24 hours, the specimens were demolded and cured in the curing room. The specimens were immersed in water at the temperature of 25±3 °C until the desired age was obtained.

2.3. METHODS

2.3.1. Workability

The performance SCM mixes was tested in terms of the workability, mechanical strength, and durability. The mini slump flow and mini V-funnel tests were carried out on the fresh mortar as per EFNARC [40] to evaluate the workability of mixes. In the mini slump flow test, the fresh mix was poured in a cone (100 mm bottom opening, 70 mm top opening, and 60 mm high) and allowed to flow under self-weight once the cone was lifted. The average diameter of the two perpendicular diameters was regarded as the mini slump flow value. The mini V-funnel test measured the filling ability of fresh mix. The test setup has a trap door underneath. The time that took the fresh mortar to flow out of the container was also calculated and reported.

2.3.2. Compressive and Flexural Strengths

The compressive strength of different mixes was examined by exerting universal compression load on the top and bottom faces of cubic specimens at the ages of 3, 7, 28, and 90 days using hydraulic universal testing machine at the loading rate of 0.5 MPa/s, according to the instruction of ASTM C109 [41]. The flexural strength of the SCM prism samples was obtained by measuring the excreted compression loads through one upper loading pin and two lower loading pins using three-point loading setup at the ages of 3, 7, 28, and 90 days, according to the instructions of ASTM C78 [42]. For each individual experiment, three specimens were prepared, and the average value was calculated. Figure 1 demonstrates some of the concrete samples made and tested in terms of their flexural strength.

Figure 1. Some concrete samples were made and tested for flexural strength testing

2.3.3. Water Absorption

In terms of the durability-related properties, the SCM specimens were tested according to ASTM C642 [43] to measure the degree of water absorption. Cubic samples at the ages of 28 and 90 days were placed in the oven at the temperature of 100-110 °C for 24 hours to ensure the complete evaporation of the maintained whole water. Then, the specimens were rested to be cooled at the ambient temperature of the laboratory for one hour.

Afterwards, the SCM cubic sample were saturated in the water at the temperature of 21 °C for 48 hours. The mass of the dried and Saturated Surface-Dried (SSD) specimens were recorded as the oven-dried and SSD mass of the samples, respectively. Water absorption value can be obtained by dividing the SSD mass by the oven-dried mass of the samples in percent. Three samples were tested for each case, and the results were averaged out.

2.3.4. Electrical Resistivity

The electrical resistivity of the cubic samples was measured through ASTM C1760 [44]. Based on the values of the electrical resistivity test, it is possible to estimate the probability of steel rebar corrosion. In case the values of electrical resistivity were higher than the suggested limits allowed by ACI Committee 222 [45], the corrosion rate of the embedded steel reinforcements in concrete would become relatively low.

2.3.5. Environmental Analysis

Mortar mixes were compared from an environmental point of view by computing their Embodied carbon dioxide emitted (ECO_2e) and Embodied Energy (EE). The ECO_2e and EE amounts for one kg of each material were taken from the previous studies [21,46], the results of which are given in Table 3. As mentioned earlier, the environmental analysis was carried out in order to provide better insights into the effect of FA and WCP on the environmental footprint of mortar mixes that is only detected in nature. For a more thorough evaluation, the contribution of other factors such as transportation, maintenance, and material wastage should be taken into account.

TABLE 3. ECO_2e and EE of materials per kg

Materials		**ECO_2e ($kgCO_2e$)**	**EE (MJ)**
Binder	OPC	0.93	5.2
	WCP	0.045	1.113
	FA	0.012	0.173
Fine Aggregates	Sand	0.0028	0.081
Water		0.00057	0.2
Admixture	SP	0.6	11.5
Processing		0.0038	0.15

Note: EE = Embodied energy
ECO_2e = Embodied CO_2 emitted

2.3.6. Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) analysis was also carried out to determine the most significant parameters involved in determining different properties of the SCM mixes [47]. The replacement ratio of FA and WCP, as well as the curing age of mixes were selected as the input variables for the two-way ANOVA.

3. RESULTS AND DISCUSSION

3.1. Workability

The flowability of mortars was evaluated based on mini slump flow and mini V-funnel tests. As illustrated in Figure 2(a), an increase in the WCP content in the fresh mortar would make it less viscous than the ordinary Portland cement mortar. The mixture containing 20 % WCP had the highest slump flow diameter among the others with constant FA amounts, which was about 5.5 % higher than that of the control mix. Clearly, incorporation of FA into the cementitious mortar would lead to increased flowability. Similar to the effect of WCP on the flow value of mixes, increasing the FA content enhanced the workability of the fresh mortar up to approximately 5 % at the FA replacement ratio of 30 %. Such enhancement can be attributed to the spherical shape of FA and WCP particles, which reduced the internal friction between the paste and aggregate and consequently increased the flow value. In addition, use of the WCP and FA combination resulted in the highest improvement in the slump flow value, where incorporation of 30 % FA and 20 % WCP increased the slump flow up to about 8.4 % in the control mix. Jalal et al. [15] reported that an increase in the FA content made the SCM less resistant to flow. They also showed that replacement of 15 % cement with the FA led to an increase up to about 7.7 % and 10 % in the slump flow diameter for binder content of 400 and 500 kg/m^3, respectively. In contrast with the results from the present research, Heidari and Tavakoli [48] observed that fresh concrete mixtures containing WCP had a slump diameter smaller than the corresponding diameter value in the control mixture. The contradiction in the results of the aforementioned research and those of the current one may be due to either the interaction between the use of different SP and WCP or the tiles grinding method. While this study employed the slump flow test, that of Heidari and Tavakoli's used the conventional slump test.

As shown in Figure 2(b), the same conclusions can be drawn as those presented in Figure 2(a). According to Figure 2(b), the flow time decreased upon increasing the WCP content until it reasched 15 % wt. The minimum time was recorded for SCM mix containing 15 % WCP. It took a little bit more time for the mix containing 20 % WCP to pass through the V-funnel than for the SCMs with 15 % WCP. As observed in Figure 2(b), the flowability of the SCM mixture increased upon increasing the FA content. However, their flow time values decreased when more FA powder was introduced into the mixture. The observed reduction in the measured V-funnel flow time values had no conflict with the estimated trend observed in the literature for the variation of corresponding values for different FA contents [34,35,49]. Jalal et al. [15] showed that the mixture containing 15 % of FA could pass through the V-funnel about three seconds faster than the control mixture.

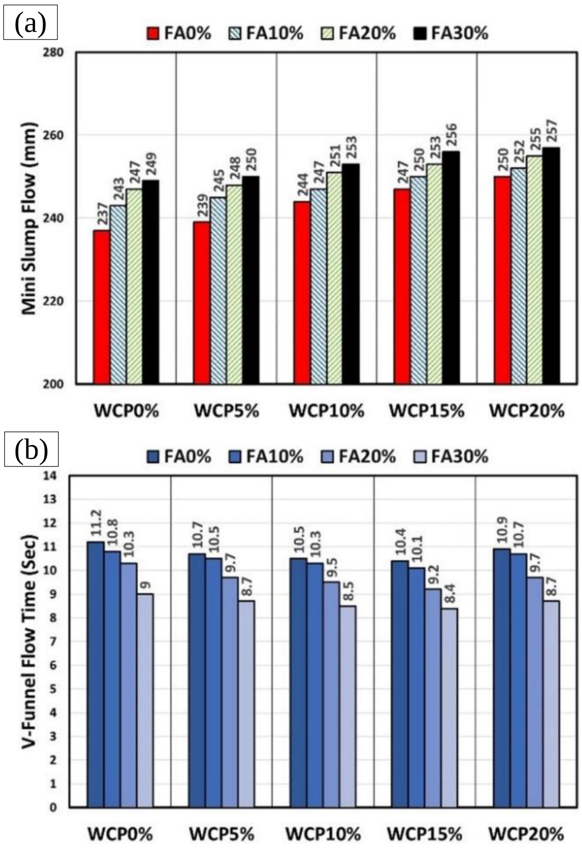

Figure 2. Effect of WCP and FA on (a) mini slump flow and (b) V-funnel flow time

3.2. Mechanical Properties

3.2.1. Compressive Strength

The SCM samples were subjected to compressive loading based on a universal test setup to evaluate their compressive strength at the ages of 3, 7, 28, and 90 days. Figure 3 presents the average values of the compressive strength of the SCM samples at different ages. Evaluation of the ratio of 28-day compressive strength to 90-day compressive strength (Maturing ratio, M) of the samples revealed that the compressive strength of the samples was notably enhanced at the age of 90 days, especially for the samples with low percentages of WCP and FA. Both control and FA30WC20 samples with the M ratio of 92 % and 65 % are characterized by the lowest and highest pozzolanic properties.

According to Figure 3, incorporation of both FA and WCP into the SCM mixtures caused a significant decrease in the compressive strength compared to the control sample at all curing ages. The reduction in the compressive strength might result from the relatively weaker cementitious properties of WCP and FA than those of the Portland cement [49,50]. Mixes containing FA as a partial replacement of OPC showed about 2 %, 21 %, and 31 %, lower 28-day compressive strength than those of the control mix at the FA replacement ratios of 10 %, 20 %, and 30 %, respectively. Utilization of WCP had the same effect on the compressive strength of mixes.

The 28-day compressive strength of mixes incorporating 5 %, 10 %, 15 %, and 20 % WCP was reduced by about 9 %, 16 %, 20 %, 28 % respectively, compared to the control mix. The combined use of FA and WCP further reduced the strength, and the reduction rates became greater upon increasing the FA and WCP contents. For example, blending 5 %, 10 %, 15 %, and 20 % WCP with 30 % FA reduced the 28-day compressive strength by approximately 34 %, 38 %, 45 %, and 49 %, respectively, compared to the control mix. The strength development of the mixes mainly depends on the physical characteristics, reactivity of the binder, and quality of ITZ, i.e., the critical factors for providing adequate physical anchorage and gel formation. FA particles with round edges are more spherical than the OPC, which can reduce the internal friction in the ITZ and lower the load-carrying capacity of mixes. On the contrary, FA has lower pozzolanic reactivity than the OPC which in turn decreases the amount of hydration products, thus reducing the mechanical strength [15,51]. Similarly, WCP particles are not as reactive as the OPC particles, and replacing OPC with the WCP negatively affects the formation of C-S-H gel which in turn makes the microstructure less compact [17,20]. In addition, the XRD results confirmed the presence of higher amount of alumina in the WCP and FA, compared to the OPC, which was already reported as one of the factors with a negative impact on the strength of the cement-based materials [52].

As further observed, incorporation of both FA and WCP had a detrimental effect on the strength development process. In the control mix, the compressive strength after 3, 7, and 90 days of curing was about 55 %, 87 %, and 108 % of the 28-day compressive strength, respectively. However, use of WCP and FA delayed the formation of hydration of products. The lowest strength gains at the ages of 3 and 7 days was recorded for FA30WC10 and FA30WC20 mixes, which was 39 % and 66 % of the corresponding value for the 28-day compressive strength, respectively. Moreover, the negative effects of both FA and WCP were more noticeable at the earlier ages, which could be attributed to their harmful effect on the hydration process. For instance, FA30WC20 mix had about 52 %, 61 %, 49 %, and 27 % lower compressive strength at the age of 3, 7, 28, and 90 days, respectively, than the control mix. As observed, the percentage reduction was higher at the earlier ages; however, with an increase in the curing age, it was considerably controlled. The immature pozzolanic reaction was completed at the later ages, which led to densification of the pore system. According to the results, the ratio of the 90-day to 28-day compressive strength was significantly higher in mixes containing both FA and WCP. As a case in point, the ratio for the FA30WC20 mix was 1.54, while the corresponding value for the control mix was 1.08.

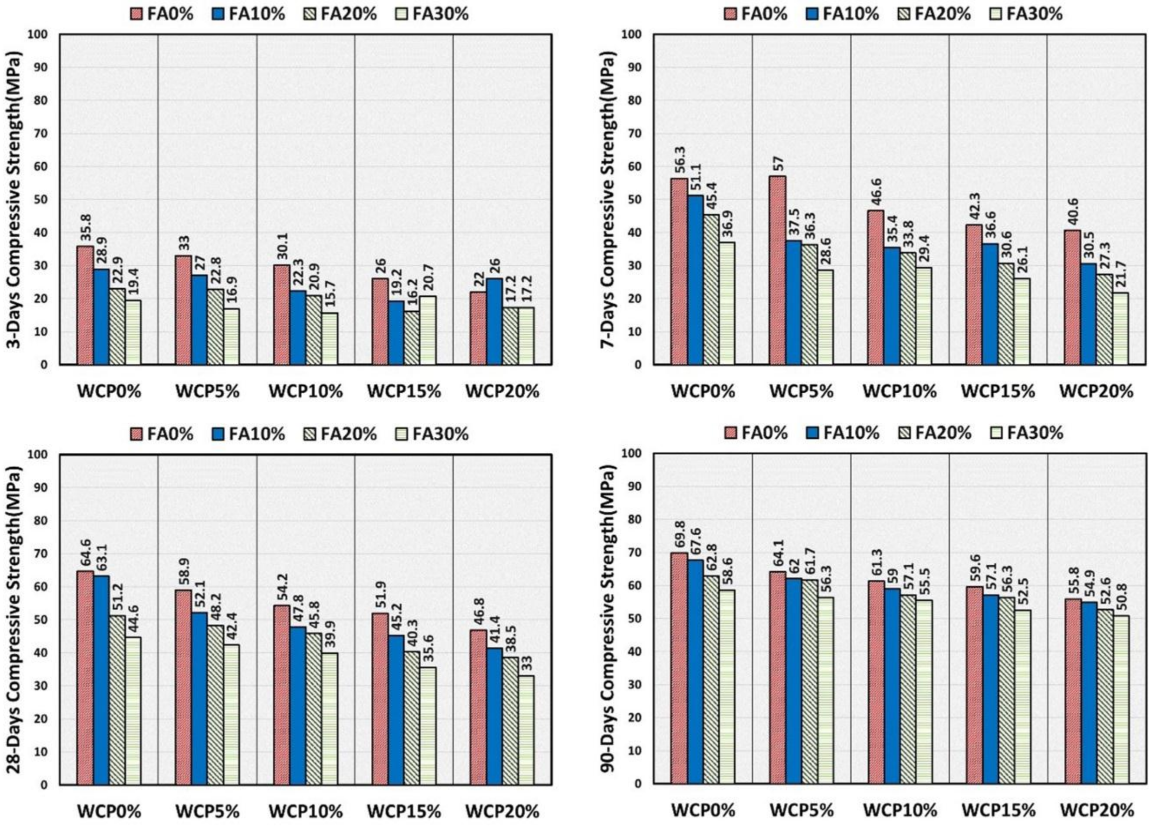

Figure 3. Compressive strength of SCM mixes at 3, 7, 28, and 90 days

The ratio was considerably lower in mixes made solely with either FA or WCP (1.31 in the FA30 mix and 1.19 in the WC20 mix), thus highlighting the remarkable impact of the combined use of these materials on the strength gain. It also indicated that the pozzolanic reaction of the supplementary materials added to the mixes proceeded at a faster rate after 28 days and that many unreacted particles participated in chemical reactions. In fact, the $Ca(OH)_2$ produced as a result of hydration of OPC was consumed by the high silica content available in the WCP and FA [20]. It produced additional gel, thereby contributing to the strength gain at later ages [17]. This conclusion was completely in agreement with the observations of previous researchers in the literature [9,17,20].

3.2.2. Flexural Strength

The flexural strength of the three identical beam specimens was determined for each mix through three-point loading flexural test, the average of which for different curing ages is presented in Figure 4. The obtained results supported those of the compressive strength, and similar trends were obseved for the flexural strength of mixes incorporating different percentages of FA and WCP. As shown in this figure, there was a reduction in the flexural strength at all curing ages with the inclusion of alternative pozzolanic materials. However, the reduction rates were much lower than the compressive strength rates, and maximum reduction was about 16 % in FA20WC20 mix after three days of curing. Use of FA or WCP alone did not have any significant impact on the flexural strength of the mixes. For instance, incorporating up to 30 % FA reduced the 28-day flexural strength by about 9 %, compared the control mix. The reduction ratio in the flexural strength of the binary mixtures contain different amounts of WCP in the range of 5-20 % were 0.9 to 9.7 %.

As already discovered, the flexural strength of the concrete samples with the WCP ratios of 10, 20, and 30 % was about 92.7, 87.9, and 85.4 % of that of the control samples [53]. The reason behind the inferior flexural performance of the mixes containing FA and WCP to that of the plain mix could be the dilution effect of cement replacement that lowered the amount of hydration products. In addition, the rounder morphology of both FA and WCP than that of OPC was another factor for the lower flexural strength of the mixed containing FA and WCP. As shown in the previous studies, FA was found to be effective in reducing the drying shrinkage of the concrete [34,54].

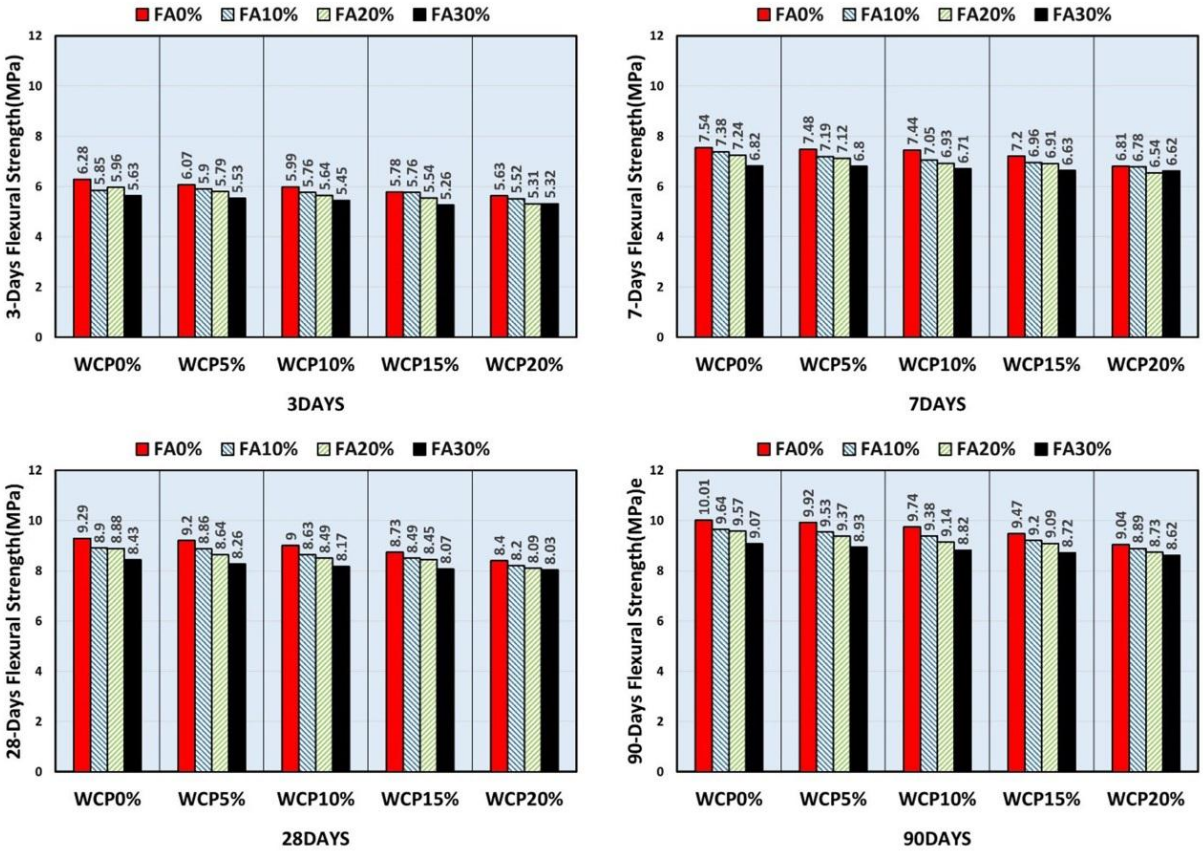

Figure 4. Flexural strength of the SCM mixes at 3, 7, 28, and 90 days

Therefore, it is expected that the number of micro-cracks induced by the drying shrinkage of mortar mixes will decrease while increasing the FA content, thus explaining the lower reduction rates in the flexural strength than those in the compressive strength. The flexural strength obtained by Ferrara et al. [55] in their study showed that the drying shrinkage strain of SCC mixes was reduced using 10 and 30 % WCP as the partial substitution for cement. Similarly, Duran-Herrera et al. [34] reported about 17 % reduction in the drying shrinkage of SCC containing 30 % FA. According to the previous studies, the samples containing FA have a flexural strength of 9.7 % lower than that of the control samples with the replacement ratio of 20 % in the SCM samples [50] and about 7-10 % lower than control concrete samples for replacement ratio of 5-20 % [56].

3.2.3. Linear Regression Analysis and Application of Design Codes for Prediction of Mechanical Strength

In this section, a linear regression model was employed to estimate the flexural strength of the concrete mixtures considering, compressive strength as the input data. Figure 5 shows the experimental data and fitted curve. As observed, the R-factor of regression was 0.88, which is indicative of the accuracy of the proposed model as well as the strong correlation between the compressive and flexural strength values of the mixes.

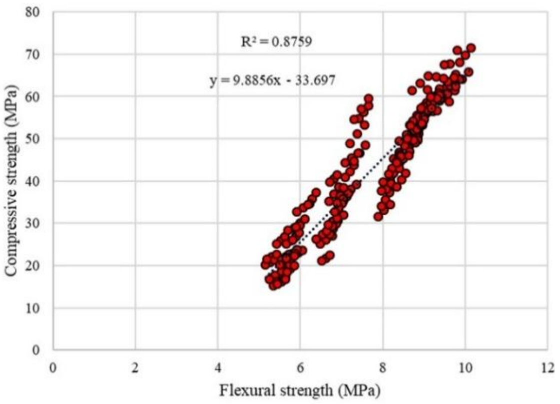

Figure 5. Linear regression model

$$f_c = 9.88f_b - 33.697 \quad (1)$$

The equations proposed by the available design codes were used to estimate the flexural strength of mixes by inserting the considered compressive strength as the input data. The proposed expressions are presented in Table 4. A comparison was made between the predicted values and those obtained from the flexural strength test. The comparison results were then used to determine the accuracy of the design code relationship in estimating the mechanical properties of SCC incorporating a blend of Portland cement, FA, and WCP.

TABLE 4. Equations proposed by codes

Standard	Flexural strength (f_r) (MPa)
ABA (Iran) [57]	$f_r = 0.60\sqrt{f'_c}$
ACI 318-14 [58]	$f_r = 0.62\sqrt{f'_c}$
CSAA23.3-04 [59]	$f_r = 0.60\sqrt{f'_c}$
EC-04 [60]	$f_r = 0.435 {f'_c}^{2/3}$
NZS 3101 [61]	$f_r = 0.60\sqrt{f'_c}$

The 28-day flexural strength of the mixes with different percentages of FA and WCP was evaluated based on the 28-day compressive strength.

Table 5 compares the predicted values with the flexural strength values obtained through the experiments. The results indicated that according to the design codes such as ABA, CSAA23.3-04, and NZS 3101, the average ratio of the flexural strength was approximately 0.48 with the standard deviation of 0.024.

In other words, the equations proposed by the previously mentioned design codes should be multiplied by 2.086 to predict the flexural strength of mixes with high accuracy. However, the equations proposed by ACI 318 and EC-04 should be multiplied by 2.019 ($\sigma = 0.025$) and 1.55 ($\sigma = 0.05$), respectively, to estimate the flexural strength of both mixes. Further, the accuracy of the linear regression equation proposed in the present study was reduced when using a combination of FA and WCP. The average ratio of the flexural strength predicted by the linear regression equation to the experimental flexural strength was about 0.96. However, the same ratio for the FA30WC20 mix was measured as 0.84, indicating that the equation underestimated the flexural strength at high replacement rates.

TABLE 5. Comparison test results with the values obtained by the design codes

Code/Mix	Test	Linear regression	ABA	ACI 318	CSAA23.3	EC-04	NZS 3101
Control	9.29	9.95	4.82	4.98	4.82	6.81	4.82
FA10	8.90	9.80	4.77	4.93	4.77	6.71	4.77
FA20	8.88	8.59	4.29	4.43	4.29	5.84	4.29
FA30	8.43	7.92	4.01	4.14	4.01	5.33	4.01
WC5	9.20	9.37	4.61	4.76	4.61	6.41	4.61
WC10	9.00	8.90	4.42	4.57	4.42	6.07	4.42
WC15	8.73	8.66	4.32	4.47	4.32	5.89	4.32
WC20	8.40	8.15	4.10	4.24	4.10	5.51	4.10
FA10WC5	8.86	8.69	4.33	4.48	4.33	5.91	4.33
FA20WC5	8.64	8.29	4.17	4.31	4.17	5.62	4.17
FA30WC5	8.26	7.71	3.91	4.04	3.91	5.16	3.91
FA10WC10	8.63	8.25	4.15	4.29	4.15	5.58	4.15
FA20WC10	8.49	8.05	4.06	4.20	4.06	5.43	4.06
FA30WC10	8.17	7.45	3.79	3.92	3.79	4.96	3.79
FA10WC15	8.49	7.98	4.03	4.17	4.03	5.38	4.03
FA20WC15	8.45	7.49	3.81	3.93	3.81	4.99	3.81
FA30WC15	8.07	7.02	3.58	3.70	3.58	4.60	3.58
FA10WC20	8.20	7.60	3.86	3.99	3.86	5.07	3.86
FA20WC20	8.09	7.30	3.72	3.85	3.72	4.84	3.72
FA30WC20	8.03	6.75	3.45	3.56	3.45	4.37	3.45

3.3. WATER ABSORPTION

Water absorption is a significant criterion for evaluation of the concrete durability and resistance to liquid penetration. Figure 6 presents the average water absorption values of the cube samples after 24 hours of immersion in water at the curing age of 28 and 90 days. Evidently, as observed in this figure, use of FA and WCP as the partial replacement materials of the OPC had a positive impact on the resistance of the SCM mixes to water penetration.

3.4. Electrical Resistivity

The electrical resistivity of the SCM mixes can elaborate the interconnectivity mechanism of the pores and quality of the ITZ. Higher electrical resistivity is indicative of the higher resistance of the material to the aggressive agents and ion transport within the matrix [62]. In this regard, the electrical resistivity of the SCM samples at the ages of 28 and 90 days were obtained through the ACIS method, as shown in Figure 7. According to this figure, the electrical resistivity of the

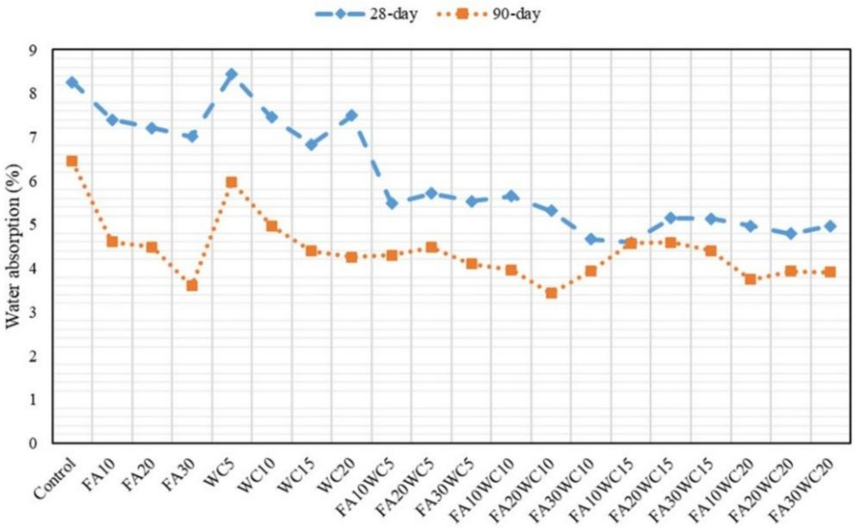

Figure 6. Water absorption of SCM mixes at 28 and 90 days

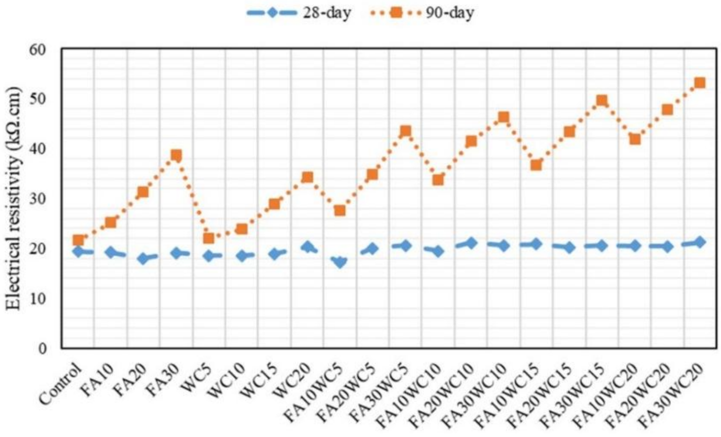

Figure 7. Electrical resistivity of SCM mixes at 28 and 90 days

SCM mixes increased upon increasing the amount of WCP and FA. This finding was in agreement with the already obtained results regarding the water absorption. Such an increase could result from the filling role of the used pozzolans in pore refinement.

In addition, such an increase can be attributed to the products that fill in the pores that are made through delayed reaction of pozzolans with the formed portlandite crystals. To be specific, C-S-H gel which is produced in the available pores densifies the mortar and consequently provides a more compact pore system [24] and lower ionic concentration [63].

The effect of pozzolan addition to the SCM mixes is more visible in the figures at the age of 90 days than at the age of 28 days. This finding is consistent with the results from the compressive strength where there was remarkable enhancement in the 90 day compressive strength, compared to the corresponding value at 28 days.

According to the test results, partial replacement of OPC with FA or WCP did not affect the electrical resistivity at 28 days, and the variations were below 10 %. On the contrary, the SCM mixes enjoyed greater degrees of electrical resistivity at 90 days than those at 28 days, indicating that the major contributions of FA and WCP particles to the chemical reactions begins after 28 days. Jain et al. [49] referred to the non-reactivity of FA at 28 days, which was responsible for the lower mechanical strength of the mix at this age. However, at later ages, the filling effect and formation of ettringite resulting from the pozzolanic reactions facilitated the microstructure densification. Duran-Herrera et al. [34] stated that partial replacement of the OPC with FA would decrease the concentration of Na^+ and K^+ ions in the pore solution which in turn reduced the ion transport, hence higher electrical resistivity.

The highest charges passing through the SCM samples in the FA30WC20 mix at the age of 28 and 90 days were estimated about 18.59 and 53.27 kΩ.cm for, respectively. In other words, use of 30 % FA in conjunction with 20 % WCP enhanced the electrical resistivity of the mortar by about 146 %, compared to that of the control mix, at 90 days. Kannan et al. [17] found that 40 % cement replacement by the WCP could increase the electrical resistivity up to about 616 % and 765 %, respectively, compared to control samples at the age of 28 and 90 days.

Behforouz et al. [9] also stated that the concrete samples with 50 % WCP content had an electrical resistivity of about 3.7, 3.3, and 4 times higher than that of the control samples at the water-to-binder ratios of 0.3, 0.4, and 0.5, respectively.

Evaluation of the electrical resistivity results provided a tool for assessing the durability of the mixes. A higher electrical resistivity is indicative of a higher density and better durability of the hardened mixture. Fewer pores in the samples make them highly resistant to harmful ions penetration. Many researchers confirmed that cloride ions could penetrate into the inner parts of the concrete elements through the micropores [64,65]. According to the electrical resistivity results, the corrosion potential of the embedded steel rebars in the concrete due to Cl^- ions can be evaluated [66]. It is worth noting that incorporation of aluminum ions into the composition of pozzolanic concretes is the another important reason for their higher durability than that of their ordinary counterpart subject to chloride ions [67]. Of note, the electrical resistivity test did not take into consideration the aforementioned issue.

As already proved in the literature, the corrosion possibility of the steel rebars is relatively low when the electrical resistivity of the samples is higher than 20 kΩ.cm [68]. The electrical resistivity of the SCM mixes in this research exceeded 20 kΩ.cm. Therefore, the corrosion rate in the samples exposed to chloride ions might be low in this project. As previously shown [17], the electrical resistivity of the samples containing WCP increased upon increasing the WCP content even up to higher amounts.

It should be noted that the slight reduction in the compressive strength was less significant than other issues such as improving the durability of the cementitious samples, reusing waste materials, and reducing the cement consumption.

The total amount of water absorbed by the pores in the SCM samples decreased upon increasing the ratios of pozzolans incorporated in the mortar. The lower the rate of the absorbed water in the pores of the samples, the higher resistance of the mortar exposed to penetration of water solute ions into the samples.

Based on the test results, the SCM mixes prepared with 10-30 % FA showed about 10-15 % and 29-44 % lower water absorption rate than the control mix at the age of 28 and 90 days, respectively. Partial replacement of OPC with WCP had similar effects on the water absorption of mixes. Here, use of 20 % WCP led to up to 9 % and 34 % reduction in the 28- and 90-day water absorption rates, respectively, compared to those in the control mix. Of note, there was a considerable difference between the diagrams of the control and pozzolan-included samples. On the contrary, there was a small difference between the water absorption of mixes made with different contents of pozzolans. In other words, incorporation of pozzolan into the mixture even with a low percentage could significantly decrease the water absorption of SCM mixes; however, further increase in the pozzolan content did not considerably change the water absorption value. As expected, lower water absorption values were obtained when FA and WCP were blended with OPC. As discussed earlier, both FA and WCP were finer than the OPC; therefore, when cement was replaced with FA and WCP, the porosity of the mixes decreased. The finer particles of the FA and WCP could fill the pores and gaps, thereby blocking the permeability channels and reducing the water intake [20,49]. An interesting finding here is that the decrease in the water absorption is contrary to the reduction in the mechanical strength of mixes, indicating that FA and WCP act more as a filler rather than a pozzolanic material. This finding can be approved by the observations of Kannan et al. [17] who showed that WCP could reduce the degree of water absorption; however, the compressive strength was reduced by introducing WCP content into the mix. Similar reports were made by Heidari and Tavakoli [48]. Previous studies highlighted that inclusion of FA also enhanced the concrete durability. Abdalhmid et al. [69] observed that the water absorption of the SCC mixes containing FA constantly decreased upon increasing the FA content. They also stated that the higher workability of the mixes due to FA introduction led to better compaction, which consequently reduced the void content as well as the water absorbed by the specimens. This finding was in agreement with those of the present research since the incorporation of FA increased the flowability of the mixes. It should be noted that both FA and WCP could mitigate the drying shrinkage, one of the critical factors in the micro-cracking of mixes [69,70]. Rafieizonooz et al. [51] observed that the drying shrinkage of the concrete mixes could be effectively controlled by incorporating 20 % FA. With less micro-cracking in the mortar, the possibility of the contraction of the paste would also decrease, and the adhesion between the aggregate and paste would be maintained which in turn improved the quality of the ITZ [54]. The reduction in the water absorption in specimens containing both WCP [9,20] and FA [15] was also reported by other researchers. For instance, Heidari and Tavakoli [20] indicated that partial replacement of OPC with 20 % WCP reduced the water absorption rate by 13.5 % of the corresponding value in the control sample. Jalal et al. [15] showed that cement replacement by FA could reduce the water absorption by 33.8 and 40 % of the those in the control samples for binder content of 400 and 500 kg/m^3, respectively.

In order to verify the obtained results, SEM analysis was carried out on samples taken from the control mix and mix FA30WC20. Figures 8(a) and (b) demonstrate the SEM images for the control specimen and sample containing 30 % FA and 20 % WCP at the age of 90 days. The Portlandite (calcium hydroxide, $Ca(OH)_2$, CH) crystals are detected in these images in the form of hexagonal plates and calcium silicate hydrate (C-S-H) gel that are identified, which surrounds aggregates and crystalline parts [9].

As indicated in Figure 8(a), the size of CH crystals is about 2 μm in the control sample. There are some micro-cracks in the control specimen, as shown in Figure 8(a). Denser microstructure in the samples containing pozzolan is clearly visible in Figure 8(b). Fewer pores and cracks, smaller or less portlandite crystals, and more C-S-H gels could be found in the microstructure images of the mortar samples containing FA and WCP (Figure 8(b)). As mentioned in the previous sections, the differences between the microstructure of the samples containing pozzolan and plain mortar are due to the delayed pozzolanic reaction, which consumes the CH crystals and produce C-S-H products [49]. Evidently, incorporation of either FA or WCP significantly reduced the number of micro-cracks by filling the micro pores. This finding mechanism was in agreement with the observations of Jain et al. [60] and Li et al. [71]. Generally, use of pozzolans would improve the microstructural properties of the mortar and provide better durability for the samples. This conclusion was previously drawn in the assessment of water absorption and electrical resistivity.

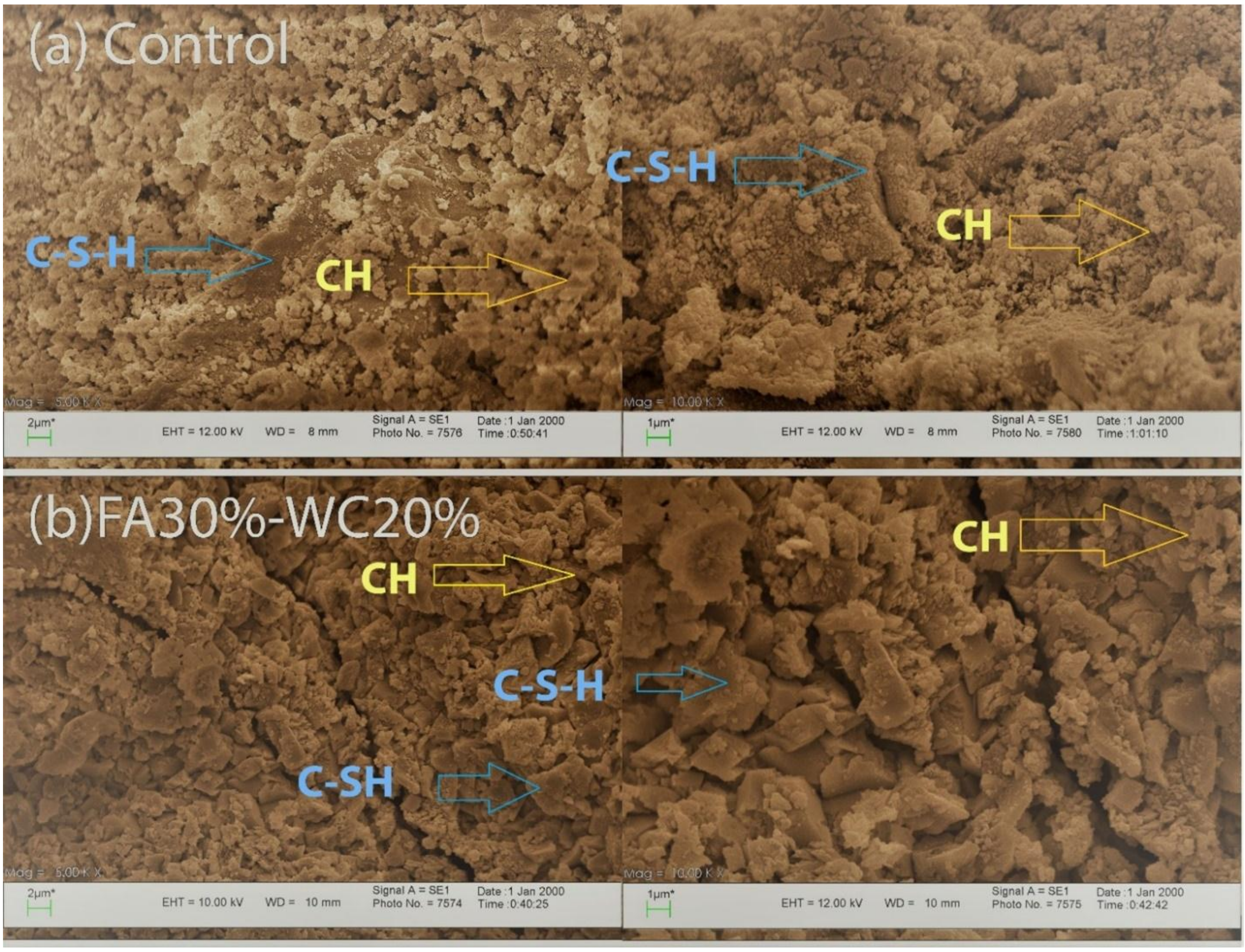

Figure 8. SEM micrograph of SCM (a) Control mix and (b) FA30WC20

3.5. Environmental Analysis

This section compares the environmental impact of the SCM mixes containing different percentages of FA and WCP from the carbon footprint and energy consumption points of view. Contribution of each material to the total ECO_2e and EE of mixes was evaluated based on the factors presented in Table 3. Table 6 presents the total carbon dioxide emission and energy consumed by each mortar calculated by adding up the contribution of each component. In addition, Figure 9(a) and (b) show the share of each material in the ECO_2e and EE of the mixes, respectively. Based on the environmental analysis results, the application of the pozzolans in this study could effectively mitigate the environmental repercussions of the SCM mixes. For example, incorporating 30 % FA reduced the carbon dioxide emissions and EE by about 28 % and 19 %, respectively. Similarly, 18 % and 10 % reduction in the amounts of ECO_2e and EE, respectively, was observed in the mixes containing WCP, while using 20 % WCP as the partial replacement of cement. As expected, the environmental impact of the ternary blended mixes was lower than the binary blended mixes. The ECO_2e and EE of the mix prepared with 30 % FA, 20 % WCP, and 50 % OPC were about 47 % and 29 %, respectively, lower than those of the control mix, indicating that by reducing the OPC content by 50 %, the carbon footprint of the mix would also be approximately halved. Figures 9(a) and (b) show the share of each component to the total ECO_2e and EE of mixes, respectively. As observed, the largest share in all mixes belonged to the OPC, contributing 95 % and 65 % to the ECO_2e and EE, respectively. The second contributing parameter to the energy demand was the curing water, which was calculated in a 5 m×5 m×0.2 m water tank.

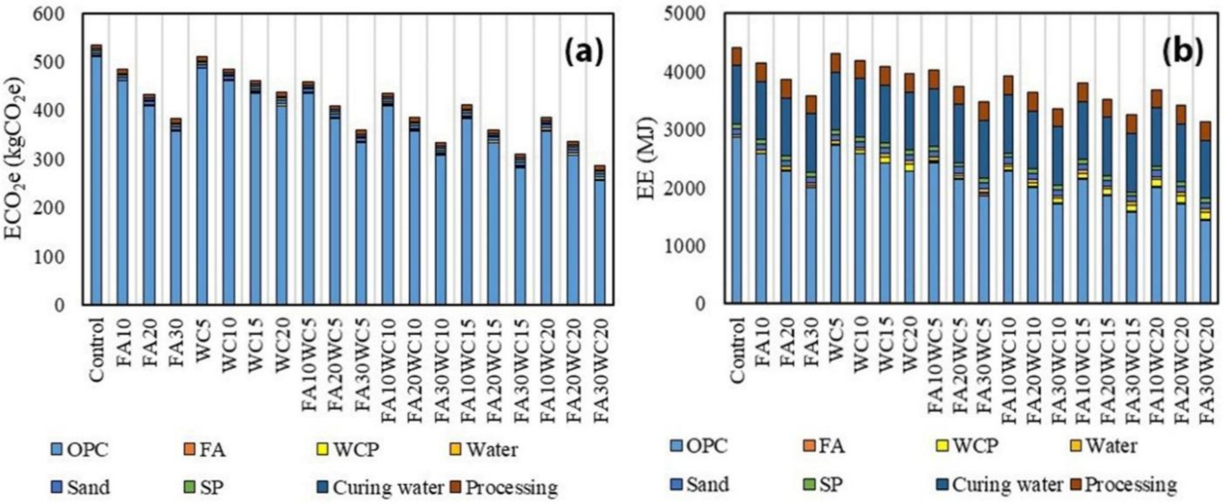

Figure 9. (a) ECO_2e and (b) EE of SCM mixes with different FA and WCP contents

TABLE 6. ECO_2e and EE of mixes

Mix	ECO_2e ($kgCO_2e$)	EE (MJ)
Control	534.2	4408.9
FA10	483.7	4132.4
FA20	433.3	3855.9
FA30	382.8	3579.4
WC5	509.9	4296.5
WC10	485.6	4184.1
WC15	461.2	4071.7
WC20	436.9	3959.3
FA10WC5	459.4	4020.0
FA20WC5	408.9	3743.5
FA30WC5	358.4	3467.0
FA10WC10	435.1	3907.6
FA20WC10	384.6	3631.1
FA30WC10	334.1	3354.6
FA10WC15	410.7	3795.2
FA20WC15	360.2	3518.7
FA30WC15	309.8	3242.2
FA10WC20	386.4	3682.8
FA20WC20	335.9	3406.3
FA30WC20	285.4	3129.8

The environmental impact assessment can also be evaluated considering the eco-strength efficiency of concrete mixes (Figure 10). This index was obtained in this research by dividing the 90-day compressive strength by the amount of carbon dioxide released in one cubic meter. According to Figure 10, upon increasing the amount of waste tiles and FA at the same time, this amount would significantly increase. This result recommends consideration of this percentage to reduce the amount of produced carbon dioxide.

3.6. ANOVA

ANOVA analysis was carried out on the experimental results to determine the contribution of each variable to the selected properties at different curing ages. Table 7 shows the analysis results for the compressive strength of mixes at different curing ages. As seen in the table, the P-value for all variables was less than 0.05, meaning that all variables had significant contributions to the results. Interestingly, the contributions of FA, WCP, and their interaction varied at different curing ages. At the age of three days, FA had the highest contribution to the compressive strength, the interaction between FA and

WCP comes next, and the WCP content has the least contribution. To be specific, it can be concluded that the FA could patriciate in the chemical reactions more quickly than the WCP at such an early age owing to its higher silica content [46]. As the curing time increased, the contribution of the WCP followed an increasing trend as well. For example, the contribution of WCP to the compressive strength at 7 and 28 days increased up to 37.4 % and 43.4 %, respectively. Meanwhile, the contribution value of the FA remained higher than 50 %, thus highlighting its major impact on the strength development in the SCM mixes. On the contrary, at 90 days, the FA and WCP contribution rates were measured as 68.6 % and 25.6 %, respectively. This finding confirmed the results of the compressive strength where the 90-day compressive strength of the mix containing 30 % FA was about 31 % higher than that of the control mix while the corresponding gain for the mix containing 20 % WCP was about 19 %. Therefore, it can be concluded that the pozzolanic reaction of FA was more productive than that of the WCP between the 28th and 90th days of curing.

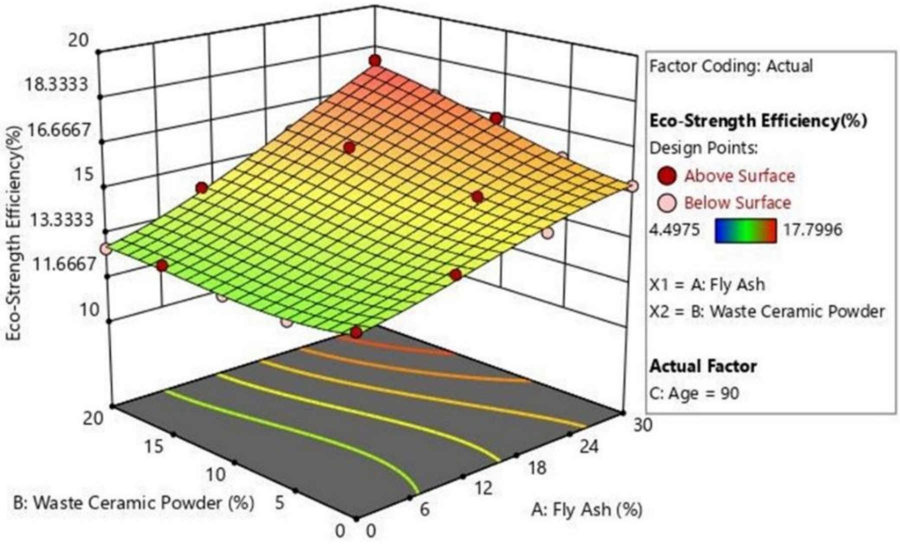

Figure 10. Eco-Strength Efficiency of concrete specimens at 90-days compressive strength

TABLE 7. ANOVA results of compressive strength of SCM mixes at different curing ages

Age	Property	SS	df	MS	F	P-value	F crit	Contribution
3 days	WCP	313.7	4	78.4	106.2	9.5E-21	2.61	17.1 %
	FA	1111.8	3	370.6	502.1	9.2E-32	2.84	60.4 %
	Interaction	384.7	12	32.1	43.4	4.3E-19	2.00	20.9 %
	Error	29.5	40	0.7				1.6 %
7 days	WCP	2097.4	4	524.3	281.3	1.1E-28	2.61	37.4 %
	FA	3169.9	3	1056.6	566.8	8.6E-33	2.84	56.5 %
	Interaction	268.6	12	22.4	12.0	9.2E-10	2.00	4.8 %
	Error	74.6	40	1.9				1.3 %
28 days	WCP	1852.0	4	463.0	170.5	1.5E-24	2.6	43.4 %
	FA	2157.5	3	719.2	264.8	2.1E-26	2.8	50.5 %
	Interaction	153.5	12	12.8	4.7	9.7E-05	2.0	3.6 %
	Error	108.7	40	2.7				2.5 %
90 days	WCP	1012.9	4	253.2	61.5	1.5E-16	2.6	25.6 %
	FA	2718.4	3	906.1	220.2	6.8E-25	2.8	68.6 %
	Interaction	65.3	12	5.4	1.3	2.4E-01	2.0	1.6 %
	Error	164.6	40	4.1				4.2 %

However, the ANOVA results for the flexural strength of mixes was, to some extent, different from those of the compressive strength. The analysis results presented in Table 8 showed that the contributions of FA and WCP did not change over time and remained relatively constant at about 38 % and 45 %, respectively. However, in agreement with the ANOVA results for the compressive strength, there was an obvious increase in the contribution of FA at the age of 90 days, which can be justified by the reactivity of FA at later ages, as discussed earlier. The ANOVA analysis was also carried out on the durability-related properties investigated in the present research, i.e., the electrical resistivity and water absorption, at 28 and 90 days.

Table 9 and Table 10 present the results regarding the electrical resistivity and water absorption, respectively. Similar to the results of the mechanical properties, it was found that FA had the highest impact on the results, and the interaction between FA and WCP was more significant at 28 days than that at the later ages. Consistent with the results regarding the compressive and flexural strengths, the FA contributions to electrical resistivity and water absorption increased from 19.6 % and 43.8 % (at 28 days) to 65.1 % and 55.8 %, respectively, at 90 days.

TABLE 8. ANOVA results of flexural strength of SCM mixes at different curing ages

Age	Property	SS	df	MS	F	P-value	F crit	Contribution (%)
3 days	WCP	1.76	4	0.44	36.81	6.6E-13	2.61	38.4 %
	FA	2.07	3	0.69	57.56	1.4E-14	2.84	45.1 %
	Interaction	0.28	12	0.02	1.93	5.9E-02	2.00	6.1 %
	Error	0.48	40	0.01				10.4 %
7 days	WCP	2.24	4	0.56	37.21	5.5E-13	2.61	37.9 %
	FA	2.64	3	0.88	58.60	1.1E-14	2.84	44.8 %
	Interaction	0.42	12	0.03	2.32	2.3E-02	2.00	7.1 %
	Error	0.60	40	0.02				10.2 %
28 days	WCP	3.51	4	0.88	33.08	3.3E-12	2.61	38.7 %
	FA	4.12	3	1.37	51.71	7.9E-14	2.84	45.4 %
	Interaction	0.38	12	0.03	1.21	3.1E-01	2.00	4.2 %
	Error	1.06	40	0.03				11.7 %
90 days	WCP	3.89	4	0.97	35.01	1.4E-12	2.61	23.2 %
	FA	11.39	3	3.80	136.69	4.6E-21	2.84	68.0 %
	Interaction	0.37	12	0.03	1.11	3.8E-01	2.00	2.2 %
	Error	1.11	40	0.03				6.6 %

TABLE 9. ANOVA results of electrical resistivity of SCM mixes at different curing ages

Age	Property	SS	df	MS	F	P-value	F crit	Contribution (%)
28 days	WCP	24.53	4	6.13	52.05	2.5E-15	2.61	33.5 %
	FA	14.33	3	4.78	40.55	3.3E-12	2.84	19.6 %
	Interaction	29.59	12	2.47	20.93	1.5E-13	2.00	40.4 %
	Error	4.71	40	0.12				6.4 %
90 days	WCP	1730.66	4	432.67	704.81	1.7E-36	2.61	33.1 %
	FA	3407.16	3	1135.72	1850.08	6.3E-43	2.84	65.1 %
	Interaction	73.74	12	6.15	10.01	1.2E-08	2.00	1.4 %
	Error	24.56	40	0.61				0.5 %

TABLE 10. ANOVA results of water absorption of SCM mixes at different curing ages

Age	Property	SS	df	MS	F	P-value	F crit	Contribution (%)
28 days	WCP	6.60	4	1.65	237.09	2.8E-27	2.61	21.5 %
	FA	13.42	3	4.47	642.77	7.3E-34	2.84	43.8 %
	Interaction	10.35	12	0.86	124.01	1.1E-27	2.00	33.8 %
	Error	0.28	40	0.01				0.9 %
90 days	WCP	33.20	4	8.30	539.20	3.3E-34	2.61	36.2 %
	FA	51.10	3	17.03	1106.55	1.7E-38	2.84	55.8 %
	Interaction	6.67	12	0.56	36.12	1.2E-17	2.00	7.3 %
	Error	0.62	40	0.02				0.7 %

4. CONCLUSIONS

The present research experimentally investigated the rheological, durability, mechanical, and environmental properties of ternary Self-Consolidating Mortars (SCMs). The mix proportions were taken into consideration to evaluate the effects of different mass ratios of WCP and FA on the workability, compressive and flexural strength, water absorption, electrical resistivity, and environmental footprint of SCM samples at different ages. Previous studies have evaluated the effects of both WCP or FA on the performance of SCC mixes; however, no comprehensive study has been conducted on the combined use of these materials. In this regard, the current research aimed to bridge this knowledge gap. Based on the test results, the following conclusions were drawn:

1. Incorporation of FA and WCP into the mixes had a positive impact on the workability of the fresh mortar mixes, which can be attributed to the more spherical shapes of FA and WCP than that of the OPC.
2. The compressive strength of the SCM mixes decreases with incorporation of FA and WCP. Such reduction was more obvious at earlier ages, which can be attributed to the retarding effect of both FA and WCP. The combined use of 20 % WCP and 30 % FA reduced the 28-day compressive strength by about 50 %; however, this value at the 90th was about 27 %, indicating the strength gain resulting from the pozzolanic reaction of both FA and WCP at later ages.
3. Partial replacement of the OPC with FA and WCP had the same effect on the flexural strength of mixes; however, the reduction in the flexural strength was much lower than that in the compressive strength. Followed by substituting 50 % of OPC with FA and WCP (mass ratio of 30:20), the flexural strength decreased by about 15 %, compared to that in the control mix.
4. The the durability-related properties were considerably enhanced by partially replacing OPC with FA and WCP, mainly due to the filling effect of FA and WCP owing to their higher specific surface area than OPC, which densifies the microstructure.
5. The water absorption value was reduced by about 40 % in the mix containing 20 % WCP and 30 % FA, compared to that in the control mix. Similarly, mixes containing pozzolanic materials were characterized by higher electrical resistivity (up to 144 % at 90 days) than the control mix, indicating improvement in interconnectivity of pores. The compact ITZ of the mixes containing pozzolan was verified by SEM examination.
6. Reduction in the mechanical strength and increase in the durability properties of the SCM mixes containing FA and WCP confirmed that these materials acted more as a filler rather than a reactive pozzolan in the OPC-based mixes.
7. The amounts of the embodied CO_2 emitted and EE of WCP and FA were much lower than that of the OPC. The application of WCP and FA as the partial replacement materials of OPC reduced the carbon footprint and energy consumption of SCM mixes by up to 47 % and 29 %, respectively.
8. In summary, ternary blends of FA, WCP, and OPC in self-compacting mixes considerably enhanced their workability and resistance to penetration of harmful substances and significantly reduced the environmental footprint. Such benefits come at a price of lower mechanical strength, which can be compensated by application of several common techniques such as fiber reinforcement or addition of nano-materials.

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