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PERFORMANCE OF ALKALI- ACTIVATED HYBRID CEMENT MORTAR INCORPORATING FLY ASH AND CONCRETE WASTE POWDER

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ABSTRACT

This paper explores the performance of alkali-activated hybrid cement mortars, which use fly ash (FA) and recycled concrete waste powder (CWP) as partial substitutes for ordinary Portland cement (OPC). Mortars were mixed with the ratio of water to binder of 0.45 and binder to sand of 1:2.75, and sodium silicate (Ms = 1.5) was used as an alkaline activator. Flowability, compressive and flexural strength, porosity, water absorption, and microstructure (SEM) were tested. This led to a finding that alkali activation had a major impact on mechanical and durability properties. But contrary to the anticipated constant increase in strength, mix F5P5 (50 FA + 50 OPC) demonstrated a decline in compressive strength during 7 to 28 days, which suggests slower strength development or even a decrease, although it had a lower porosity and water absorption than the reference mortar that had not been activated. Incorporation of CWP resulted in reduced strength and higher porosity and absorption at 7 and 28 days. This is explained by the fact that CWP is less reactive, is high in $CaCO_3$, and is prone to forming micro-voids and particles that are not reactive in the matrix. SEM analyses confirmed that activated mixes formed denser gels, while CWP-containing mixes exhibited discontinuous gel phases and weak interfacial zones, which negatively affected long-term durability.

Keywords: Fly ash (FA), Cement (OPC), Concrete Waste Powder (CWP).

INTRODUCTION

Concrete is the second most utilized material on earth, just after water, and it comprises about 20% Portland cement (PC). The production of one ton of PC generates roughly one ton of carbon dioxide (CO_2) emissions into the environment (Davidovits, 1991). As a result, researchers continue to explore more sustainable and eco-friendly construction materials that can reduce energy use and lessen environmental impacts. Geopolymers emerge as an innovative binder with the probable to replace Portland cement in concrete applications (Ababneh et al., 2020). Geopolymers are synthetic alkali aluminosilicate

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materials formed during the reaction of aluminosilicate substances with aqueous alkaline solutions, for example sodium hydroxide or silicate solutions (Davidovits, 2008). Geopolymer concrete (GPC) is an innovative, sustainable, and eco-friendly binding agent derived from geological raw materials or by-products containing aluminosilicates, such as calcined kaolin clay (CKC), fly ash , red mud, and ground granulated blast furnace slag (GGBFS), which entirely substitute cement in concrete (Kumar, 2015).

Geopolymer cement is an amorphous material made up of molecular units (monomers) that are interconnected by covalent bonds. It is regarded as an innovative material with unique properties (Y.-M. LIEW, C.-Y. Heah and H. kamarudin 2016). There are two main categories of aluminosilicate materials used in geopolymer cement production: commercial by-products like blast furnace slag and fly ash , and rock-based minerals for example kaolin and metakaolin. Recycling these materials to be used in construction may reduce disposal costs and cut down expenses incurred in concrete making. Davidovits invented the name "geopolymer," where the prefix "geo" means an inorganic aluminosilicate of geological origin, which interacts to form a binder through polycondensation using an alkaline solution. Al-Jaberi et al. (2023) investigated the development of geopolymer reactive powder concrete by examining the influence of various mix ratios on its mechanical and durability performance.The experiment based on the impact of fly ash to pozzolanic material ratio, sand to pozzolanic material ratio, finer sand to coarse aggregate ratio as well as alkaline solution to pozzolanic material ratio. The results showed that the compressive strength rose to 70.01 megapascals when the ratio of the alkaline solution and the degree of binder rose to 100 percent compared to 62.28 megapascals when the alkaline to binder ratio was 62.5 percent. Furthermore, there was an increase in the workability of the mixture of 15 to 17.3 mm under the same conditions. The paper has decided that a balance between alkaline activator and binder materials is key to enhancing the strength and the workability of concrete and geopolymer reactive powder concrete has a potential to be a sustainable and high-performance construction material. Gao et al. (2024) examined how the main parameters such as Si/Al ratio and curing time affected the geopolymerization reaction, and flexural strength was examined with the help of SEM, FTIR, peak deconvolution, and XRD. The microstructure of geopolymers was transformed to be not stacked smooth particles of kaolinite but a 3D network porous structure that was similar to sodalite. The geopolymer architecture that is related to the attachment of sodium aluminum silicate hydrate (N-A-S-H) had attained a range of special properties at 973 cm -1. The space below this spectrum is a total value to indicate the degree of the geopolymerization reaction. Moreover, reaction degree was also controlled by changing ratio of Si/ Al and curing time with maximum degree of reaction 55 percent reached at Si/ Al 1.94 after a week of curing. The relationship between flexural strength and the degree of response was obtained as linear, which provided flexural strength values of 21.11 MPa and a degree of response of 45 percent. The article sheds some light on the formation of mechanical strength based on the manipulation of the reaction process. Lvi et al. (2024) developed a high-strength geopolymer cementitious material by curing a water-bath geopolymer at 90°C with varying proportions of YRS additive. Through the XRD, SEM, and FT-IR analyses, the paper assessed the impact of YRS on the setting time, workability, compressive strength, porosity, and permeability of the dense and porous geopolymer concretes and their microstructure and environmental behavior. The findings showed that YRS was a potential retarder and increased the setting time by more than 150 percent and enhanced the compressive strength at an early age to 86.7 MPa after three days of curing. The compressive strength of the porous geopolymer concrete obtained was 28.1 MPa after 28 days. Although the strength was improved, the influence of YRS and curing conditions on porosity was negligible, and permeability was marginally influenced. Moreover, porous geopolymer exhibited high adsorption capacity with regard to heavy metals and slow pH neutrality, suggesting that it could find application in long-term constructions and remediation of the environment. Razak et al. (2020) conducted an assessment on the effect of porosity and water absorption on the globe strength of fly ash-based geopolymer and Ordinary Portland Cement (OPC) paste. The porosity tests were performed using the Brunauer, Emmett, and Teller method, in which a synthesis of the graph of nitrogen probe adsorption/desorption was prepared. Water absorption and compressive strength were measured after 7 and 28 days of curing, respectively. As the results display, the fly ash geopolymer paste contains less surface area, volume density of pores, and size of pores as compared to the ordinary Portland cement paste geopolymer. The microscopic pores of the geopolymers containing fly ash were composed of high proportions of micropores in comparison to the mesopores in the paste pores of Ordinary Portland Cement. When the pore size is smaller and the water absorption is lower, the compressive strength of a fly ash-based geopolymer can reach 76.723 MPa after 28 days. As a result, the paste made from geopolymeric components is more durable and resistant to harsh environments than ordinary Portland cement paste. Muhsin & Fawzi (2021) prepared special reactive powder concrete through 800 kg per m³ cementitious content, a 0.275 water-to-binder ratio, and micro steel fibers at 1% volume of the concrete. Other research studies in the experimental program involved replacing fly ash with a weight of cement (8, 12, or 16 percent) in order to determine the optimum ratio to provide maximum mechanical characteristics of RPC at 7, 28, and 90 days under usual curing conditions. It has been corroborated that some of the mechanical characteristics of responsive powder concrete have been verified. At 28 days, the findings increased to give the compressive strength (96.5 MPa), tensile strength (9.38 MPa), and density (2395 kg/m³). Through the results, the optimum proportion level was obtained to be 8 percent in situation of pure fly ash, as well as with 5 and 10 percent replacement of fly ash with cement, which attained the greatest resistance among the others. The findings also showed that RPC may be developed by utilizing fly ash that has great withstand stress, tensile strength, and density. Nasr et al. (2022) investigated the effect of the partial substitution of cement with a blend of silica fume (SF) and fly ash (FA) on the mechanical and physical properties of reactive powder concrete (RPC). In the study, mixtures with different proportions of SF and FA, along with a reference mix, were used to estimate the essential parameters, including flow ability, compressive and flexural strength, ultrasonic pulse velocity (UPV), and density. Findings indicated that the replacement of 10 percent silica fume and 40 percent fly ash with cement resulted in a sustainable RPC that has enhanced workability and compressive strength, albeit at the expense of other performance measures by a small percentage. The results proved that the use of these additional materials may minimize the use of cement and increase the durability of concrete. The paper also indicated the eco-benefit of geopolymer-based materials that emit 0.15-0.20 tons of CO_2/ton of material produced is much lower than the 1 ton of CO_2 emitted by a typical Portland cement, indicating their potential in substituting regular Portland cement as an environmentally friendly material.

The proposed research is designed to evaluate the effect of cement mortars using fly ash and waste powder of concrete as a sustainable replacement for conventional construction materials. The main aim is to examine the impact of activating such secondary materials, especially with the addition of fly ash at optimal proportions of 50% of the binder content, on the key performance indicators: the water absorption, compressive strength, flexural strength, and corrosion resistance, which are critical in determining the behavior of such under adverse environmental conditions. The strategy encourages the adoption of sustainable materials and minimizes the use of high-carbon Portland cement. Moreover, the research promotes the transition of sustainable construction strategies that increase the mechanical performance in the long term and reduce the environmental impact of the waste in concrete.

EXPERIMENTAL WORK

MATERIAL

The materials that were utilized in this research were ordinary Portland cement with brand Almas following the Iraqi standard (IQS-No. 5)/2019, the fly ash type F obtained from Eurobuild and examined according to ASTM C618 criteria, liquid sodium silicate (SS) with alkali modulus ($Ms = SiO_2/Na_2O$) equal to 3.3, with silicon dioxide (SiO_2) content of 43.25%, and sodium oxide (Na_2O) content of 13.1%. The silicates contain a certain amount of solids, and their alkalinity was adjusted to 1.5 by addition 99% pure sodium hydroxide (NaOH) flakes to the silicate solution to adjust the total alkalinity within the desired range for alkaline polymerization. The activator was used in 10% (as solid content) of the binder. The chemical and physical characteristics of the binders are revealed in Table 1. Moreover, aluminum foil was used in small amounts to increase solvent and reactivity of fly ash. Recycled concrete waste powder obtained from different types of demolished cube waste was ground into fine materials that were completely mixed well and passed through a 600-micron sieve and used as a partial replacement for binder, as shown in the mix details presented in Table 2 and Figure 1. The water/binder ratio was 0.45 for very mortars, whereas binder/sand ratio was 1:2.75.

Table 1. The specific gravity and chemical composition of cement and fly ash.

Chemical Composition (%)	**Cement**	**Fly Ash**	**IQS No.5 (Cement)**	**ASTM C618 (Fly Ash)**
SiO_2	20.9	48.15	-	-
Al_2O_3	6.2	18.868	-	-
Fe_2O_3	3.1	4.538	-	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	-	-	≥ 70%
SO_3	1.75	1.532	≤ 2.5–3.0%	≤ 5%
CaO	62.3	14.52	-	-
MgO	2.7	2.477	≤ 5%	-
Loss on Ignition (L.O.I)	3.3	6.0	≤ 4%	≤ 6%
Specific Gravity	3.15	2.320	-	-

Fig. 1. Some materials that used in this study (a) OPC; (b) Fly Ash; (c) Concrete Waste Powder (CWP); (d) sodium silicate (activator solution).

MIX PROPORTIONS

The alkaline solution utilized in this research was prepared by mixing sodium silicate liquid with sodium hydroxide to adjust the alkali modulus (Ms = SiO_2/Na_2O) from 3.3 to 1.5, followed by adding mixing water and aluminum foil. The components were thoroughly stirred for 10–15 minutes using a continuous mixer under constant heating at 90°C, then left to rest for 24 hours before mortar casting to ensure a homogeneous alkaline activator. The dry ingredients (cement, sand, and recycled concrete waste powder) were first dry-mixed for 3 minutes using an 8-liter batch mixer. Separately, fly ash was blended with the prepared alkaline solution and varied for 3 minutes to ensure uniformity.

This mix was then combined with the dry ingredients and mixed for at least 5 minutes to form the cement mortar. Fresh properties were then experimented on. With hardened properties, the molds were washed and oiled, and the mortar was cast and pressed by hand with a vibrating table according to ASTM C109 (C109/109M-16a, 2016) for compressive strength and ASTM C348 (1998) for flexural strength. The specimens were then covered with nylon sheets after casting to avoid the loss of moisture (Al-Bayati et al., 2022). The samples were put in closed plastic bags and maintained at room temperature until the required testing ages of 7 and 28 days.

Table 2. Mix proportions (kg/m^3).

No	**Mix ID**	**Fly Ash (Kg)**	**Portland Cement (Kg)**	**Fine Agg. (Kg)**	**Water (Kg)**	**Sodium silicate (SS)(Kg) Ms =1.5**	**Aluminum (Kg)**	**Concrete waste powder (Kg)**	**Super plasticizer %**
1	Ref 1	----	3.6	9	1.62	----	----	----	1
2	Ref 2	1.8	1.8	9	1.62	----	0.0014	----	1
3	F_5 P_5	1.8	1.8	9	1.62	1.3	0.0014	----	----
4	$F_5P_4W_1$	1.8	1.44	9	1.62	1.3	0.0014	0.360	----
5	$F_5P_3W_2$	1.8	1.08	9	1.62	1.3	0.0014	0.720	----
6	$F_5P_2W_3$	1.8	0.720	9	1.62	1.3	0.0014	1.08	----
7	$F_5P_1W_4$	1.8	0.360	9	1.62	1.3	0.0014	1.44	----
8	F_5W_5	1.8	----	9	1.62	1.3	0.0014	1.8	----

Where: The suffixes denoted of mix ID are: F : fly ash, P: Portland cement, W: concrete waste powder, Mix $F_5P_4W_1$: 50% FA+40% PC+10% CWP

TESTS

HARDENED PROPERTIES

In evaluating the mechanical properties of the mortars, both the flexural and compressive strengths of the mortars were assessed. Compressive strengths of the (50*50*50) mm specimens were determined according to the C109 standard (C109/109M-16a, 2016). Testing was carried out at 7 and 28 days, and the mean of 3 specimens at each age was reported. The rate of loading was 900 N/sec. For the flexural strength of cement mortars, prism specimens of 40x40x160 mm were used at 28 days as per the C348 standard (C348, 1998) under one-point bend loading.

In addition to mechanical properties, other durability-related properties that were determined include porosity and water absorption. The two properties were established using ASTM C642—Standard Test Method in Density, Absorption, and Voids in Hardened Concrete. Porosity was evaluated by calculating the volume of voids in the hardened mortar specimens, while water absorption was determined by immersing oven-dried samples in water overnight and measuring the weight gain.

SCANNING ELECTRON MICROSCOPY (SEM)

Microstructural analysis of the hardened mortar was performed utilizing a scanning electron microscope (SEM), according to ASTM C 1723 (2010) standards. Microscopic fragments were collected from the samples used for compressive strength testing after 28 days. These samples included the reference mix and the best and worst G5 mixes. High-magnification scanning electron microscope (SEM) analysis was performed to study the changes and developments in the microstructure of the mortar which was carried out at the College of Materials Engineering, University of Babylon.

RESULTS AND DISCUSSION

COMPRESSIVE STRENGTH TEST RESULTS

The compressive strength results presented in Figure 2 indicate that the binder composition and activation conditions are the primary factors influencing strength evolution in the tested mortars. The reference OPC mix (Ref1) achieved 20 MPa at 7 days and 28 MPa at 28 days, which reflects the typical continuous hydration process of Portland cement.

Unlike the other alkali-activated hybrid mixes, the one with 50% FA and 50% OPC, the F5P5 mix, reached early strengths of 19 MPa at 7 days but diminished to 10 MPa at 28 days. This suggests that initial geopolymer gel formation occurred but was followed by diminished strength gain or possible loss. This could be from the partial dissolution of some of the primary reaction products, the carbonation of alkali-activated gels, or long-term polymerization that was inadequate. Therefore, rather than continuous strength gain, this mix exhibits considerable instability in the alkali-activated matrix. The other mixes follow other trends. For example, F5P3W2 still showed relatively low strength at early ages, but it was the only mix that showed significant strength gain at 28 days. This suggests a slow, but, in fact, continuous geopolymerization was occurring. In contrast, mixes with higher CWP contents, specifically F5P2W3 and F5W5, had markedly lower compressive strengths in the range of 5.5 to 7.5 MPa, and these showed no considerable increase in strength over time, similarly to F5P3W2. This can be attributed to the reduced availability of reactive silica and alumina due to the dilution effect caused by CWP, as well as its high $CaCO_3$ and inert residue content, which hinder gel formation and increase porosity.

These findings align with previous literature: elevated-temperature curing and sufficient alkali activator promote rapid geopolymerization and early strength gain (Luhar & Luhar, 2019; Temuujin et al., 2009), while low reactivity, limited activator dosage, or inadequate curing conditions can cause delayed or unstable strength development (Van Jaarsveld et al., 2002; Komnitsas & Zaharaki, 2007; Duxson et al.). Overall, the OPC reference mix still demonstrated superior 28-day strength compared to most alkali-activated formulations; however, selected fly ash-based mixes showed competitive early strength depending on binder composition, activator type/concentration, and curing conditions.

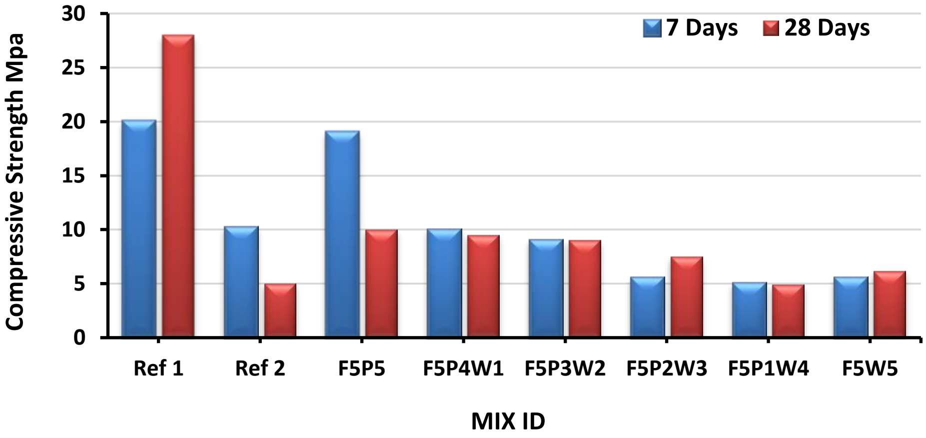

Fig. 2. Compressive strength test results of mortar mixes at 7 and 28 days.

FLEXURAL STRENGTH TEST RESULTS

The results displayed in Figure 3, the mechanical properties of cement mortar with fly ash and concrete waste powder, provide a good understanding, as the flexural strength test was performed on the 28th day. The flexural strength of 4.5 MPa was attained in the mixture (F5P5) made using an alkali activator, as opposed to the mixture (F5P5) in the absence of an alkali activator (4.05). Such an increment underlines the valuable role played by the alkali activators, which contribute to augmenting the cohesion of the matrix and tensile strength by the efficacy of geopolymerization (Temuujin et al., 2009; Hardjito et al., 2004). Kumar et al. (2010) also experienced the same, as they found that an improvement in the composition of a binder results in improved gel formation and flexural behavior due to microstructure integration.

Among the mixes without active medication, combination F5P4W1 showed the highest flexural strength (3.2 MPa). This may be due to the ratio of FA and CWP that helped develop proper microstructures and reasonable encapsulation (Parthiban et al, 2015). However, slight differences in flexural performance were observed in the mixes (F5P4W1, F5P2W3, and F5P1W4), indicating that the design of the mix had a very strong influence on the tensile properties. Mixture (F5W5) had the lowest flexural strength (1.7 MPa), which may suggest a weak binder and low interfacial bonding as evidenced by the CWP mass, which diluted the reactive aluminosilicate and increased porosity (Chindaprasirt et al, 2010).

In this study, the conventional OPC control mix Ref 1 was also tested; for which, at 28 days, the flexural strength yielded 10 MPa. The flexed alkali-activated F5P5 blend (4.5 MPa) performs at least on par with the OPC control which demonstrates that optimized blends of FA/CWP with activators may reach or exceed the tensile strength of conventional OPC mortars. These results validate that activators exist and the rigorous control of the ratios of raw materials play a primary role in maximizing flexural performance (Kumar et al., 2010; Hardjito et al., 2004).

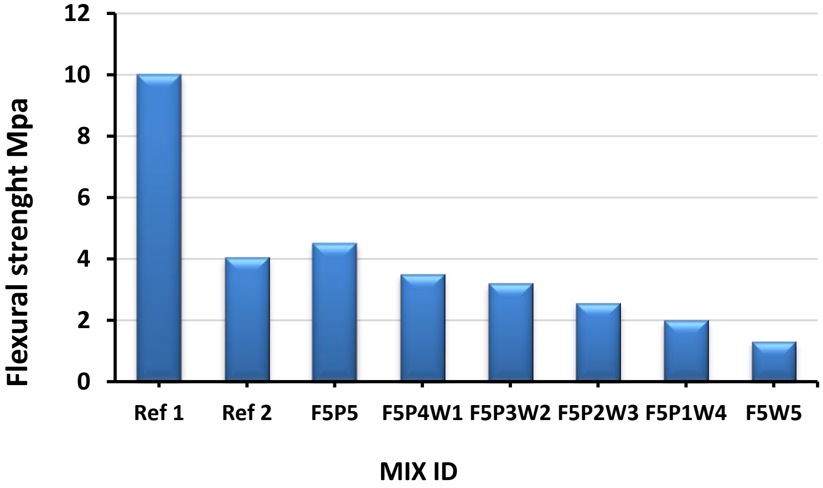

Fig. 3. Flexural strength test results of mortar mixes at 28-day.

POROSITY TEST RESULTS

The porosity results, as illustrated in Figure 4, after a 28-day duration, elucidate the influence of activator dosage on the microstructure of hybrid alkali-activated cement mortars. It is imperative to note that in Table 2, mix (F5P5) is characterized as a composition comprising 50% fly ash and 50% concrete waste powder, activated with an alkaline solution. Nevertheless, for comparison in this phase, the porosity value of 0.203 corresponds to a comparable composite formulation (50% FA, 50% PC) devoid of an excessive activator dosage, which is similar to the reference mix (Ref 2). This particular mix demonstrated the lowest porosity (0.203), signifying a denser matrix with a reduced number of internal voids, which aligns with prior research indicating that a moderate or slow geopolymer reaction promotes the development of a compact and homogeneous microstructure (Hardjito et al., 2004).

Conversely, the same mixture composition (50% FA with 50% PC), but activated with a better attentiveness of alkaline solution, in this work cited as mixture (F5P5), gave a greater porosity amounting to 0.250. This increase in porosity is due to greater geopolymerization from an excess of activator, causing micro-cracking, incomplete gel formation, and better pore connectivity (Temuujin et al., 2009). This explanation eliminates the apparent contradiction existing by being able to separate (F5P5) with great dosages of activator and the same powders proportioned as to the components without any stimulation (Ref. 2).

For the remaining mixes (F5P4W1, F5P3W2, F5P2W3, F5P1W4, and F5W5), porosity values ranged from 0.217 to 0.293. Mix (F5P2W3) exhibited the highest porosity (0.293), followed closely by (F5P1W4) at 0.291, likely due to inadequate mix proportions and poor particle interaction, leading to weak gel structure and interconnected pores (Heah et al., 2012). Conversely, mix (F5P3W1) recorded a relatively lower porosity of 0.217, which may be associated with a balanced activator-to-binder ratio resulting in improved particle packing and matrix densification (Sofi et al., 2007).

For evaluation, the traditional OPC manipulate blend (Ref 1) confirmed a porosity of about 0.300 at 28 days. This shows that the combination of 50% FA and 50% PC without a high activator dosage (Ref 2) can attain microstructural density akin to OPC, while other FC/CWP mixes (together with F5P2W3 and F5P1W4) display better porosity that might negatively affect durability. These findings showed that the microstructure of alkali-activated hybrid mortars is especially sensitive to activator/binder ratio, mix design, strength content, and curing situations (Deb et al., 2014). The variance in porosity a number of the tested mixes similarly emphasizes the significance of proper proportioning and gold standard activator awareness in enhancing microstructure and durability performance.

ABSORPTION TEST RESULTS

The results of water absorption after 28 days are shown in Fig. 4 and give an indication of the capacity of the cement mortar mixtures for resistance to moisture attack, one of the important factors that influence durability (Zuhua et al., 2009). The absorption value for the mixture (F5P5) was 0.200, while the previous mixture with the alkaline activator (Ref 2) gave the lowest absorption of all mixes (0.085). This indicates that the degree of densification of the matrix associated with the alkaline activator was very great, which lowers the capillary porosity and thus increases the operative resistance to moisture (Davidovits, 2011).

On the other hand, the mixture (F5P4W1) gave the maximum absorption value, which amounted to 0.151, which could be ascribed to a more open matrix or interconnected pore structure, thereby indicating a lack of interaction or poor particle arrangement (Temuujin et al., 2010). The mixtures F5P3W2, F5P2W3, F5P1W4, and F5W5 gave intermediate absorption values ranging between 0.126 and 0.135, which was attributed to slight internal porosity or diminished microstructural integrity (Al-Bakri et al., 2012).

Comparisons were made with the conventional OPC control mixture (Ref. I), which was tried in this experiment; it had an absorption of approximately 0.085 at 28 days. This puts it on an equal basis with the alkali-activated mixture Ref 2, and lower than the level of the un-activated mixture F5P5 (0.200). The high performance of Ref 2 shows the effect of the chemical activation in giving a very large increase in packing density of the matrix as well as the permeability. The results are in agreement with the porosity results and admit to the fact that good microstructural adhesion gives low permeability and a good long-term response for the cement mortars (Ravikumar & Neithalath, 2012).

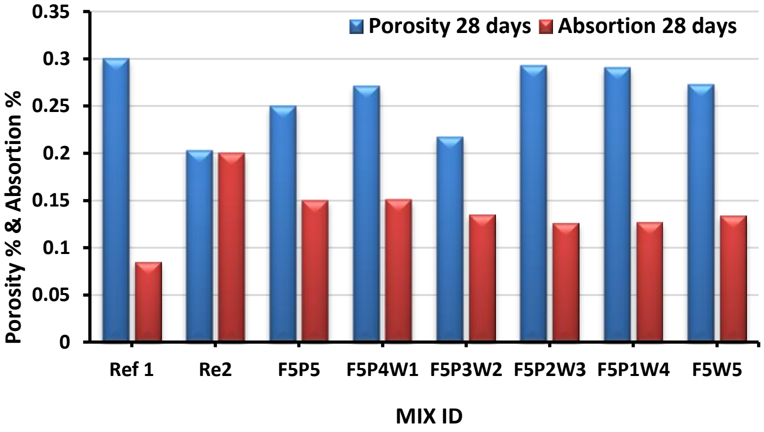

Fig. 4. Water absorption and porosity values at 28 Days for cement mortar mixes.

Scanning Electron Microscopy (SEM)

The SEM test results showed the tested mixes with clear microstructural differences, strongly supporting the quantitative results described in Sections 4.1 (compressive strength) and 4.3 (porosity). The mixes with a higher percentage of concrete waste powder (F5P2W3 mix and F5P1W4 mix) have the greatest porosities (0.293 and 0.291, respectively), together with the corresponding lowest compressive strengths (5.5–7.5 MPa), and exhibit very notable microstructural deficiencies. These deficiencies were reflected in the large voids, micro-cracks, and collections of unreacted fly ash or CWP particles embedded in a weak gel matrix. The presence of such unreacted spherical or semi-spherical fly ash particles and loosely bonded calcium-rich residues confirms the incomplete geopolymerization process and explains the increased pore connectivity reported in Section 4.3. The dominance of these features is consistent with inadequate availability of reactive silica/alumina due to CWP dilution and insufficient activator–binder interaction.

In contrast, the mix with balanced activator dosage and no excess CWP (Ref 2: 50% FA + 50% PC without high activator dosage) exhibited a denser and more homogeneous matrix with fewer visible voids, which aligns with its low porosity value (0.203) and relatively better compressive strength. Similarly, mixes such as F5P3W1 showed partially filled pores and more cohesive gel structures, supporting their intermediate porosity (0.217) and stable strength development. On the other hand, in mixes with high activator concentration (e.g., F5P5), localized micro-cracks and gel shrinkage were observed, which correspond to the increased porosity (0.250) and the strength reduction from 19 MPa at 7 days to 10 MPa at 28 days reported earlier. This indicates that excessive activator accelerates reaction kinetics but leads to non-uniform gel formation and microstructural instability at later curing stages.

Consequently, the observations derived from SEM analysis corroborate the mechanical property and porosity data by showing that unreacted particles, a network of voids, and coalesced gels are the main source of high porosity and low compressive strength for CWP-rich or highly activated mixes. Alternatively, optimized activator-to-binder ratios and balanced FA/CWP contents foster gel coalescence, lower micro voids, and, in turn, increase the performance.

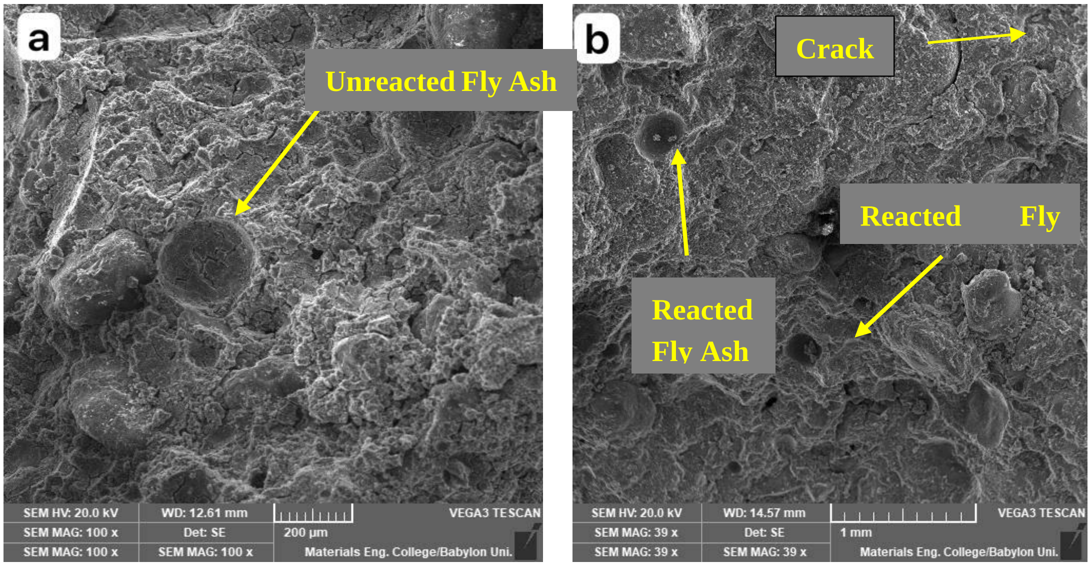

Fig. 5. SEM analysis test results mortars at 28-day age, (a) Mix Ref 2 (50% FA + 50% OPC Without Activators), (b) Mix $F_5P_2W_3$ (50% FA + 20% OPC + 30% CWP).

CONCLUSION

1. This study demonstrates the feasibility of fly ash (FA) and recycled concrete waste powder (CWP) as sustainable supplementary binders in alkali-activated cement mortars. Compared to conventional OPC, the optimized blends showed improved microstructure, consistent improved durability in two strength levels, and comparable mechanical characteristics. Thus, with fewer CO_2 emissions, they are fully able due to engineering performance.
2. The alkali-activated blend F5P5 (50% FA + 50% PC) had good quality flexural performance to the other blends of about 4.5 MPa at 28 days, roughly 12.5% higher than the OPC control mix, which had 4.0 MPa .Additionally, its early compressive strength (19 MPa at 7 days) closely approached that of OPC (20 MPa), although a strength drop to 10 MPa at 28 days indicated matrix instability due to excessive activator and micro-crack development.
3. The durability performance of the optimized mix was also evident: the activated F5P5 mix recorded the lowest porosity (0.203) and water absorption (0.200) among all alkali-activated mixes. In contrast, mixes with higher CWP content such as F5P2W3 exhibited porosity exceeding 0.293, water absorption above 0.130, and compressive strength as low as 5.5–7.5 MPa, confirming that excessive CWP reduces reactive silica/alumina content and weakens gel formation.

4. SEM observations supported the quantitative results by showing dense, continuous geopolymer gel and well-bonded particles in low-porosity mixes (e.g., Ref2 and F5P3W1), whereas high-CWP mixes displayed widespread voids, micro-cracks, and unreacted FA/CWP particles. These microstructural flaws directly explain the higher porosity and lower strength reported in Sections 4.1 and 4.3.
5. Overall, the results show that the mixture design parameters, primarily the FA/CWP ratio, activator concentration, and curing system, are fundamental for optimizing the performance. The appropriate balance in the activation can reduce porosity by about 30% with respect to OPC, to improve flexural strength by 10–15%, and obtain comparable results of early compressive strength. Consequently, this work offers a clear way for the valorization of industrial wastes in cementitious materials, ensuring simultaneously mechanical reliability and ecological sustainability.

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