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Research Article

Modification of high-calcium fly ash to meet ASTM requirements when used as a binder

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ABSTRACT

The expeditious setting time and poor workability of high-calcium fly ash have limited its feasibility as an eco-sustainable binder in cementitious systems, despite its off-setting cost and environmental benefits. This study focuses on the alteration of high-calcium fly ash mortar to achieve the ASTM standard and enhancement in performance through the alkali activation method. The methodology implied the variation of the ratio of sodium silicate to sodium hydroxide, sodium hydroxide molarity (8M and 10M), and the use of two types of plasticizers (polycarboxylate ether and polymelamine sulfonate). The findings revealed that the reduction of the Na_2SiO_3/NaOH ratio and the use of polycarboxylate ether enhanced the setting time for up to 190 min and achieved a 28-day compressive strength of 44.9 MPa. The flexural strength was also increased to 5.11 MPa, and the drying shrinkage was decreased to as low as 0.03%. All the optimized mixes complied with the thresholds of ASTM C191, C109, and C596. These results indicate that mortars based on high calcium fly ash can substitute ordinary Portland cement on a 1:1 basis for both structural and nonstructural applications, thereby decreasing CO_2 emissions and improving the sustainability of the materials used. The novelty of this study is that full cement replacement is possible in an HCFA-based geopolymer system, which is tailored from an optimized activator chemistry and plasticizer selection, and exceeds previous efforts that had to use as alternative to cement blending or compromise strength or workability.

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INTRODUCTION

Waste by-products from diverse industrial processes are being increasingly integrated into construction materials in response to environmental concerns. This study utilized high-calcium fly ash (HCFA) from the earth as a substitute for ordinary Portland cement (OPC). However, complete replacement of OPC considerably affects the performance of construction materials irrespective of the economic

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advantages. Mortars composed of HCFA are expected to exhibit shorter setting times compared with those containing cement. These affordable resources can be used in applications that employ mortars, such as geopolymers [1, 2]. An estimated 750–850 million tons of fly ash are produced worldwide by coal-fired power plants [3], and the market for fly ash is worth USD 14.26 billion in 2024. It is expected to reach USD 21.92 billion by 2033, driven by sustainability policies and expansion of the construction industry [4]. However, only 45–50 % of this material is reused effectively, while the rest is thrown away into landfills or ash ponds, contributing to land degradation and environmental pollution. With the intensification of pressure on the construction industry to switch to environmentally conscious practices, the use of HCFA as an alternative to cement is a potential step towards decreasing carbon emissions and material costs, in addition to recycling industrial waste [5]. The most prominent problem that limits the use of HCFA is its relatively short hardening time. Many researchers have attempted to produce HCFA mortar but failed to do so. For example, Topark-Ngarm et al. [6] tried to control the setting time of HCFA by controlling the molar concentration of sodium hydroxide solution; they obtained obtain an acceptable setting time when they used some concentrations, but the mechanical properties decreased dramatically in the same mixtures. Antoni et al. [7] used two types of fly ash from two high-calcium sources; one contained higher calcium oxide than the other, but both had short setting times. They tried to increase the setting time by adding acids, such as sulfuric, nitric, hydrochloric, and citric, but achieved negative results. Citric acid, whose behavior prolongs the setting time of cement [8] did not exhibit such behavior when it was used with HCFA. Antoni et al. [9] also studied the incorporation of borax powder into two different types of fly ash derived from high-calcium sources. One type had a higher content of calcium oxide than the other. However, both types exhibited short setting times. When borax with a weight percentage of 20% was incorporated into HCFA, the initial setting time of the mortar exceeded the specified limit. However, at this concentration, the compressive strength of the mortar substantially declined. Mohamed et al. [10] investigated the feasibility of regulating the solidification period of HCFA mortar by manipulating the molar concentration of sodium hydroxide solution. However, the compressive strength value decreased in the combinations that achieved acceptable setting times. According to previous research, HCFA, a waste material, must be utilized because of its potential for recycling and development. The primary aspect that requires improvement is the duration of the setting process; the setting time must be acceptable and must not adversely affect the mechanical characteristics. Recent research has focused on eliminating the disadvantages of high-calcium fly ash (HCFA) applied to the binder with the help of studies on chemical and mineral enhancement. Phiangphimai et al. [11] showed that the adding of certain chemical additives, namely, sugar and calcium chloride, efficiently prolonged setting time of HCFA-based geopolymers and increased compressive strength. Likewise, Hasan et al. [12] reported that the partial replacement of HCFA with recycled glass powder potentially enhanced the compressive strength and significantly reduced the drying shrinkage. This approach is a sustainable construction practice that uses industrial waste in a value-added manner. Moreover, Liu et al. [13] studied the addition of calcium hydroxide to HVFA mortars and discovered that it advanced the early setting and strengthened the development of strength, particularly in Class F fly ash. Together, these studies imply that such attentive adjustments, either chemical, mineral, or material-based, can significantly improve the characteristics of HCFA binders and make them closer to practical application criteria. The objective of this study is to develop a mortar composed of HCFA that meets the setting time and mechanical quality requirements of international criteria. Developing sector sustainability programs are driving the use of industrial waste by-products to curtail the impact of environmental degradation. HCFA is a byproduct of coal combustion in power plants with high capacities worldwide. The environmental problems exemplified by this byproduct have stimulated researchers to study its application as a substitute for ordinary Portland cement (OPC). Nevertheless, the weak point of the HCFA mortar is the fast setting time that prevents its workability and use in applications that do not involve shedding. The aim of this study was to maximize the set time and mechanical properties of HCFA mortar and comply with the ASTM standards for setting time. In this study, some key parameters were investigated, such as the variation of the Na_2SiO_3/NaOH molar ratio by using 8M or 10M NaOH and addition of either polycarboxylate ether (PCE) or polymelamine sulfonate (PMS) plasticizers. This study allows a unique comparison to show that OPC-based systems perform as well as or even better than systems based on non-properly activated HCFA mortar. This research helps close the gap that exists between the scientific literature and strives to develop a binder system based on ASTM C 191 and C109.

MATERIALS AND METHODS

Materials

The methodology used in the current study is systematic in nature, as it is based on an experimental design. First, distinct alkaline activator solutions were prepared by dissolving sodium hydroxide pellets in distilled water at concentrations of 8M and 10M, and then sodium silicate solution was added to meet the targeted masses of Na_2SiO_3 and NaOH of 1.5, 2.0, and 2.5 After a 24-hour resting time, the activators were employed to prepare mortar mixes with high-calcium fly ash, sand, and polycarboxylate ether (PCE) or polymelamine sulfonate (PMS) plasticizers. The setting time was measured using the Vicat apparatus, and

the compressive and flexural strengths were tested according to ASTM at 3, 7, and 28 d. The shrinkage of drying was tested according to ASTM C596. Below is a simplified flowchart (Fig. 1), and the findings of the chemical study conducted on HCFA and its composition are presented in tabular format (Table 1). The authors used an XRF test to experimentally determine the chemical composition.

The pozzolanic activity of the high-calcium fly ash (HCFA) used in this study was experimentally tested based on ASTM C311 [14] . Four mortar samples were subjected to a strength activity index (SAI) test by replacing 20% of the ordinary Portland cement with HCFA. At 28 d, the compressive strength was determined and compared with that of the control specimens, which contained 100% cement. The results obtained indicated that the HCFA-based mortar had an SAI value of 82% compared to the ASTM C618 [15] required minimum of 75%. This proves that HCFA possessed adequate pozzolanic activity to be a pozzolanic material on standardized testing.

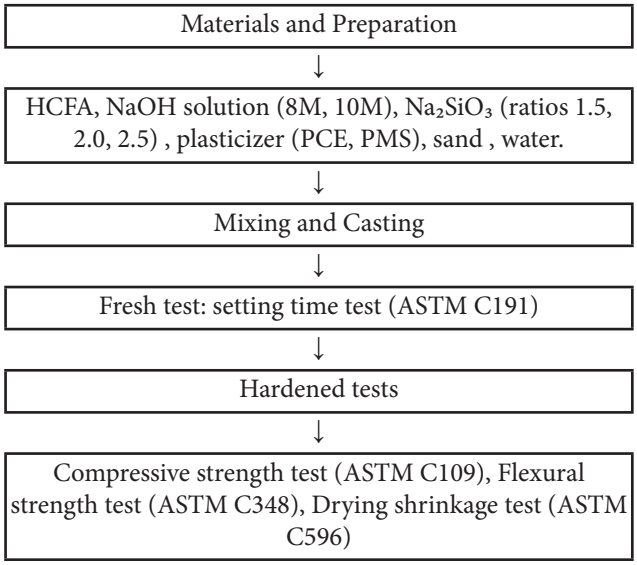


Figure 1. Flowchart of the experimental methodology.

Table 1. Chemical analysis of HCFA

Oxide	Content (%)
SiO_2	32.35
TiO_2	0.71
CaO	21.44
K_2O	1.36
Al_2O_3	16.93
MgO	7.05
Na_2O	2.91
P_2O_5	0.29
Fe_2O_3	15.23
SO_3	1.20
MnO_2	0.18
LSF	0.35

Table 2. Properties of the plasticizers that provided by supplier

Properties	PCE	PMS
pH	9	8
Density	600 kg/m^3	550 kg/m^3
Appearance	Powder	Powder
Chloride content	≤ 0.04	≤ 0.05

The study employed a blend of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) as an alkaline activator. The compound Na_2SiO_3, which was provided by O&T Tech Firm, consisted of 7.9% Na_2O, 26% SiO_2, and 66.1% H_2O. Its specific gravity was 1.35.

The pellets supplied by Eau de Senteur Company consisted of NaOH with purity above 99%. Solutions were prepared at two discrete concentrations: 8 and 10 molar. The 8 molar solution had a concentration of 262 g/L of NaOH, and the 10 molar solution had a concentration of 314 g/L of NaOH; the rest of the volume was distilled water. The solution was allowed to rest undisturbed for 24 h after its preparation. This study adhered to the specifications in ASTM C778 [11] by utilizing normal sand. Pure water was employed to minimize the effect of impurities. Two distinct plasticizers, namely, polycarboxylate (PCE) provided by Kingsun Company and polymelamine sulfonate (PMS) provided by JK Chemicals Company, were utilized. The features of these plasticizers are given in Table 2.

Design of the Mixes

The mixing ratios in this research varied in the different tests. For instance, the determination of the initial and final setting times relied mostly on the consistency test. Numerous mixes were tested in accordance with the guidelines of the ASTM C187 standard [16] until the desired consistency was achieved [12]. Prior to the test, consistency was assessed to ascertain the appropriate quantity of water to be utilized. The ideal proportion for combination with the plasticizer PMS was 341.08 g of HCFA, 6 g of PMS, and 186.92 g of activator solution. The Na_2SiO_3-to-NaOH ratio was 2:1. The percentage of solids in the activator solution was included in the calculation of the binding material, and the remaining portion was regarded as water for the reaction. Additionally, the plasticizer powder was considered in the binding material. As a result, the water-to-binding material ratio was 29%. The ideal mixing ratio for the plasticizer PCE was 342.9 g of HCFA, 6 g of PCE, and 163.1 g of activator solution; the Na_2SiO_3-to-NaOH ratio was 2:1. By factoring in the ratio of solids in the activator solution and the plasticizer powder, the water/binding material ratio was 28%.The remaining fraction was designated as water for the reaction.

After the consistency test, a setting time test was performed on HCFA mortar by using ideal samples. Several variables, including the molar concentration of NaOH and the ratio of Na_2SiO_3 to NaOH, were introduced. Notably, the ratio of water to the binding material remained constant. Table 3 displays the constituents of each blend used for HCFA mortar in the first and final setting time examinations.

The mixing ratios used for the compressive and flexural strength tests were not based on the beginning and final setting times of HCFA mortar. Instead, they were designed in accordance with the specifications given by ASTM, as indicated in Table 4.

Test in This Study

This section presents all the examinations conducted on HCFA mortar.

Initial and final setting times

Crucial factors that show how quickly the mortar paste begins to lose its elasticity and how long it takes for it to completely harden are the initial and final setting times of the mortar. Figure 2a illustrates the Vicat apparatus used to quantify the durations. For the mortar paste to transition from elastic to solidified state, an initial setting time is necessary. The amount of time required for the cement paste to fully solidify and lose its ability to maintain its shape is

Table 3. Specific information on the compositions of the mixes used to determine the initial and final setting times for HCFA mortar

Mixtures	HCFA (gr)	W*/binder (%)	Na_2Sio_3/NaOH	Activator solution (gr)	NaOH	Plasticizer (gr)
FM1	340.16	29	2.5	169.84	8	PMS 6
FM2	341.15	29	2	168.85	8	PMS 6
FM3	342.31	29	1.5	167.69	8	PMS 6
FM4	336.35	29	2.5	173.65	10	PMS 6
FM5	336.68	29	2	173.32	10	PMS 6
FM6	337.12	29	1.5	172.88	10	PMS 6
FC1	342.02	28	2.5	163.98	8	PCE 6
FC2	342.90	28	2	163.10	8	PCE 6
FC3	344.10	28	1.5	161.90	8	PCE 6
FC4	338.37	28	2.5	167.63	10	PCE 6
FC5	338.66	28	2	167.34	10	PCE 6
FC6	339.08	28	1.5	166.92	10	PCE 6

* Water is not an additional component but an integral part of the activator solution.

Table 4. Specific information on the compositions of various mixtures in relation to their compressive and flexural strengths

Mixtures	HCFA (gr)	Sand (gr)	Na_2Sio_3/NaOH	NaOH	W*/binder (%)	Activator solution (gr)	Plasticizer (gr)
FM1	303.96	1100	2.5	8	48.5	284.04	PMS 6
FM2	305.61	1100	2	8	48.5	282.39	PMS 6
FM3	307.57	1100	1.5	8	48.5	280.43	PMS 6
FM4	297.58	1100	2.5	10	48.5	290.42	PMS 6
FM5	298.14	1100	2	10	48.5	289.86	PMS 6
FM6	298.88	1100	1.5	10	48.5	289.12	PMS 6
FC1	303.96	1100	2.5	8	48.5	284.04	PCE 6
FC2	305.61	1100	2	8	48.5	282.39	PCE 6
FC3	307.57	1100	1.5	8	48.5	280.43	PCE 6
FC4	297.58	1100	2.5	10	48.5	290.42	PCE 6
FC5	298.14	1100	2	10	48.5	289.86	PCE 6
FC6	298.88	1100	1.5	10	48.5	289.12	PCE 6

* Water is not an additional component but an integral part of the activator solution
* FM referred to fay ash with PMS
* FC referred to fly ash with PCE

known as the final setting time. The test was conducted in accordance with the ASTM C191 guidelines.

Compressive and flexural strengths

The compressive strength (fc) of mortar is a numerical indication of its ability to withstand axial loads and a vital property for construction materials, this test illustrated in Figure 2b. Testing often entails the utilization of mortar cubes in accordance with the ASTM C109 [17] standard, with a binder–sand–water mixing ratio of 1:2.75:0.485. In this study, the samples used to measure the compressive strength of mortar had dimensions of 50 × 50 × 50 mm.

The flexural strength (fr) of mortar is a numerical evaluation of its ability to resist bending forces. This property is essential for materials used in structural applications where massive bending loads are present. In this study, the dimensions of the samples used to evaluate the flexural strength of cement mortar were determined based on ASTM C348 [18]. The samples measured 40 mm × 40 mm × 160 mm as shown in Figure 2c and had a binder–sand–water mixing ratio of 1:2.75:0.485.

Drying shrinkage

Drying shrinkage, also known as desiccation, is the process by which a hardened paste, mortar, or concrete gradually contracts in size as it loses moisture. Measuring shrinkage is crucial because of its potential to generate cracks and other structural issues. Several institutions have created standardized examinations to evaluate the extent of shrinkage in cement throughout the drying process. A commonly employed standard is ASTM C596 [19] as shown in Figure 2d.

RESULTS AND DISCUSSION

This section presents the findings of the tests and comprehensive examination and interpretation of the data.

Results on Initial and Final Setting Times

All setting time measurements were performed in triplicate, and the standard deviations were reported to record the values of experimental variability.

Table 5 and Figures 3 and 4 presents the results of the initial and final setting time test for HCFA mortar.

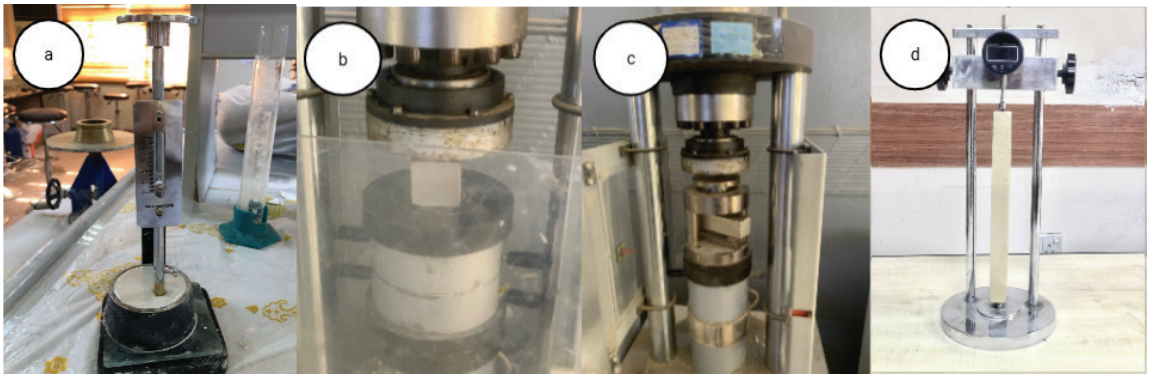


Figure 2. Photographs of test setups: (a) Vicat apparatus for setting time, (b) Compressive strength test, (c) Flexural strength test, (d) Drying shrinkage test.

Table 5. Initial and final setting times

Mixtures	Initial setting time (min)	Initial setting time±SD	Final setting time (min)	Final setting time±SD
FM1	60	60±0	150	150±5
FM2	55	55±0	130	130±5
FM3	45	45±0	105	105±5
FM4	50	50±0	160	160±0
FM5	45	45±0	135	135±5
FM6	40	40±0	110	110±0
FC1	75	75±5	185	185±5
FC2	70	70±5	175	175±5
FC3	60	60±0	140	140±0
FC4	70	70±5	190	190±5
FC5	60	60±0	185	185±5
FC6	50	50±0	150	150±5

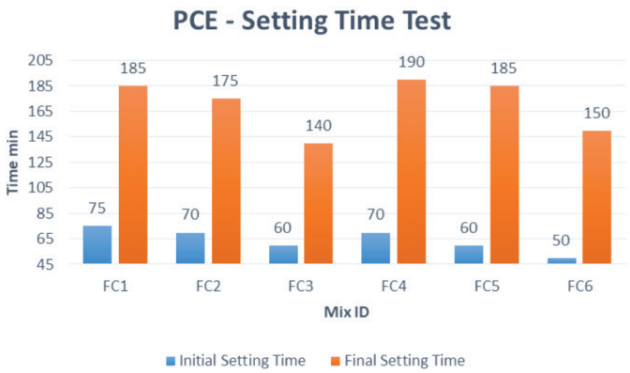


Figure 3. The outcomes of setting time when using PCE.

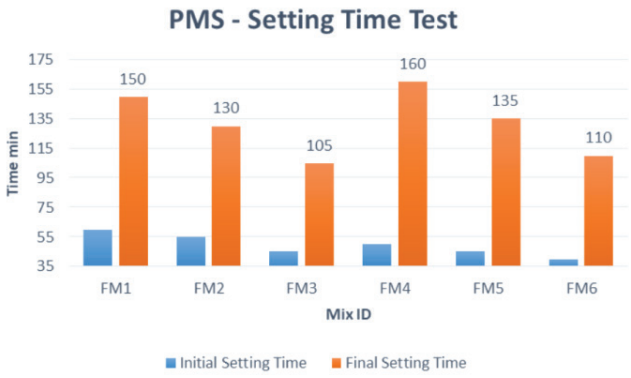


Figure 4. The outcomes of setting time when using PMS.

The results in Table 5 indicate that all the mixes, except for the FM6 mixture, satisfied the restrictions specified by ASTM C191. The FM6 mixture had an initial setting time of 40 min, which does not meet the minimum requirement of 45 min required by ASTM C191. The study also found that lowering the ratio of Na_2SiO_3 to NaOH decreased the setting time. Comparison of FM1 with FM2, FM3, FM5, and FM6 showed that these mixes also contained FC2, FC3, FC5, and FC6. This finding is consistent with those of prior studies [20, 21]. The molarity of NaOH has two distinct effects on HCFA mortar setting time: it decreases and increases HCFA mortar setting time. Previous studies have shown that increasing the molar concentration of NaOH speeds up the dissolution of alumina and silica, which in turn decreases the setting time. NaOH solutions that have low molarity make it easy for calcium ions to react with water, thus creating C-S-H and C-A-H gels. Meanwhile, a high concentration of NaOH solution increases the presence of Na+ and OH- ions, which accelerates the dissolution rate of aluminosilicate precursors and reduces calcium ion extraction. Conversely, the geopolymerization processes associated with high concentrations are slower than those involving the hydration of calcium ions. This situation results in a prolonged setting time [22, 23]. Given that the calcium content in HCFA is less than half of that in HCFA, its influence is much smaller than that of the calcium in HCFA.

In comparison to the results of Topark-Ngarm et al. [6] ,who were able to constrain the setting time for HCFASM by using a low molarity of NaOH at the cost of strength loss, our research has delivered extended setting times (FC4 – 190 minutes) with no loss in strength. In a similar way, unlike the work done by Antoni et al. [7], who reported unfavorable results in terms of the setting time extension when using acids, our results provide information on the fact that the usage of polycarboxylate ether along with the best Na_2SiO_3/NaOH ratios can be more effective and practical.

Results on Compressive and Flexural Strengths

The compressive and flexural strengths are the averages of three specimens, and the standard deviations were imputed to improve the precision of the results.

Table 6 and Figures 5,6,7 and 8 displays the outcomes of the compressive strength (fc) tests conducted in 3-, 7-, and

Table 6. Outcomes of the compressive strength test

Mixtures	fc at 3 days (MPa) ±SD	fc at 7 days (MPa) ±SD	fc at 28 days (MPa) ± SD	fr at 28 days (MPa) ± SD
FM1	13.0±0.2	30.0±0.3	37.4±0.6	3.76±0.2
FM2	13.2±0.3	31.4±0.4	39.5±0.8	3.98±0.2
FM3	14.5±0.5	32.7±0.4	40.3±0.5	4.21±0.1
FM4	13.7±0.2	30.6±0.3	38.0±0.6	3.82±0.2
FM5	14.3±0.1	32.2±0.2	39.0±1.0	4.05±0.1
FM6	14.8±0.4	33.5±0.3	40.8±0.9	4.24±0.1
FC1	16.4±0.3	33.4±0.5	40.2±0.7	4.53±0.1
FC2	16.9±0.2	34.6±0.7	43.1±0.4	4.84±0.1
FC3	17.5±0.6	37.1±0.4	42.8±0.7	5.07±0.2
FC4	16.7±0.2	33.6±0.5	41.1±0.3	4.63±0.1
FC5	17.3±0.3	35.0±0.4	43.6±0.8	4.91±0.1
FC6	17.6±0.3	37.4±0.8	44.9±0.5	5.11±0.2

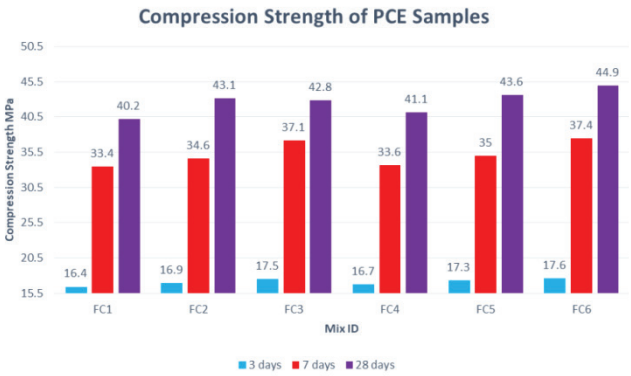


Figure 5. The outcomes of compressive strength when using PCE.

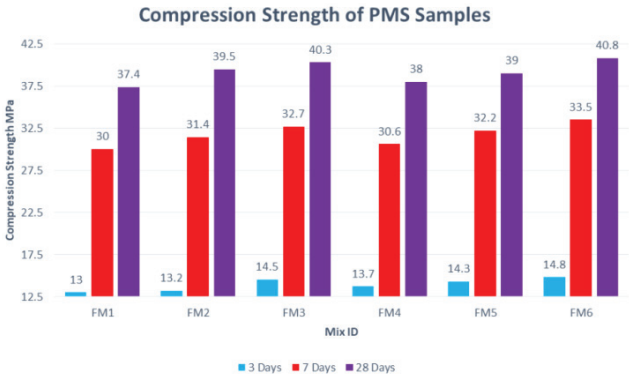


Figure 6. The outcomes of compressive strength when using PMS.

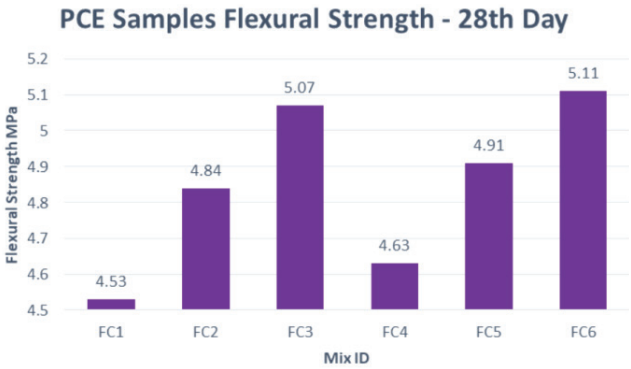


Figure 7. The outcomes of flexural strength when using PCE.

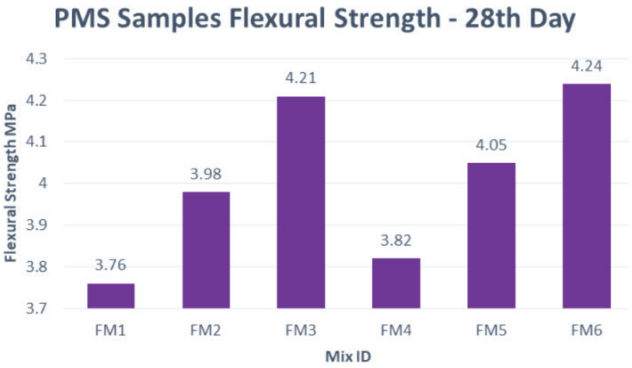


Figure 8. The outcomes of flexural strength when using PMS.

28-day periods and the flexural strength (fr) test results at 28 days.

The table shows that all values meet the requirements of the ASTM C150 specification [24]. Among all the mixtures, FC6 had the highest performance, but it was not considered the best because of its slightly higher value compared with the value of the PC3 mixture. Considering that a high molar concentration of NaOH leads to increased carbon dioxide emissions [25], which contradicts the objective of green building, PC3 was concluded that is the optimal mixture in terms of mechanical properties (compressive and flexural strengths). Furthermore, a decrease in the Na_2SiO_3/NaOH ratio enhanced compressive strength. The role of silicate was given credit for the rise in voids. This is clear in Figures 9 and 10, where the FC4 mixture has more and bigger gaps compared to the FC6 mixture. This is because there is a higher ratio of sodium silicate to sodium hydroxide, as seen in other studies [20, 26]. A high molar concentration of NaOH increases the interaction between hydroxide ions and alumina and silica molecules. This increased interaction creates additional monomers and enhances compressive strength [10].

Compared to other studies by Mohamed et al. [10], in which an increase in NaOH molarity led to a decrease in strength, our results showed that a high molarity (10M) combined with a low Na_2SiO_3/NaOH ratio (as in FC6) maintained and increased the compressive strength (44.9 MPa). This emphasizes an important scientific discovery: thorough optimization, as opposed to randomly separating the values of parameters, is more efficient. The findings of this study are consistent with the increasing evidence that geopolymer mortar may achieve superior strength and dimensional stability compared to traditional formulations. showed that alternative binder formulations could enhance the mechanical properties of traditional mortars. This agreement with the literature highlights the feasibility of HCFA-based mortars as a technically and environmentally superior replacement for OPC-based systems [27, 28].

Results of the Dry Shrinkage Test

Drying shrinkage tests were also carried out in triplicate, and the results are presented as mean values with standard deviations.

Prior to conducting the dry shrinkage test, a flow table test was performed in a designated flow table facility for each

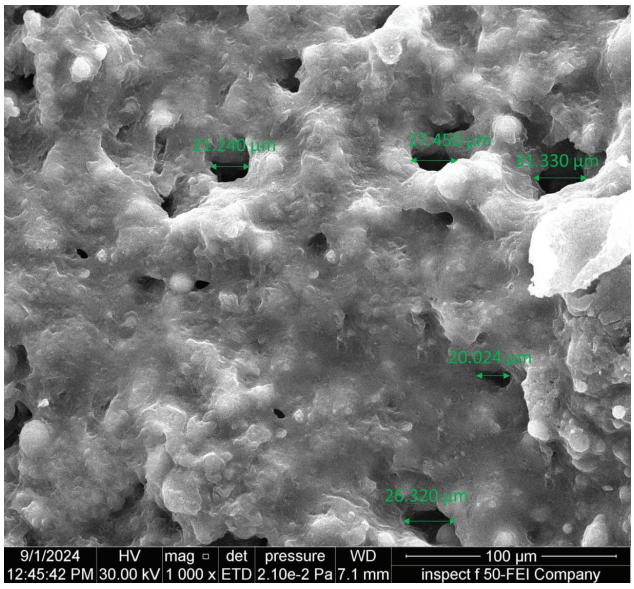


Figure 9. FESEM for FC4 mixture*.

*The samples were scanned on a Field Emission Scanning Electron Microscope: Inspect F50, manufactured by FEI Company. Imaging situation was as follows: an accelerating voltage of 30 kV; a magnification of 120, 000×, and working distance of 7.0 mm. Electron detection was made using an Everhart-Thornley Detector (ETD) at the chamber pressure of 1.10×10^{-3} Pa.

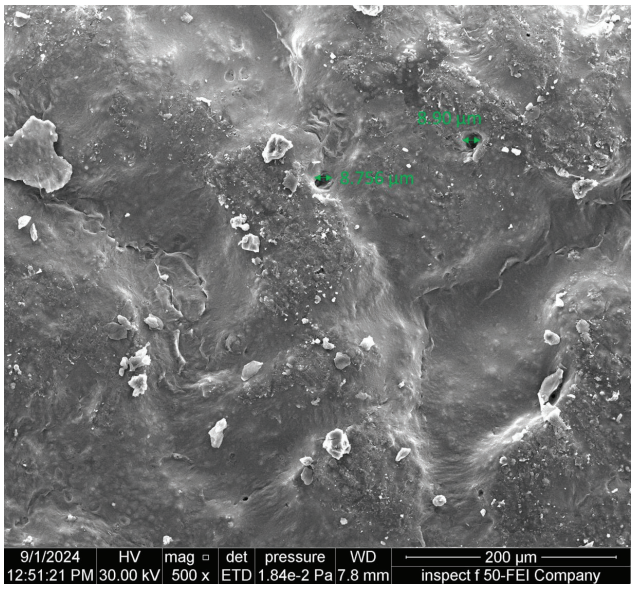


Figure 10. FESEM for FC6 mixture*.

*The samples were scanned on a Field Emission Scanning Electron Microscope: Inspect F50, manufactured by FEI Company. Imaging situation was as follows: an accelerating voltage of 30 kV; a magnification of 120, 000×, and working distance of 7.0 mm. Electron detection was made using an Everhart-Thornley Detector (ETD) at the chamber pressure of 1.10×10^{-3} Pa.

mixture in accordance with the guidelines of ASTM C596 [19]. The water ratio was changed until a flow of 210% was achieved. Table 7 and Figures 11 and 12 presents a comprehensive compilation of the dry shrinkage test outcomes.

Table 7 shows a disparity in the dry shrinkage values, indicating a preference for mixes that include PCE plasticizers. PCE enhances water retention and decreases evaporation rates, which helps maintain the structural integrity of the mortar during curing and drying [29]. The second

Table 7. Results of the dry shrinkage test

Mixtures	w/b for 210% flow	Dry shrinkage % ±SD
FM1	0.54	0.07±0.01
FM2	0.54	0.06±0.00
FM3	0.57	0.06±0.00
FM4	0.56	0.08±0.00
FM5	0.57	0.08±0.01
FM6	0.59	0.08±0.01
FC1	0.51	0.04±0.01
FC2	0.51	0.03±0.00
FC3	0.53	0.03±0.01
FC4	0.52	0.05±0.01
FC5	0.52	0.04±0.00
FC6	0.54	0.04±0.01

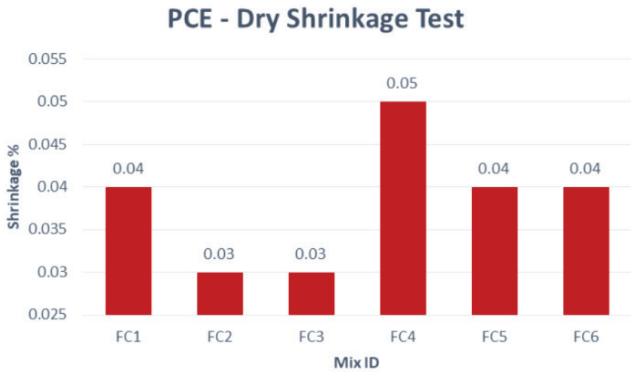


Figure 11. The outcomes of dry shrinkage test when using PCE.

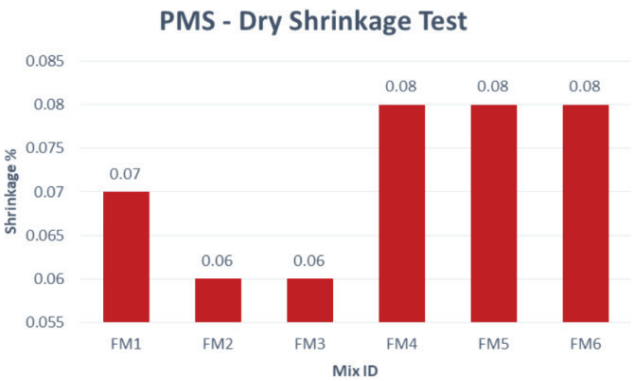


Figure 12. The outcomes of dry shrinkage test when using PMS.

Table 8. Adherence of critical material properties to the relevant ASTM standards

Property	ASTM Standard	Threshold	Compliance
Initial Setting Time	ASTM C191	≥ 45 minutes	Accepted (except FM6)
28-day Compressive Strength	ASTM C109	≥ 20 MPa	Accepted for All mixes
Loss on Ignition (LOI)	ASTM C618	≤ 6% (Class C)	Accepted (per supplier)
Fineness (sieve #325)	ASTM C618	≤ 34% retained	Accepted (per supplier)
Pozzolanic Activity	ASTM C618	Strength index ≥ 75%	Accepted

influential component is the elevated ratio of Na_2SiO_3 to NaOH. An increase in the proportion of Na_2SiO_3 increases the number of voids [30], leading to an escalation in drying shrinkage [31, 32]. The third determinant is the molar concentration of the NaOH solution. An increase in molar concentration leads to a rise in reaction temperature, resulting in an increase in drying shrinkage [33]. The last notable determinant is the moisture content of the mixture. One of the variables that contributes to an increase in drying shrinkage is the rise in water content. Water is prone to evaporation and leaves empty spaces behind, ultimately increasing drying shrinkage [34]. Previous studies (for example, Ma et al. [29]); Omur et al. [30]) state that there was increased shrinkage occurring when more sodium silicates were used or with increased water contents. Our results are in line with these findings and quantitatively support our findings that mixes with PCE and a less Na_2SiO_3/NaOH ratio (such as FC2 and FC3) obtained significantly lower drying shrinkage (0.03%) while demonstrating superior workability (flow up to 210%) which is material to the durability optimization.

Summary of Results Modification Effects

Improvement in setting time and mechanical properties after the modifications can be explained by the further improvement in the geopolymerization environment. A higher ratio of Na_2SiO_3 to NaOH brought about a less reactive alkaline environment, which allowed for the dissolution of the aluminosilicate elements of the HCFA at a slower rate, giving slower gel formations and network connections. Also, the increase in the NaOH molarity from 8M to 10M enhanced the break-down of glassy phases leading to increased quantities of silicate and aluminate monomers. The addition of PCE helped further to carry out better particle dispersion and thus lessen the internal friction which resulted in better compaction and lower porosity. And these collectively contributed to strength values and better dimensional stability.

Compliance with ASTM Specifications

A brief comparison between the experimental results and ASTM thresholds is presented in Table 8. All the mixes delivered compressive strength values within 28 days, which were above the minimum requirement of ASTM C109 (20 MPa). The time settings also conformed to the lower limit of 45 min for the first time setting of ASTM C191, excluding FM6. Although the LOI and fineness were not directly determined in this study, the HCFA tested was procured from a certified source and had adequate properties to satisfy the ASTM C618 Class C fly ash requirement.

CONCLUSION

This study validates that high-calcium fly ash (HCFA), when suitably treated, can completely substitute conventional cement in mortar production, while burned mortar surpasses ASTM standards. The optimal Na_2SiO_3-to-NaOH ratio with polycarboxylate ether (PCE) plasticizer additions showed notable improvements in the setting time, workability, and mechanical performance of the mortars. Specifically, mix FC3 exhibited a 28-day compressive strength of 42.8 MPa and a flexural strength of 5.07 MPa, along with compliance with customary setting time standards in ASTM C191. Furthermore, the HCFA-based mortar exhibited higher dimensional stability owing to reduced drying shrinkage. Its strong potential for industrial-scale production and incorporation into sustainable building standards is indicated by its encouraging performance. To measure environmental benefits, a thorough Life Cycle Assessment (LCA) is recommended for future research.

Replacing cement with HCFA enables a more sustainable and economically advantageous approach in the construction sector. These results endorse the modified HCFA mortar for general masonry works, pre-cast elements, and low-heat region applications, where environmental control and material cost reduction are prioritized. Employing HCFA directly supports circular economy principles by transforming industrial waste into high-quality construction material.

Research on the long-term durability of HCFA mortars should include freeze–thaw cycle resistance, sulfate attack, and performance in varying climatic conditions for field testing from an exterior perspective. Long-term structural reliability should also be established by examining factors, such as chloride penetration and carbonation resistance.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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