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Modifying the Properties of Granulated Blast Furnace Slag Mortar to Adhere to International Standards

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ABSTRACT

The need for environmentally friendly binders is driven by the high carbon footprint of Portland cement. Alkali-activated slag mortar is a promising alternative, but its application is limited by how quickly it sets. The ASTM specifications for mechanical strength and setting time were met by optimizing the granulated blast furnace slag mortar developed in this study. The mortar was activated using different SS/SH ratios (1.5 to 2.5) and sodium hydroxide molarities (8M and 10M), in addition to the two superplasticizers (PMS and PCE). The optimal formulation (SS/SH = 1.5, 8M NaOH, with PCE) had a flexural strength of 6.3 MPa, compressive strength of 42.5 MPa, and initial and final setting times of 45 and 130 min, respectively, after 28 d. In comparison to PMS, the PCE-enhanced mixes exhibited improved mechanical performance and a 23% decrease in shrinkage. This study demonstrates that optimizing the SS/SH ratio and NaOH molarity offers a more straightforward, scalable, and economical method for producing alkali-activated slag mortars that satisfy international standards while improving durability and workability, in contrast to more sophisticated approaches such as encapsulated activators or CO_2-modified slag.

1. INTRODUCTION

Cement production is a major cause of global environmental problems [1, 2]. The cement industry accounts for approximately six to eight percent of global CO_2 emissions, and by exploring alternative, environmentally friendly types of binders, it is possible to offer a way out to reduce how much cement is used and also lower their corresponding carbon emissions [3, 4]. Currently, alkali-reacted materials such as geopolymers are effective in utilizing by-products and recycling materials. In either case, they can indirectly reduce the dumping of by-products as industrial waste [5]. Granulated ground blast furnace slag serves as the primary component of alkali-activated slag concrete, which is a relatively new building material that is also beneficial to the environment [6-8]. However, because its setup time is quite short, the speed with which slag mortar sets is a major drawback for its practical use [9], which could greatly restrict its use in transportation and building. This issue must be addressed in future studies [10]. Many researchers have discussed the possibility of solving the problem of rapid setting, including Wang et al. [11], who examined the impact of calcium sulfate on the solidification duration of slag mortar. Their findings indicate that the addition of 4%, 5%, and 6% calcium sulfate resulted in dramatically increased setting times, yet a substantial proportion of calcium sulfate notably diminished the compressive strength of the slag mortar. Jin et al. [12] assessed the workability of alkali-activated one-part slag mortar and found that the specimen was unworkable after 20 minutes. Subsequently, calcium formate was used to prolong the duration of the mortar's effectiveness. However, this addition decreased the mortar's compressive strength, which can be attributed to the presence of calcium formate, which hinders the production of C-S-H gel. In another study, in order to lengthen the amount of time it takes for slag mortar to set, Xiang et al. [13] developed a method that involved the use of carbon dioxide as a pretreatment for slag. This technique effectively extended the working duration of the mortar without negatively affecting its characteristics. Nevertheless, this technique precludes the fundamental objective of utilizing slag as an eco-friendly, sustainable construction material.

Sun et al. [14] devised a technique to enclose alkaline activators in capsules or tablets, which are subsequently integrated into the structure of alkali-activated slag concrete. The purpose of this technique is to manage the initial rate at which the slag dissolves and hydrates, hence altering the time it takes for the alkali-activated material to harden. Specifically, the technique can increase the duration of the hardening process by almost 40%. Nevertheless, it brings significant difficulties, incurs high costs, and necessitates the use of sophisticated technologies while also demanding special techniques to control the heat generated by the activator materials. Shortly thereafter, Huo et al. [15] conducted a study comparable to that of Sun et al. in which they utilized alkali activators in the form of pills and capsules. When Mohamed et al. [16] investigated the effect that the activator concentration had on the amount of time it took for slag mortar to set, they found that the setting time never went beyond thirty minutes. This is significantly less than the forty-five minutes that are required by the majority of standards. Depending on the above considerations, the main objective of this research seeks to create an alkali-activated slag mortar that fulfils international standard requirements for initial and final setting duration and demonstrates superior mechanical and physical properties. The research studies activator solution composition together with superplasticizer types to enhance slag-based binder workability while providing sustainable solutions to overcome rapid setting issues for a Portland cement mortar substitute.

2. MATERIALS AND METHODS

2.1 Materials

This section provides an analysis of the materials employed in this investigation and their respective characteristics.

2.1.1 Slag

The DCP Company was the source of the slag that was utilised in this investigation. For the purpose of determining its chemical composition, which is detailed in Table 1, analytical testing was carried out.

Table 1. Chemical analysis of the slag

Oxide	Content (%)
SiO_2	29.90
CaO	40.65
Al_2O_3	17.18
MgO	8.92
Fe_2O_3	1.44
SO_3	1.56
LSF	0.39

2.1.2 Sodium silicate and sodium hydroxide

As the activator solution, the combination of sodium silicate (SS) and sodium hydroxide (SH) was utilized. This combination was supplied by O&T Tech and contains 66.1% water, 26.0% SiO_2 and 7.9% sodium hydroxide (NaOH). The specific gravity of this substance is 1.35.

SH in pellet form and with a purity exceeding 99% was the product of Eau de Senteur. This research involved preparing solutions at two distinct concentrations: 8 and 10 molar. The 8 molar solution contained 262 g of SH scales per liter, whereas the 10 molar solution contained 314 g of SH scales per liter, with the remaining volume consisting of distilled water. The solution was left to stand for 24 hours after preparation.

2.1.3 Sand

This research followed ASTM C778 [17] by using standard sand.

2.1.4 Water

Distilled water was employed in this research to mitigate the influence of contaminants.

2.1.5 Superplasticizers

This research employed two types of plasticizers, namely, polycarboxylate (PCE) supplied by Kingsun company and polymelamine sulfonate (PMS) supplied by JK Chemicals. Table 2 lists their properties.

Table 2. Properties of plasticizers

Oxide	PCE	PMS
Appearance	Powder	Powder
Density	600 kg/m^3	550 kg/m^3
pH	9	8
Chloride content	≤ 4%	≤ 0.05

2.2 Mixing ratio design

Various mixing ratios were used in the experiments in this study. For example, the evaluation of the beginning and end of the set is based on a consistency test. Several mixtures were tested until the right consistency was obtained, according to the ASTM C187 norm [18]. It may be noted that a consistent amount of water is to be checked before testing.

The optimal mixture proportion of PMS plasticizer combined was 335.37 g slag, 8 g PMS, and 178.62 g activator solution with a mass ratio of SS to SH of 2.5/1.0. In calculating the solid content of the activator solution contained in the binding substance, the remainder was classed as water in the reaction, and the powder plasticizer was regarded as part of the binding material. Hence, the water/binding material was calculated to be 30.5%. The optimal mixing amounts of slag, PCE plasticizer, and activator solution were 338.16, 8, and 169.84 g, respectively, while the SS/SH ratio was 2.5/1.0. Considering the solid quantity of the activator solution and plasticizer powder, the mass ratio of water to binding material was estimated to be 29%, with the remainder being allotted to the reaction as excess water.

The initial and final setting times of the optimized slag mortar mixtures were assessed after the consistency tests. The water-to-binder ratio was the same for all mixtures, but two important factors were investigated: sodium hydroxide molarity (8M and 10M) and sodium silicate-to-sodium hydroxide (SS/SH) ratio (ranging from 1.5 to 2.5). The mix designs and matching setting times are listed in Table 3. Prior research demonstrating the efficacy of these activator concentrations and ratios in improving the performance of alkali-activated binders served as a guide for selecting the activator-to-binder ratio. In particular, Omur et al. [19] showed that the ideal NaOH molarities for balancing workability and strength development in slag-based mortars are 8M to 10M. Furthermore, Özbayrak et al. [1] established empirical connections between the activator composition and the stress–strain behavior of geopolymer concrete, confirming the applicability of the chosen SS/SH ratios.

Owing to different testing requirements, the water-to-binder (W/B) ratios utilized in this study varied between the setting time and strength evaluation stages. Lower W/B ratios (29.0–30.5%) were optimized for the setting time measurements (Table 3) based on consistency tests to represent real-world alkali-activated mortar application conditions. On the other hand, a fixed W/B ratio of 48.5% was used for the compressive and flexural strength tests (Table 4), in accordance with the standard mortar mix proportions recommended by ASTM C109 (1:2.75:0.485). Consequently, rather than reflecting an inconsistent experimental design, the variation adheres to pertinent testing standards [20].

In the flexural strength and compressive strength tests, the mixing ratios were adjusted in accordance with ASTM standards specified in Table 4, distinct from the ratios of the slag mortar's initial and final setting time.

2.3 Tests conducted in this study

This section describes all the tests carried out on the slag mortar.

2.3.1 Initial and final setting time

The setting time (both initial and final) of mortar is an important factor influencing the time after which mortar paste begins to lose its plasticity and the time required for full setting. These times are usually measured by tests, such as the Vicat test. The initial setting time refers to the duration needed for the mortar paste to transition from a plastic, workable condition to the beginning of solidification. In contrast, the final set shows the stage where the malleability of the paste is lost, and the paste is finally set. The Vicat test was conducted according to ASTM C191 [20].

2.3.2 Compressive strength and flexural strength

Compressive strength measures a material's capacity to resist axial forces and is considered a vital characteristic of construction materials. In accordance with ASTM C109 [21], this property is typically evaluated using mortar cubes prepared with a binder-to-sand-to-water ratio of 1:2.75:0.485. The specimens used for testing were cube-shaped, each with dimensions of 50 × 50 × 50 mm.

Flexural strength, another key mechanical property, reflects a material's resistance to bending stresses, which is especially relevant in structural applications subjected to significant flexural loads. As per ASTM C348 [22], the standard size for mortar samples used in flexural strength testing is 40 × 40 × 160 mm, with the same mix proportion of 1:2.75:0.485 for binder, sand, and water. The standard deviation (SD) values have been added to the pertinent tables, in addition to the average outcomes for every tested property. These additions offer more insight into the dependability of the measured values and help clarify the variability in data across triplicate specimens.

2.3.3 Dry shrinkage

Dry shrinkage is the reduction in dimensions that takes place in a solidified paste, mortar, or concrete as it gradually loses moisture. Shrinkage can cause cracks and other structural problems, so quantifying this characteristic is critical. Various organizations have developed standardized tests to assess cement-drying shrinkage, with one widely used standard being ASTM C596 [23]. In addition to the average outcomes for each tested property, the standard deviation (SD) values were incorporated into the relevant tables. In addition to providing additional insight into the dependability of the measured values, these additions also assist in clarifying the variability in data across triplicate specimens.

Table 3. Details of mixtures for the initial and final setting time

Distinguish	Slag g	W*/binder %	NaOH	$Na_2SiO_3/NaOH$	Activator Solution g	Plasticizer g
PM1	335.37	30.5	8	2.5	178.62	PMS 8
PM2	336.45	30.5	8	2.0	177.54	PMS 8
PM3	337.65	30.5	8	1.5	176.36	PMS 8
PM4	331.36	30.5	10	2.5	182.64	PMS 8
PM5	331.72	30.5	10	2.0	182.28	PMS 8
PM6	332.18	30.5	10	1.5	181.82	PMS 8
PC1	338.16	29.0	8	2.5	169.84	PCE 8
PC2	339.15	29.0	8	2.0	168.85	PCE 8
PC3	340.31	29.0	8	1.5	167.69	PCE 8
PC4	334.35	29.0	10	2.5	173.65	PCE 8
PC5	334.68	29.0	10	2.0	173.32	PCE 8
PC6	335.12	29.0	10	1.5	172.88	PCE 8

* The water (W) is not extra; it is part of the activator solution.

Table 4. Details of mixtures for compressive and flexural strength

Distinguish	Slag g	W*/binder %	NaOH	$Na_2SiO_3/NaOH$	Activator Solution g	Sand g	Plasticizer g
PM1	301.96	48.5	8	2.5	284.04	1100	PMS 8
PM2	303.61	48.5	8	2.0	282.39	1100	PMS 8
PM3	305.57	48.5	8	1.5	280.43	1100	PMS 8
PM4	295.58	48.5	10	2.5	290.42	1100	PMS 8
PM5	296.14	48.5	10	2.0	289.86	1100	PMS 8
PM6	296.88	48.5	10	1.5	289.12	1100	PMS 8
PC1	301.96	48.5	8	2.5	284.04	1100	PCE 8
PC2	303.61	48.5	8	2.0	282.39	1100	PCE 8
PC3	305.57	48.5	8	1.5	280.43	1100	PCE 8
PC4	295.58	48.5	10	2.5	290.42	1100	PCE 8
PC5	296.14	48.5	10	2.0	289.86	1100	PCE 8
PC6	296.88	48.5	10	1.5	289.12	1100	PCE 8

3. RESULTS AND DISCUSSION

All experimental procedures used in this investigation were performed in compliance with the applicable ASTM standards. Compressive and flexural strength tests were conducted in accordance with ASTM C109 and ASTM C348, respectively, while the setting time tests were conducted in accordance with ASTM C191. The shrinkage tests met the requirements of ASTM C596. The testing procedures were rigorously followed to guarantee uniformity and comparability, even though alkali-activated mortars are not specifically covered by these standards. Any modifications, such as changing the water-to-binder ratio or mix design, were made to account for the distinct rheological characteristics of the alkali-activated systems and are amply supported by the methodology.

3.1 Results of initial and final setting time

This section presents and analyzes the results of the initial and final setting time tests conducted on slag mortar, as illustrated in Figure 1. It is evident from Figure 1 that all the blends complied with the requirements set by ASTM C191. The data also show that the setting time decreases when a lower SS/SH ratio is used. This was also observed when mixtures PM2, PM3, PM5, and PM6 were compared with PM1, as well as for PC2, PC3, PC5, and PC6 compared with PC1, which is consistent with the results in the study [24, 25]. In addition, a small increase in the SH molar concentration was observed to increase the setting time under certain conditions. This was manifested by comparing mixtures PM4, PM5, and PM6 to PM1, PM2, and PM3, and mixtures PC4, PC5, and PC6 to PC1, PC2, and PC3, respectively. The delayed setting time can be attributed to the increased concentration of free calcium ions, which promotes the formation of both C-A-H and C-S-H gels in low-molarity NaOH environments. In contrast, increasing the molarity will cause more Na+ and OH− ions to exist, which can speed up the dissolution of aluminosilicate precursors and result in a reduction in the extraction of calcium ions. The effect of higher molarity mechanisms is associated with slower geopolymerization reactions than those of Ca ion hydration reactions, thus contributing to an increase in the hardening time [26].

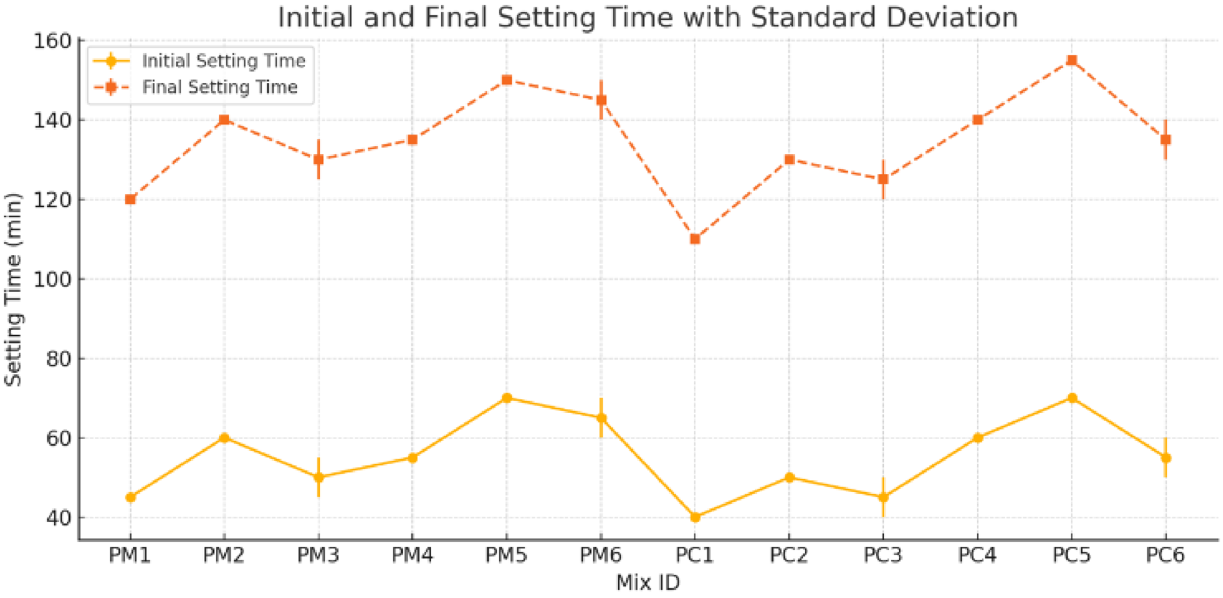

Figure 1. Initial and final setting time results

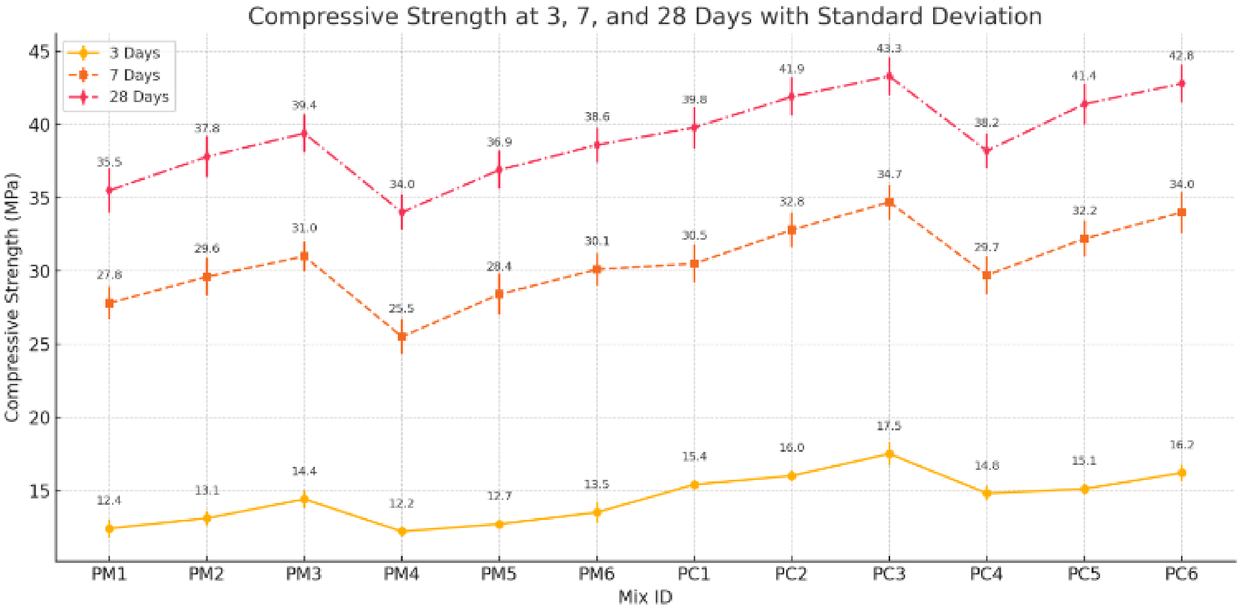

Figure 2. Compressive strength results

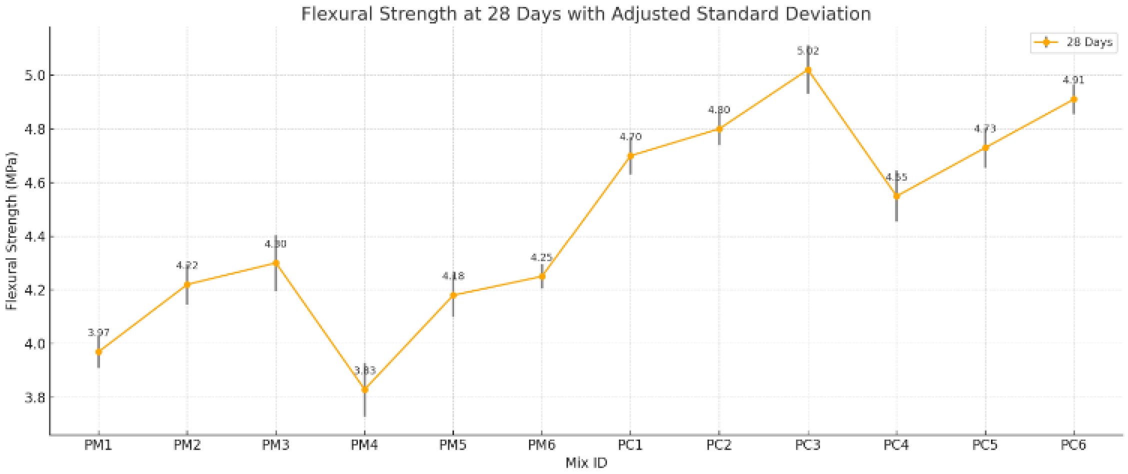

Figure 3. Flexural strength results

3.2 Results of compressive strength and flexural strength tests

Figures 2 display the compressive strength test results at different ages in comparison to the control sample, while those of the flexural strength test at 28 d are shown in Figures 3. All peaks in both figures correspond to the ASTM C150 norm [27], with the best composition resulting in PC3. The compressive strength of the concrete material increased visibly as the SS to SH ratio decreased, as shown in Figure 2. The research findings support the statement of earlier investigations [24, 28]. Figure 4 and Figure 5 illustrate how void formation brought on by an excess of silicate has been linked to a decrease in strength at higher silicate contents. In particular, Figure 4 demonstrates that Mix PC1, which has a higher SS/SH ratio than Mix PC3, has more voids. Using image analysis software, a quantitative void analysis was carried out to verify these findings. According to the results, Mix PC1 had a void ratio of about 12.4%, whereas Mix PC3 had a much lower void ratio of 7.8%. These results support the visual examination and the inference that higher porosity results from an increase in the SS/SH ratio. The mechanical behavior observed in this study is consistent with the microstructural evidence presented in the SEM images.

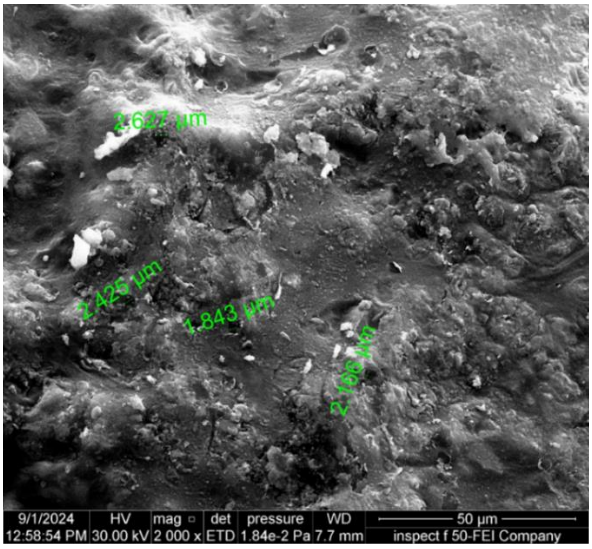

Figure 4. SEM for PM3 mixture

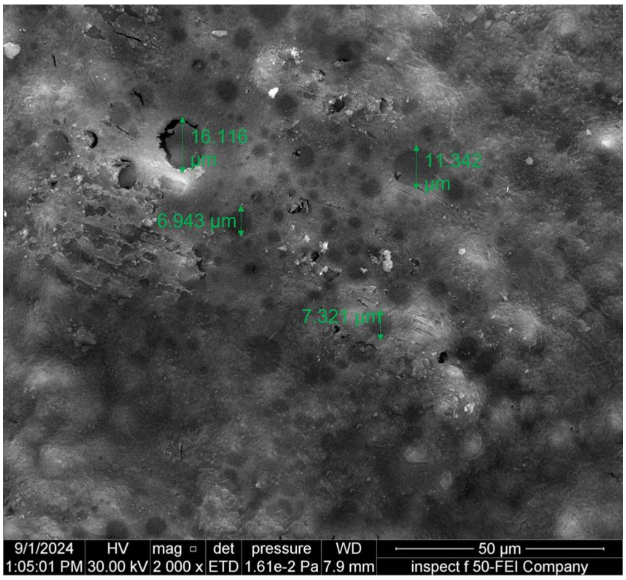

Figure 5. SEM for PM1 mixture

The reason for the reduction in the compressive strength of the alkali-activated materials with increasing molarity is attributed to the hindrance of polycondensation because of the rapid decomposition of alumina and silica at higher concentrations of the alkaline solutions [19]. Furthermore, excessive NaOH solution can suppress the dissolution of calcium; therefore, the content of the hydration product is not high [29]. In particular, the highest flexural strength value was obtained for the PC3 mix, using the same variable conditions as those applied in the compressive strength tests (Section 3.1). Owing to variations in their dispersion mechanisms, PCE performs better than PMS. The main mechanism by which PCE works is steric hindrance, in which Tenure, where its lengthy side chains physically separate particles in the pore solution, improves dispersion and lowers water demand. In contrast, PMS primarily uses electrostatic repulsion, which is typically less successful in high-alkaline environments, such as alkali-activated systems. The reason PCE-enhanced mortars exhibited less shrinkage and greater mechanical strength than mortars containing PMS can be explained by this mechanistic difference. Recent developments in alkali-activated materials have introduced more sophisticated methods for maximizing mechanical performance and setting behavior. To improve the setting time and long-term durability, Sun et al. [14] suggested using encapsulated alkali activators to regulate the early dissolution kinetics in slag-based systems. Despite their technological promise, these approaches are frequently expensive and require intricate processes. In contrast, the current study shows that comparable improvements can be achieved without encapsulation by carefully choosing the SS/SH ratio and NaOH molarity. Additionally, the significance of the 1.5–2.5 SS/SH ratio range used in this study was validated by Özbayrak et al. [1], who created empirical models connecting activator ratios to the stress–strain response of geopolymer concrete. These results support the scientific foundation and practical applicability of the current mixed-design strategy.

3.3 Results of the dry shrinkage test

Before testing the dry shrinkage, it is necessary to test the flow table in a flow table apartment for each mixture, depending on ASTM C596 [23], so that the water ratio is adjusted until a flow of 210% is obtained. There is a comprehensive presentation of the results of the drying shrinkage experiments in Figure 6.

The range of dry shrinkage values shown in Figure 6 highlights the enhanced performance of mixtures incorporating PCE plasticizers. The improved water retention and reduced evaporation rates provided by PCE contribute to the preservation of the mortar's integrity during the curing and drying stages [30]. Additionally, the process is affected by the increasing ratio of SS to SH. Section 3.2 explains that increasing the SS ratio creates more solution voids, which results in increased drying shrinkage [19, 31, 32]. Finally, the molar concentration of the SH solution is a significant component that plays a role in the process. The reaction temperature increases because of the higher molar concentration, which leads to enhanced drying shrinkage behavior [33]. The fourth influential factor is the mixture's water content. Increasing the water content is identified as a factor that causes an increase in drying shrinkage, as water is susceptible to evaporation and leaves voids in its place, thus increasing drying shrinkage [34].

3.4 Environmental impact estimation

Compared to regular Portland cement (OPC), the use of alkali-activated slag mortar considerably lowers CO_2 emissions in terms of environmental performance. According to published life cycle assessment (LCA) studies, alkali-activated slag binders emit only 0.20–0.30 tons of CO_2 per ton, depending on the type and dosage of alkaline activators, while the production of OPC releases approximately 0.85–0.95 tons of CO_2 per ton of cement. According to this study, the optimized mix designs (such as PC3) are expected to reduce CO_2 emissions by approximately 65–75% compared to mortars based on OPC. This significant drop emphasizes the sustainability benefits of the suggested binder system [35, 36].

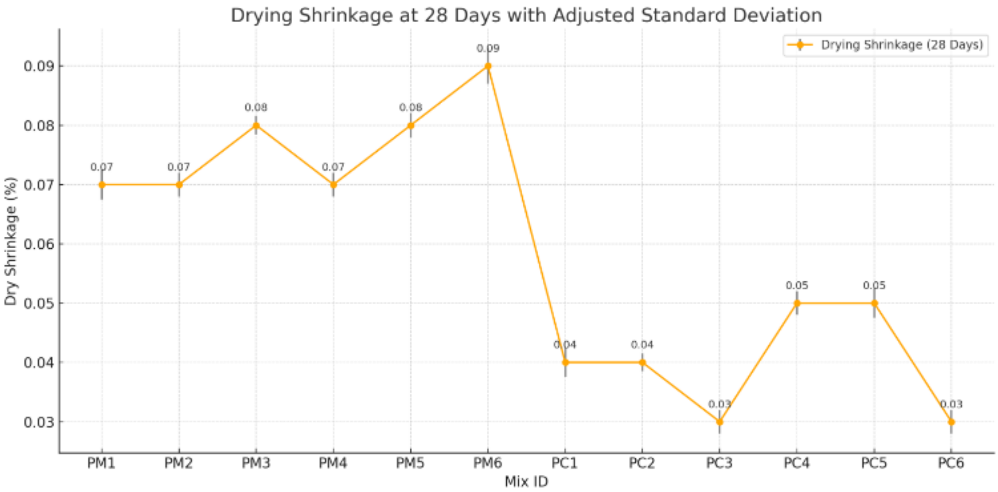

Figure 6. Dry shrinkage test results

4. LIMITATIONS AND FUTURE WORK

Although slag mortar compositions have been successfully optimized to meet international performance standards, a number of issues still need to be resolved.

a. Performance under Cold Weather and Field Applicability:

This study was conducted only in a laboratory setting. It is crucial to test these mixes in field settings, particularly in cold climates, to confirm their real-world performance. Zhang et al.'s recent research from 2025 highlighted how behavior under sub-zero conditions is greatly influenced by SS/SH ratios and NaOH molarity [37]. The study [38] showed the importance of choosing the right alkali cations (K^+ vs. Na^+, for example) to preserve strength and hydration under freezing conditions.

b. Long-Term Durability:

This section did not address extended durability factors such as drying shrinkage in cold climates, carbonation, chemical resistance, or freeze-thaw cycles. For example, a recent study found that MK-modified slag mortar exhibited better freeze-thaw resistance [39, 40].

5. CONCLUSION

This study reveals that all tested combinations satisfy ASTM standards because they meet established requirements, although some variations emerge among them. The essential results of the examination appear below:

a) Reducing the SS to SH ratio enhances the properties of slag mortar.
b) Molar concentration: Decreasing the molar concentration enhances mechanical characteristics. Elevated molar concentrations lead to heightened carbon dioxide emissions.
c) A PCE plasticizer demonstrates more efficacy than a PMS plasticizer.
d) Application of slag mortar: By implementing the necessary alterations, slag can function as a feasible alternative to cement. The slag mortar may be easily manipulated and carried once it has undergone sufficient time for setting.
e) After these results, we can produce slag cement with a complete mixture, and only the activator solution is added to it.
f) The results suggest that optimizing the composition of slag mortar makes it possible to achieve compliance with international requirements while enhancing both performance and sustainability.

It is crucial to remember that PCE is typically more costly, even though it shows better mechanical performance and less shrinkage than PMS. However, in high-performance or durability-critical applications, where long-term structural integrity is a top concern, its improved dispersion efficiency and durability advantages might make the extra expense worthwhile.

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