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The Effect of Partial Replacement of Cement with Alkali-Activated Electric Arc Furnace Slag on the Compressive Strength of Mortar: A Comparison between Alkaline Curing and Early Thermal Curing

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تأثير الاستبدال الجزئي للإسمنت بخبث فرن القوس الكهربائي المنشط قلوياً على مقاومة انضغاط المونة: مقارنة بين المعالجة قلويا والمعالجة الحرارية المبكرة

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ABSTRACT

This study aimed to evaluate the effect of the partial replacement of cement with alkali-activated electric arc furnace slag (EAFS) on the compressive strength of cementitious mortar, while also examining the influence of different curing regimes on strength development. Mortar specimens were prepared with a sand-to-binder ratio of 1:2.75. Five levels of cement replacement with slag were investigated: 4, 8, 12, 16, and 20%. A sodium hydroxide solution was used as the sole alkaline activator at a concentration of 10 M, and a superplasticiser was incorporated to improve workability. After casting the mortar into 50 × 50 × 50 mm cubes, different curing regimes were applied. The reference specimen was cured by immersion in water, whereas the other specimens were either immersed in a 10 M sodium hydroxide solution for 28 days or subjected to early thermal curing immediately after demoulding at 65 °C for 24 hours, followed by sealing in plastic wrapping for 27 days until the testing age. The results showed that the reference specimen cured in water achieved the highest compressive strength among all specimens (41 MPa). In contrast, curing by immersion in the sodium hydroxide solution reduced the strength to 22 MPa, while early thermal curing resulted in the lowest compressive strength (18 MPa). Furthermore, the alkali-activated slag mixtures exhibited a noticeable reduction in strength compared with the reference specimen, although early thermal curing produced a relative improvement at certain replacement levels. These findings indicate the limited effectiveness of a single alkaline activator in activating slag within the investigated replacement ratios. A comparison with previous studies that utilised the same type of slag but activated it using a combination of sodium silicate and sodium hydroxide, together with curing at higher temperatures, suggests that the combined presence of a soluble silica source and intensive heat treatment enhances the microstructural development and densification of slag-based systems, thereby resulting in higher compressive strength.

Keywords:

Electric Arc Furnace Slag; Alkaline Activation; Cement Mortar; Compressive Strength; Thermal Curing; Cement Replacement

الملخص

هدفت هذه الدراسة إلى تقييم تأثير استبدال الاسمنت جزئيا بخبث فرن القوس الكهربائي المنشط قلوياً على مقاومة الانضغاط لمونة الأسمنتية، مع دراسة أثر اختلاف نوع المعالجة على تطور المقاومة. تم تحضير عينات المونة بنسبة رمل: مادة رابطة 1:2.75، مع خمس نسب لاستبدال الأسمنت بالخبث وهي: 4، 8، 12، 16، و20%، واستخدم محلول هيدروكسيد الصوديوم كمنشط قلوي وحيد بتركيز 10 مولار، بالإضافة إلى استخدام الملدن الفائق لتحسين قابلية التشغيل. بعد صب عينات المونة في مكعبات 50×50×50 ملم، تم تطبيق طرق معالجة مختلفة: الغمر في الماء للعينة المرجعية فقط، والغمر في محلول هيدروكسيد الصوديوم بتركيز 10 مولار لمدة 28 يومًا، والمعالجة الحرارية المبكرة عقب فك القوالب مباشرة عند 65°م لمدة 24 ساعة ثم التغليف بعازل بلاستيكي لمدة 27 يومًا حتى موعد الاختبار لجميع العينات. بينت النتائج أن العينة المرجعية المعالجة بالغمر في الماء سجلت أعلى مقاومة انضغاط بين جميع العينات (41 *MPa*)، بينما أدت المعالجة بالغمر في محلول هيدروكسيد الصوديوم إلى انخفاض المقاومة إلى 22 *MPa*، وسجلت المعالجة الحرارية المبكرة أقل مقاومة (18 *MPa*). كما أظهرت عينات الخبث المنشط انخفاضًا ملحوظًا في المقاومة مقارنة بالعينة المرجعية، مع حدوث تحسن نسبي للمعالجة الحرارية عند بعض نسب الاستبدال، ما يشير إلى محدودية فعالية المنشط القلوي الأحادي في تنشيط الخبث ضمن نسب الاستبدال المدروسة. وأشارت المقارنة بالدراسات السابقة التي استخدمت نفس نوع الخبث مع تنشيطه باستخدام مزيج من السيليكات وهيدروكسيد الصوديوم ومعالجة عند درجة حرارة معالجة أعلى إلى أن الجمع بين مصدر السيليكا الذائبة والتسخين المكثف يعزز بنية الخبث وكثافته، مما يحقق مقاومة أعلى.

الكلمات المفتاحية:

خبث فرن القوس الكهربائي; التنشيط القلوي; مونة أسمنتية; مقاومة الانضغاط; معالجة حرارية; استبدال الأسمنت.

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1. INTRODUCTION

The text that is prepared on all the production of Portland cement results in high carbon emissions in addition to substantial consumption of natural resources, which has encouraged researchers to develop more sustainable and environmentally friendly alternatives such as alkali-activated materials [1, 2]. Among the materials receiving considerable attention is furnace slag, a by-product generated from the iron and steel industry during smelting operations in various types of furnaces [3].

During this process, oxides present in iron ores are reduced and the associated impurities are separated and collected as a secondary by-product that is removed from the manufacturing process. The resulting slag is then discharged and cooled either in air or by water quenching [4]. The properties and chemical composition of slag are influenced by several factors, including the raw materials used in iron and steel production (iron ore or scrap steel), the type of furnace employed in the smelting process (blast furnace or electric arc furnace), the additives introduced during manufacturing, and finally the cooling method used. Rapid cooling produces slag with a predominantly glassy structure, whereas slow cooling results in a crystalline structure [5].

It is worth noting that blast furnace slag is characterised by a high glassy phase content, which has enabled its widespread use as a supplementary material in the production of ordinary Portland cement at replacement levels exceeding 60% [6, 7]. Electric arc furnace slag (EAFS) can also be used as an alternative precursor to blast furnace slag in alkali-activated cementitious systems. Despite containing a higher proportion of crystalline phases compared with blast furnace slag, EAFS can be effectively activated in a strongly alkaline environment that facilitates the gradual dissolution of reactive elements such as calcium, silicon and aluminium. This process leads to the formation of cementitious gel-like reaction products. The reactivity of slag is closely related to its chemical composition and the proportion of amorphous phases; however, the provision of an appropriate alkaline medium enhances the activation process and enables the development of relatively acceptable mechanical properties, thereby supporting its potential as a sustainable alternative material in alkali-activated systems [8].

Electric arc furnace technology has become the most widely used method in many developed countries for melting scrap steel, owing to its environmental advantages compared with conventional production routes. In this process, scrap iron is recycled to produce iron and steel with the addition of certain materials to improve the properties of the primary product, while electric arc furnace slag (Electric Arc Furnace Slag – EAFS) is generated as a secondary by-product [9].

Furnace slag is rich in mineral constituents, which makes it a promising candidate for partial replacement of cement once activated with strong alkaline solutions such as sodium hydroxide or sodium silicate solutions [10]. When slag rich in CaO and SiO_2 is activated using sodium hydroxide (NaOH), the alkali-activation process begins with the dissolution stage, during which OH^- ions attack the crystalline network and release ions such as Si^{4+}, Al^{3+} and Ca^{2+} into the solution. The rate of dissolution depends on factors such as the molarity of the activator, the Ca/Si ratio and the proportion of the glassy phase in the slag. Following dissolution, a reorientation stage occurs in which the released ions reorganise and the gel phase begins to form. This is followed by the polycondensation or hardening stage, where two possible products may form depending on the chemical composition of the slag. In systems with high calcium content, a hydration gel similar to that produced during Portland cement hydration, namely C-(A)-S-H gel, is formed. In contrast, when calcium content is low and aluminium content is high, a sodium aluminosilicate gel (N-A-S-H gel) may develop. Since electric arc furnace slag is typically rich in calcium, the first reaction product—C-(A)-S-H gel—is generally formed during its alkali activation [11–13].

The sodium oxide content in the activator (%Na_2O) and the molarity of the NaOH solution play a significant role in the strength development of alkali-activated mortars. Compressive strength generally increases up to an optimum %Na_2O value and a certain molarity level, after which it may decline when these parameters exceed their optimal ranges [14, 15]. The partial replacement of cement with furnace slag has therefore been investigated in numerous studies addressing sustainable alternatives in both mortar and concrete. Some studies have demonstrated that replacing 5–15% of cement with activated slag can improve compressive strength compared with conventional mortar [16].

However, the behaviour and performance of alkali-activated slag are strongly influenced by curing conditions, including temperature and immersion. Different curing regimes can lead to significant variations in the development of gel networks, which in turn affect the final compressive strength values [17–19]. Previous studies have indicated that increasing the molarity of sodium hydroxide solution enhances the dissolution of slag components and promotes the formation of strength-bearing gel up to an optimum level that may reach approximately 12 M. Nevertheless, very high concentrations (above 14 M) can lead to rapid precipitation and the formation of a less homogeneous microstructure [20, 21].

Thermal curing at temperatures ranging from 40–80 °C has also been reported to accelerate strength development at early ages due to an increased rate of alkaline reaction [22]. Conversely, moist curing or immersion curing helps maintain the alkaline environment, reduces porosity and improves microstructural densification compared with air curing [23].

Despite the large number of international studies addressing the alkali activation of electric arc furnace slag (EAFS), local research in Libya concerning the incorporation of this material into conventional cement mortar at specific replacement levels (4, 8, 12, 16 and 20%), with direct activation using NaOH and under different curing regimes, remains limited or largely absent in the published scientific literature. Therefore, this study represents an original and significant contribution to the scientific community interested in sustainability and its integration with engineering applications.

2. AIM OF STUDY

- Evaluate the effect of the partial replacement of cement with alkali-activated electric arc furnace slag (EAFS) on the compressive strength of cementitious mortar.
- Investigate the influence of different slag replacement levels (4%, 8%, 12%, 16%, and 20%) on the mechanical performance of mortar compared with the reference mixture.
- Examine the effect of different curing regimes (immersion in sodium hydroxide solution and early thermal curing) on the development of compressive strength in slag-containing mortars.
- Assess the effectiveness of sodium hydroxide (NaOH) solution as a sole alkaline activator for activating electric arc furnace slag within the investigated replacement ratios.
- Compare the performance of alkali-activated mortars with the water-cured reference mortar in order to determine the feasibility of using electric arc furnace slag as a partial cement replacement.
- Contribute to sustainable construction practices by exploring the potential utilisation of an iron and steel industry by-product in cement-based materials.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Materials of the Reference Mix

– Cement

The cement used in this study was Ordinary Portland Cement (OPC), CEM I 42.5 N, produced by the Beni Suef Cement Company in Egypt. It was used as the binding material in all mixtures. The cement complies with the Egyptian Standard ES 4756-1/2022 and the European Standard EN 197-1:2011. It is characterised by a compressive strength of ≥ 42.5 MPa after 28 days, an initial setting time of ≥ 60 minutes, and a soundness (expansion) value of ≤ 10 mm. The chemical composition of the cement is presented in Tables 1 and 2.

Table 1: Chemical oxides composition (wt.%) of Beni Suef cement [24]

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CL	Cr+6
Percentage (%)	20.38	4.77	3.75	62.44	1.25	2.53	0.04	1.75ppm

Table 2: Chemical compounds composition (wt.%) of Beni Suef cement [24]

Compounds	C_3A	C_4AF	C_2S	C_3S
Percentage (%)	6.29	11.40	19.14	52.07

– Sand

Locally sourced sand from the Genzour area, eastern Libya was used (see Figure 1). The sand underwent laboratory testing to determine its physical properties, as summarised in Table 3. Additionally, the particle size distribution of the sand was compared with the American standard ASTM C33 for grading, as illustrated in Figure 2.

Figure 1: The sand used.

Table 3: Physical properties of the sand used.

Fineness (%)	Bulk density (kg/m³)	Specific gravity	Water absorption (%)	Fineness modulus
0.70	1610	2.71	1	1.69

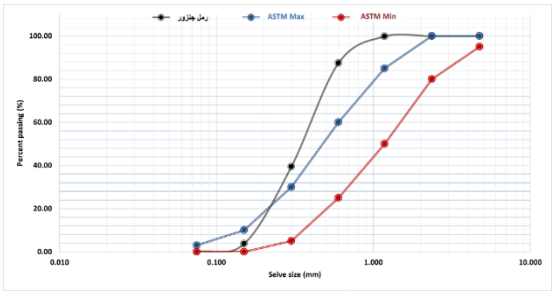

Figure 2: Particle size distribution of the sand compared with ASTM C33 standard.

– Water

Tap water was used as the water source, complying with the American standard for mixing water (ASTM C1602) in terms of chemical and physical properties. It was used both as mixing water in the mortar and as immersion water in the curing tanks for the specimens.

– Chemical Admixtures

The superplasticiser Sikament-R4PN was employed in this study. It is a dark brown liquid with a density of approximately 1.21 kg/L at room temperature and conforms to ASTM C-494. This superplasticiser has a dual effect: it is used to produce high-flow concrete by reducing the water content in the mix by up to 20%, enabling the production of concrete with high strength. It is suitable for use with both conventional cementitious concrete and pozzolanic concrete containing furnace slag.

3.1.2 Materials for Alkali-Activated Slag Mortar Specimens

In addition to the materials described in section 3.1.1, slag and alkaline activator were used to prepare the alkali-activated slag mortar specimens.

– Slag

Electric arc furnace slag (EAFS) was used as a partial replacement for cement in the alkali-activated mortar specimens. It is a by-product from the iron and steel plant in Misrata, northwest Libya. The full quantity of slag, its chemical composition, and the grinding and sieving procedures were obtained from a previous local study on replacement and activation. According to that study, the oxide composition was determined using X-ray fluorescence (XRF), as shown in Table 4, while the physical properties of the slag are presented in Table 5.

In that study, the slag was ground to a relatively fine powder and then sieved through a 75 µm sieve, with the retained portion excluded and the passing fraction used in the current experiments.

Table 4: Chemical oxides composition (wt.%) of EAFS [25].

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	TiO_2
Percentage (%)	17.54	5.45	25.90	33	7.11	0.35	0.25	0.94

Table 5: Physical properties of EAFS [25].

Surface area (cm^2/g)	Colour	Density (kg/m^3)
2251	Dark grey	3300

– Alkaline Activator

Sodium hydroxide (NaOH) flakes with a purity of 99% were used to prepare the alkaline solution by dissolving a measured amount in distilled water. The solution was prepared in the laboratory at a molarity of 10 M. Since the reaction is exothermic, the solution was prepared 24 hours prior to use.

This solution was added to the mortar components during mixing to activate the alkali-activated slag. It was also used to fill the immersion tanks during the alkaline curing of the alkali-activated slag mortar specimens. Figure 3 illustrates the preparation of the materials used in the alkali-activated slag mortar.

Figure 3: Materials used for the preparation of alkali-activated slag mortar specimens.

3.2 Methodology

3.2.1 Mix Proportions

A modified methodology from a previous study using the same slag was adopted [25]. In the present study, the specimens were prepared with a sand-to-binder ratio of 1:2.75, where the binder consisted of either cement alone or a cement/slag blend, depending on the specimen. The liquid components included mixing water, the alkaline activator, and the superplasticiser. Sodium hydroxide solution was used as the sole alkaline activator, with an activator-to-binder ratio (AAS/B) of 0.35.

This ratio was selected to control the total liquid content, reduce expected porosity, and maintain acceptable workability, given the high alkalinity of the activator used in this study compared with the previous study, which employed a combination of sodium silicate and sodium hydroxide at a maximum molarity of 8 M and an activator-to-binder ratio of 0.40. It is noteworthy that the previous study used a dual-alkali activation system, providing an additional source of soluble silica, unlike the single-activator system applied in the present study. The superplasticiser-to-binder ratio (SP/B) was set at 2%. The specimens were designed as follows: the reference sample (R) contained cement only as the binder with no alkaline activator added during mixing, while partial replacement of cement with alkali-activated slag was carried out at 4% (B4), 8% (B8), 12% (B12), 16% (B16), and 20% (B20). These labels were used to facilitate identification of each specimen during testing and data analysis (Table 6).

Table 6: Mix designations, corresponding weights, and proportions.

Mix designation	Binder content (%)		Binder weight (kg/m^3)		Sand weight (kg/m^3	SP/B %	W/B	AAS/B
	OPC	EAFS	OPC	EAFS				
R	100	0	500	0	1375	2	0.42	0
B4	96	4	480	20	1375	2	0.42	0.35
B8	92	8	460	40	1375	2	0.42	0.35
B12	88	12	440	60	1375	2	0.42	0.35
B16	84	16	420	80	1375	2	0.42	0.35
B20	80	20	400	100	1375	2	0.42	0.35

3.2.2 Preparation and Mixing Procedures

The liquid components were mixed according to the specimen type with the cement/slag blend and sand using a mechanical mixer. The mixing was carried out in controlled stages with timed intervals, using a timer, to achieve a total mixing time of 4 minutes from the moment the cement/slag was added, in accordance with the American standard ASTM C306 (Figure 4).

Figure 4: Mixing of an alkali-activated slag mortar specimen.

3.2.3 Specimen Casting

All specimens, including the reference mortar and alkali-activated slag mortar samples, were cast into compressive strength testing cubes measuring 50 × 50 × 50 mm (Figure 5). The mortar was poured in two layers, with manual tamping and surface levelling applied for each layer. The specimens were left to set in the molds for 24 hours before demoulding, after which they were cured according to the procedures described in Section 3.2.4.

Figure 5: Casting of several alkali-activated slag mortar specimens.

3.2.4 Curing Methods

After 24 hours from casting, the specimens were demoulded and divided into groups according to the curing methods adopted in this study. The first curing method involved immersion in water, which was applied only to the reference specimens (Figure 6). Both the reference specimens and the alkali-activated slag mortar samples were subjected to two additional curing regimes:

Immersion in sodium hydroxide solution for 28 days (Figure 7).

Early thermal curing, applied immediately after demoulding. In this method, the cubes of the reference and slag mortar specimens were placed in a thermal incubator at 65 °C for 24 hours (Figure 8). Afterward, they were removed and allowed to cool in air on the laboratory bench, then sealed in transparent plastic wrapping for 27 days until the testing age (Figure 9).

Figure 6: Curing of the reference specimens in water immersion tanks.

Figure 7: Curing of the reference and alkali-activated slag mortar specimens in sodium hydroxide immersion tanks.

Figure 8: Thermal curing of the reference and alkali-activated slag mortar specimens in an incubator at 65 °C for 24 hours.

Figure 9: Sealing of the reference and alkali-activated slag mortar specimens in plastic wrapping for 27 days following thermal curing.

3.4 Testing

The compressive strength test was conducted in accordance with the American standard ASTM C109 for all reference mortar cubes and alkali-activated slag mortar specimens previously subjected to different curing regimes. The purpose was to evaluate the effect of cement replacement levels with slag and the influence of curing conditions on the 28-day compressive strength. The test was performed using a compressive testing machine (Figure 10) at a loading rate of 0.9 kN/s until failure, and the readings were recorded.

Figure 10: Compressive strength testing of a specimen at 28 days.

4. RESULTS & DISCUSSION

4.1 Effect of Curing Regime on the Compressive Strength of the Reference Specimens

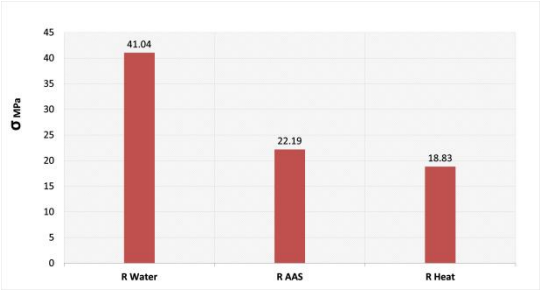

Figure 11: Comparison of the effect of different curing regimes on the compressive strength of the reference specimens.

When examining the effect of curing conditions on compressive strength, the highest compressive strength of the reference specimens was observed under water curing (R Water), followed by immersion in sodium hydroxide solution (R AAS). The lowest compressive strength of the reference specimens was recorded under thermal curing (R Heat) (Figure 11).

4.2 Comparison of Compressive Strength between Reference Specimens and Alkali-Activated Slag Mortar Specimens

4.2.1 Under Immersion in Sodium Hydroxide Solution

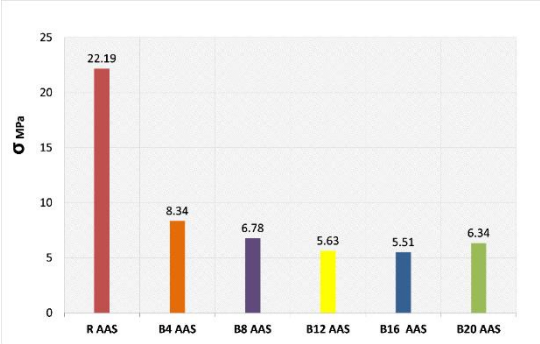

Figure 12: Comparison of compressive strength results between the reference specimens and alkali-activated slag mortar specimens under sodium hydroxide immersion curing.

The results shown in Figure 12 indicate that partial replacement of cement with 4–20% alkali-activated electric arc furnace slag (EAFS) using a 10 M sodium hydroxide solution, under sodium hydroxide immersion curing, led to a significant reduction in compressive strength of the slag mortar specimens compared with the reference specimens. It can therefore be concluded that the alkaline system used (sodium hydroxide only) was insufficient to efficiently activate the slag at the replacement levels investigated in this study, and that the reduction in cement content was the dominant factor controlling the compressive strength behaviour under these conditions.

4.2.2 Under Early Thermal Curing Followed by Plastic Wrapping

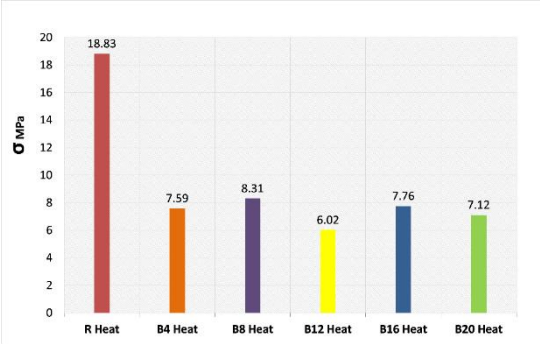

Figure 13: Comparison of compressive strength results between the reference specimens and alkali-activated slag mortar specimens under thermal curing at 65 °C.

When comparing the results of the specimens subjected to early thermal curing (65 °C for 24 hours after demoulding, followed by sealing in plastic wrapping until 28 days) (Figure 13), the reference specimen recorded a compressive strength of 18 MPa, whereas the compressive strength of the cement-replaced alkali-activated slag specimens was significantly lower. Specifically, the strength reached 7.59 MPa at 4% replacement, increased slightly to 8.31 MPa at 8%, then decreased to 6.02 MPa at 12%, before rising again at 16% (7.76 MPa) and 20% (7.12 MPa). This fluctuation can be explained by the fact that the early thermal curing did not result in an improvement in the performance of the hybrid system (cement/slag) at the replacement levels studied. While thermal acceleration can increase the reaction rate in highly slag-rich alkaline systems, the relatively low slag proportions in this study were likely insufficient to form a cohesive gel structure capable of compensating for the reduced cement content.

Moreover, the early thermal acceleration may have produced rapid reaction products that were less homogeneous and more porous, which could account for the reduced strength of the alkali-activated slag specimens compared with the reference specimens. The relative improvement observed at certain replacement levels (8% and 16%) may indicate a partial contribution of slag to enhancing the microstructure; however, this effect was neither linear nor sufficient to achieve a high mechanical performance that could be clearly correlated with the replacement ratio.

4.3 Effect of Curing Regime on the Compressive Strength of Alkali-Activated Slag Mortar Specimens

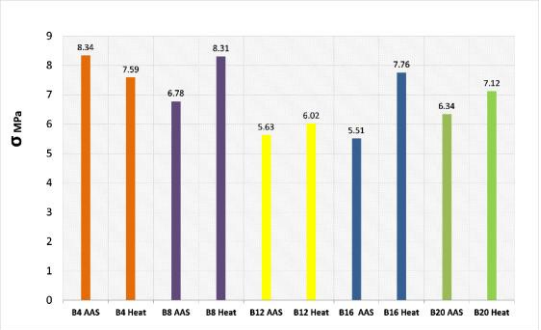

Figure 14: Comparison of the effect of different curing regimes on the compressive strength of alkali-activated slag mortar specimens: sodium hydroxide immersion curing and thermal curing at 65 °C.

From Figure 14, a comparison of alkali-activated slag mortar specimens with equal replacement levels under the two curing regimes—sodium hydroxide immersion (10 M for 28 days) and early thermal curing (65 °C for 24 hours followed by plastic wrapping)—reveals that thermal curing generally resulted in relatively higher compressive strength values. At 4% replacement, the compressive strength increased from 8.34 MPa (alkaline immersion) to 7.59 MPa (thermal curing), showing a relatively small difference. At 8% replacement, the strength improved markedly from 6.78 MPa (alkaline immersion) to 8.31 MPa (thermal curing). At 12% replacement, the strength

slightly increased from 5.63 MPa to 6.02 MPa, while at 16%, it rose from 5.51 MPa to 7.76 MPa.

Similarly, at 20% replacement, the compressive strength increased from 6.34 MPa to 7.12 MPa. These results indicate that early thermal curing accelerated the alkali activation reactions of electric arc furnace slag compared with continuous immersion in a high-concentration alkaline solution (10 M). Heat generally enhances the dissolution of slag components, particularly silica, calcium, and aluminium, thereby accelerating the formation of the C-A-S-H binding gel and improving the microstructural density.

On the other hand, prolonged immersion in a highly alkaline solution can increase the ionic saturation that dissolves slag components but may not achieve an optimal gel structure, and the high sodium hydroxide concentration could also increase porosity. It is also evident that the effect of thermal curing was most pronounced at intermediate replacement levels (8–16%), suggesting that these replacement ranges may represent the minimum threshold for effectively benefiting from thermal activation. Very low replacement levels showed insufficient response to demonstrate noticeable improvement under early thermal curing

5. CONCLUSION & RECOMMENDATIONS

The results of this study indicate that the compressive strength of the reference specimens cured in water reached 41 MPa, confirming the effectiveness of water curing in promoting hydration reactions and forming a dense microstructure compared with the two other curing methods used in this study. In contrast, the compressive strength of cement-replaced alkali-activated slag specimens (4–20%) decreased under 10 M sodium hydroxide immersion curing, while some specimens exhibited relative improvement under early thermal curing in an incubator at 65 °C. This highlights the limited effectiveness of slag activation when using a single alkaline activator at low temperature, compared with the previous study [25], which employed a combined sodium silicate and sodium hydroxide activator with late thermal curing in an oven at 200 °C for 2 hours followed by 27 days of curing in sealed plastic bags, achieving a maximum compressive strength of 36.3 MPa at 5% replacement and an activator ratio of R = NS/NH = 0.5.

From these observations, it can be concluded that combining a soluble silica source with late high-temperature thermal curing under sealed moist conditions provides a better environment for the formation of C-A-S-H binding gel and improves the microstructural density, whereas the modified system used in this study requires additional soluble silica to enhance the performance of alkali-activated slag. As a result, it is recommended to:

- Employ a dual-alkali activation system.
- Increase the grinding and fineness of electric arc furnace slag to approach the fineness of cement, enhancing the surface area available for alkaline reaction.
- Carefully optimize the replacement ratios and thermal curing conditions.
- Conduct detailed microstructural analyses and correlate them with long-term compressive strength to better understand the mechanical performance development of the hybrid system.

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