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Impact of Alkaline Activators on the Compressive Properties of Steel Slag Mortar

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ABSTRACT

This study investigates the effectiveness of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as alkaline activators in steel slag-blended mortar, with the dual aims of valorizing industrial waste and reducing the environmental burden associated with Portland cement. A two-phase experimental programme was implemented. In Phase 1, steel slag was incorporated at replacement levels of 0%, 5%, 10%, 15%, 20%, and 25% to identify the optimal dosage. Phase 2 employed this optimal 10% blend and examined the influence of varying NaOH and Na2SiO3 concentrations (2%, 4%, 6%, 8%, and 10%). Compressive strength was measured at 7, 14, 28, and 56 days. The physico-chemical characteristics of the slag were characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM). The findings reveal that although the steel slag possesses moderate or low pozzolanic reactivity, incorporating 10% slag improved the compressive strength compared to the control mortar, primarily due to its notable silica (SiO_2) content and filler effects. However, alkaline activation using NaOH and Na2SiO3 did not produce meaningful strength enhancements over the slag-only mixes within the tested concentration ranges. The findings suggest that ground steel slag is a sustainable partial cement substitute, but its limited pozzolanic reactivity constrains the effectiveness of conventional alkali activation.

Keywords - *Alkaline activator, Cement mortar, Compressive strength, Sodium hydroxide, Sodium silicate, Steel slag/waste*

I.INTRODUCTION

Cement mortar, a crucial binding material in construction, is predominantly composed of cement, sand, and water. Its significance lies in its application for masonry, rendering, and plastering, which require robust mechanical properties to ensure structural stability and longevity (Zhang et al., 2006). However, the traditional production of Portland cement, a primary component of cement mortar, is associated with high carbon emissions and energy consumption, contributing significantly to environmental degradation(Hossain and Hossain, 2024; Pinheiro et al., 2023). In response to these sustainability challenges, there is a pressing need to identify alternative materials that can partially replace Portland cement without compromising the mechanical performance of the mortar. Researchers have worked on utilization of many silica-rich waste products such as rice husk ash (RHA) and steel slag based silicate solution as a low-cost alternative to cement in concrete production. The effect of RHA content of 0–50% and sodium hydroxide (NaOH) solution of 8–14 M on compressive strength of concrete has been investigated(Hwang and Huynh, 2015). The geopolymer samples prepared with a NaOH concentration of 10 M and a RHA content of 35% exhibited high compressive strengths that were comparable with or even much higher than the free-RHA samples. Steel slag is a by-product discharged from the steelmaking process, which is characterized by abundant free calcium/magnesium oxide, low cementitious properties, and high contents of heavy metals (Douglas and Brandstetr, 1990; Shi and Qian, 2000). Its high content of silicates and aluminates makes it a viable supplementary material in cementitious composites. According to the United States Geological Survey, global steel slag production in 2019 was 190.0–280.0 million tons (Hussain and Hussaini, 2022). China alone produces around 80.0 million tons of steel slag annually, and the steel slag production reached 120.0 million tons in 2021 (Gencel, O. et al., 2021). The incorporation of steel slag into cement mortar can enhance the compressive strength, durability, and resistance to various environmental factors. However, to fully realize these benefits, it is crucial to activate the slag to increase its reactivity. This is achieved through alkaline activation, a process which involves treating the slag with alkaline solutions such as sodium hydroxide or sodium silicate. These activators promote the dissolution of aluminosilicate species, leading to the formation of a dense, hydrated gel that contributes to the mortar's compressive strength (Qin et al., 2022).

Alkaline activation is not only an effective way to utilize industrial by-products but also aligns with the principles of sustainable construction by reducing reliance on traditional cement. By enhancing the reactivity of fly ash, this process can significantly improve the mechanical properties of cement mortars, offering an eco-friendly alternative to conventional materials(Palomo et al., 1999). Alkali-activated materials have garnered significant attention as sustainable alternatives to coarse aggregate due to their utilization of industrial by-products, such as steel slag(Kashyap et al., 2024; Siddika et al., 2021). This approach not only addresses environmental concerns related to waste disposal but also offers the potential for superior mechanical properties compared to traditional cementitious binders(Naqi et al., 2023). Specifically, the interaction between alkaline activators and steel slag in cement mortar matrices profoundly influences the resulting compressive strength, durability, and microstructural development(Li et al., 2019; Taghvayi et al., 2018). The precise nature and concentration of the alkaline activator, such as sodium hydroxide or sodium silicate, critically dictate the reaction kinetics and the formation of hydration products, ultimately governing the mechanical performance(Huang et al., 2024). For instance, the concentration of sodium hydroxide and sodium silicate can significantly enhance the solubility and dissolution of slag, promoting the formation of hydration phases like Calcium–Silicate–Hydrate, which are critical for high mechanical performance(Ruan et al., 2020). Moreover, the molarity of the alkaline solution, ranging from 6 to 16 M, has been shown to directly influence parameters such as setting time, workability, and long-term durability, alongside compressive strength(Abhishek et al., 2022). An optimal alkali dosage, typically around 5%, has been observed to yield the highest ultimate compressive strength, with higher dosages potentially leading to strength reduction due to micro-crack formation(Dener et al., 2024).

The hydration mechanisms of Na_2CO_3-activated recycled slag systems have been investigated, showing that the combined use of MgO and Na_2CO_3 significantly affects the microstructural evolution and mechanical performance of the resulting mortars. These findings indicate that chemically induced interactions arising from specific activator combinations play a decisive role in determining the ultimate compressive strength of slag-based mortars(Liu et al., 2024). Various parameters influencing the strength development of alkali-activated slag and fly ash mortars have been critically reviewed, with particular emphasis on the dosage and type of alkaline activator. It was concluded that higher activator concentrations generally enhance compressive strength; however, the optimum dosage is highly dependent on the nature of the precursor materials and the curing conditions(Cai et al., 2021).

Composite cementitious materials incorporating steel slag and carbide slag as alkali activators have been examined, with results demonstrating that steel slag contributes positively to compressive strength development. This improvement was attributed to the formation of stable hydration products and enhanced microstructural densification within the cement matrix(Yang et al., 2024).

Furthermore, the use of alkali-activated materials in cement mortars presents a promising approach for advancing modern construction practices. This strategy not only offers the potential to reduce greenhouse gas emissions but also to improve the performance characteristics of construction materials. This study investigates the effect of alkaline activators on the compressive properties of cement mortar incorporating steel slag as a partial cement replacement, providing valuable insights into the development of sustainable and durable construction materials.

Although extensive studies have been conducted on alkali-activated slag systems, limited attention has been paid to the combined use of sodium hydroxide and sodium silicate activators in steel slag–based cement mortars, particularly at low cement replacement levels. Moreover, existing studies rarely establish an optimum steel slag replacement level before evaluating activator performance, resulting in fragmented conclusions. This study addresses this gap by first determining the optimum level of steel slag replacement for cement mortar, and subsequently employing this optimum replacement level to systematically investigate the individual effects of sodium hydroxide and sodium silicate activators on compressive strength. The findings provide new insights into the synergistic role of two different alkaline activators in enhancing the mechanical performance of steel slag cement mortars, thereby contributing to the development of sustainable and high-performance construction materials.

II. MATERIALS AND METHODS

2.1 Materials

The materials used in this study comprised Ordinary Portland Cement (OPC), fine aggregate, potable water, steel slag waste, and the alkaline activators sodium hydroxide (NaOH) and sodium silicate (Na2SiO3).

2.1.1 Cement

A commercially available Ordinary Portland Cement, Dangote 42.5R grade, was used for this study. The cement belongs to the 42.5 MPa (42.5 N/mm²) strength class(BS 12, 1996)

2.1.2 Fine Aggregate

The fine aggregate was thoroughly washed with clean water to remove organic matter, dirt, debris, and other impurities. It was then air-dried and sieved to eliminate oversized particles and any remaining unwanted materials. This is in accordance with BS EN 12620:2002+A1(2008).

2.1.3 Water

The mixing water was obtained from the Civil and Environmental Engineering Structural and Materials Laboratory. It was clean, clear, and free from impurities such as oils, salts, acids, or other substances that could adversely affect cement hydration or mortar performance. The water used was potable and conformed to the requirements of BS 1008(BS:EN:1008:2002 and EN 1008:2002, 2003; EN, 2002).

2.1.4 Steel Slag

The steel waste (slag) used in this study was sourced from the steel fabrication workshop dumping yard of VITA Construction Limited, located at Eric Moore in the Surulere area of Lagos [6°05′12″N, 3°36′43″W]. The slag, generated from extensive steel cutting, fabrication and modification processes, is typically regarded as waste and routinely discarded through conventional disposal procedures. As shown in Plate 1, the steel slag/waste used for this experimental work is the slag generated from extensive burning cuts on structural steels and plates, notably regarded as cutting slag. A representative sample of the collected slag is presented in Plate 1, which also illustrates the systematic selection and subsequent grinding of the material to a fine powder suitable for use in mortar production.

2.1.5 Alkaline Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3)

The alkaline activators used in this study were procured from a chemical and materials supplier located along Chemical Line, Ojota, Lagos State [6°35′16″N, 3°22′56″E]. Sodium hydroxide was purchased in solid granular form and subsequently dissolved in water to prepare the required solution, whereas sodium silicate was obtained in its commercial aqueous form. These materials are shown in Plates 2 (a) and 2(b).

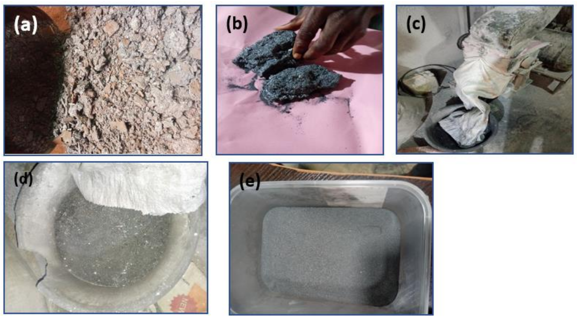

Plate 1. Steel slag/waste: (a) Dumping area at the fabrication workshop; (b) Selected steel slag samples; (c) Heavy-duty grinding machine; (d) Ground steel slag obtained after grinding; (e) Sieved steel slag in its final processed form.

Plate 2. Alkaline activators used in this study: (a) Sodium hydroxide (b) Sodium silicate

2.2 Methods

2.2.1 Characterization

Representative samples of the ground steel slag, sieved to particle sizes passing 0.15 mm and 0.075 mm, were collected and prepared for material characterization. The physicochemical properties of the steel slag were examined using X-ray diffraction (XRD) to identify crystalline phases and scanning electron microscopy (SEM) to investigate surface morphology and microstructural features (Plate 3). SEM analysis was performed using a PHENOM ProX scanning electron microscope under standard operating conditions. XRD characterization was conducted at the Central Research Laboratory, Umaru Musa Yar'adua University, Katsina State, Nigeria, using a Thermo Scientific ARL X'TRA X-ray diffractometer, also operated under standard analytical conditions.

Plate 3. SEM equipment used for the characterization

2.2.2 Sieve analysis

Grain size analysis, commonly known as sieve analysis, is conducted to determine the proportion of different particle sizes within a sample of soil or granular material. The results enable the construction of particle size distribution curves, which are essential for material classification and for predicting the engineering behavior of the material. In this study, sieve analysis was performed on three materials: fine aggregate, steel slag, and cement. The aim was to obtain particle size distribution curves and to identify specific particle size ranges of the fine aggregate and steel slag for use in subsequent experimental procedures. The sieve sizes were selected in accordance with ASTM D6913. For fine aggregate, six sieve sizes (9.5 mm, 3.35 mm, 2 mm, 1.18 mm, 0.6 mm, and 0.3 mm) were used. For steel slag, six sieve sizes (1.18 mm, 0.71 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm) were employed. For cement, four sieve sizes (0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm) were utilized.

2.2.3 Production of mortar

The mortar produced for this research work are in two (2) phases. The first phase was for zero alkaline activator, that is, the ground steel slag alone was used in partial replacement of cement without the activating alkaline. This is to study the behavior and properties of the steel slag itself when used in partial replacement of cement at varying percentage in the mortar. The percentage of steel slag used in partial replacement of cement with the highest strength was then subjected to the use of alkaline activator as the second phase.

2.2.4 Mortar production mix design

The mortar cubes cast in this study measured 100 mm × 100 mm × 100 mm, corresponding to a volume of 1,000,000 mm³ (0.001 m³). The mix proportion employed was 1:3 (cement: fine aggregate) with a water–

cement ratio of 0.5. For the control mix without alkaline activators, a total of 72 cubes were cast, with 12 cubes designated for each steel slag replacement level. Prior to batching, a 50% shrinkage factor was applied to the dry weights of the materials to account for potential losses during mixing. Consequently, the effective dry weights used in batching were 6.61 kg for cement and 21.89 kg for fine aggregate per 12 cubes. Steel slag was incorporated as a partial replacement for cement, with replacement levels of 0%, 5%, 10%, 15%, 20%, and 25% by weight. At 0% steel slag, the cement weight remained 6.61 kg, while the partial replacement weights for each percentage level were calculated accordingly. Table 1 presents the corresponding weights of cement and steel slag used for mortar production in this study.

Table 1: Cement and Steel slag partial replacement weight.

Slag replacement (%)	Weight of slag (kg)	Weight of Cement (kg)
0	0	6.61
5	0.33	6.28
10	0.66	5.95
15	0.99	5.62
20	1.32	5.29
25	1.65	4.96

Following the first phase of casting and testing, a 10% partial replacement of cement with steel slag was found to yield the highest mortar strength. In the second phase, the alkaline activators—NaOH and Na_2SiO_3 were applied separately to activate the steel slag at this optimal 10% replacement level. As indicated in Table 1, the weight of steel slag at 10% replacement was 0.66 kg, while the corresponding cement weight was 5.95 kg. The steel slag weight was kept constant for this phase, whereas the weight of the alkaline activators was varied as a percentage of the cement weight. The replacement levels for the activators were 2%, 4%, 6%, 8%, and 10%. Table 2 presents the calculated weights of the alkaline activators corresponding to these replacement levels, based on a cement weight of 5.95 kg at 0% activator.

Table 2: Cement and Alkaline activator partial replacement weight.

Slag replacement (%)	Weight of Alkaline activator (kg)	Weight of Cement (kg)
2	0.12	5.83
4	0.24	5.71
6	0.36	5.59
8	0.48	5.47
10	0.6	5.35

2.2.5 Mixing and casting of mortar

The mortar was mixed manually on the floor of the Civil and Environmental Engineering Structural Laboratory using a shovel. After accurately weighing the materials, cement and fine aggregate were first mixed in their dry state until a uniform blend was achieved, as shown in Plate 4(a). The designated quantity of steel slag for each replacement level was then incorporated into the dry mixture, with a representative sample illustrated in Plate 4(b). For mixes containing activated steel slag, the alkaline activator at the specified percentage was first combined with the steel slag before being added to the cement–aggregate mixture. Thorough mixing continued until the components were uniformly blended. The calculated quantity of water was then gradually added, and mixing was performed until a homogeneous mortar was obtained, as depicted in Plate 4(c). The prepared mortar was subsequently cast into preformed molds measuring 100 × 100 × 100 mm, as shown in Plate 4(d).

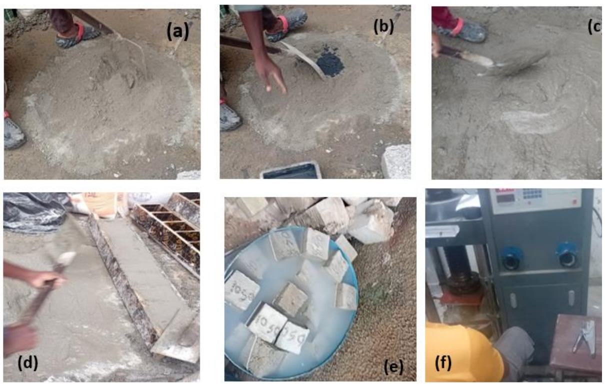

Plate 4: Mixing and casting of mortar. (a) dry mix. (b) inclusion of steel slag. (c) mortar wet mix. (d) casting in moulds. (e) curing of specimen (f) crushing of mortar.

2.2.6 Characterization

2.2.6 Compressive strength test

The mortar cubes for each phase of the study were grouped according to the respective partial replacement levels and cured for periods of 7, 14, 28, and 56 days as shown in Plate 4(e). The 56 days test was conducted to understand the long term effect of the replacement on the concrete. It has been established that pozzolanic materials develop their maximum strength after 28 days(BS EN 1015-11, 2019). Compressive strength tests were performed on each set of cubes immediately following the designated curing period. The tests were conducted in the Civil and Environmental Engineering Structural Laboratory using a 2,000 kN capacity compressive testing machine as shown in Plate 4(f).

III. RESULTS AND DISCUSSION

3.1 Scanning electron microscope – energy differential x-ray (SEM-EDX)

The Scanning Electron Microscope coupled with Energy-Dispersive X-ray analysis (SEM-EDX) provides high-resolution imaging to determine the elemental composition of a material. Figure 1 presents the SEM images of the ground and sieved steel slag/waste used in this study. The corresponding elemental composition obtained from EDX analysis, is shown in Figure 2. The results indicate that the steel slag contains 16.30% oxygen (O), 10.40% silicon (Si), 53.6% iron (Fe), 3.30% calcium (Ca), 3.22% sodium (Na), 0.37% magnesium (Mg), 8.50% aluminum (Al), 0.11% manganese (Mn), and 4.20% carbon (C).

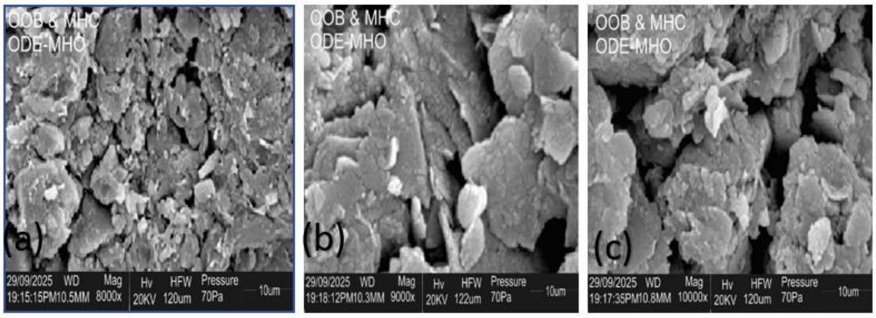

Figure 1: SEM analysis of Steel slag (a) 8000x (b) 9000x (c) 10000x

The results in Figure 2 indicate a relatively low carbon (C) content, which corresponds to increased proportions of silicon (Si) and oxygen (O) in the steel slag. However, the combined silicon and oxygen content, representing the silica (SiO_2) fraction, is insufficient to classify this steel slag as a pozzolanic material.

3.2 XRD (X-ray Diffractometer)

The X-ray diffraction (XRD) analysis identifies the chemical compounds and crystalline phases present in the steel slag. The results reveal that the steel slag primarily consists of four major compounds: magnetite, hematite, clinochlore, and quartz. Figure 3 presents a graphical representation of the relative quantities and composition of these compounds in the steel slag sample.

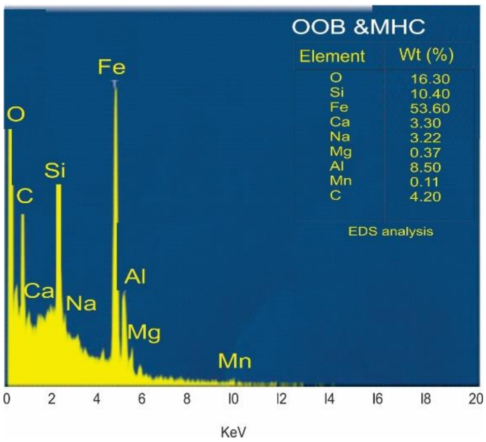

Figure 2: SEM-EDX Analysis graph of Steel slag.

3.3 Sieve Analysis

Particle size distribution curves were generated for the fine aggregate (sand), cement, and ground steel slag/waste, as shown in Figures 4a and 4b. Figure 4a presents the particle size distribution of the sand, indicating a well-graded fine aggregate in accordance with ASTM standards. Figure 4b shows the combined particle size distribution of cement and steel slag, highlighting the fineness of these materials used in this study.

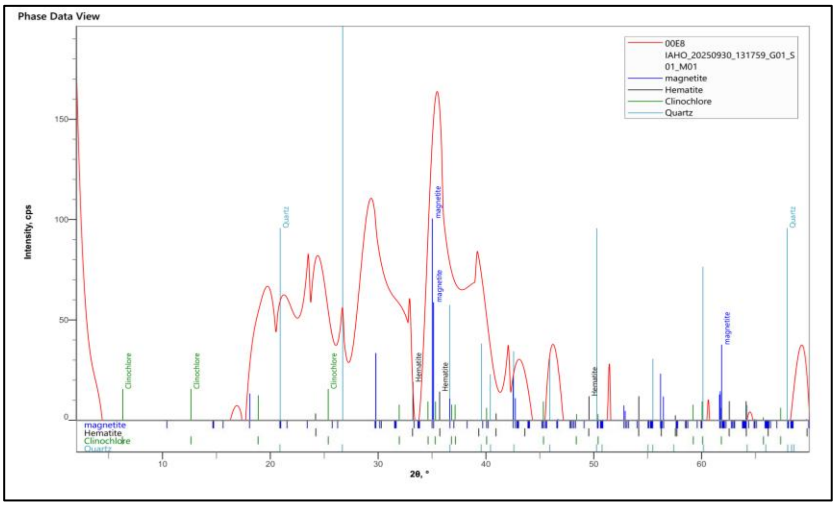

Figure 3: XRD Analysis graph of Steel slag.

The fine aggregate exhibited a coefficient of uniformity (Cu) of 2.86 and a coefficient of curvature (Cc) of 0.79. The steel slag used had particle sizes in the range of 0.075–0.15 mm, selected to be comparable to the average cement particle size (0.01–0.03 mm).

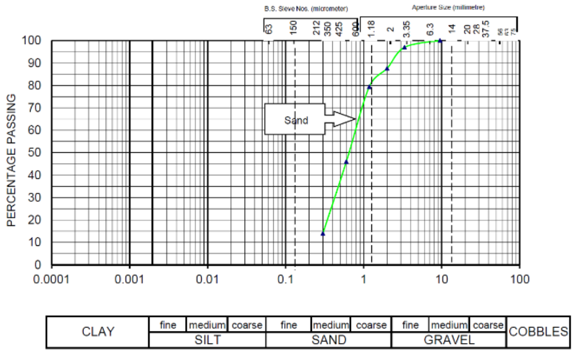

Figure 4a: Particle sizes distribution graph for Sand.

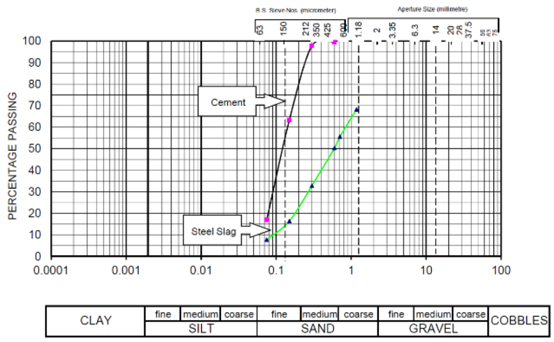

Figure 4b: Particle sizes distribution graph for Cement and Ground steel slag/waste

3.4 Compressive Test

The compressive strength results for both phases of the cast mortar, across the different curing periods, are presented below. The first phase, which did not involve the use of alkaline activators, is shown in Figure 5. Compressive strengths are reported for curing periods of 7, 14, 28, and 56 days, with the various percentages of steel slag used to partially replace cement indicated in the color legend.

Generally, the partial replacement of cement with varying percentages of steel slag generally resulted in higher compressive strengths compared to ordinary cement mortar after 7 days of curing. Throughout the curing period, the compressive strength exhibited intermittent fluctuations with increasing slag content, reflecting both increases and decreases depending on the replacement level and curing age. This non-linear behavior suggests that the effect of steel slag on strength development is complex, influenced by factors such as the slag's reactivity, the availability of calcium and silica for hydration, and the role of any alkaline activator. At low replacement levels, the slag can enhance microstructural densification and promote secondary hydration reactions, whereas higher replacement levels may lead to dilution effects and incomplete activation, reducing mechanical performance.

From the first phase of the study, it was observed that a 10% partial replacement of cement with steel slag yielded the highest mortar strength. This optimal 10% slag content was subsequently used as the basis for alkaline activation studies. Figures 6 and 7 present the compressive strength results of alkali-activated steel slag–

cement mortar after curing periods of 7, 14, 28, and 56 days. Figure 6 shows the results for sodium hydroxide-activated mortar, while Figure 7 presents the corresponding results for sodium silicate-activated mortar.

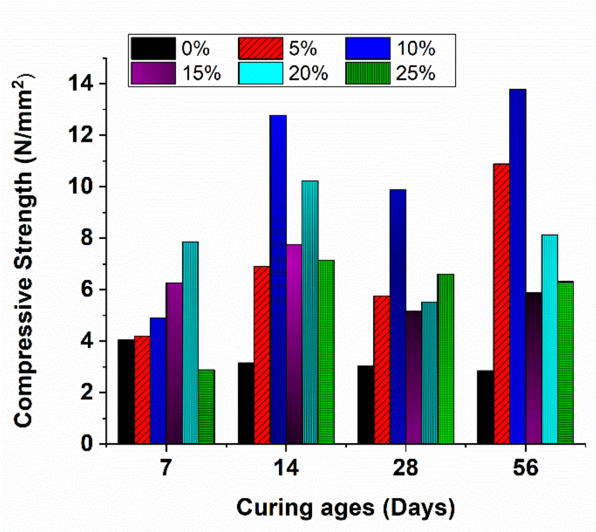

Figure 5: Compressive strength of zero-alkaline steel slag/cement mortar.

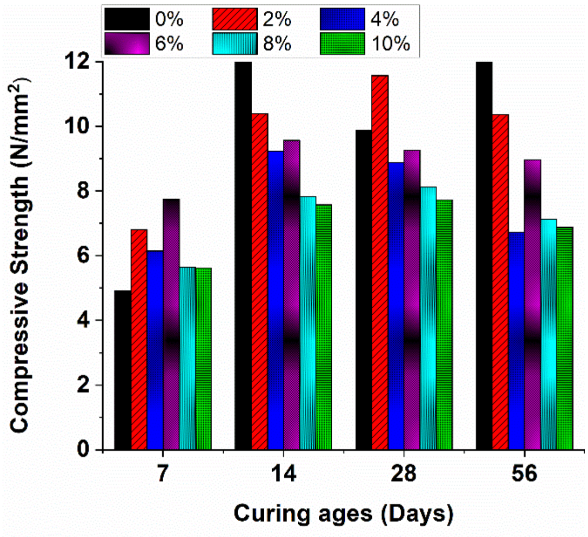

Figure 6: Compressive strength of Sodium Hydroxide activated steel slag/cement mortar.

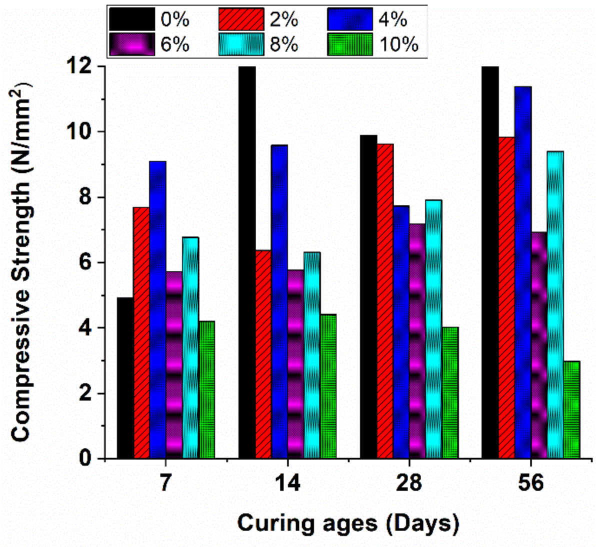

Figure 7: Compressive strength of Sodium Silicate activated steel slag/cement mortar.

Although experimental observations indicate that sodium hydroxide does not readily bond with steel slag, unlike sodium silicate which forms a more uniform aqueous solution, the compressive strength results show that a 2% sodium hydroxide activation produced the highest strength among the NaOH-activated mixes. This suggests that the optimum activation level for sodium hydroxide is 2%. It is observed from the two alkaline activations experiments that the addition of the alkaline did not improve the compressive strength of the mixes.

Experimental observations indicate that the optimal sodium silicate concentration for maximizing compressive strength lies between 2% and 4% of the binder weight. Within this range, alkali activation proceeds efficiently, facilitating the dissolution of calcium, silicon, and aluminum species and promoting the formation of binding gels without introducing excessive alkalinity.

At these concentrations, the steel slag mortar develops a well-connected, compact microstructure, resulting in higher compressive strengths and a consistent strength gain over the curing period. The gradual increase in strength suggests that hydration and polymerization reactions occur at a balanced rate, allowing sufficient time for the formation of stable hydration products while minimizing premature setting or cracking.

At around 4% activator concentration, the mortar exhibits the highest early-age strength, attributable to the accelerated dissolution of reactive components and rapid gel formation during the initial curing stages. This early strength gain is advantageous for applications requiring quick demolding or early loading; however, the high early reactivity may also introduce potential drawbacks at later curing ages.

IV.CONCLUSION

This study demonstrates the potential of ground steel slag as a partial replacement for cement in mortar production. In the first phase, a 10% replacement of cement with steel slag produced the highest compressive strength, serving as the benchmark for subsequent alkali-activation experiments. In the second phase, alkali activation of the 10% steel slag with sodium hydroxide and sodium silicate was investigated. The results indicate that 2% sodium hydroxide and 4% sodium silicate provided the highest compressive strengths for their respective activators. However, neither alkali-activated mix surpassed the strength of the mortar containing only steel slag without activators. Overall, a 10% steel slag replacement is optimal for enhancing compressive strength, while conventional alkali activation, within the investigated dosage range, does not confer additional mechanical advantages.

Although partial replacement of cement with steel slag generally enhanced mortar strength compared to ordinary cement mortar, this does not imply that the slag is pozzolanic. Characterization through X-ray diffraction (XRD) and scanning electron microscopy (SEM) confirmed that, while steel slag contains some chemical components similar to ordinary Portland cement, its silica (SiO_2) content is insufficient to classify it as a pozzolanic material. True pozzolanic activity requires a significant fraction of reactive silica in an amorphous or glassy structure capable of chemically reacting with calcium hydroxide to form cementitious compounds. Steel slag, formed from rapidly cooled molten steel particles, does not meet these criteria. The findings confirm that finely ground steel slag can serve as a sustainable partial cement substitute, improving mortar strength at modest replacement levels, but its limited pozzolanic activity restricts the effectiveness of conventional alkali activation. Future research should explore alternative activation strategies or supplementary materials to fully exploit the latent reactivity of steel slag.

AUTHOR(S) CONTRIBUTIONS

M. O. Habeeb designed the methodology, performed the experiment, initial draft of the manuscript, O. E. Oluwaseyi designed the methodology, performed the experiment, initial draft of the manuscript. O. Oribayo, designed the methodology, Formal analysis, supervision and editing of the manuscript. A. O. Oyelade, Conceptualization, Data curation, Formal analysis, supervision and final approval of the manuscript, Y. O. Abiodun, supervision, final draft of the manuscript.

AI DISCLOSURE

AI-assisted language tools were used solely for grammar correction and improvement of readability.

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DECLARATION OF CONFLICT OF INTEREST

Authors have no conflict of interest to declare

REFERENCES

Abhishek, H.S., Prashant, S., Amath, M. V., Kumar, M., 2022. Fresh mechanical and durability properties of alkali-activated fly ash-slag concrete: a review. Innov. Infrastruct. Solut. 7, 116.

BS:EN:1008:2002, EN 1008:2002, 2003. Mixing water for concrete — Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete, BSI Standards Publication.

BS 12, 1996. Specification for Portland Cement.

BS EN 1015-11, 2019. Methods of test for mortar for masonry - Determination of flexural and compressive strength of hardened mortar.

BS EN 12620:2002+A1, 2008. Aggregates for concrete.

Cai, T., Zandi, Y., Agdas, A.S., Selmi, A., Issakhov, A., Roco-Videla, A., 2021. The Compressive Strength of Concrete Retrofitted with Wind Ash and Steel Slag Pozzolans with A Water-cement Based Polymers. Adv. Concr. Constr. 11, 507–519.

Dener, M., Altunhan, U., Benli, A., 2024. A green binder for cold weather applications, enhancing mechanical performance of alkali-activated slag through modulus alkali dosage, and Portland cement substitution. Arch. Civ. Mech. Eng. 24, 176.

Douglas, E., Brandstetr, J., 1990. A preliminary study on the alkali activation of ground granulated blast-furnace slag. Cem. Concr. Res. 20, 746–75.

EN, B. (2002). 1008: 2002, 2002. Mixing water for concrete-Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concret. British Standards Institution, London.

Gencel, O., Karadag, O., Oren, O.H., Bilir, T., 2021. Steel slag and its applications in cement and concrete technology: A review. Constr. Build. Mater. 283.

Hossain, M.A., Hossain, K.M., 2024. Rheological, Fresh State, and Strength Characteristics of Alkali-Activated Mortars Incorporating MgO and Carbon Nanoparticles. Materials (Basel). 17, 5931.

Huang, Y., Marsh, A.T., Yue, Z., Krishnan, S., Adu-Amankwah, S., Bernal, S.A., 2024. Hybrid Organic–Inorganic Blast Furnace Slag Binders Activated with Alkali Acetates. CS omega 99, 35888–35905.

Hussain, A., Hussaini, S.K.K., 2022. Use of steel slag as railway ballast: A review. Transp. Geotech. 35.

Hwang, C.L., Huynh, T.P., 2015. Effect of alkali-activator and rice husk ash content on strength development of fly ash and residual rice husk ash-based geopolymers. Constr. Build. Mater. 101, 1–9.

Kashyap, R., Saxena, M., Gautam, A., Mishra, P., Yadav, S., Jaiswal, A., Rajpoot, A., 2024. A study on enhancing mechanical properties of concrete with steel slag for sustainable construction. J. Build. Pathol. Rehabil. 9, 130.

Li, Q., Yang, Y., Yang, K., Chao, Z., Tang, D., Tian, Y., Yang, C., 2019. The role of calcium stearate on regulating activation to form stable, uniform and flawless reaction products in alkali-activated slag cement. Cem. Concr. Compos. 103, 242–251.

Liu, J., Tian, Y., Ge, X., Liu, B., Liu, K., Song, G., 2024. Experimental study on MgO-Na2CO3 combined excitation recycled fine-powder-slag cementitious system and modification. Buildings 14, 592.

Naqi, A., Delsaute, B., Königsberger, M., Staquet, S., 2023. Monitoring early age elastic and viscoelastic properties of alkali-activated slag mortar by means of repeated minute-long loadings. Dev. Built Environ. 16, 100275.

Palomo, A., Grutzeck, M.W., Blanco, M.T., 1999. Alkali-activated fly ashes: A cement for the future. Cem. Concr. Res. 29, 1323–1329.

Pinheiro, V.D., Alexandre, J., Xavier, G. de C., Marvila, M.T., Monteiro, S.N., de Azevedo, A.R.G., 2023. Methods for Evaluating Pozzolanic Reactivity in Calcined Clays: A Review. Materials (Basel). 16. https://doi.org/10.3390/ma16134778

Qin, Y., Qu, C., Ma, C., Zhou, L., 2022. One-part alkali-activated materials: state of the art and perspectives. Polymers (Basel). 14, 5046.

Ruan, S., Zhu, W., Yang, E.H., Weng, Y., Unluer, C., 2020. Improvement of the performance and microstructural development of alkali-activated slag blends. Constr. Build. Mater. 261, 120017.

Shi, C., Qian, J., 2000. High performance cementing materials from industrial slags—a review. Resour. Conserv. Recycl. 29, 195–207.

Siddika, A., Mamun, M.A. Al, Alyousef, R., Mohammadhosseini, H., 2021. State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. J. King Saud Univ. - Eng. Sci. 33, 294–307. https://doi.org/10.1016/j.jksues.2020.10.006

Taghvayi, H., Behfarnia, K., Khalili, M., 2018. The effect of alkali concentration and sodium silicate modulus on the properties of alkali-activated slag concrete. J. Adv. Concr. Technol. 16, 293–305.

Yang, G., Li, C., Xie, W., Yue, Y., Kong, C., Li, X., 2024. Effect of carbide slag and steel slag as alkali activators on the key properties of carbide slag-steel slag-slag-phosphogypsum composite cementitious materials. Front. Mater. 11.

Zhang, G., Song, J., Yang, J., Liu, X., 2006. Performance of mortar and concrete made with a fine aggregate of desert sand. Build. Environ. 41, 1478–1481.