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Enhancing early-age strength of alkali-activated slag cement with high- and low-calcium fly ash: Impact of water-to-slag ratio under steam curing

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Abstract

This study investigates the influence of high-calcium fly ash (HCFA), low-calcium fly ash (LCFA), and water-to-slag cement (W/SC) ratios on the early-age strength and workability of alkali-activated slag cement (AASC) under steam curing. AASC, recognized as a sustainable alternative to Ordinary Portland Cement (OPC), was prepared using slag cement as the primary binder, with HCFA and LCFA incorporated as partial substitutes for fine aggregate. Experimental results demonstrated that HCFA accelerates early-age strength development due to its higher calcium content, whereas LCFA enhances long-term durability. Lower W/SC ratios (45% and 50%) led to higher early strength but reduced workability, while higher W/SC ratios (55%) improved flowability but compromised strength. Steam curing significantly enhanced the early-age mechanical performance, particularly in HCFA-based mixtures. These findings emphasize the importance of optimizing fly ash type and W/SC ratio for achieving a balance between workability, strength, and durability in sustainable construction applications.

Keywords: Alkali-Activated Slag Cement; High- and Low-Calcium Fly Ash; Water-to-Slag Cement Ratio; Early-Age Strength; Eco-Friendly and Sustainable Construction Materials

1. Introduction

Alkali-Activated Slag Cement (AASC) is a type of cementitious material produced by the activation of slag with an alkaline solution, typically sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). AASC is considered a more sustainable alternative to Ordinary Portland Cement (OPC) due to its reduced environmental impact. The production of OPC contributes significantly to global CO_2 emissions, whereas AASC offers the potential for a low-carbon footprint since slag and fly ash are industrial by-products, and the energy required for their activation is substantially lower than that of traditional cement production [1]. Recent studies have shown that AASC demonstrates superior durability properties, including enhanced resistance to sulfate attack, chloride ion penetration, and high-temperature exposure, compared to traditional OPC. These beneficial properties have made AASC an attractive option for construction applications that demand durability and sustainability, such as in marine environments and for infrastructure exposed to aggressive chemical conditions [2]. In addition to sustainability, AASC has shown higher compressive strength and improved mechanical properties due to the chemical interaction between the alkaline solution and the slag [3].

Fly ash, a by-product from coal combustion in power plants, has become a widely used supplementary cementitious material (SCM) in both conventional concrete and alkali-activated systems. Fly ash is classified into two categories based on its calcium content: High-Calcium Fly Ash (HCFA, Class C) and Low-Calcium Fly Ash (LCFA, Class F). The chemical composition of fly ash influences the strength development and durability of AASC mixtures. HCFA has a higher calcium oxide (CaO) content, which accelerates the hydration process and results in higher early-age strength development. LCFA, on the other hand, contains lower calcium and higher silica and alumina, leading to a slower hydration process

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but greater long-term strength and durability [4]. Several studies have explored the effects of incorporating fly ash into AASC. The combination of fly ash with slag can result in synergistic effects, improving both the workability and mechanical properties of the material. Research has shown that the incorporation of HCFA accelerates the early hydration of AASC, producing higher early compressive strength, while the addition of LCFA enhances the long-term durability and reduces heat generation during hydration [5], [6]. The optimal combination of slag and fly ash can enhance the performance of AASC in terms of strength, workability, and environmental benefits.

The water-to-binder (W/B) ratio is a critical parameter in determining the performance of cementitious materials, including AASC. The water-to-slag cement ratio (W/S) influences the rheological properties, workability, and strength development of the AASC mixture. Lower W/S ratios typically result in higher compressive strength, as the hydration products are denser and more compact. However, reducing the water content can also reduce workability, making it more difficult to mix and place the material, especially in large-scale applications such as concrete casting and precast production [7].

Higher W/S ratios generally improve the flowability and ease of placement, but they can result in lower strength and durability due to a less dense microstructure. The W/S ratio must, therefore, be carefully controlled to balance between achieving high strength and maintaining adequate workability for practical use in construction. In AASC, the W/S ratio also affects the alkali activation process and the rate of hydration, which in turn impacts the early-age strength development. Researchers have studied various W/S ratios to optimize the strength development and workability of AASC, considering factors such as fly ash content, steam curing, and curing temperature [8].

Steam curing is a common technique used to accelerate the hydration of cement-based materials, including AASC. This method involves exposing the material to steam at elevated temperatures, typically around 60°C to 90°C, which accelerates the chemical reactions between the alkaline activator and the slag or fly ash. Steam curing is particularly useful in precast concrete production, where rapid strength development is required for efficient casting and handling. Several studies have demonstrated the effectiveness of steam curing in enhancing the early-age strength of AASC. For example, a study by Yang et al. [9] showed that steam curing significantly increased the compressive strength of AASC by promoting faster hydration of the slag and fly ash. The effect of steam curing is more pronounced at lower W/S ratios, where the material is more compact and able to retain moisture during the curing process. However, excessive steam curing temperatures or prolonged exposure to steam can negatively affect the long-term durability of the material by causing thermal shrinkage or inducing cracks [10]. Thus, optimizing the steam curing conditions, such as temperature and duration, is essential for achieving the desired mechanical performance without compromising durability.

While significant progress has been made in understanding the individual effects of fly ash types, W/S ratios, and curing conditions on AASC, there is still a lack of comprehensive studies that integrate all these factors. Most research has focused either on the use of HCFA or LCFA in AASC but rarely have both been studied in the same mix design. Furthermore, the interaction between these factors under accelerated curing conditions remains underexplored. This research aims to fill these gaps by examining the combined effects of HCFA and LCFA on the workability, flow loss, and compressive strength development of AASC.

The specific objectives of this study are to investigate the effects of different fly ash types (HCFA and LCFA) and various water-to-slag cement (W/SC) ratios (45%, 50%, and 55%) on the workability and early-age strength development of AASC under steam curing conditions.

2. Experimental Approach

2.1. Materials and Mix Proportions

Slag cement (SC), sourced from municipal activities, was used as the primary binder, replacing traditional Portland cement. High-calcium fly ash (HCFA) and low-calcium fly ash (LCFA), obtained from the combustion of different coal types in power plants, were incorporated as partial substitutes for fine aggregate. The chemical composition and physical properties of SC, HCFA, and LCFA are provided in Tables 1 and 2, respectively. Sodium metasilicate (Na_2SiO_3), a fine white powder, served as the alkali activator, while crushed sandstone acted as the fine aggregate. The use of these materials aimed to enhance the sustainability and performance of the final composite, offering an alternative to conventional concrete mixtures. Additionally, the study focused on optimizing the properties of the materials to ensure their suitability under steam curing conditions. The investigation also aimed to assess the impact of these materials on the overall environmental footprint, highlighting their potential for reducing carbon emissions in construction. This approach promotes the use of industrial by-products, contributing to a more sustainable and resource-efficient building practice.

Table 1 Chemical Composition of Slag Cement (SC), High-Calcium Fly Ash (HCFA) and Low-Calcium Fly Ash (LCFA).

Chemical Compositions	**CaO (%)**	**SiO_2 (%)**	**Al_2O_3 (%)**	**MgO (%)**	**Fe_2O_3 (%)**	**Na_2O (%)**	**TiO_2 (%)**	**P_2O_5 (%)**	**LOI (%)**
Slag Cement (SC)	43.1	32.5	13.5	2.9	2.7	1.8	1.3	0.8	1.4
High-Calcium Fly Ash (HCFA)	18.8	48.8	19.8	1.5	3.8	1.2	3.9	0.5	1.7
Low-Calcium Fly Ash (LCFA)	6.3	57.6	26.5	1.2	4.2	0.5	1.9	0.3	1.5

Table 2 Physical Properties of Slag Cement (SC), High-Calcium Fly Ash (HCFA) and Low-Calcium Fly Ash (LCFA).

Physical Properties	**Specific gravity (g/cm^3)**	**Specific surface area (cm^2/g)**	**Average particle size of D_{50} (μm)**
Slag Cement (SC)	2.8	3750	6.48
High-Calcium Fly Ash (HCFA)	2.8	3780	16.25
Low-Calcium Fly Ash (LCFA)	2.14	3630	18.35

The composite mix proportions are outlined in Table 3. All mixtures were prepared at a room temperature of approximately 20 ± 1°C and a relative humidity of around 65 ± 5%, followed by curing under steam conditions. This study primarily utilized slag cement (SC) as the binder, completely replacing Portland cement, with fly ash (FA) incorporated at 20% as a partial substitute for fine aggregate (S). Both high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) were used in the mix. A fixed alkali activator-to-slag cement (AL/SC) ratio of 20% was maintained, while different water-to-slag cement (W/SC) ratios (45%, 50%, and 55%) were applied to achieve a balance between cost-efficiency, enhanced performance, and sustainability.

Table 3 Composite Mix Proportions.

Group No.	**FA: (HCFA – LCFA)**	**W/SC (%)**	**AL/SC (%)**	**FA/S (%)**	**Mix Proportioning (kg/m3)**				
					Slag Cement (SC)	Water (W)	Alkali-Activator (AL)	Fly Ash (FA)	Sand (S)
I	FA: HCFA	45	20	20	600	270	120	200	1000
		50				300			
		55				330			
II	FA: LCFA	45	20	20	600	270	120	200	1000
		50				300			
		55				330			

2.2. Sample Preparation and Testing Procedures

All composite mixtures were prepared at a room temperature of approximately 20 ± 1°C and a relative humidity of around 65 ± 5%. The raw materials (SC, FA, AL, and S) were blended in a pan mixer for 90 seconds, followed by the addition of water, with mixing continuing for an additional 90 seconds to create a fresh composite mixture.

Various tests were conducted to evaluate the effect of incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) at 20% as a partial replacement for fine aggregate (S) with different water-to-slag cement (W/SC) ratios (45%, 50%, and 55%) on the slump flow, flow loss for fresh properties, and early-age compressive strength enhancement for hardened properties of the composite. Fresh properties were assessed using a flow test, where the initial flow and flow loss were measured immediately and after 15 minutes of mixing, respectively.

After casting, all mold specimens were stored at 20 ± 1°C and a relative humidity of 65 ± 5%, covered with sheets. For steam curing, specimens were moved to a steam chamber for one-hour post-casting. The temperature increased from 20°C to 65°C at a rate of 15°C per hour, held at 65°C for 5 hours, and then allowed to cool naturally to 20°C. After 24 hours, the molds were removed, and the specimens were stored at 20 ± 1°C and 65 ± 5% RH until testing.

Compressive strength tests were conducted using a universal testing machine to evaluate the hardened properties, applying a gradual load until failure. The specimens were carefully positioned to ensure uniform loading, and measurements were recorded at 1, 3, 7, and 28 days to assess strength development under steam curing conditions.

3. Results and Discussion

3.1. Slump Flow and Flow Loss

Slump flow and flow loss are critical parameters in evaluating the workability of alkali-activated slag cement (AASC) incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA). Slump flow measures the initial fluidity of the mixture, influencing ease of placement and compaction. Flow loss, representing the reduction in workability over time, is affected by the water-to-slag cement ratio and the reactivity of fly ash components. HCFA and LCFA alter the rheological behaviour by affecting particle packing and reaction kinetics. Understanding these properties is essential for optimizing mix designs to enhance early-age strength while maintaining adequate workability.

3.1.1. Impact of High- and Low-Calcium Fly Ash

High-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) significantly influence the slump flow and flow loss of alkali-activated slag cement (AASC) mixtures. HCFA, with its higher reactivity and calcium content, tends to accelerate early hydration, reducing initial slump flow and increasing flow loss over time. In contrast, LCFA, with its lower calcium content and slower reaction rate, enhances workability and retains slump flow for longer durations.

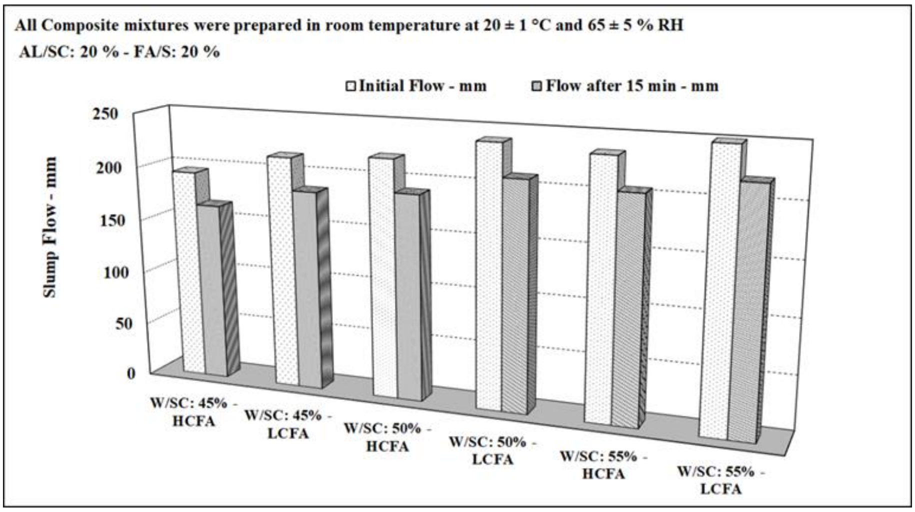

Figure 1 Impact of high- and low-calcium fly ash on initial slump flow and flow after 15 min

Figure 1 illustrates the slump flow behavior of alkali-activated slag cement mixtures incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) at different water-to-slag cement (W/SC) ratios. It compares the initial slump flow with the flow after 15 minutes, showing that mixtures with higher W/SC ratios exhibit greater initial fluidity. However, flow loss over time is more pronounced in HCFA-based mixes due to its higher reactivity and faster setting, while LCFA-based mixes maintain workability for longer durations. These results highlight the role of fly ash composition and W/SC ratio in optimizing workability and setting time, contributing to better mix designs for improved early-age strength in alkali-activated slag cement applications.

3.1.2. Impact of Water-to-Slag Cement Ratio

The water-to-slag cement (W/SC) ratio plays a crucial role in determining the slump flow and flow loss of alkali-activated slag cement (AASC) mixtures. A higher W/SC ratio increases initial slump flow, enhancing workability and ease of placement. Conversely, lower W/SC ratios result in reduced fluidity and higher viscosity, accelerating flow loss over time. Figure 2 shows the slump flow behavior at different water-to-slag cement (W/SC) ratios of alkali-activated slag cement mixtures incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA).

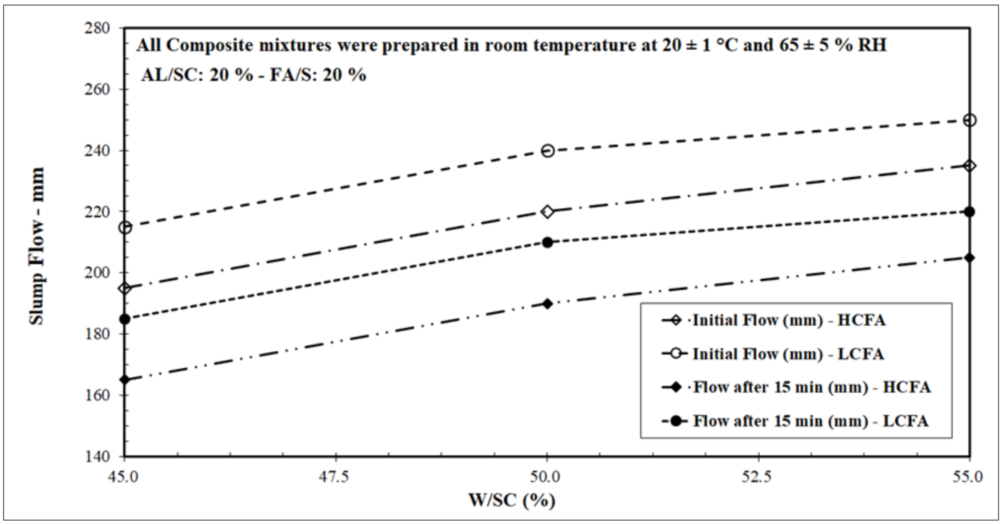

Figure 2 Impact of water-to-slag cement ratio on initial slump flow and flow after 15 min.

The results indicate that mixtures with a higher W/SC ratio exhibit greater initial flow, enhancing workability. However, HCFA-based mixtures show a more significant reduction in flow after 15 minutes due to their higher reactivity and faster hydration, leading to quicker stiffening. In contrast, LCFA-based mixtures maintain their flowability for a longer duration, benefiting from their lower calcium content and slower reaction kinetics. These findings highlight the importance of optimizing the fly ash composition and W/SC ratio to balance workability and setting time. Achieving this balance ensures better placement, reduces segregation risks, and enhances early-age strength, making the mix more suitable for practical applications in sustainable construction.

3.2. Early-Age Compressive Strength Enhancement

Early-age compressive strength is a crucial factor in alkali-activated slag cement (AASC) performance, influencing construction speed and structural stability. The incorporation of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) significantly impacts strength development due to their varying reactivity and calcium content. HCFA accelerates early hydration, enhancing strength gain, while LCFA contributes to long-term durability and stability. The water-to-slag cement (W/SC) ratio also plays a vital role, affecting reaction kinetics and microstructure formation. Optimizing the blend of HCFA, LCFA, and W/SC ratio can lead to improved early-age strength, making AASC a more viable alternative to traditional cement.

3.2.1. Impact of High- and Low-Calcium Fly Ash

The incorporation of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) plays a significant role in enhancing the compressive strength of alkali-activated slag cement (AASC). HCFA, with its high calcium content, accelerates early-age strength development by promoting rapid geopolymerization and the formation of additional calcium-silicate-hydrate (C-S-H) gel. In contrast, LCFA, due to its lower calcium content and slower reactivity, refine the microstructure over time, contributing to long-term strength and durability.

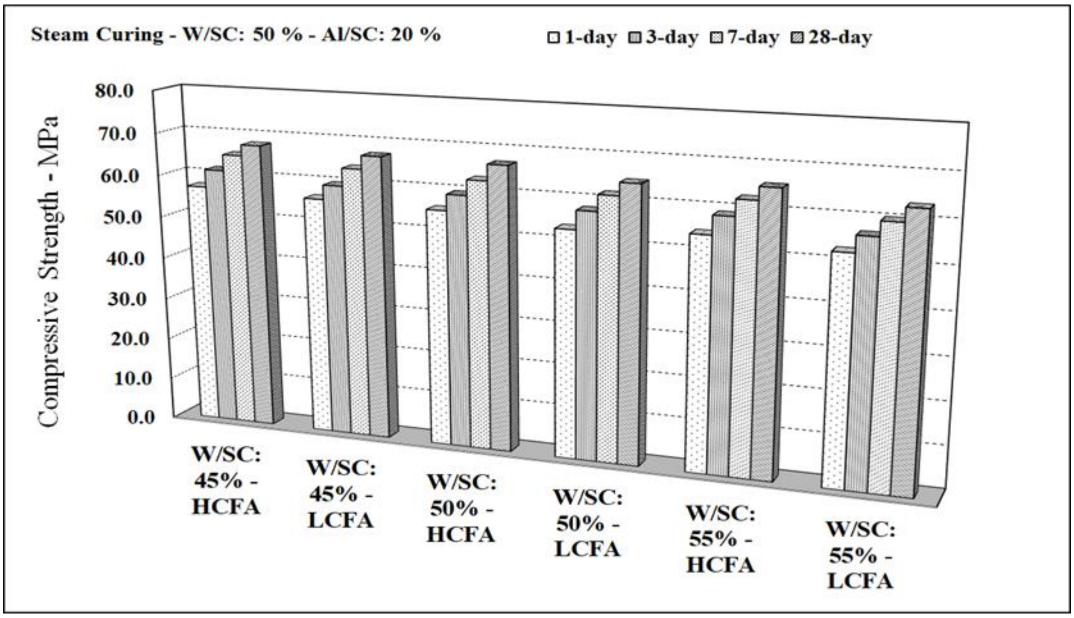

Figure 3 Impact of high- and low-calcium fly ash on compressive strength development

Figure 3 illustrates the compressive strength development of alkali-activated slag cement mixtures incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) at different water-to-slag cement (W/SC) ratios under steam curing conditions.

The results show that mixtures with HCFA exhibit higher early-age strength, particularly at lower W/SC ratios (45% and 50%), due to its higher calcium content, which accelerates hydration reactions. In contrast, LCFA-based mixtures demonstrate a more gradual gain in strength, contributing to long-term durability. Increasing the W/SC ratio generally leads to a reduction in compressive strength due to a higher water content weakening the matrix. These findings highlight the importance of optimizing W/SC ratios and fly ash composition to achieve a balance between workability, early-age strength, and long-term performance, making AASC a promising sustainable alternative to conventional cement.

3.2.2. Impact of Water-to-Slag Cement Ratio

The water-to-slag cement (W/SC) ratio is a key factor influencing the compressive strength development of alkali-activated slag cement (AASC). The lower W/SC ratio enhances early-age strength by promoting a denser microstructure and reducing porosity, leading to improved mechanical performance. However, excessively low W/SC ratios may hinder workability and homogeneity, affecting practical application. In contrast, higher W/SC ratios improve flowability but can compromise strength by increasing pore volume and weakening the cement matrix.

The optimal W/SC ratio balances hydration kinetics and workability, ensuring sufficient reaction products for strength gain without excessive water-induced defects. Proper controlling this ratio is crucial for achieving superior early-age strength, enhancing durability, and making AASC a viable alternative for sustainable construction.

Figure 4 illustrates the compressive strength development of alkali-activated slag cement at varying water-to-slag cement (W/SC) ratios with incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) under steam curing conditions. The results indicate that mixtures with lower W/SC ratios exhibit higher early-age strength, particularly with HCFA, due to enhanced calcium-driven hydration and geopolymerization. As the W/SC ratio increases, a decline in strength is observed, attributed to increased porosity and reduced matrix densification. LCFA-based mixtures show a more gradual strength gain, benefiting long-term durability.

These findings highlight the importance of optimizing W/SC ratios and fly ash composition to achieve a balance between workability, early-age performance, and long-term structural integrity, making AASC a promising alternative for sustainable construction applications.

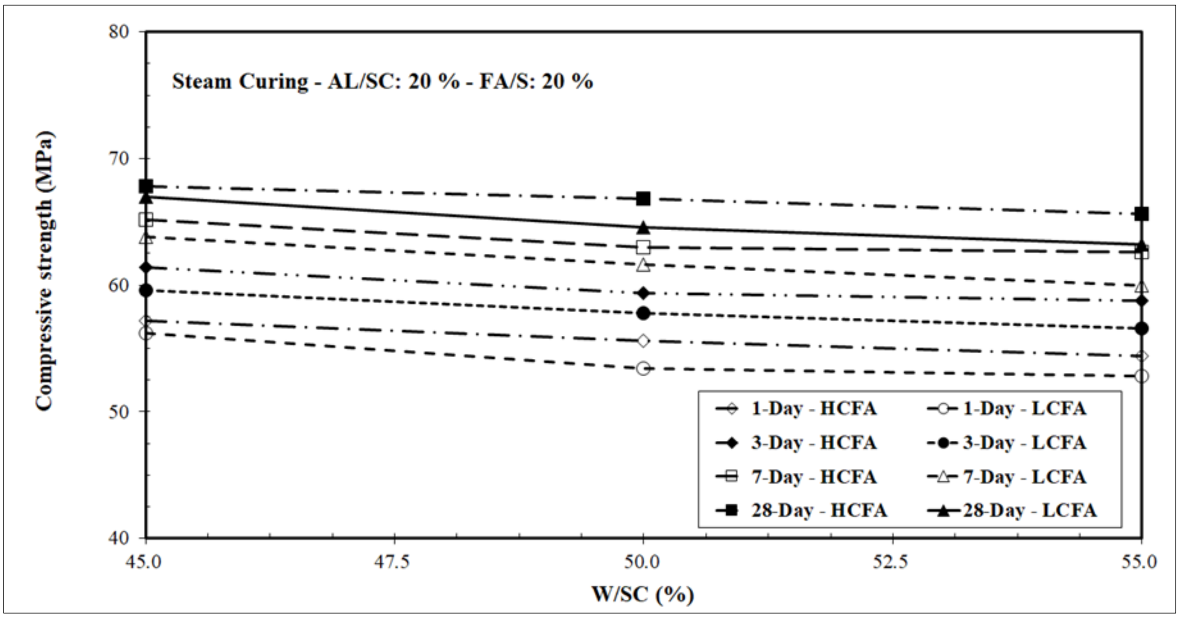

Figure 4 Impact of water-to-slag cement ratio on compressive strength development

3.2.3. Impact of Age Curing

Curing age plays a crucial role in the compressive strength development of alkali-activated slag cement (AASC). The early-age strength gain is significantly influenced by the reaction kinetics of slag and fly ash in an alkaline environment, with rapid strength improvement observed within the first 7 days. Steam curing accelerates hydration and geopolymerization, leading to a denser microstructure and higher early strength. However, ambient curing results in a slower but more continuous development, contributing to long-term durability. The high-calcium fly ash (HCFA) enhances early strength due to its reactive calcium content, low-calcium fly ash (LCFA) contributes to later-age strength through gradual geopolymeric reactions. Understanding the impact of curing age helps optimize AASC formulations for improved mechanical performance, ensuring both early-age strength and long-term stability in construction applications.

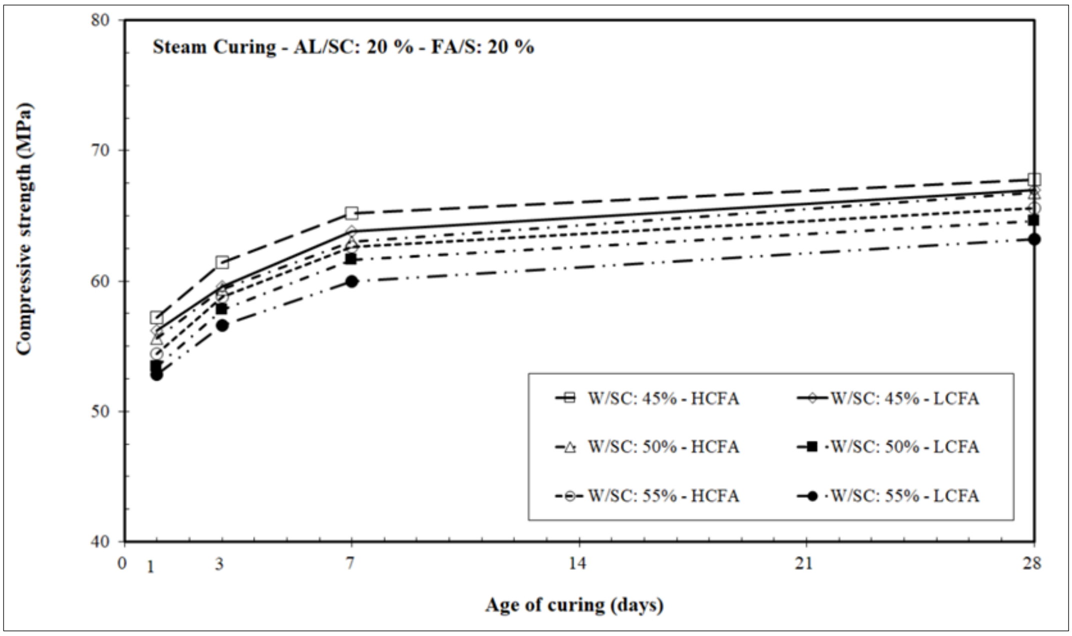

Figure 5 Impact of age curing on compressive strength development

Figure 5 illustrates the compressive strength development of alkali-activated slag cement (AASC) at various ages (1, 3, 7, and 28 days) incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) at different water-to-slag cement (W/SC) ratios over a 28-day period.

A general upward trend in strength is observed for all mixes, with higher early-age strength seen in HCFA-based specimens due to its enhanced pozzolanic reactivity and calcium content, promoting rapid geopolymerization. In contrast, LCFA-based specimens exhibit slower strength gain but continue improving over time due to extended polymerization reactions. Lower W/SC ratios (45%) lead to higher compressive strength, confirming that reduced water content enhances matrix densification. These results highlight the critical role of fly ash type and W/SC ratio in optimizing early and long-term mechanical performance, offering sustainable alternatives for construction applications.

4. Conclusion

The findings of this study highlight the significant influence of high-calcium fly ash (HCFA), low-calcium fly ash (LCFA), and water-to-slag cement (W/SC) ratios on the workability and early-age strength development of alkali-activated slag cement (AASC) under steam curing. HCFA accelerates early hydration, enhancing compressive strength at lower W/SC ratios, while LCFA improves long-term durability by refining the microstructure. Lower W/SC ratios contribute to higher early strength but may compromise workability, necessitating a balanced approach for optimal performance. Steam curing effectively enhances early-age strength, particularly in HCFA-based mixtures, making AASC a viable alternative to conventional cement.

These insights provide a foundation for optimizing AASC formulations to achieve both sustainability and superior mechanical properties, promoting its adoption in durable and eco-friendly construction applications. The results emphasize the importance of carefully selecting fly ash type and W/SC ratio to balance workability, strength, and long-term durability. By optimizing these parameters, AASC can serve as a sustainable, high-performance alternative for modern construction, reducing carbon emissions while maintaining structural integrity.

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