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(Research Article)

Comparative evaluation of high- and low-calcium fly ash in alkali-activated slag composites under steam curing conditions

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Abstract

This study explores the feasibility of utilizing sustainable composites made from alkali-activated slag-fly ash as an eco-friendly alternative to traditional Portland cement. It further evaluates the influence of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) on the fresh and hardened properties of alkali-activated slag cement (AASC) composites under steam curing conditions. The fresh properties examination indicates that increasing fly ash (FA) content reduces workability, with HCFA exhibiting a more pronounced slump flow reduction than LCFA. Compressive strength results reveal that HCFA enhances early-age strength due to accelerated hydration, whereas LCFA contributes to long-term strength through sustained pozzolanic activity. The most significant strength gain occurs between days 1 and 7, followed by a gradual increase up to 28 days. These findings underscore the potential of FA as a sustainable alternative material in cementitious composites, optimizing both early-age and long-term performance for construction applications.

Keywords: High- and Low-Calcium Fly Ash; Alkali-Activated Slag Composites; Sustainable Construction; Steam Curing; Environmentally Friendly

1. Introduction

Alkali-activated slag-fly ash composites have gained significant attention as sustainable alternatives to traditional cementitious materials. By utilizing industrial by-products like fly ash and slag, these composites contribute to environmental sustainability while offering unique performance characteristics. This study explores the role of calcium oxide (CaO) variations in fly ash on the properties of alkali-activated slag composites under steam curing conditions. The interaction of CaO influences critical factors like workability and strength gain, making it a focal point for optimizing composite performance for construction applications [1]. Alkali activation is a process that induces geopolymerization in materials like slag and fly ash to form strong binding gels, such as calcium-silicate-hydrate (C–S–H) and sodium-aluminosilicate-hydrate (N–A–S–H) gels. These gels significantly affect the mechanical properties and durability of the composites [2]. Calcium-rich fly ash enhances the formation of C–S–H gels, contributing to early strength development [3]. However, variations in CaO content can alter the hydration process and impact long-term performance, especially under steam curing conditions [4].

Steam curing conditions play a critical role in determining the strength gain of these composites. Steam curing accelerates the geopolymerization process, improving early-age strength of composites [5]. The interaction between CaO content and curing regime influences the porosity and hydration product formation, which are crucial for the mechanical performance and durability of the material [6]. Recent studies have shown that the optimization of steam curing regimes can lead to higher compressive strengths and reduced setting times, which is highly beneficial for large-scale construction applications [7]. This improvement in early strength is particularly advantageous for prefabricated

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concrete elements that are produced under controlled conditions [8]. In addition, some researchers have pointed out that the impact of steam curing on alkali-activated composites is closely related to the molecular structure of the geopolymer gels formed, which is influenced by the CaO content in fly ash [9].

This research builds on the understanding of alkali-activated materials by examining how varying CaO content in fly ash impacts the hydration kinetics and microstructural development. Previous studies have highlighted the importance of optimizing the slag-to-fly ash ratio and alkali activator composition for improved performance [10]. A recent study indicated that high-calcium fly ash (HCFA) accelerates the geopolymerization process, leading to superior early strength, while low-calcium fly ash (LCFA) tends to offer better long-term durability properties due to its slower reaction kinetics [11]. Additionally, incorporating calcium-rich additives has been shown to enhance the formation of dense microstructures, reducing porosity and improving long-term mechanical properties [12]. Moreover, the combination of HCFA with slag has demonstrated significant synergy in improving the overall mechanical properties, including tensile and flexural strength, when compared to using low-calcium fly ash alone [13].

Several studies have proposed the incorporation of additional calcium-bearing materials to boost the CaO content in fly ash composites, resulting in enhanced microstructure development and reduced shrinkage [14]. Other research has suggested that optimizing the particle size distribution of fly ash can further enhance the performance of alkali-activated slag composites, as finer particles provide a greater surface area for the alkali activator to interact with, thus improving the reactivity [15]. The findings of this study will provide valuable insights into tailoring fly ash composition and steam curing conditions to achieve optimal performance for sustainable construction applications. The interplay of CaO content and steam curing regimes offers opportunities to enhance the eco-friendliness and efficiency of alkali-activated materials, paving the way for their broader adoption in the construction industry [16].

This research examines the effect of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) on the performance of alkali-activated slag cement (AASC) composites under steam curing conditions. By investigating these interactions, the study seeks to develop optimized formulations that improve mechanical performance, minimize environmental impact, and enhance practical usability in construction.

2. Experimental Details

2.1 Materials and Mix Proportions

Slag cement (SC) obtained from municipal activities was utilized as the core binder, replacing conventional Portland cement. This study incorporated high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) as partial replacements for fine aggregate. Table 1 presents the chemical composition and physical characteristics of slag cement (SC), high-calcium fly ash (HCFA), and low-calcium fly ash (LCFA). Sodium metasilicate (Na_2SiO_3), a fine white powder, served as an alkali activator, while crushed sandstone was used as fine aggregate.

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

Chemical Compositions & Physical Properties	**Slag Cement (SC)**	**High-Calcium Fly Ash (HCFA)**	**Low-Calcium Fly Ash (LCFA)**
Calcium oxide, CaO (%)	43.1	18.8	6.3
Silicon dioxide, SiO_2 (%)	32.5	48.8	57.6
Aluminum oxide, Al_2O_3 (%)	13.5	19.8	26.5
Magnesium oxide, MgO (%)	2.9	1.5	1.2
Ferric oxide, Fe_2O_3 (%)	2.7	3.8	4.2
Sodium oxide, Na_2O (%)	1.8	1.2	0.5
Titanium dioxide, TiO_2 (%)	1.3	3.9	1.9
Phosphorus pentoxide, P_2O_5 (%)	0.8	0.5	0.3
Loss on ignition, LOI (%)	1.4	1.7	1.5

Specific gravity (g/cm^3)	2.80	2.80	2.14
Specific surface area (cm^2/g)	3750	3780	3630
Average particle size of D_{50} (μm)	6.48	16.25	18.35

The composite mixture compositions are given in Table 2. All mixtures were prepared at a room temperature of approximately 20±1°C and a relative humidity of around 65±5% and then cured in steam conditions. The study examined slag cement (SC) as the primary binder, completely replacing Portland cement, while fly ash (FA) was incorporated at 0.0%, 10.0%, and 20.0% as a partial substitute for fine aggregate (S). Both high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) were used. A consistent alkali activator-to-slag cement (AL/SC) ratio of 20.0% and a water-to-slag cement (W/SC) ratio of 50.0% were applied to all mixtures to achieve a balance between economic feasibility, enhanced performance, and sustainability.

Table 2 Composite Mixture Proportions.

FA/S (%) - HCFA or LCFA	W/SC (%)	AL/SC (%)	Mix Proportioning (kg/m3)				
			Slag Cement (SC)	Water (W)	Alkali-Activator (AL)	Fly Ash (FA)	Sand (S)
FA/S: 0.0 %	50	20	600	300	120	0	1200
FA/S: 10 % - HCFA	50	20	600	300	120	100 - HCFA	1100
FA/S: 10 % - LCFA						100 - LCFA	1100
FA/S: 20 % - HCFA	50	20	600	300	120	200 - HCFA	1000
FA/S: 20 % - LCFA						200 - LCFA	1000

2.2 Preparation and Testing Methodology

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 mixed in a pan mixer for 90 seconds, followed by the addition of water, after which mixing continued for another 90 seconds to form a fresh composite mixture.

Various tests were conducted to assess the impact of different fly ash (FA) contents (0.0%, 10.0%, and 20.0%, using HCFA and LCFA) as a partial replacement for fine aggregate (S) on both the fresh and hardened properties of the composite. The fresh properties were examined using a flow test, where the initial flow and flow loss were recorded immediately and then again after 15 minutes of mixing.

Following casting, all mold specimens were stored at a room temperature of 20±1°C and a relative humidity of 65±5%, covered with sheets. For steam curing, specimens were transferred to a steam chamber one hour after 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 naturally cooled to 20°C. After one day, the molds were removed, and the specimens were stored at 20±1°C and 65±5% RH until testing.

To evaluate the hardened properties, the early-age compressive strength development under steam curing conditions was measured on three samples at the ages of 1, 3, 7, and 28 days. The hardened properties were determined through compressive strength tests.

3. Results and Discussion

3.1 Fresh Properties: Initial Flow and Flow Loss of Composites

Figure 1 shows the slump flow measurements for different composite mixtures, highlighting both the initial flow and the flow after 15 minutes. The data is categorized based on the fly ash (FA) content used as a partial replacement for fine aggregate (S), with two types of fly ash: high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA). The mixture with FA/S: 0.0% exhibits the highest initial flow, approximately 280 mm, and experiences a relatively smaller reduction after 15 minutes, indicating better workability retention over time.

For mixtures with fly ash replacement (FA/S: 10.0% & 20.0%), an increase in fly ash content leads to a decrease in initial slump flow for both HCFA and LCFA. The reduction in slump flow is more pronounced in HCFA mixtures than in LCFA mixtures, suggesting that high-calcium fly ash has a greater impact on flowability. The loss of flow after 15 minutes is noticeable in all cases but is more significant in HCFA-based mixtures, indicating a higher water demand.

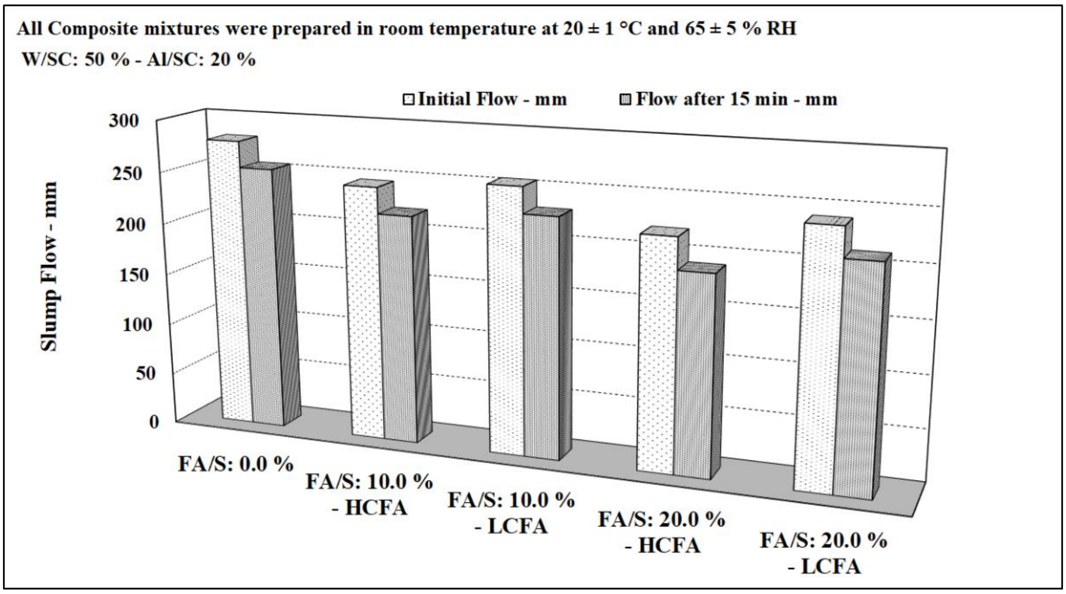

Figure 1 Effect of varying of fly ash replacement to fine aggregate for both HCFA and LCFA on the initial slump flow and flow after 15 min of the composite mixtures

A comparison between HCFA and LCFA mixtures shows that LCFA-based mixes consistently exhibit higher slump flow values than HCFA at the same replacement level. This suggests that LCFA enhances workability more effectively than HCFA, likely due to its lower reactivity and slower water absorption.

As a result, incorporating fly ash affects the mixture's workability, necessitating adjustments in water content or admixtures to maintain the desired flowability. LCFA appears to be the better choice for improving workability, whereas HCFA may require additional water or superplasticizers to achieve proper flow. A slower flow loss, as observed in LCFA-based mixes, is beneficial for extended workability, reducing the risk of re-tempering and improving placement consistency.

Overall, variations in fly ash (FA) content (0.0%, 10.0%, and 20.0%, with HCFA and LCFA) have a significant impact on the fresh composite properties.

3.2 Hardened Properties: Early-Age Compressive Strength Development of Composites

The early-age compressive strength development of composites is a crucial factor in determining their structural integrity and long-term durability. One of the key influences on this development is the incorporation of supplementary cementitious materials like fly ash, which alters hydration reactions and affects strength gain.

The distinct chemical compositions of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) lead to varying mechanical properties, making their impact on strength development particularly significant. Additionally, curing conditions, especially steam curing, play a vital role in accelerating hydration kinetics and enhancing strength gain.

This section examines the effects of different fly ash (FA) contents (0.0%, 10.0%, and 20%) and types (HCFA and LCFA) on the early-age compressive strength of alkali-activated slag composites at 1, 3, 7, and 28 days under steam curing conditions.

By investigating these interactions, this study highlights the role of FA in optimizing strength gain and enhancing composite performance. A deeper understanding of these factors enables the development of more efficient and sustainable construction materials tailored to specific engineering requirements.

3.2.1 Influence of High- and Low-Calcium Fly Ash on Strength Development

Figure 2 illustrates the compressive strength development of composite mixtures at 1, 3, 7, and 28 days under steam curing conditions. The mixtures incorporate varying fly ash (FA) replacement levels (0.0%, 10.0%, and 20.0%), using both high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) as partial substitutes for fine aggregate (S).

The results indicate a general increase in compressive strength over time, with the most significant gain occurring between 1-day and 7-day curing, followed by a more gradual increase up to 28 days. Mixtures containing FA (10% & 20%) demonstrate higher long-term compressive strength than the control mixture (0.0% FA/S), despite exhibiting slightly lower early-age strength, particularly in HCFA-based mixes. HCFA-based mixtures consistently achieve higher compressive strength than LCFA-based counterparts, emphasizing the influence of calcium content on hydration and strength development. However, LCFA contributes to enhanced long-term strength through sustained pozzolanic activity and improved microstructural bonding, making it more suitable for applications requiring extended strength gain and durability.

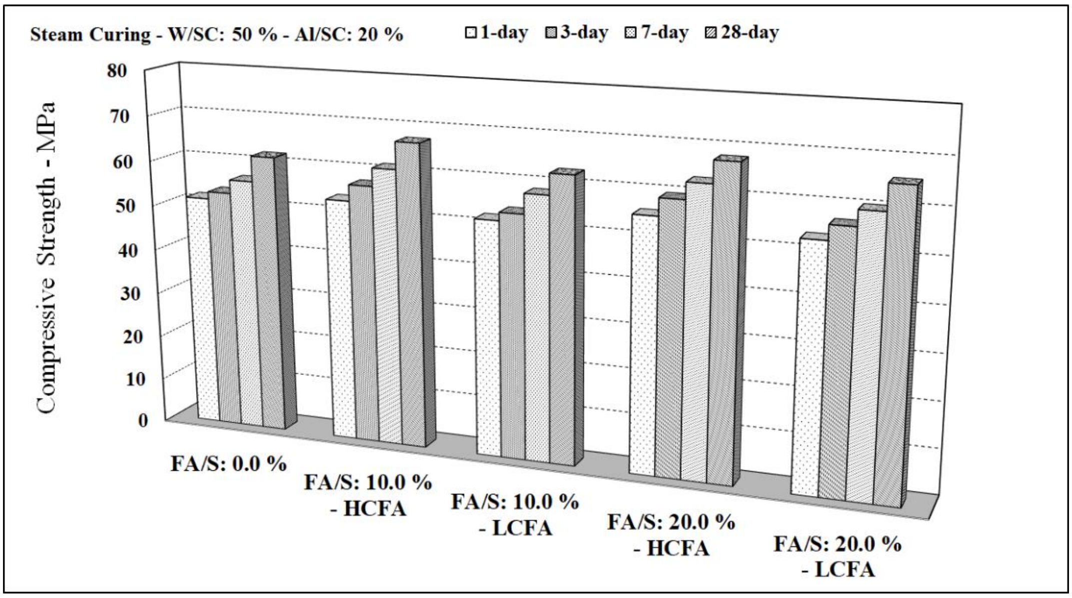

Figure 2 Effect of varying of fly ash replacement to fine aggregate for both HCFA and LCFA on the compressive strength of composite mixtures

These findings suggest that HCFA is preferable for applications demanding high early-age strength, while LCFA is advantageous for long-term structural performance, reinforcing the role of FA as a sustainable and effective partial replacement for fine aggregate in cementitious composites.

Therefore, the variation in fly ash (FA) content (0.0%, 10.0% and 20.0% with HCFA and LCFA) significantly influenced the compressive strength of the composite. Mixtures incorporating high-calcium fly ash (HCFA) exhibited higher early-age compressive strength due to its rapid hydration and heat generation. Conversely, low-calcium fly ash (LCFA) contributed to a slower strength gain but improved long-term performance.

The replacement level of 20% FA affected the overall strength development, with HCFA mixtures showing accelerated strength gain while LCFA mixtures demonstrated more gradual but steady improvement.

3.2.2 Influence of Curing Age on Strength Development

Figure 3 demonstrates the growth of compressive strength in composite mixtures at 1, 3, 7, and 28 days under steam curing conditions. The mixtures incorporate varying levels of fly ash (FA) replacement (0.0%, 10.0%, and 20.0%), with both high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) used.

The results highlight a notable increase in compressive strength over time, with the most rapid gain occurring between days 1 and 7, followed by a more gradual improvement up to 28 days. Mixtures with FA replacement demonstrate higher long-term strength than the control (0.0% FA/S), with HCFA-based mixtures achieving superior compressive strength compared to LCFA-based ones due to the higher calcium content accelerating early hydration. However, LCFA contributes to enhanced long-term strength due to its pozzolanic reactivity, which refines the microstructure over time.

These findings suggest that HCFA is preferable for applications requiring high early-age strength, whereas LCFA is beneficial for long-term structural performance. The results reinforce the viability of FA as a sustainable material for partial fine aggregate replacement in cementitious composites, offering environmental and structural benefits.

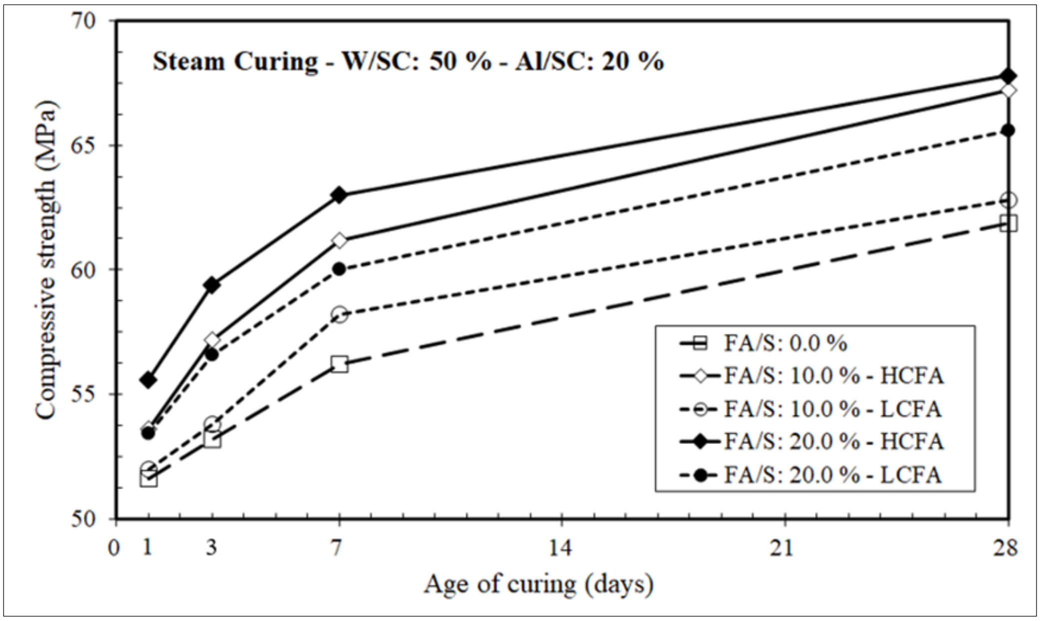

Figure 3 Compressive strength growth of composite mixtures cured in steam at various ages

4. Conclusion

This study investigated the effects of high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA) as partial replacements for fine aggregate on the fresh and hardened properties of composite mixtures.

The fresh properties investigation revealed that increasing FA content reduced initial slump flow, with HCFA mixtures exhibiting a more pronounced decline in workability than LCFA-based mixes. This suggests that LCFA enhances flow retention, making it a preferable choice for improving workability, whereas HCFA may require additional water or admixtures to maintain adequate flow.

In terms of hardened properties, the compressive strength results demonstrated that mixtures with FA replacement exhibited superior long-term strength compared to the control mixture (0.0% FA/S). HCFA-based mixtures showed higher early-age strength due to accelerated hydration, while LCFA-based mixtures achieved better long-term strength through pozzolanic activity and improved microstructural bonding. Furthermore, the compressive strength gain was most significant between 1-day and 7-day curing, followed by a more gradual increase up to 28 days.

These findings highlight the potential of FA as a sustainable alternative material in cementitious composites, balancing both early-age and long-term performance. HCFA is suitable for applications requiring rapid strength development, whereas LCFA is advantageous for long-term structural durability. The study underscores the importance of optimizing FA content and type based on specific engineering needs to enhance the performance and sustainability of construction materials.

This study also emphasizes the significance of tailoring fly ash content and type to meet the specific requirements of construction projects, ensuring that both immediate and enduring performance needs are met. By incorporating high-calcium fly ash (HCFA) and low-calcium fly ash (LCFA), the study supports the advancement of more environmentally friendly and cost-effective construction materials, aligning with sustainable building practices and contributing to reduced carbon footprints in the construction industry.

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