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# Performance and Viability of Lightweight Slag-Based Alkali-Activated Cement (SAAC) as an Eco-Friendly Alternative to API Oil Well Cement

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**Abstract**

This study aimed to develop and evaluate a lightweight slag-based alkali-activated cement (SAAC) system as a sustainable alternative to conventional API Class G oil well cement and to assess its engineering performance under laboratory conditions relevant to oil and gas well cementing operations. An experimental laboratory study was conducted using ground granulated blast furnace slag activated by alkaline solutions containing sodium hydroxide, sodium silicate, and sodium metasilicate. Both two-component and powdered SAAC systems with different Blaine fineness values (2900 and 4200 $cm^2/g$) were designed and evaluated. A series of ASTM and API-standard tests were performed, including setting time, compressive strength, flexural strength, autoclave expansion, slurry density, thickening time, free-water measurement, ultrasonic compressive strength development, and scanning electron microscopy (SEM). Optimized mixtures were further modified with microsilica and compared directly with conventional API Class G oil well cement under elevated temperature and pressure conditions. The results demonstrated that increasing slag fineness significantly reduced setting time and enhanced compressive strength. Two-component SAAC formulations generally exhibited higher compressive strength than powdered systems, although both achieved strengths comparable to or exceeding those of Portland and Class G oil well cements. Optimized SAAC mixtures showed continuous strength development over time, acceptable autoclave expansion values, and favorable flexural performance. Under API testing conditions, the selected SAAC formulations achieved thickening times within the acceptable operational range and produced no measurable free water. The microsilica-modified SAAC mixture exhibited superior early-age and long-term compressive strength compared with Class G cement. Ultrasonic strength measurements further indicated faster strength development and greater compressive resistance under high-temperature and high-pressure curing conditions. SEM observations confirmed a denser microstructure with fewer cracks in the optimized SAAC formulations, supporting the observed mechanical performance. The developed slag-based alkali-activated cement satisfied key API performance requirements and demonstrated superior environmental and engineering characteristics compared with conventional oil well cement. The optimized SAAC system showed excellent mechanical strength, adequate thickening behavior, negligible free-water production, and enhanced performance under elevated temperature and pressure conditions, indicating strong potential as a sustainable substitute for conventional oil and gas well cement.

***Keywords:*** *Slag-based Alkali-Activated Cement (SAAC), American Petroleum Institute (API) Oil Well Cement, Cementing.*

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## 1. Introduction

The cementing of oil and gas wells is one of the most technically sensitive stages in drilling operations because the cement sheath must provide zonal isolation, support the casing, protect steel components from corrosive fluids, and prevent the migration of formation fluids through the annular space. Unlike ordinary construction cement, oil well cement is exposed to highly variable downhole environments, including elevated temperature, high pressure, aggressive chemical media, and long-term mechanical loading. Therefore, the cement slurry used in these environments must satisfy multiple performance requirements simultaneously: sufficient pumpability during placement, controlled thickening time, early strength development after placement, dimensional stability, low permeability, chemical resistance, and long-term durability. Conventional API oil well cements, particularly Class G cement, have been widely used because of their predictable chemistry and compatibility with industrial additives; however, their production is associated with substantial energy consumption and carbon dioxide emissions. In addition, conventional Portland-based systems may experience durability limitations in chemically aggressive environments, including acid attack and strength degradation under severe thermal exposure. These limitations have encouraged increasing research attention toward alternative cementitious binders that can reduce environmental burden while preserving or improving the functional properties required for oil and gas well cementing.

The environmental challenges associated with Portland cement production have placed cement chemistry at the center of global efforts to develop sustainable construction and drilling materials. Portland cement manufacture relies on the calcination of limestone and the formation of clinker phases at high temperatures, which leads to both process-related and fuel-related $CO_2$ emissions. From a materials-design perspective, any viable alternative must reduce clinker dependency while maintaining the mechanical and rheological performance expected from industrial cement systems. Alkali-activated binders have gained prominence within this context because they can utilize industrial by-products such as ground granulated blast furnace slag and convert them into high-performance cementitious matrices through alkaline activation. The broader field of alternative cementitious binders has shown that industrial by-products can serve not merely as supplementary materials but also as primary binders when appropriate activation mechanisms are provided [1]. Among these materials, slag has attracted particular interest due to its calcium-rich amorphous structure, latent hydraulic behavior, and ability to form binding gels under alkaline conditions [2]. This makes slag-based alkali-activated cement a strong candidate for applications where high early strength, dense microstructure, and chemical durability are required.

Ground granulated blast furnace slag is particularly relevant for alkali-activated cement because its chemical composition differs from low-calcium aluminosilicate precursors such as fly ash and metakaolin. The relatively high CaO content of slag enables the development of calcium-rich reaction products, especially C-S-H or C-A-S-H type gels, which are responsible for strength development and matrix densification. Classic cement chemistry has shown that the structure and composition of calcium silicate hydrate strongly influence strength, permeability, and durability in cementitious systems [3]. In alkali-activated slag systems, however, the Ca/Si ratio and gel structure differ from those of hydrated Portland cement, producing a microstructure that may exhibit distinct mechanical and durability behavior [4]. The hydration and activation of slag are controlled by slag chemistry, fineness, activator composition, alkalinity, curing temperature, and water content. For example, the chemical composition of slag, including MgO content, can alter hydration pathways and phase assemblage in alkali-activated blast furnace slag [5]. These observations indicate that slag-based alkali-activated cement cannot be treated as a simple Portland cement replacement; rather, it requires independent optimization based on activator chemistry, particle fineness, and target service conditions.

The theoretical and technological foundation of alkali-activated binders has developed over several decades. Early studies on the reaction of slag with alkaline solutions established that slag can acquire cementitious properties when exposed to high-pH activators, while later developments in geopolymer science broadened the concept of alkali activation to include aluminosilicate polymerization mechanisms [6]. Although geopolymers and alkali-activated slag cements are sometimes discussed together, their reaction mechanisms are not identical. Low-calcium geopolymer systems are primarily governed by aluminosilicate dissolution and polycondensation, whereas alkali-activated slag systems typically form calcium-rich hydrate gels that resemble, but are chemically distinct from, those in Portland cement. Sodium silicate activation has been shown to strongly influence the setting characteristics of slag pastes, confirming the importance of activator type and silicate modulus in controlling fresh-state behavior [7]. The setting behavior is particularly important in oil well cementing because the slurry must remain pumpable long enough to reach the target zone but must also develop sufficient strength soon after placement. Therefore, activator design is not only a chemical issue but also an operational requirement.

Oil and gas wells impose stricter constraints on cement than many surface construction applications. A cement slurry with excessively short setting or thickening time may set prematurely during pumping, while excessive thickening time delays operations and may compromise zonal isolation. Furthermore, the cement sheath must withstand pressure and temperature gradients, chemical attack, and mechanical stresses induced by casing movement, pressure cycling, and thermal expansion. Research on acid attack has demonstrated that cementitious materials can experience substantial degradation when exposed to aggressive media, depending on binder composition and protective mechanisms [8]. Alkali-activated slag concrete has shown promising acid resistance in comparison with ordinary Portland cement systems, although its behavior under carbonation and other durability exposures must be evaluated carefully [9]. These durability considerations are highly relevant for oil well cementing because downhole environments may contain $CO_2$, $H_2S$, brines, and other chemically aggressive fluids. The potential of alkali-activated slag systems to reduce permeability and improve durability therefore provides a strong rationale for investigating their use as oil well cement alternatives.

The performance of alkali-activated slag systems is also influenced by microstructural refinement. Silica-rich additives, nanomaterials, and pozzolanic modifiers can improve the pore structure of cementitious matrices by enhancing packing density, promoting secondary gel formation, and reducing capillary porosity. In conventional concrete, nano-silica and nano-alumina have been shown to improve frost resistance and mechanical performance by modifying hydration products and densifying the matrix [10]. In oil well cement systems, nanomaterials can influence hydration kinetics and mechanical properties, indicating that nanoscale additives may be useful tools for tailoring slurry performance under operational conditions [11]. Nano-silica has also been studied specifically in Class G oil well cement slurries, where it improved hydration and affected rheological and strength-related performance [12]. For slag-based alkali-activated systems, silica fume has been reported to improve durability by reducing permeability and refining the pore system [13]. These findings support the inclusion of microsilica or other silica-rich modifiers in slag-based alkali-activated cement formulations intended for high-performance well cementing applications.

In addition to sustainability and durability, weight reduction is an important issue in well cementing and advanced cementitious materials. Lightweight cement slurries are often required in weak or fractured formations where excessive hydrostatic pressure can cause lost circulation. The development of lightweight binders must balance density reduction with adequate strength, stability, and low permeability. Recent research on lightweight geopolymer concrete has emphasized mix optimization as a key requirement for achieving suitable density and mechanical performance [14]. Similarly, lightweight sustainable concretes produced through geopolymer technology have been studied for sulfate resistance, demonstrating the relevance of alkali-activated systems in aggressive environments [15]. Lightweight concrete research has also explored the use of waste materials as aggregate substitutes, highlighting the broader sustainability value of incorporating industrial or recycled materials into cementitious composites [16]. Although many of these studies focus on structural concrete rather than well cementing, they demonstrate a growing movement toward multifunctional cementitious materials that combine low density, durability, and environmental efficiency.

The use of slag and other industrial by-products also aligns with circular economy principles in construction materials. Steel slag has been investigated as a partial replacement for natural river sand in concrete production, showing that metallurgical by-products can reduce natural resource consumption while contributing to material performance when properly processed [17]. Alkali-activated slag concrete has also been proposed for specialized infrastructure applications such as railway sleepers, where strength, durability, and dimensional stability are required [18]. These applications demonstrate that slag-based alkali-activated materials are not limited to experimental binder systems but may be adapted for high-demand engineering uses. The same logic can be extended to oil well cementing, provided that the slurry meets API-related requirements for thickening time, free water, density, early compressive strength, and stability under pressure and temperature. Therefore, the transition from general slag-based cement research to well cementing requires targeted formulation and testing rather than direct transfer from concrete applications.

Recent developments in lightweight and aerated cementitious materials further show that pore structure control is central to balancing density and mechanical performance. Aerated geopolymer concrete research has demonstrated that precursor source type can significantly influence pore structure and resulting properties, reinforcing the importance of raw material selection in alkali-activated systems [19]. Lightweight heat-insulating and sound-insulating concrete blocks have also been studied as examples of multifunctional cement-based materials, showing how density, porosity, and functional performance can be engineered simultaneously [20]. Internal curing approaches using lightweight superabsorbent materials have been reviewed as another strategy for controlling hydration and moisture availability within cementitious systems [21]. Although such approaches differ from oil well cement slurry design, they emphasize a common principle: high-performance cementitious materials require careful control of internal water, pore structure, and reaction kinetics. In oil well cementing, this principle is especially important because free water, excessive porosity, and delayed strength development can create channels for fluid migration and compromise zonal isolation.

Despite the promising properties of alkali-activated slag cement, its application in oil and gas well cementing remains technically challenging. One major challenge is the short setting time that can occur when highly alkaline activators accelerate slag dissolution and gel formation. Another challenge is compatibility with drilling-industry additives, including retarders, dispersants, and fluid-loss control agents. Moreover, a cement system intended for oil well applications must be assessed not only through ordinary strength tests but also through API-based procedures such as slurry density, thickening time, free water, and compressive strength development under high-pressure and high-temperature conditions. Previous research has clarified many aspects of alkali-activated slag chemistry, setting behavior, microstructure, and durability, but fewer studies have directly addressed whether slag-based alkali-activated cement can be formulated as a practical substitute for API Class G oil well cement. This gap is important because a binder may perform well in ordinary concrete yet fail to satisfy the specific operational window required for cementing deep wells.

Accordingly, the present study investigates the performance and viability of lightweight slag-based alkali-activated cement as an eco-friendly alternative to API oil well cement by designing two-component and powder SAAC formulations, optimizing their activator composition and slag fineness, evaluating their mechanical and rheological properties, and testing the selected slurry under API-relevant oil and gas well cementing conditions.

## 2. Methodology

The study employed an experimental laboratory design aimed at evaluating the performance of slag-based alkali-activated cement (SAAC) in comparison with conventional Portland cements, including Type 2 and Type 5, as well as API Class G oil well cement. The experimental setup was divided into two main groups of tests: one conducted under ASTM C standards, relevant to general Portland cement properties, and another conducted according to API standards, specifically for oil and gas well cementing applications. The purpose of the ASTM C tests was to determine the optimal proportion of slag and alkaline activators to achieve mechanical and rheological properties suitable for well cementing, while the API-based experiments examined the performance of the selected SAAC mixtures under conditions representative of actual drilling operations. The study used Class G oil well cement produced by Delijan Cement Factory as the control reference. Its chemical composition is summarized in Table 1, and its physical properties, including Blaine fineness, initial and final setting times, specific gravity, compressive strength at two and three days, and autoclave expansion, are presented in Table 2. Type 2 and Type 5 Portland cements produced by Behn Sazan Sanaye Asia Titan Cement Company were also included to benchmark SAAC performance.

The materials employed in this research comprised blast furnace slag from Isfahan Steel Company, ground to specific surfaces of 2900 and 4200 $cm^2/g$, standard Ottawa sand, sodium hydroxide, sodium silicate solution, sodium metasilicate powder, microsilica, nanosilica, carbon nanotubes, and industrial drilling additives such as lignosulfonate-based retarders, polymeric dispersants, and fluid loss control agents. Microsilica was characterized chemically and physically according to ASTM C1240 standards (Tables 8 and 9). Nanosilica chemical composition and physical properties are provided in Tables 10 and 11, while carbon nanotube specifications are in Table 12. The alkaline activator solutions were prepared using sodium hydroxide and sodium silicate or metasilicate in controlled molar ratios, with care taken to prevent water loss due to exothermic dissolution. The mixtures were produced in both two-component and powdered forms, with water-to-slag ratios maintained at 0.43, consistent with API 10A Class G cement guidelines.

Data collection included a comprehensive range of tests on the prepared cement slurries. Setting times were measured using the Vicat needle apparatus; compressive strength was evaluated at 24 hours, 48 hours, and at one, three, and seven days using standard compression testing; flexural strength was determined for selected optimized mixtures; autoclave expansion tests were conducted to assess dimensional stability under high temperature and pressure; slurry density, thickening time, and free water content were measured to verify pumpability and consistency; ultrasonic testing devices were used to monitor early-age compressive strength development under 38°C and 20.7 MPa. Microstructural analyses were performed using scanning electron microscopy to observe C-S-H gel formation and crack patterns in both two-component and powder SAAC samples.

Data analysis involved comparing the performance of SAAC mixtures with Portland cements and Class G oil well cement using inferential statistics to evaluate compressive and flexural strength trends over time. Setting time, thickening time, and free water data were analyzed for compliance with API standards. Comparisons across different Blaine fineness levels and alkali activator ratios were performed to identify optimal mixture designs. Microstructural SEM images were interpreted qualitatively to corroborate mechanical performance. The integrated analysis enabled the selection of SAAC formulations with superior early-age and long-term strength, appropriate setting characteristics, and enhanced structural density, demonstrating their suitability for practical oil and gas well cementing applications.

**Table 1.** Chemical Composition of Class G Oil Well Cement

| % | $SiO_2$ | CaO | $Al_2O_3$ | MgO | $SO_3$ | $Fe_2O_3$ |
|---|---|---|---|---|---|---|
| G | 21.1 | 67.9 | 6.1 | 0.8 | 2.7 | 0.8 |

**Table 2.** Physical Properties of Class G Oil Well Cement

| Physical Parameters | Blaine ($cm^2/g$) | Initial Setting (min) | Final Setting (min) | Specific Gravity ($g/cm^3$) | Compressive Strength 2 days (MPa) | Compressive Strength 3 days (MPa) | Autoclave Expansion (%) |
|---|---|---|---|---|---|---|---|
| Class G Cement | 3200 | 180 | 260 | 3.24 | 18.8 | 20.8 | – |

## 3. Findings and Results

To use alkali-activated cement as a binder, the alkaline activator was combined with slag under two preparation strategies. In the first strategy, the alkaline solution was prepared separately by dissolving solid sodium hydroxide in water, allowing the mixture to reach thermal equilibrium for two hours, and then combining it with liquid sodium silicate before adding slag and mixing for three minutes. This system was considered the two-component alkali-activated slag cement. In the second strategy, solid sodium hydroxide and sodium metasilicate powder were first blended with slag, after which the required water was added and the mixture was stirred for three minutes. This system was considered the powder alkali-activated slag cement. The slag was ground to two Blaine fineness levels, 2900 $cm^2/g$ and 4200 $cm^2/g$, and the mechanical and rheological behavior of both systems was evaluated. The alkaline activator was controlled through two parameters, namely the sodium silicate modulus, expressed as M_s = $SiO_2/Na_2O$, and the sodium oxide-to-slag ratio, expressed as n = $Na_2O$/slag. In this study, M_s values of 0.45, 0.65, and 0.85 and n values of 0.035, 0.045, 0.055, 0.065, and 0.075 were selected. The water-to-slag ratio was maintained at 0.43 according to the API 10A reference value for Class G cement, and the slag content was fixed at 800 $kg/m^3$. The results were calculated based on the average of three specimens.

**Table 3.** Material Composition of Two-Component and Powder Alkali-Activated Slag Cement Mixtures

| System | Mixture | n | M_s | Water Glass / Sodium Metasilicate ($kg/m^3$) | NaOH ($kg/m^3$) | $H_2O$ ($kg/m^3$) |
|---|---|---|---|---|---|---|
| Two-component | LN3M4 | 0.35 | 0.45 | 37.56 | 29.12 | 344.74 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Two-component | LN4M4 | 0.45 | 0.45 | 48.30 | 37.44 | 344.94 |
| Two-component | LN5M4 | 0.55 | 0.45 | 59.04 | 45.76 | 345.16 |
| Two-component | LN6M4 | 0.65 | 0.45 | 69.76 | 54.06 | 345.18 |
| Two-component | LN7M4 | 0.75 | 0.45 | 80.50 | 62.38 | 345.58 |
| Two-component | LN3M6 | 0.35 | 0.65 | 54.26 | 26.00 | 338.16 |
| Two-component | LN4M6 | 0.45 | 0.65 | 69.76 | 33.42 | 336.50 |
| Two-component | LN5M6 | 0.55 | 0.65 | 85.26 | 40.86 | 334.82 |
| Two-component | LN6M6 | 0.65 | 0.65 | 100.76 | 48.28 | 333.16 |
| Two-component | LN7M6 | 0.75 | 0.65 | 116.28 | 55.72 | 331.15 |
| Two-component | LN3M8 | 0.35 | 0.85 | 70.96 | 22.88 | 331.58 |
| Two-component | LN4M8 | 0.45 | 0.85 | 91.22 | 29.42 | 328.04 |
| Two-component | LN5M8 | 0.55 | 0.85 | 111.50 | 35.96 | 324.50 |
| Two-component | LN6M8 | 0.65 | 0.85 | 131.78 | 43.10 | 320.96 |
| Two-component | LN7M8 | 0.75 | 0.85 | 152.04 | 49.04 | 317.40 |
| Powder | SN3M4 | 0.35 | 0.45 | 12.6 | 19.86 | 344 |
| Powder | SN4M4 | 0.45 | 0.45 | 16.2 | 25.52 | 344 |
| Powder | SN5M4 | 0.55 | 0.45 | 19.8 | 31.22 | 344 |
| Powder | SN6M4 | 0.65 | 0.45 | 23.4 | 36.90 | 344 |
| Powder | SN7M4 | 0.75 | 0.45 | 27.0 | 42.58 | 344 |
| Powder | SN3M6 | 0.35 | 0.65 | 18.2 | 12.60 | 344 |
| Powder | SN4M6 | 0.45 | 0.65 | 23.4 | 16.26 | 344 |
| Powder | SN5M6 | 0.55 | 0.65 | 28.6 | 19.86 | 344 |
| Powder | SN6M6 | 0.65 | 0.65 | 33.8 | 23.48 | 344 |
| Powder | SN7M6 | 0.75 | 0.65 | 39.0 | 27.10 | 344 |
| Powder | SN3M8 | 0.35 | 0.85 | 23.8 | 5.42 | 344 |
| Powder | SN4M8 | 0.45 | 0.85 | 30.6 | 6.69 | 344 |
| Powder | SN5M8 | 0.55 | 0.85 | 37.4 | 8.52 | 344 |
| Powder | SN6M8 | 0.65 | 0.85 | 44.2 | 1.06 | 344 |
| Powder | SN7M8 | 0.75 | 0.85 | 51.0 | 11.62 | 344 |

The setting-time results showed that increasing the amounts of sodium hydroxide and liquid sodium silicate in the two-component mixtures reduced the setting time. A similar trend was observed in the powder mixtures, where increasing sodium hydroxide and sodium metasilicate changed the setting behavior. However, sodium metasilicate also showed a retarding effect; therefore, increasing sodium metasilicate content extended the setting time in some powder mixtures. In both preparation systems, increasing slag fineness from 2900 cm²/g to 4200 cm²/g reduced setting time by approximately 10%, because the higher specific surface area accelerated the reaction between slag particles and the alkaline activator. The powder alkali-activated slag cement generally showed longer setting time than the two-component system, mainly because liquid sodium silicate reacts faster than sodium metasilicate powder and activates slag more rapidly.

**Table 4.** Setting Time of Two-Component and Powder Alkali-Activated Slag Cement

| System | Mixture | Initial Setting (min) | Final Setting (min) |
|---|---|---|---|
| Two-component | LN3M4 | 280 | 300 |
| Two-component | LN4M4 | 245 | 288 |
| Two-component | LN5M4 | 160 | 220 |
| Two-component | LN6M4 | 110 | 195 |
| Two-component | LN7M4 | 145 | 180 |
| Two-component | LN3M6 | 235 | 274 |
| Two-component | LN4M6 | 229 | 270 |
| Two-component | LN5M6 | 200 | 250 |
| Two-component | LN6M6 | 145 | 200 |
| Two-component | LN7M6 | 189 | 250 |
| Two-component | LN3M8 | 250 | 305 |
| Two-component | LN4M8 | 225 | 270 |
| Two-component | LN5M8 | 142 | 220 |

| | | | |
|---|---|---|---|
| Two-component | LN6M8 | 95 | 145 |
| Two-component | LN7M8 | 130 | 190 |
| Powder | SN3M4 | 300 | 350 |
| Powder | SN4M4 | 280 | 325 |
| Powder | SN5M4 | 180 | 230 |
| Powder | SN6M4 | 143 | 215 |
| Powder | SN7M4 | 190 | 210 |
| Powder | SN3M6 | 260 | 305 |
| Powder | SN4M6 | 255 | 300 |
| Powder | SN5M6 | 230 | 295 |
| Powder | SN6M6 | 200 | 245 |
| Powder | SN7M6 | 275 | 290 |
| Powder | SN3M8 | 275 | 345 |
| Powder | SN4M8 | 250 | 300 |
| Powder | SN5M8 | 175 | 230 |
| Powder | SN6M8 | 120 | 172 |
| Powder | SN7M8 | 185 | 225 |

The 24-hour compressive strength results indicated that both two-component and powder alkali-activated slag cement mixtures developed measurable early-age strength. Increasing the Blaine fineness from 2900 cm²/g to 4200 cm²/g consistently increased compressive strength. This improvement can be attributed to the larger specific surface area, more complete reaction, better particle packing, and more uniform particle size distribution. The lower strength of the 2900 cm²/g mixtures was related to the coarser and less uniform slag particles, which reduced matrix compactness. Overall, the two-component system produced higher 24-hour compressive strength than the powder system, which was attributed to the stronger and faster binding effect of liquid sodium silicate.

**Table 5.** Twenty-Four-Hour Compressive Strength of Two-Component and Powder Alkali-Activated Slag Cement

| System | Mixture | Blaine 4200 cm²/g, Compressive Strength (MPa) | Blaine 2900 cm²/g, Compressive Strength (MPa) |
|---|---|---|---|
| Two-component | LN3M4 | 7.3 | 4.59 |
| Two-component | LN4M4 | 7.5 | 4.58 |
| Two-component | LN5M4 | 6.8 | 4.58 |
| Two-component | LN6M4 | 8.0 | 4.78 |
| Two-component | LN7M4 | 9.4 | 5.00 |
| Two-component | LN3M6 | 7.5 | 4.47 |
| Two-component | LN4M6 | 7.9 | 4.63 |
| Two-component | LN5M6 | 8.0 | 4.78 |
| Two-component | LN6M6 | 10.5 | 4.98 |
| Two-component | LN7M6 | 10.7 | 5.42 |
| Two-component | LN3M8 | 6.9 | 4.78 |
| Two-component | LN4M8 | 10.7 | 4.75 |
| Two-component | LN5M8 | 7.1 | 4.98 |
| Two-component | LN6M8 | 8.5 | 4.78 |
| Two-component | LN7M8 | 7.3 | 4.40 |
| Powder | SN3M4 | 6.5 | 3.72 |
| Powder | SN4M4 | 6.9 | 3.70 |
| Powder | SN5M4 | 6.3 | 3.71 |
| Powder | SN6M4 | 7.0 | 3.86 |
| Powder | SN7M4 | 8.5 | 4.32 |
| Powder | SN3M6 | 6.9 | 3.53 |
| Powder | SN4M6 | 7.0 | 3.73 |
| Powder | SN5M6 | 7.9 | 3.91 |
| Powder | SN6M6 | 9.5 | 4.05 |
| Powder | SN7M6 | 10.3 | 4.52 |
| Powder | SN3M8 | 6.5 | 3.89 |
| Powder | SN4M8 | 6.3 | 3.80 |
| Powder | SN5M8 | 6.9 | 3.18 |

| | | | |
|---|---|---|---|
| Powder | SN6M8 | 7.0 | 3.88 |
| Powder | SN7M8 | 7.0 | 3.53 |

Because 24-hour compressive strength is critical in oil and gas well cementing, six mixtures with superior combinations of setting time and compressive strength were selected for further investigation: LN7M4, LN6M6, LN7M6, SN7M4, SN6M6, and SN7M6. The results showed a clear increase in compressive strength from three to seven days. The two-component mixtures generally had approximately 10% higher compressive strength than the powder mixtures, although the powder mixtures approached the strength level of the two-component system in several cases. For example, SN7M4 reached a seven-day compressive strength of 12.8 MPa. When compared with Portland cement, the alkali-activated slag cement achieved comparable or higher strength; Type 2 Portland cement reached 10.3 MPa at seven days, whereas Type 5 Portland cement reached 9.5 MPa at seven days. The flexural strength results also increased over time, and the powder alkali-activated cement showed flexural performance comparable to the two-component system, particularly at Blaine 4200 cm²/g.

**Table 6.** Compressive and Flexural Strength of Selected Alkali-Activated Slag Cement Mixtures

| System | Mixture | 3-Day Compressive Strength (MPa) | 7-Day Compressive Strength (MPa) | 3-Day Flexural Strength (MPa) | 7-Day Flexural Strength (MPa) |
|---|---|---|---|---|---|
| Two-component | LN7M4 | 11.0 | 12.9 | — | — |
| Two-component | LN6M6 | 12.9 | 16.3 | 12.5 | 13.35 |
| Two-component | LN7M6 | 17.1 | 20.8 | 14.9 | 16.1 |
| Two-component | LN3M4 | — | — | 9.35 | 10.0 |
| Powder | SN7M4 | 10.4 | 12.8 | — | — |
| Powder | SN6M6 | 12.2 | 15.1 | 10.5 | 12.3 |
| Powder | SN7M6 | 14.4 | 18.9 | 10.05 | 13.65 |
| Powder | SN3M4 | — | — | 9.34 | 11.0 |

The autoclave expansion results showed that all optimized mixtures had expansion values below 0.8%, which is the acceptable threshold according to ASTM C151. Therefore, the mixtures demonstrated adequate dimensional stability under autoclave conditions. Among the tested mixtures, the expansion values ranged from 0.07% to 0.10%, confirming that both two-component and powder alkali-activated slag cement systems remained stable under severe curing conditions.

**Table 7.** Autoclave Expansion of Optimized Alkali-Activated Slag Cement Mixtures

| Mixture | Blaine 2900 cm²/g (%) | Blaine 4200 cm²/g (%) |
|---|---|---|
| LN7M4 | 0.10 | 0.08 |
| LN6M6 | 0.09 | 0.10 |
| LN7M6 | 0.08 | 0.07 |
| SN7M4 | 0.10 | 0.08 |
| SN6M6 | 0.09 | 0.09 |
| SN7M6 | 0.07 | 0.08 |

The microstructural findings supported the mechanical results. The SEM images of the two-component alkali-activated slag cement showed a denser matrix and fewer cracks than the powder form. The formation of C-S-H gel was visible, indicating the development of cementitious binding products. In contrast, the powder alkali-activated slag cement showed wider cracks and a less compact hardened structure, which explains its slightly lower compressive strength compared with the two-component system.

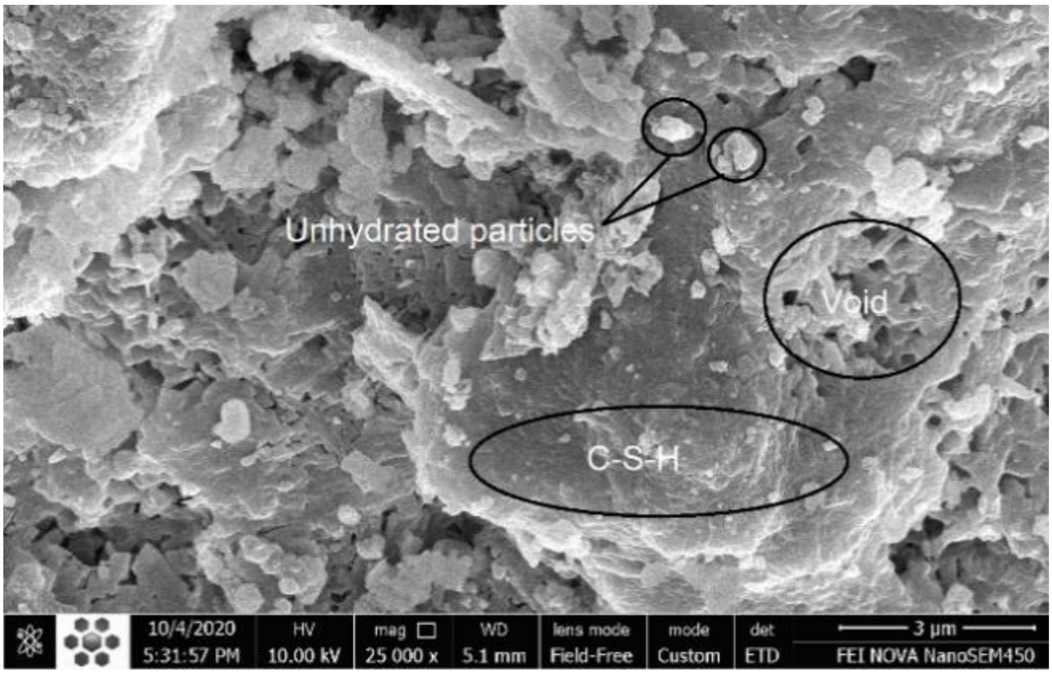

**Figure 1.** SEM Images of Two-Component Alkali-Activated Slag Cement

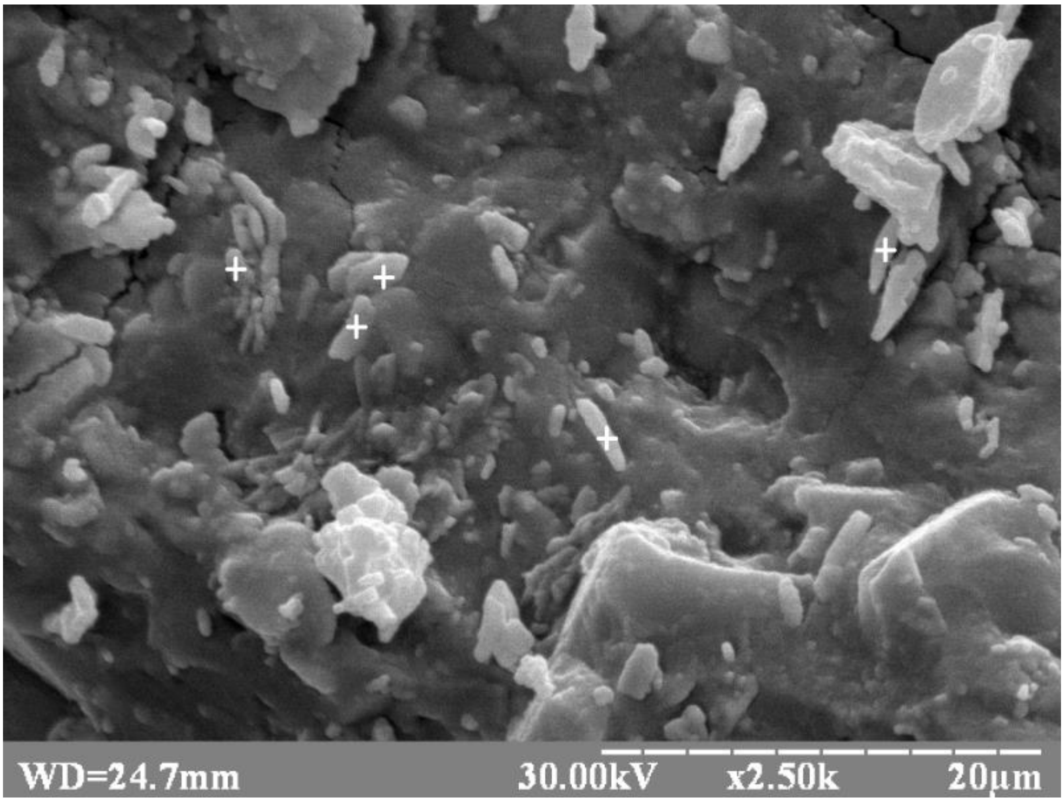

**Figure 2.** SEM Images of Powder Alkali-Activated Slag Cement

Based on the previous results, an optimized alkali-activated slag cement mixture suitable for drilling applications was selected and evaluated according to API 10A standards. In this stage, microsilica was added to the selected mixture at 5% by weight of slag, and the performance of the modified slurry was compared with Class G oil well cement. The mixture S1 contained slag, sodium metasilicate, sodium hydroxide, and water, whereas S2 included microsilica in addition to these components. The control mixture, OC, was prepared using Class G cement.

The density results showed that S1 had a density of 116 pcf, equivalent to 1858.32 kg/m$^3$, S2 had a density of 113 pcf, equivalent to 1810.26 kg/m$^3$, and OC had a density of 118 pcf, equivalent to 1890.18 kg/m$^3$. These density values indicate that the alkali-activated slag cement slurries were lighter than the Class G cement slurry. The thickening time was also within the acceptable API 10A range of 90 to 120 minutes. S1 reached a thickening time of 95 minutes, S2 reached 90 minutes, and OC reached 100 minutes. The S2 mixture started setting earlier because microsilica absorbs water and accelerates the development of consistency. Both alkali-activated slag cement slurries showed no free water, indicating that the mixing water was fully consumed or incorporated into hydration and reaction products. This is a significant advantage for oil and gas well cementing because API standards limit free water in Class G cement to a maximum of 3.5 ml.

**Table 8.** API Slurry Mixture Design, Density, Thickening Time, and Free-Water Behavior

| Mixture | Slag (kg/m$^3$) | Sodium Metasilicate (kg/m$^3$) | NaOH (kg/m$^3$) | Microsilica (kg/m$^3$) | $H_2O$ (kg/m$^3$) | Class G Cement (kg/m$^3$) | Density (pcf) | Density (kg/m$^3$) | Thickening Time (min) | Free Water |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 774 | 45.2 | 30.8 | — | 252 | — | 116 | 1858.32 | 95 | None observed |
| S2 | 687.8 | 45.2 | 30.8 | 26.2 | 252 | — | 113 | 1810.26 | 90 | None observed |
| OC (Type G) | — | — | — | — | 252 | 800 | 118 | 1890.18 | 100 | API limit: ≤3.5 ml |

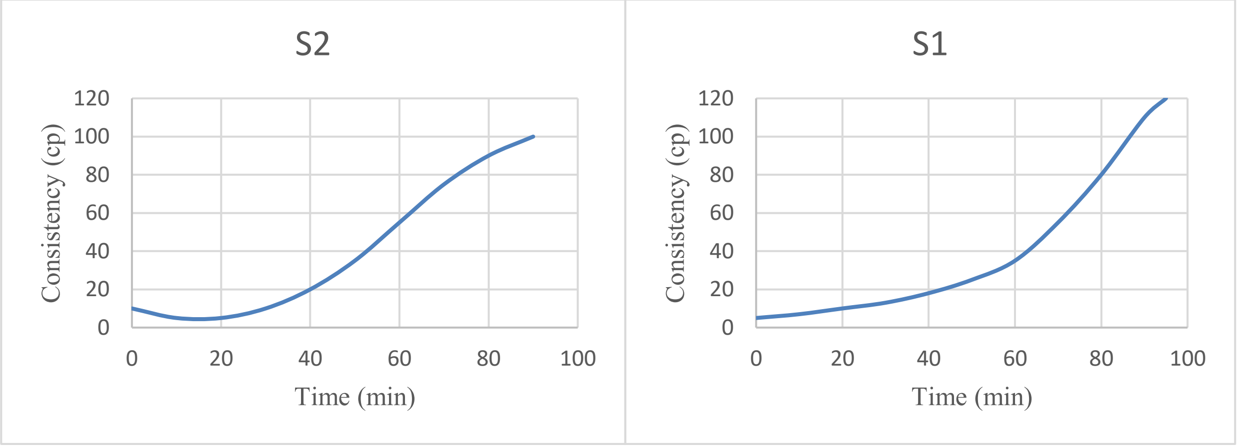

**Figure 3.** Thickening Time of Alkali-Activated Slag Cement

The eight-hour compressive strength results showed that both alkali-activated slag cement samples exceeded the compressive strength of Class G cement at both curing temperatures. At 38°C, S1 reached 9.59 MPa, S2 reached 18.62 MPa, and OC reached 7.21 MPa. At 60°C, S1 reached 12.05 MPa, S2 reached 22.34 MPa, and OC reached 10.34 MPa. The increase in strength at 60°C compared with 38°C indicates that elevated temperature accelerated the hydration and alkali-activation reactions, resulting in higher early-age compressive strength. The microsilica-modified mixture S2 demonstrated the best performance among all slurries.

**Table 9.** Compressive Strength After Eight Hours of Curing

| Mixture | Curing Temperature °C (°F) | Compressive Strength MPa (psi) |
|---|---|---|
| S1 | 38 (100) | 9.59 (1391) |
| S1 | 60 (140) | 12.05 (1747) |
| S2 | 38 (100) | 18.62 (2700) |
| S2 | 60 (140) | 22.34 (3250) |
| OC (Type G) | 38 (100) | 7.21 (1050) |
| OC (Type G) | 60 (140) | 10.34 (1500) |

The 24- and 48-hour compressive strength development was measured using an ultrasonic cement analyzer under 38°C and 20.7 MPa pressure. The results showed that S1 reached the initial set threshold of 0.34 MPa in 28 minutes and the 3.4 MPa threshold in 36 minutes, while S2 reached these thresholds in 85 and 102 minutes, respectively. The OC slurry required 109 minutes to reach 0.34 MPa and 146 minutes to reach 3.4 MPa. Although S1 developed strength rapidly, its 24- and 48-hour strengths were lower than those of Class G cement. In contrast, S2 achieved 21.1 MPa at 24 hours and 21.4 MPa at 48 hours, exceeding the corresponding values of Class G cement, which were 17.1 MPa and 17.9 MPa. These results confirm that the microsilica-modified alkali-activated slag cement had superior strength development and did not show strength retrogression under high-temperature and high-pressure conditions.

**Table 10.** Compressive Strength Results Measured by Ultrasonic Cement Analyzer

| Mixture | Initial Set 50 psi, 0.34 MPa (min) | 500 psi, 3.4 MPa (min) | 24-Hour Compressive Strength MPa (psi) | 48-Hour Compressive Strength MPa (psi) |
|---|---|---|---|---|
| S1 | 28 | 36 | 10.1 (1471) | 10.5 (1522) |
| S2 | 85 | 102 | 21.1 (3067) | 21.4 (3100) |
| OC (Type G) | 109 | 146 | 17.1 (2479) | 17.9 (2594) |

The strength development trend further confirmed the superiority of the S2 alkali-activated slag cement slurry over Class G cement at early ages. The S2 slurry reached approximately 19.3 MPa, equivalent to 2800 psi, after eight hours, whereas Class G cement reached approximately 13.8 MPa, equivalent to 2000 psi, during the same period. This faster strength gain is an important advantage for oil well cementing because early mechanical integrity is required to support casing, prevent fluid migration, and continue drilling operations safely.

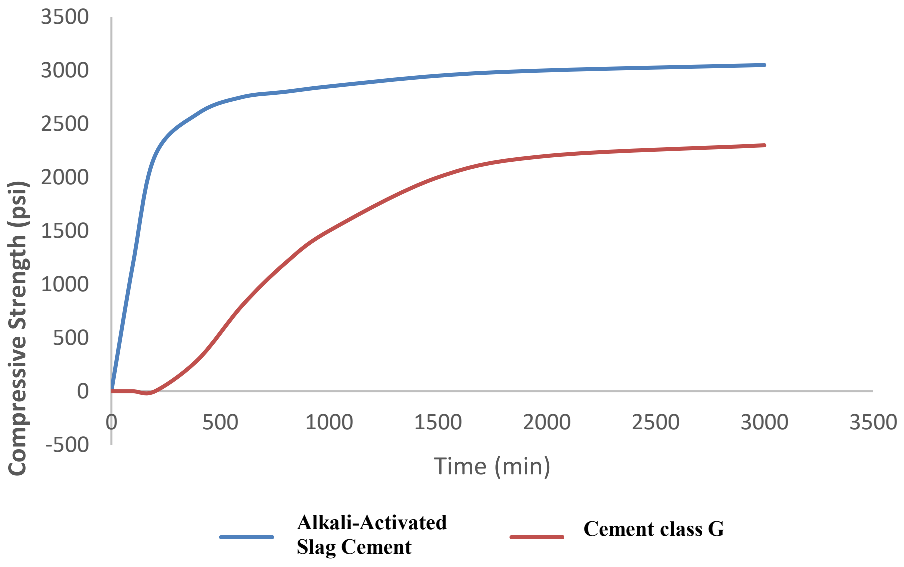

**Figure 4.** 48-Hour Compressive Strength Results for Oil Well Cement and Alkali-Activated Slag Cement

The microscopic images of the final slurry samples showed that S2 had a denser and more compact structure than S1. The presence of microsilica contributed to pore refinement, improved particle packing, and reduced cracking. As a result, S2 developed higher compressive strength and outperformed Class G cement under high-temperature and high-pressure conditions. These microstructural observations are consistent with the mechanical findings and confirm that the optimized microsilica-modified alkali-activated slag cement slurry is a technically viable alternative to conventional Class G oil well cement.

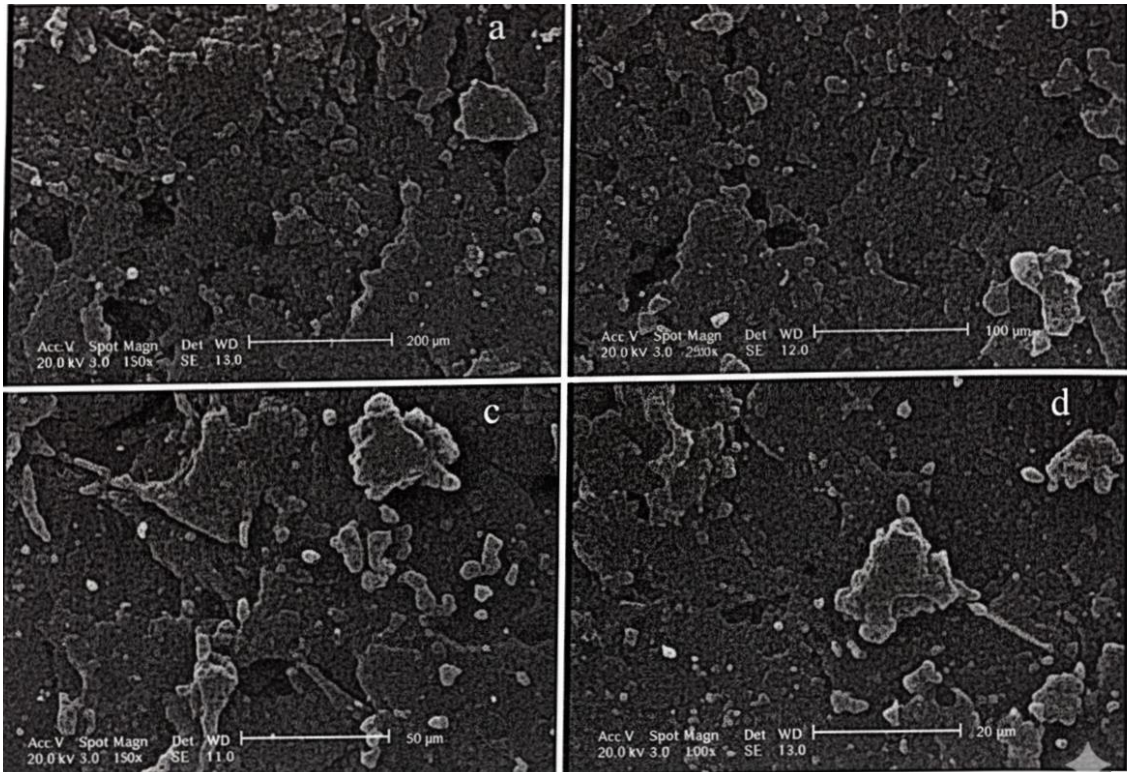

**Figure 5.** Microscopic Images of Slurry S1 (a = 200 µm, b = 100 µm, c = 50 µm, d = 20 µm)

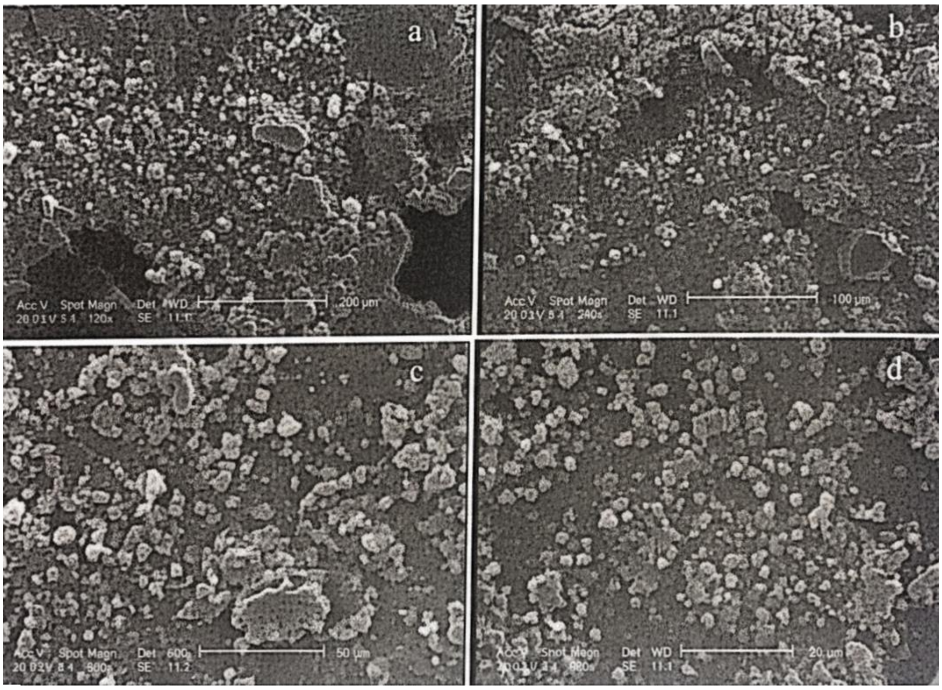

**Figure 6.** Microscopic Images of Slurry S2 (a = 200 µm, b = 100 µm, c = 50 µm, d = 20 µm)

## 4. Discussion and Conclusion

The findings of the present study demonstrate that slag-based alkali-activated cement (SAAC) possesses significant potential as a sustainable alternative to conventional API Class G oil well cement. The results showed that both the two-component and powder alkali-activated systems achieved acceptable setting times, satisfactory mechanical properties, and favorable rheological behavior. More importantly, the optimized SAAC formulations fulfilled the principal operational requirements established by API standards, including appropriate thickening time, adequate compressive strength development, dimensional stability, and compatibility with drilling applications. These findings support the growing body of evidence indicating that alkali-activated slag binders can provide engineering performance comparable to, and in some cases superior to, conventional Portland cement systems while simultaneously reducing environmental impacts associated with clinker production [1, 2]. The successful development of lightweight SAAC formulations is particularly important because it addresses both sustainability objectives and the operational demands of oil and gas well cementing.

One of the most notable findings was the influence of activator composition and slag fineness on setting behavior. The results demonstrated that increasing the content of sodium hydroxide and sodium silicate reduced setting time, while increasing slag fineness from 2900 cm²/g to 4200 cm²/g accelerated hydration and activation reactions, resulting in approximately 10% shorter setting times. These findings are consistent with previous studies showing that the setting characteristics of alkali-activated slag systems are highly sensitive to activator chemistry and silicate modulus [7]. The observed reduction in setting time with increased fineness can be explained by the greater specific surface area available for dissolution and reaction, which promotes faster gel formation and microstructural development. Similar conclusions have been reported regarding the role of particle fineness in accelerating slag activation and increasing reaction kinetics [4, 5]. The shorter setting times observed in the two-component system compared with the powder system may also be attributed to the higher reactivity of liquid sodium silicate, which facilitates more rapid dissolution of slag particles and earlier formation of cementitious reaction products.

The compressive strength results further confirmed the effectiveness of alkali activation in transforming blast furnace slag into a high-performance binder. Both one-day and longer-term compressive strengths increased substantially with increasing slag fineness, demonstrating the importance of particle size distribution and reaction efficiency. The two-component formulations consistently produced higher strengths than the powder formulations, which may be attributed to improved activator dispersion and more effective gel formation. The superior performance of finer slag particles is consistent with hydration and activation models that describe increased dissolution rates and accelerated formation of calcium silicate hydrate gels when larger reactive surface areas are available [4]. Furthermore, the strength values obtained for several optimized SAAC mixtures exceeded those measured for Type 2 and Type 5 Portland cements, indicating that alkali-activated slag systems can achieve strength levels comparable to traditional cementitious binders. These findings align with previous reports that alkali-activated slag binders can develop rapid early-age strength while maintaining excellent long-term mechanical performance [1, 2].

The observed increase in compressive strength from one day to seven days confirms the progressive development of hydration and activation products within the binder matrix. Particularly noteworthy was the superior performance of mixtures LN7M6 and SN7M6, which achieved the highest seven-day strengths among the investigated formulations. These results are consistent with previous studies demonstrating that slag chemistry, activator dosage, and curing conditions strongly influence the quantity and morphology of hydration products formed during alkali activation [5]. The results also support the conclusions of Taylor regarding the importance of calcium silicate hydrate gel development as the primary source of strength in cementitious systems [3]. Although alkali-activated slag systems produce C-S-H gels with chemical characteristics that differ somewhat from those formed in Portland cement, these gels nevertheless provide an effective binding network capable of supporting substantial mechanical loads [4]. Consequently, the enhanced strength performance observed in this study may be attributed to the formation of a dense and continuous reaction-product matrix.

The flexural strength results followed trends similar to those observed for compressive strength. Both the two-component and powder systems exhibited progressive increases in flexural strength over time, with higher values obtained in mixtures produced using finer slag. Flexural performance is particularly important because it reflects the ability of the hardened matrix to resist cracking and tensile stresses that may develop during service. Oil well cement is frequently exposed to thermal cycling, pressure fluctuations, and casing deformation; therefore, improved flexural performance contributes directly to long-term zonal isolation and well integrity. The favorable flexural strengths observed in this study support the view that alkali-activated slag binders produce a dense microstructure capable of distributing stresses more effectively than conventional brittle cement systems. This interpretation is consistent with previous findings regarding the mechanical behavior of alkali-activated slag concretes in structural applications [18].

The autoclave expansion results provide further evidence regarding the dimensional stability of the investigated formulations. All optimized mixtures exhibited expansion values well below the ASTM threshold, indicating that the alkali-activated systems remained stable under severe thermal and pressure conditions. Dimensional stability is particularly important in oil well applications because excessive expansion or shrinkage can generate microcracks, compromise zonal isolation, and facilitate fluid migration. The excellent expansion performance observed in this study suggests that the hydration and activation products formed within the SAAC matrix are structurally stable and resistant to deleterious volume changes. Such stability is essential for maintaining long-term integrity in deep wells where cement sheaths may be subjected to substantial thermal gradients and mechanical stresses.

The microstructural observations obtained through SEM analysis strongly support the mechanical findings. The images revealed a denser microstructure in the two-component alkali-activated slag cement compared with the powder system, with fewer cracks and more extensive development of C-S-H gel. The reduction in crack width and increase in matrix compactness provide a clear explanation for the higher compressive strengths observed in the two-component formulations. Previous investigations have shown that the formation of a dense C-S-H network is one of the defining characteristics of successful alkali activation and is directly responsible for enhanced durability and strength [3, 4]. The SEM results therefore confirm that the selected activator compositions effectively promoted slag dissolution and reaction-product formation. Similar relationships between microstructural densification and mechanical performance have been reported in studies examining the hydration mechanisms of alkali-activated slag binders [5].

The drilling-related tests conducted according to API standards represent one of the most important aspects of the present research because they directly evaluate the suitability of SAAC for oil and gas well cementing applications. The optimized SAAC slurries exhibited densities slightly lower than those of conventional Class G cement, which may be advantageous in formations where reduced hydrostatic pressure is desirable. Lightweight cement systems have attracted considerable attention because they can reduce the risk of lost circulation and formation damage while maintaining sufficient mechanical strength [14, 15]. The results obtained in the present study support this perspective by demonstrating that lightweight SAAC formulations can simultaneously achieve reduced density and high compressive strength. This combination is particularly valuable in challenging drilling environments where both mechanical integrity and pressure management are critical.

The thickening-time results further confirmed the practical viability of the developed formulations. Both SAAC slurries exhibited thickening times within the operational window recommended by API standards, ensuring sufficient pumping time without excessive delays in strength development. The slightly shorter thickening time observed in the microsilica-modified mixture is likely related to the high surface area and water demand of microsilica particles, which accelerate reaction kinetics. Similar effects of silica-rich additives on hydration and rheological behavior have been reported previously in both conventional and oil well cement systems [11, 12]. From an operational standpoint, the ability to control thickening behavior through additive selection is highly advantageous because it allows slurry properties to be tailored to specific well conditions.

A particularly important finding was the complete absence of free water in the SAAC slurries. Free water is a significant concern in oil well cementing because it can create channels that facilitate fluid migration and reduce zonal isolation. The absence of measurable free water indicates that the mixing water was effectively incorporated into hydration and activation reactions, producing a stable and homogeneous slurry. This characteristic represents a substantial advantage over many conventional cement systems and may contribute to the improved durability and sealing performance of alkali-activated slag cement in downhole environments.

The compressive strength results obtained under elevated temperature conditions demonstrated the superior performance of the microsilica-modified SAAC mixture. At both 38°C and 60°C, the modified formulation achieved substantially higher strengths than Class G cement. These findings suggest that the alkali-activated system is particularly effective in environments where elevated temperatures accelerate reaction kinetics. Similar observations have been reported regarding the beneficial effects of silica-rich materials on pore refinement, hydration enhancement, and strength development [12, 13]. The improved performance of the microsilica-modified formulation can therefore be attributed to a combination of microstructural densification and enhanced gel formation.

The ultrasonic compressive strength measurements provided additional insight into the behavior of the cement slurries under simulated downhole conditions. The microsilica-modified SAAC mixture not only achieved higher ultimate strength than Class G cement but also developed strength more rapidly. Rapid strength gain is particularly beneficial in drilling operations because it reduces waiting-on-cement time and allows subsequent operations to proceed sooner. Moreover, the absence of strength retrogression under elevated temperature and pressure conditions represents a significant advantage over some conventional cement systems. The ability of SAAC to maintain and increase strength under such conditions supports its suitability for high-temperature wells and aligns with previous observations regarding the durability and chemical stability of alkali-activated slag binders [9, 13].

Overall, the findings of the present study indicate that lightweight slag-based alkali-activated cement possesses a combination of mechanical, rheological, microstructural, and operational properties that make it a promising substitute for conventional API oil well cement. The results support broader trends in sustainable cement research, where industrial by-products such as slag are increasingly being utilized to reduce environmental impacts while enhancing performance [16, 17]. Furthermore, the successful adaptation of alkali-activated technology to oil well cementing extends previous applications of these materials in infrastructure, lightweight concrete, and advanced construction systems [18-20]. Consequently, the present research contributes to both sustainable materials development and drilling engineering by demonstrating that carefully designed SAAC formulations can satisfy the demanding requirements of oil and gas well cementing operations.

One limitation of this study is that the experimental program was conducted under laboratory conditions, which may not fully reproduce the complex thermal, chemical, and mechanical environments encountered in deep oil and gas wells. Although API-standard tests were performed, actual field conditions involve fluctuating temperatures, pressure cycling, formation-fluid interactions, and long-term exposure periods that cannot be completely simulated in laboratory experiments. In addition, only a limited number of activator compositions, slag fineness levels, and additive dosages were investigated, which may restrict the generalizability of the findings to other material combinations and operating conditions.

Future studies should evaluate the long-term durability of slag-based alkali-activated cement under realistic downhole conditions, including exposure to carbon dioxide, hydrogen sulfide, brines, and thermal cycling. Additional research is needed to investigate the influence of alternative alkaline activators, supplementary nanomaterials, and different slag sources on the rheological and mechanical performance of SAAC systems. Field-scale trials should also be conducted to validate laboratory findings and assess the operational behavior of these cement systems during actual drilling and cementing operations. Furthermore, numerical modeling and microstructural characterization techniques could be employed to better understand reaction mechanisms and strength development under high-pressure and high-temperature conditions.

The results of this study suggest that slag-based alkali-activated cement can be considered a practical alternative to conventional Class G oil well cement in applications where reduced environmental impact and improved mechanical performance are desired. Engineers and drilling operators may benefit from incorporating microsilica-modified SAAC formulations in wells requiring rapid strength development and enhanced durability. The lower density and absence of free water observed in the optimized mixtures indicate potential advantages in formations vulnerable to lost circulation and fluid migration. Industrial implementation should focus on developing standardized mixing procedures, quality-control protocols, and compatibility assessments with commonly used drilling additives to facilitate broader adoption of this technology.

## Authors' Contributions

Authors equally contributed to this article.

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## Declaration of Interest

The authors report no conflict of interest.

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## Ethical Considerations

All procedures performed in this study were under the ethical standards.

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