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Evaluation of Belite Calcium Sulfoaluminate (BCSA)-Based Concrete Mixtures for High Early Strength and Low-Carbon Concrete Masonry Units (CMUs)

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Abstract

The masonry industry worldwide is seeking thermally efficient masonry materials, sustainable manufacturing and construction practices, and the integration of these technologies. Belite Calcium Sulfoaluminate (BCSA)-based concrete offers a promising solution, with benefits such as a 34–48% reduction in carbon footprint, rapid strength development, reduced drying shrinkage, and enhanced durability. This study is the first part of research program that aims to develop new BCSA-based concrete mixtures to produce high-performance concrete masonry units (CMUs) and assess their early-age mechanical properties and dimensional stability.

The study presents a review of CSA-based concrete and describes an ASTM- and ACI-based aggregate preparation process for normal-weight CMU production, following ACI 211 grading guidelines. The well-graded particle distribution, characterized by a fineness modulus (FM) of 3.79, is expected to enhance packing density, minimize voids, and improve mechanical performance. A carefully designed cement-aggregate mix was developed to balance cement content, water-to-cement ratio, and aggregate proportions for optimal fresh and hardened properties.

An experimental approach following ASTM standards will systematically evaluate material properties and mixture performance based on lab-scale samples. Expected outcomes, which will be presented at the conference, include improved early-age mechanical properties, enhanced dimensional stability, reduced curing time, and lower production costs by minimizing reliance on energy-intensive processes, such as high-temperature and high-pressure steam curing, typically used to accelerate early strength gain, contributing to a lower-carbon CMU manufacturing process.

Keywords

belite calcium Sulfoaluminate cement, concrete masonry units, durability, mechanical properties, sustainable construction, thermal performance

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INTRODUCTION

Concrete masonry units (CMUs) are versatile materials widely used worldwide for their convenience and cost-effectiveness in constructing load-bearing elements, such as foundations, basements, and exterior walls, as well as non-load-bearing interior partitions in residential and commercial buildings. The demand for CMU products is growing steadily, driven by urbanization, infrastructure expansion, and the rising demand for durable, energy-efficient building materials.

This worldwide increasing demand highlights the need to address the environmental impact associated with the production of CMUs. The Global Warming Potential, or embodied carbon, of market-available CMUs during the cradle-to-gate phase—which includes raw material extraction, various types of cement production, transportation, manufacturing, and high-temperature-controlled curing—is significant. Dahmen et al. [1] reported an embodied carbon baseline of 216.9 kg CO_2-eq/m^3 for conventional concrete blocks (390 × 190 × 190 mm) with a density of 1840 kg/m^3. However, studies show that market-available CMUs often exhibit a wider range of embodied carbon, from 204.1 to 395 kg CO_2-eq/m^3, depending on the block type, binder composition, and curing process [2,3]. It is important to note that these values take into account the ability of CMUs to absorb CO_2, which has been estimated at 21 kg CO_2-eq/m^3 [4,5]. Moreover, in cold climate regions, embodied carbon is approximately 21.5% higher than in warmer climates, primarily due to the increased energy consumption required for curing and handling CMU products [2].

Overall, while advancements in CMU production—such as the use of alternative fuels and industrial by-products—have helped reduce emissions, the process remains highly carbon-intensive. This is largely due to the binders used, particularly Ordinary Portland Cement (OPC), which accounts for 69–82% of total global warming potential, alongside high energy demands for curing [2]. The cement industry is responsible for approximately 8% of global CO_2 emissions, primarily due to the energy-intensive production of OPC. Addressing these challenges requires more sustainable approaches, such as adopting low-carbon cementitious materials and optimizing curing processes.

One promising approach is utilizing low-carbon cementitious materials, particularly CSA-based cement, which, although primarily used in repair work for its fast-setting properties [6], has been recognized as a sustainable binder that could offer lower embodied carbon and reduce energy consumption in curing and handling in the production of CMUs and masonry grout, as highlighted in a 2022 survey by Subasic [7]. Various studies further support this, demonstrating that utilizing CSA-based cement can reduce the carbon footprint of concrete production by 34–48% compared to traditional OPC [8–12].

Research Objectives

This study aims to evaluate the early-age performance of CSA-OPC blended concrete for low-carbon CMU production, with a specific focus on early strength development, drying shrinkage, and water absorption. Water absorption will be examined to assess permeability, a key factor influencing resistance to moisture ingress, freeze-thaw cycles, and long-term deterioration. By lowering curing energy and production time, CSA-OPC blends can reduce the embodied carbon of CMU products. The findings will provide insights into the material's performance and support its application in low-carbon masonry construction.

LITERATURE REVIEW

Researchers have explored alternatives such as supplementary cementitious materials (SCMs) and carbon capture technologies to minimize these emissions. Among these, ye'elimite-based clinkers such as BCSA have drawn significant research interest for their low embodied carbon and available commercial technology for production [10,12–16].

Historical Development of CSA Cement

CSA belongs to the family of cement types rich in ye'elimite. Its development dates back to the 1950s when ye'elimite was discovered in Israel, leading Alexander Klein to explore CSA clinker for shrinkage compensation in OPC concrete. Further advancements in the 1960s and 1970s resulted in ASTM Type K cement and China's "Third Cement Series," both widely adopted in precast concrete production. CSA's high early-age strength, lower shrinkage, stable crystalline structure and ability to continue hydration at low temperatures have made it highly applicable in cold climate environments [6,10,14–20].

Production and Environmental Benefits of CSA Cement

The production of CSA-based binders can reduce CO_2 emissions by approximately 34–48% compared to conventional OPC production. This reduction is largely attributed to key efficiencies in the CSA production process. The production of ye'elimite, CSA's primary compound, generates about 62% less CO_2 than alite, the main component of OPC, with its clinker requiring a kiln temperature nearly 200°C lower and its softer nature further reducing energy demand during grinding, thereby significantly lowering emissions and energy consumption [8–12,18,21–23]. Additionally, CSA clinker with high belite content offers even greater reductions, lowering CO_2 emissions to nearly half that of OPC. This is achieved by increasing the use of supplementary cementitious materials, incorporating more dicalcium silicate (C_2S), and reducing ye'elimite (C_4A_3S), which not only decreases the carbon footprint but also reduces reliance on expensive raw materials like bauxite, making BCSA a cost-effective and sustainable alternative [9]. While ye'elimite-based clinkers show strong potential for reducing the environmental impact of concrete, their widespread adoption depends on a thorough evaluation of their mechanical performance, long-term durability, and thermal properties, along with market availability and cost considerations.

Microstructure and Composition of CSA Cement

CSA clinker is produced from raw materials such as limestone, bauxite, gypsum, and industrial by-products like fly ash and slags. Its primary phase, ye'elimite (50–80%), is accompanied by belite, ferrite, and anhydrite. Unlike OPC, which typically contains 8 wt.% gypsum, CSA requires 15–25 wt.% to optimize setting time, strength development, and volume stability. The hydration process, driven by ye'elimite, requires significantly more water than OPC. The main hydration products are ettringite, monosulfoaluminate, and amorphous alumina hydroxide (AH_3). When belite is present, it reacts with water to form strätlingite, C-S-H, and portlandite [12,14,21]. Notably, ettringite plays a key role in CSA's rapid strength development, enabling it to reach 28-day compressive strength within days, and its crystalline structure contributes to a stable form with smaller pores than OPC, enhancing durability [8,10,12].

Fresh and Hardened Properties Of CSA-Based Mixtures

CSA cement is characterized by its rapid setting, making it highly suitable for time-sensitive applications such as infrastructure repairs. Unlike OPC, which sets within 30 minutes to 10 hours, CSA can set in under 10 minutes due to the rapid reaction of ye'elimite with water and calcium sulfate [8,24,25]. While this rapid setting is beneficial for highway and airport runway repairs [6], it is a challenge for precast concrete and applications that need longer placement and finishing times [24].

To regulate setting time and improve workability, various chemical retarders, including citric acid, sodium gluconate and tartaric acid, are commonly used. However, as the dosage increases, they can significantly alter the morphology of the hydration products and cause a notable reduction in early-age compressive strength [8,21,26–29]. Tartaric acid has proven to be particularly effective, extending the initial setting time from 5 to 48 minutes at dosages of 0.25%–0.5% (by cement mass), outperforming other commonly used retarders at lower concentrations. While dosages between 0.25% and 0.5% temporarily reduce early compressive strength, recovery occurs within 6 to 24 hours, but dosages above 0.75% impact belite hydration, which affects long-term strength. For applications requiring both extended workability and early-age strength development, a 0.25%–0.5% dosage of tartaric acid provides an effective balance, expanding CSA cement's application to a wider range of uses [29].

Maintaining adequate moisture and temperature, known as the curing process, is crucial for the hardening of CSA cement. Unlike OPC, which typically requires seven days of curing, CSA mixtures can achieve full hydration and sufficient strength within two days of moist curing at 22–24°C. This faster hardening reduces resource consumption, minimizes shrinkage-related issues and improves the durability of the structure [19,30]. Additionally, CSA concrete continues to hydrate and harden at subzero temperatures, though at a slower rate, showing a strength reduction of 5–14% at 0°C and 26–37% at -10°C compared to curing at 23°C [17]. These findings highlight the rapid hardening characteristics of CSA cement and the importance of optimized curing strategies, particularly in cold environments.

Fresh and Hardened Properties of CSA and OPC Blends

The higher cost of CSA-based cement is one of the main factors that it is not widely applied in the industry, reaching up to three times the cost of OPC. However, considering the additives used in OPC to accelerate strength development and minimize shrinkage, the cost difference is reduced to 1.2 times [31]. Thus, most research focuses on optimizing CSA/OPC blends to enhance economic feasibility and capitalize on CSA's low-carbon benefits. This approach balances CSA's rapid setting with OPC's long-term performance, though determining the optimal composition for mechanical and durability properties remains a key research challenge [16].

The OPC/CSA ratio significantly affects early hydration, with cumulative heat decreasing by approximately 32% as CSA content decreases from 100% to 30%. Mixtures with higher CSA content (40–60%) exhibit enhanced early hydration compared to those with more OPC, facilitated by the OPC reaction by-product (CH), which increases pore solution alkalinity and promotes CSA hydration, enhancing overall reaction efficiency [16]. Additionally, CSA content in this range extends setting time and enhances workability, improving handling and placement [32]. The OPC/CSA ratio significantly influences chemical and drying shrinkage. High CSA content increases chemical shrinkage due to its reactivity, while higher OPC content reduces it. Drying shrinkage follows a similar trend, with most shrinkage occurring within the first 10 days. A summary of the performance of CSA-OPC blends at varying CSA contents is presented in Table 1..

Table 1: CSA-OPC blend performance summary

CSA Content (%)	Observation	Source
40–50	Significantly reduces both chemical and drying shrinkage compared to pure CSA or OPC.	Yang et al. [16]
10 and 60–90	Achieves high early-age strength (>30 MPa at 3 days) and compressive strength ranging from 35–50 MPa at 28 days.	Yang et al. [16]
60–100	Demonstrates a well-balanced strength profile, with average values of 21 MPa at 1 day and 31 MPa at 28 days.	Yang et al. [16]; Huang et al. [32]
50	Shows a 13–32% reduction in compressive strength due to microcracks caused by expansive ettringite formation.	Afroughsabet et al. [20]

To address these limitations by the binary system of CSA and OPC, ternary systems incorporating additives such as ground-granulated blast-furnace slag, fly ash and anhydrite have been explored. These additives enhance workability, long-term strength, dimensional stability, permeability and pore Structure. However, they significantly reduce early-age strength, highlighting the challenge of balancing strength development across different curing stages [16,20,33,34].

Research Gaps and Challenges in Adopting CSA-OPC Blends for CMU Production

Blending CSA cement with OPC offers a practical solution to offset the higher cost of pure CSA while improving the performance of the mixture. This combination balances CSA's rapid setting time with OPC's long-term durability, making it particularly beneficial for CMU production. The high early strength of CSA-OPC blends could potentially reduce operational costs by minimizing curing energy, shortening production cycles, and supporting a more sustainable manufacturing process. However, the application of CSA-OPC blends in CMU production lacks extensive research. Further studies are needed to determine the ideal CSA-to-OPC ratio, which is crucial for developing a workable mix that achieves high early strength, reduces cracking risk, and enhances dimensional stability for CMU applications.

This research explores the early-age mechanical and physical performance of CSA-OPC blended concrete for low-carbon CMU production, focusing on early strength development and dimensional stability, which could pave the way for successfully integrating CSA-based CMUs into sustainable, high-performance masonry construction.

MATERIALS AND METHODS

Materials

The fineness modulus (FM) of the selected fine aggregates is 2.5, which falls within the recommended range of 2.20 to 2.80, and the percentage of fine aggregate passing through a number 50 (0.3 mm) sieve is 27%, also within the recommended range of 25% to 35%. The proportion of coarse aggregate relative to the total aggregates is 21%, which is also within the recommended range of 20% to 40%. Although it is within the lower bound, this reduction in the coarse aggregate proportion will result in a smoother finish and improved compaction of the mixture [35–37]. The sieve analysis was conducted based on the ASTM C136 [38] and the grading curves are presented in Figure 1. The bulk oven-dry density, specific gravity and absorption of the aggregates were determined based on ASTM C29, C127 and C128 [39–41] and are presented in Table 2. Furthermore, as shown in Figure 2, a series of sieve analyses were conducted to determine better aggregate gradation by taking different proportions of fine and coarse aggregate and comparing them to the ideal gradation curve recommended by the ACI 211[42].

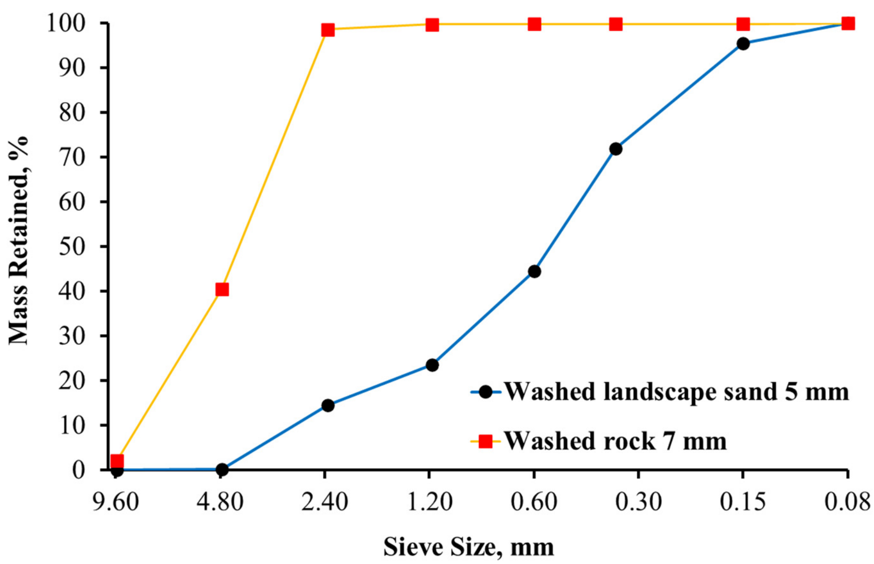

Figure 1. The gradation curve of washed landscape sand-5 mm and washed rock-7 mm.

Table 2: Fine and coarse aggregates bulk oven-dry density

Aggregates	Bulk oven-dry density, kg/m^3	Specific gravity	Absorption, %
Washed landscape sand 5 mm	1,718.78	2.66	1.21
Washed rock 7 mm	1,307.63	2.67	1.57

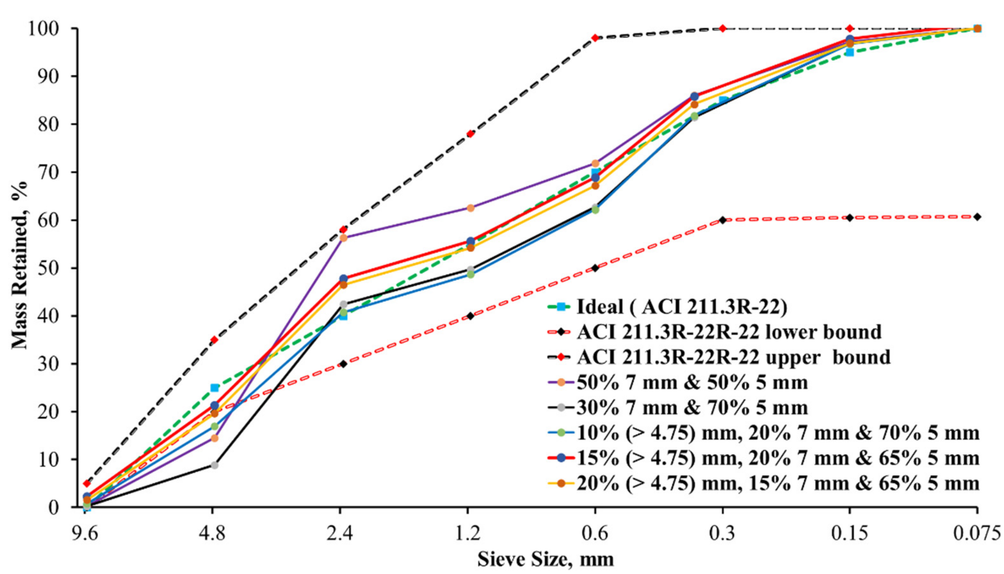

Figure 2: Grading curve of washed landscaping sand 5 mm and Washed rock 7 mm with varying proportions.

The mix design has been developed in accordance with ACI 211[42] guidelines for no-slump concrete, based on oven-dry aggregate conditions, with a water-to-cement ratio of 0.4 and 3% air content. Concrete mixtures will be prepared using varying proportions of CSA and OPC binders, following this baseline design. The detailed mix design is presented in the Preliminary Results and Discussion section.

Two reference groups will consist of 100% CSA and 100% OPC, while four additional mixes will include 20-80% CSA, with OPC making up the remainder. To determine the ideal curing duration, three early age curing intervals will be assessed: 6 hours, 12 hours, and 24 hours under controlled conditions of 23°C and 100% relative humidity (RH). The 6-hour and 24-hour durations are commonly applied to rapid-hardening hydraulic cement, such as CSA-based cement based on ASTM C1600 [43]. Moreover, ASTM C1074 [44] and C918 [45] also allow early-age testing at 12 hours to estimate and project the potential strength of concrete at later stages. These early age curing durations can benefit CMU production by meeting demand and reducing time and resources allocated for extended curing, typically done at high temperatures.

Table 3: Mixture proportions

Sample labels	Mixtures proportions
OPC	100% OPC
20CSA	20%CSA/80%OPC
40CSA	40%CSA/60%OPC
60CSA	60%CSA/40%OPC
80CSA	80%CSA/20%OPC
CSA	100% CSA

Method

Three different tests will be carried out to evaluate the properties of the fresh concrete mixes. The slump of all fresh concrete mixes will be tested based on ASTM C143 [46], the density based on ASTM C138 [47], and the air content based on the pressure gauge method according to ASTM C231 [48]. These fresh properties reflect workability, density, and cohesion, ensuring the mix is suitable for CMU production and meets performance requirements. The mechanical strength will be tested using cylindrical specimens with a diameter of 50 mm and a height of 100 mm, in accordance with ASTM C39 [49]. This test is crucial for understanding the mechanical performance of the mixture and its suitability for CMU production. According to ASTM C39 [49], the specimen diameter must be at least three times the nominal maximum aggregate size, and the height-to-diameter ratio should be 2:1. With a 7 mm aggregate, a 50 mm × 100 mm cylinder meets both requirements. Additionally, three specimens will be tested to ensure reliable results.

Dry density, water absorption, and void content will be tested according to ASTM C642 [50] to evaluate the physical and mechanical performance of the concrete mixture. The dry density is a critical parameter influencing the strength and load-bearing capacity of the concrete mixture. Additionally, water absorption and void content provide essential insights into microstructural development, offering a better understanding of the material's longevity and resistance to environmental conditions. Finally, to assess both drying shrinkage and overall volume stability, a length change test will be conducted on a 25x25x285 mm beam sample. This test, based on ASTM C490 [51], aims to evaluate how the fast-hardening nature of the CSA-OPC blend affects the dimensional stability of the concrete.

PRELIMINARY RESULTS AND DISCUSSION

The initial analysis of aggregate properties and the gradation curve confirms that the selected locally sourced aggregates meet standard requirements for CMU production. The specific gravity and absorption values indicate a well-balanced combination of density, workability, and strength, essential for producing an optimized concrete mix. During the development of the gradation curve and mix design, the ACI 211 [42] guidelines and recommendations from previous research were followed [35–37,39,42,52]. A detailed evaluation was conducted to optimize the gradation curve, ensuring it closely aligns with ACI [42] recommendations and industry best practices [35,37,42,52].

After careful consideration, a blend of fine and coarse aggregates with a FM of 3.79 was selected. The particle size distribution, smaller than 2.36 mm, closely aligns with the ACI 211 [42] optimal grading curve for normal-weight aggregates with a FM of 3.7 as shown in Figure 3. This blend was chosen to balance the benefits of coarse aggregates and their impact on the mixture's texture and cohesion [35]. The selected well-graded particle distribution is expected to enhance packing density, minimize continuous voids, and improve mechanical performance, providing a strong foundation for CMU applications.

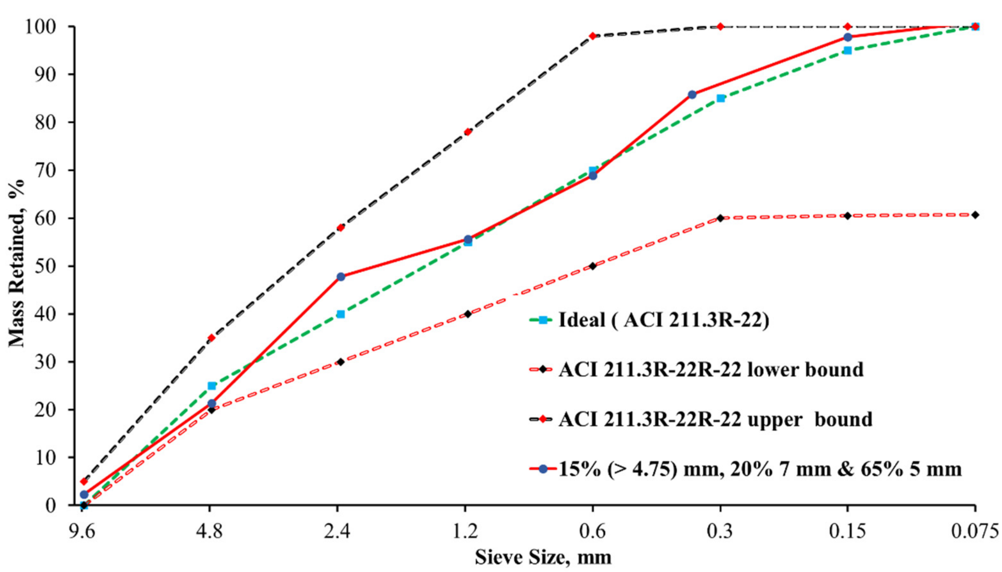

Figure 3: Grading curve of washed landscape sand 5 mm and washed rock 7 mm with fineness modulus of 3.79.

Based on these findings, an initial mix design was carefully developed according to ACI 211 [42], taking into account cement content, water-to-cement ratio, and aggregate proportions to achieve the desired balance of fresh and hardened properties as shown in Table 4. The well-graded aggregate structure is expected to improve the mechanical performance of the final concrete while maintaining ease of handling during production.

Table 4: Mix design is based on ACI 211[42] for no-slump concrete

Material	Cement	Coarse Aggregate	Fine Aggregate	Water
Weight, kg/m³	385.08	793.75	989.53	154.03

These preliminary results establish a strong starting point for further testing. The next phase will focus on evaluating fresh and hardened concrete properties, including workability, strength, and overall performance. Based on these findings, necessary adjustments will be made to further improve the mix design for CMU applications. The development of a well-graded aggregate mix is a key milestone, providing a strong foundation for ongoing research and pushing forward advancements in low-carbon, high-performance CMU production.

CONCLUSION

The initial analysis confirms that the selected locally sourced aggregates meet standard requirements for CMU production, with a well-graded particle distribution expected to enhance packing density and mechanical performance. Following ACI guidelines a mix design has been developed to achieve a balanced combination of strength and durability. These findings provide a strong foundation for further testing, where fresh and hardened concrete properties will be evaluated and adjusted to enhance performance in CMU applications.

The integration of CSA-based concrete presents a viable solution, offering significant benefits such as low embodied carbon, rapid strength development, enhanced durability, and improved thermal efficiency.

Moreover, CSA-based concrete has the potential to lower production costs by reducing reliance on energy-intensive curing methods, such as high-temperature and high-pressure steam curing, which are standard in CMU manufacturing. By systematically evaluating the properties of CSA-based CMUs through experimental testing, this study aims to advance the development of innovative, high-performance masonry units, promoting a more sustainable, cost-effective, and energy-efficient approach to construction.

FUTURE WORK

Future work will focus on further improving the mix properties to reduce concrete density while enhancing thermal performance, ensuring the material meets both structural and energy efficiency requirements. This will involve adjusting the composition to balance strength, durability, and insulation properties while maintaining workability and production feasibility. Additionally, the optimized material will be used for the production and testing of both conventional CMUs and novel insulated composite blocks. The mechanical properties and dimensional stability will be comprehensively evaluated to confirm their suitability for structural applications. Simultaneously, thermal performance assessments will be conducted to analyze heat transfer characteristics, thermal resistance, and potential energy-saving benefits. These investigations will provide critical insights into the material's applicability for large-scale manufacturing and practical use in energy-efficient and sustainable construction.

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