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Studies on Calcium Sulfoaluminate-Belite (CSAB) Cement Using Industrial Wastes

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ABSTRACT

Researchers and engineers have been looking at novel approaches to develop cementitious materials with decreased environmental impact without sacrificing performance and durability in response to these difficulties. Calcium Sulfoaluminate-Belite cement (CSAB) is a value-added binder that has gained popularity for its unique qualities and benefits. The CSAB cement system is regarded as an innovative and promising sustainable construction material that helps to mitigate the environmental consequences of regular Portland cement. CSAB cement has been developed as a more sustainable alternative to Portland cement because of its lower energy consumption and CO₂ emissions. The presented study examines the modern research to develop newly produced cement known as CSAB cement. Also, ongoing research activities at the author institute to synthesize CSAB binders using different kinds of low-graded industrial waste materials such as low-grade limestone and phosphogypsum has been presented, which makes it innovative. Physico-mechanical parameters such as setting time and compressive strength were compared in various investigations. CSAB cement quick setting periods and early strength development allow for a greater amount of work to be accomplished within the project timeline. In the various investigations the compressive strength data revealed impressive results ranging from 39.0 to 45.10 MPa, demonstrating the material robust structural capabilities. The mineralogical composition of CSAB cement primarily consists of yelite (C₄A₃S), belite (C₂S), ferrite (C₄AF), and anhydrite (CS), contributes to both the rapid setting characteristics and the development of substantial compressive strength. It has been observed that CSAB cement manufacturing can provide up to

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30% reduction in carbon footprint as its manufacturing process requires lower kiln temperatures which results in lower energy consumption and associated emissions from fuel combustion.

Keywords: Low Carbon Cement; Compressive Strength; Setting Time; CSAB Cement; Sustainability

1. Introduction

The cement industry in India, the second largest consumer after China, has a total capacity of 435 million tons. It is projected to grow at 6–7% from 2018 to 2025, currently producing 280 million tons for domestic use and 5 million tons for export. This growth suggests the market could double every 10 to 12 years. The production of Ordinary Portland Cement (OPC) is responsible for about 2–3% of the world primary energy consumption and 8% of the CO₂ emissions, which contributes to greenhouse gas emissions and global warming. Ordinary Portland Cement formation requires a substantial quantity of calcium-rich materials and high-temperature sintering^[1]. Researchers and engineers have been looking at novel approaches to developing cementitious materials with decreased environmental impact without sacrificing performance and durability in response to these difficulties. A binder known as calcium sulfoaluminate (CSA binder) was developed to create environmentally friendly binders with reduced CO₂ emissions and high early strengths. It has been used as a concrete binder in many different applications such as low-temperature construction, shotcrete, precast concrete, prestressed concrete elements, leaky constructions, and bridges. The primary disadvantage of CSA cements is that they rely on aluminum-rich raw materials, which are usually costlier and have limited availability based on location^[2–4].

Belite cement is recognized for its unique composition and serves as a potential substitute for Portland cement. The use of industrial waste improves the carbon footprint and strength, makes CSAB cement an alternative to ordinary Portland cement. Indeed, CSAB cement is increasingly being recognized as eco-friendly, as it emits much less greenhouse gas compared to ordinary Portland cement. The CSAB is suitable for a variety of time-sensitive building projects. Its quick setting and early strength growth ensured faster completion times. Additionally, its low alkali content contributes to the longevity of concrete constructions by reducing the likelihood of alkali-silica interactions. CSAB

binder have generated interest in the production of precast concrete products. CSAB has gained attention owing to its innovative manufacturing processes. The calcium sulfoaluminate and calcium belite phases constitute the majority of CSAB cement. The main components of CSAB cement consist of ye'elinite, belite, ferrite, and calcium sulfate^[5–7]. These phases are produced during the burning process by physical and chemical interactions of the oxides contained in the raw mixture. This unique combination produces cement with exceptional early strength development and lower carbon emissions when compared to conventional Portland cement. CSAB cements are ideally suited for short-period construction. The CSAB cement shows such an outstanding performance that C₄A₃S reacts extremely rapidly with calcium sulfates and water to form ettringite. Ettringite is a first-formed hydration product with an expansive nature and also increases strength and adapts to material stress changes without changing its shape^[8].

Calcium Sulfoaluminate-Belite (CSAB) cement has been developed as a more sustainable alternative to Portland cement because of its lower energy consumption and CO₂ emissions. A study of sustainable cement options concludes that CSAB cement differs from Geopolymers and LC³ Cement regarding their distinctive properties. CSAB and LC³ Cement reduce their CO₂ emissions by 25–30% and 30–40% than Portland Cement. CSAB Cement uses limestone together with bauxite and gypsum and industrial waste materials. Whereas LC³ Cement contains calcined clay, gypsum and limestone combined with OPC clinker. Geopolymers follow unique methods because their production is based on fly ash along with slag as main components. CSAB Cement uses lower clinkering temperatures of 1200 °C while LC³ Cement needs moderate energy for clay calcination. Geopolymers do not require clinker but need alkali activators to initiate the reaction process. CSAB Cement proves its performance success through its lowered CO₂ emissions and effective application of sustainable binders across its manufacturing operations. Through its waste materials-based manufacturing approach, CSAB cement reduces the utilization of natural

raw materials and simultaneously decreases production costs by utilizing red mud alongside phosphogypsum, steel slag, fly ash, etc. [9–11].

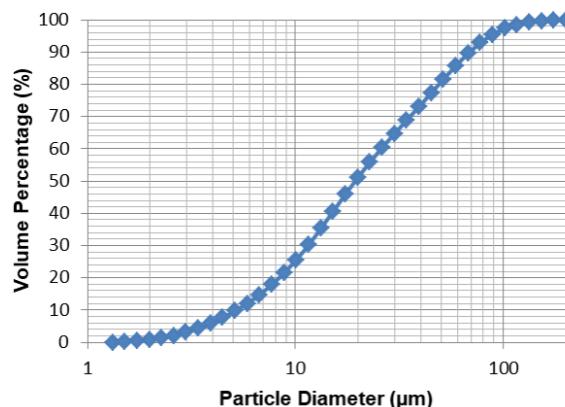
This study provides a thorough evaluation of CSAB cement by synthesizing findings and perspectives from various CSAB research papers. These studies, in addition to further knowledge of the CSAB components and properties, reveal its potential as a revolutionary green construction material. A comprehensive view of the present state of CSAB, its importance for the construction industry, and its way to a sustainable future have been described. This review provides useful information for researchers, engineers, and stakeholders in the construction industry. The methodology includes the chemical and mineralogical compositions of the raw materials that have been used in various studies. The physio-mechanical properties—setting time and compressive strength—of the CSAB cement from previous studies have been discussed. An in-depth analysis of a wide

range of CSAB documents was conducted to contribute to a better comprehension of this eco-friendly binder performance features and its significance to the green approach in construction.

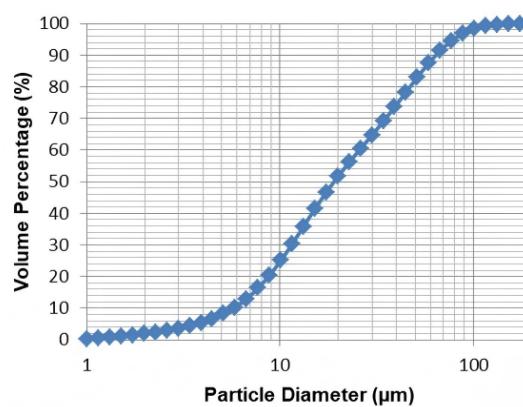
2. Materials and Methods

2.1. Chemical Composition of Raw Materials & CSAB Clinkers

To achieve optimum homogeneity and reactivity, the raw ingredients were ground to a fine powder after being chosen. The particle size analysis (PSA) of the some basic raw materials such as limestone, and bauxite are used in the production of CSAB cement, as shown in **Figure 1**. To obtain the necessary chemical composition of CSAB cement, finely ground raw ingredients were properly combined in precise amounts.



(a) High grade limestone.



(b) Bauxite.

Figure 1. Represents the grain size distribution curve of the raw materials used in production of CSAB cement.

In the kiln, the combined raw ingredients are subjected to step heating at heat rate of 8 °C/min, first at a temperature of 700 to 1000 °C for 30–60 min, and then fired at a temperature at 1200–1350 °C for 1–2 h. Chemical reactions occur during the clinkering process, resulting in the formation of calcium sulfoaluminate and calcium belite phases. Temperature management is essential to obtain the correct CSAB cement phases and qualities. After clinkering, the finished clinker was cooled by blowing compressed air over it to room temperature. The clinker is subsequently processed into a powder form by fine grinding. After the clinker formation CSAB cement was mixed with sand in a 1:3 ratio with op-

timum water-to-cement ratio to cast the cube of 50 mm for compressive strength test as per ASTM C109.

The properties and functionality of CSAB cement clinker are largely dependent on its chemical composition. It is essential to understand the chemical composition of the CSAB cement clinker to optimize production and ensure the desired characteristics. **Table 1** lists the chemical compositions of the raw materials used in the different investigations. The chemical composition of the CSAB cement clinker is approximately similar to that of Portland cement clinker in that it contains minerals such as C₂S, C₃A, and C₄AF. Limestone, with a dominating calcium oxide (CaO) content of 55.49%

is a crucial resource with other minor constituents of 0.61% silicon dioxide (SiO_2) and 0.05% aluminum oxide (Al_2O_3). Owing to its low TiO_2 and P_2O_5 contents, it is suitable for applications where high purity is required. The chemical compositions of limestone shows the necessary ingredients that enable the formation of CSAB cement^[12]. Blast furnace slag (GBFS) is a by-product of the steel industry and is characterized by high silicon dioxide (SiO_2) and calcium oxide (CaO) contents. Due to its composition, it can be used as a raw material in binder production in building applications to improve the performance of binding properties^[13]. Chen and Juenger^[14] used flue gas desulfurization sludge (FDG) for CSAB cement production, which is considered to originate from flue gas desulfurization systems, and contains a large amount of calcium oxide (CaO) and sulfur trioxide (SO_3).

Due to its large amount of sulfur content, improper disposal could harm the environment. FGD sludge, which is abundant in calcium and sulfur oxides, is a distinctive and valuable resource for the production of CSA clinker. This resource facilitates the deliberate creation of the desired phases through controlled synthesis^[14]. AOD slag contained large amounts of aluminum oxide (Al_2O_3), magnesium oxide (MgO), and calcium oxide (CaO), with a calcium oxide content of 53.2%. High CaO content shows that it has potential as a cementitious material for construction. Owing to its characteristics, AOD slag is ideal for use as a supplemental cementitious material in the manufacturing of CSAB cement because of its high calcium oxide content and oxides of magnesium and aluminium^[15].

Table 1. Chemical composition (%) of the raw material including industrial waste.

Waste Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	Ref.
Limestone	0.61	0.05	0.08	55.49	0.21	0.002	0.004	0.002	Ma et al. ^[12]
Blast-furnace slag (GBFS)	38.83	12.92	1.46	38.70	4.63	0.28	0.37	0	Ke et al. ^[13]
Flue gas desulfurization sludge	2.8	0.2	0.2	37.9	0.2	0.1	0	-	Chen and Juenger ^[14]
AOD slag	28.0	1.7	0.6	53.2	8.7	0	0	0.34	Isteri et al. ^[15]

The various properties of calcium sulfoaluminate-belite (CSAB) cements were studied by adding calcium carbonate powder. The chemical composition of the CSAB clinker was found to contain significant amounts of SiO_2 (8.7%), Al_2O_3 (32.8%), CaO (44.6%), and smaller percentages of other oxides such as MgO, Na_2O , K_2O , and TiO_2 ^[16]. Based on the investigation, two CSAB clinkers (CSAB#2 and CSAB#4)

can be produced using circulating fluidized bed combustion (CFBC) coarse bottom and finer fly ash and the chemical mineral composition of the cements formed were found to be comparable to the ordinary Portland cement^[17]. **Table 2** lists the chemical compositions of the CSAB cement samples studied in various investigations.

Table 2. Chemical composition of CSAB.

Cement	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	Ref.
CSAB	8.7	32.8	2.1	44.6	2		0.4	1.4	Jeong et al. ^[16]
CSAB#2	5.89	20.48	2.39	47.1	2.25	0.15	0.68	-	Jewell et al. ^[17]
CSAB#4	8.21	24.30	2.59	40.02	1.32	0.14	0.62	-	Jewell et al. ^[17]

2.2. Mineralogical Composition

Table 3 represents the mineralogical compositions of various CSAB clinkers after sintering at different temperatures and dwelling times. The materials used included Class C fly ash, flue gas desulfurization (FGD) sludge, bauxite,

limestone, fluidized bed ash, and phosphogypsum (PG). The mineralogical phases reported was $\text{C}_4\text{A}_3\text{S}$ (tetra-calcium tri-aluminate sulfate), C_2S (di-calcium silicate), CS (calcium silicate), C_4AF (tetra-calcium aluminoferrite), CSH_2 (calcium silicate hydrate), C (free lime), and $\text{C}_5\text{S}_2\text{S}$ (terra-calcium di-silicate).

Table 3. Mineralogical composition of the raw materials used in production of CSAB cement in various investigation.

Raw Material	Sintering Temp.	C ₄ A ₃ S	Mineralogical Composition (%)						Ref.
			CS	C ₄ AF	CSH ₂	C	C ₅ S ₂ S		
Class C fly Ash, FGD sludge, bauxite, Limestone	1250 °C	40	42	4	8	26	1	-	Chen and Juenger ^[14]
Class C fly Ash, FGD sludge, bauxite, Limestone, fluidized bed ash	1250 °C	39	41	7	7	24	2	-	Chen and Juenger ^[14]
Limestone, bauxite, PG	1100–1270 °C	34.5–39.4	6.1–33.8	2.9–17.8	34.5–39.4	0	0	0–44.5	Shen et al. ^[18]
Limestone, fly ash, desulfurization	1250 °C	55–75	8–37	0	3–10	0	0	0	Ma et al. ^[19]

Chen and Juenger^[14] examined the mix of Class C fly ash, FGD sludge, bauxite, and limestone were sintered at 1250 °C, the resulting materials contained approximately 40% C₄A₃S, 42% C₂S, 4% CS, 8% C₄AF, 26% CSH₂, and 1% C. Similarly in another experiment, authors used Class C fly ash, FGD sludge, bauxite, limestone, and fluidized bed ash, and the sintered material at 1250°C had a composition of 39% C₄A₃S, 41% C₂S, 7% CS, 7% C₄AF, 24% CSH₂, and 2% C^[14]. Further, Shen et al.^[18] studied the sintering of three different sources, namely limestone, bauxite, and phospho-gypsum (PG), and the temperature ranged between 1100 °C and 1270 °C. The obtained CSAB clinker had compositions ranging from 34.5% to 39.4% C₄A₃S, 6.1% to 33.8% C₂S, 2.9% to 17.8% CS, 34.5% to 39.4% C₄AF, and 0% to 44.5% C₅S^[18]. According to Ma et al.^[19] the sintering of a mixture comprising limestone, fly ash, and desulfurization material at 1250 °C was carried out, yielding a phase with 55% to 75% C₄A₃S, 8% to 37% C₂S, 0% CS, and 3% to 10% C. Mineralogical phases developed during the sintering of different types of cementitious materials such as fly ash, FGD sludge, bauxite, limestone, fluidized bed ash, phospho-gypsum, clay, and gypsum. The principal phases observed are C₄A₃S, C₂S, CS, C₄AF, CSH₂, C, and C₅S₂S, the proportions of which vary depending on the raw materials and sintering conditions^[19].

3. Result and Discussions

3.1. Setting Time

Initial setting time refers to the interval of time between the beginning of harder cement paste and the beginning of less plasticity of paste. The term final setting time refers to the time between the cement first contact with water and when it has fully hardened and this test are conducted as per

IS 4031(Part-5). When speedy construction activities are necessary, a fast setting time of the CSAB cement is useful.

Rungchet et al.^[20] examined the initial and final setting times of CSAB cement ((FAS-cement from fly ash (FA 20%), bottom ash (BA 0%) and FGD-gypsum (FGDG 10%), Al-rich sludge (AS 25%), and commercial-grade hydrated lime (CH 45 %)), and BAS-cement (bottom ash (BA 20%), fly ash (FA 0%), FGD-gypsum, (FGDG 10%), Al-rich sludge (AS 25%), and commercial-grade hydrated lime (CH 45%) with 25 wt% blended FGDG (flue gas desulfurization)) were examined. The initial and final setting time of BAS cement took much longer to set at 13 minutes and 26 minutes, respectively. Whereas, FAS cement was set at just 11 minutes and 24 minutes, respectively. Because of the large surface areas of both cements and the presence of highly reactive phases, such as C₄A₃S and C₁₂A₇, the setting times were especially short^[20]. The initial and final setting times of the combinations were shortened when fly ash was substituted for CSAB cement. According to Shen et al.^[21] investigation revealed that the use of ternesite also reduced the setting times when fly ash was present. As the concentration of fly ash increases, the setting time decreases significantly^[21]. Portland cement (PC) and calcium sulfoaluminate (CSA) cement mixtures were investigated at different temperatures. Further Qin et al.^[22] the mix contained different dosages of CSA cement added to replace Portland cement for obtaining PC-CSA blends, to evaluate the hydration behavior of Portland cement (PC) and calcium sulfoaluminate (CSA) cement mixtures at temperatures from –5 °C to 20 °C. The study shows that increasing the CSA content in PC-CSA blends reduces the setting time across various PC-CSA ratios. Due to rapid production of overlapping ettringite crystals, CSA cement hydrates and hardens rapidly^[22].

The effect of the combination of aluminum sulfate and

quicklime on the setting time for the double liquid grouting material, where the calcium sulfoaluminate (CSA) and water content remained constant. The effects of different contents of aluminum sulfate on the initial and final setting times of the mixtures were studied (**Table 4**). Mix M1 to M4, which contain aluminium sulfate 1–4%, were compared with the control group (Mix 0 represents 0% of aluminium sulfate). The initial and final setting times of M1 and M2 decreased, as shown in **Figure 2**. Upon further increasing the amount

of aluminum sulfate, there were no changes in their setting times. In addition, the effect of different amounts of quicklime on the initial and final setting times of mix M1–M4 with 10–40% quicklime was studied (**Table 5**). The initial and final setting times of Mix 1 were decreased from 78 and 133 minutes to 8 and 16 minutes, respectively, compared with Mix 0 (0% quicklime). Aluminum sulfate and quicklime reduce the setting time of double liquid grouting materials owing to the development of early ettringite^[23].

Table 4. Initial and final setting times due to the addition of different amounts of aluminium sulfate.

Aluminum Sulfate (wt.%)	Initial Setting Time (min)	Final Setting Time (min)
0	65.5	113.2
1	11.4	30.5
2	8	14
3	8.4	16.4
4	10	20

Table 5. Initial and final setting times due to the addition of different amounts of quicklime.

Quicklime (wt.%)	Initial Setting Time (min)	Final Setting Time (min)
0	78.3	133.5
10	9.4	48.8
20	8.7	15.8
30	6.4	18.5
40	5.2	21.1

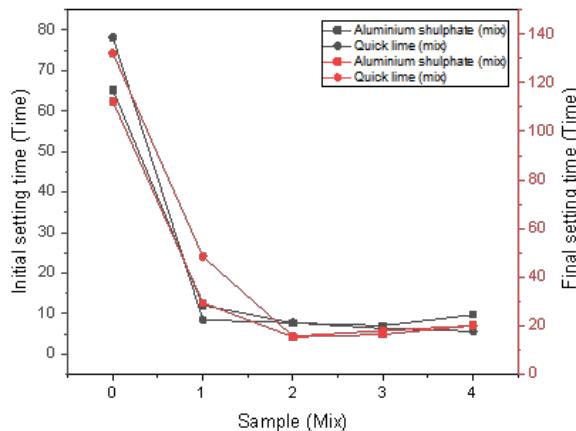


Figure 2. Initial and final setting times of samples with various concentrations of aluminium sulfate and quicklime^[23].

Hence, the addition of various materials affects the setting times of cement. In conclusion, the fresh quality of CSAB cement hydration shows a quick early age strength development and quick cure. These features help speed up the building process and make CSAB cement an excellent choice for projects that must be completed quickly with-

out sacrificing the quality and performance of the resulting structures.

3.2. Compressive Strength

The compressive strength was measured using a universal testing machine (UTM). It is being calculated using the maximum stress that a cubic specimen can withstand before cracking. The compressive strength is an important characteristic to consider when evaluating the performance and longevity of construction materials, particularly CSAB cement.

Various studies have been conducted to examine the effect of replacing raw materials with various industrial wastes on compressive strength as shown in **Figure 3**. Chen and Juenger^[14] studied the incorporation of coal combustion residuals into CSAB cement clinkers. Three CSAB cement clinkers were synthesized from reagent-grade chemicals or natural and waste materials namely MS (a clinker with equal amounts of C_2S and C_4A_3S (40%) synthesized from

reagent-grade chemicals), MC ((a clinker with the same C₂S and C₄A₃S) contents synthesized from a limestone, bauxite, FGDS and large amount of Class C fly ash), and MF (a clinker with medium C₂S and C₄A₃S contents synthesized from a limestone, bauxite, FGDS and high amount of fluidized bed ash). Despite having similar phase compositions, the compressive strengths of the MC and MF CSAB cement were higher than those of the MS CSAB cement. This is because more C₂S reacted later in the hydrated MC and MF CSAB cement, contributing to the long-term development of the compressive strength. As a result, MS, MF, and MC have higher compressive strengths after 7 and 28 days than ordinary Portland cement (OPC), as shown in **Table 6**^[14]. The study findings showed that lower compressive strengths in the paste and mortar samples were caused by a higher water-to-cement ratio (w/c) in the case of CSAB cement. The reduced compressive strength was the outcome of longer setting times and increased total hydration caused by an increase in the w/c ratio^[24]. According to this study, CSAB cement based on bottom ash and lignite fly ash had good early compressive strengths after 7 and 28 days, as shown in **Table 6**. This might be due to ettringite, a dominant hydration product, being synthesized rapidly along with other phases such as calcium silicate hydrate, mono-sulfate, and strätlingite, which are responsible for the formation of strong CSAB cement. The presence of these waste materials facilitates the synthesis of CSAB cement as an affordable alternative to conventional alumina-silica-containing materials.

The rapid setting periods and early strength development of the cement was attributed to the inclusion of highly reactive phases, such as C₄A₃S and C₁₂A₇^[20]. Hence, the addition of various materials, such as fluidized bed ash, bottom ash, and lignite fly ash, improved the compressive strength of CSAB cement. The primary strength contributor in OPC during the first seven days comes from tricalcium silicate (C₃S) through its reaction to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) structures. The strength development mechanism in CSAB follows ye'elimit formation and the formation of C₂S happens gradually which contributes to long-term durability.

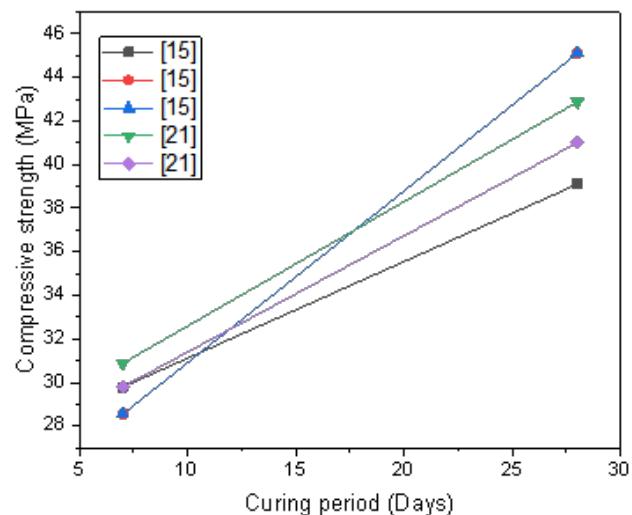


Figure 3. Compressive strength after curing 7 and 28 days.

Table 6. Range of CS at 7 and 28 days for different authors.

Compressive Strength (MPa)		References/Sample
7 Days	28 Days	
29.79	39.0	Chen and Juenger ^[14]
28.55	45.10	Chen and Juenger ^[14]
28.55	45.10	Chen and Juenger ^[14]
30.88	42.87	Rungchet et al. ^[20]
29.80	41.0	Rungchet et al. ^[20]

4. Recent Research Activities at Author's Institute

The authors conducted research to reduce the negative environmental effects of cement production while preserving or raising current performance requirements^[25,26]. The objective of this study is to optimize an alternative envi-

ronmentally friendly low-energy binder, such as calcium sulfoaluminate-belite (CSAB) cement. Low-energy cement clinkers were produced using certain appropriate fluxes, which reduced the sintering temperature or developed the phase formation at a lower temperature. However, the reactivity of industrial waste is less. Prior to using industrial waste material in the production of CSAB, pre-heating or

grinding techniques help to boost the reactivity. Enabling higher reactivity of industrial waste materials before CSAB production allows clinkering reactions to produce cement with required physico-mechanical characteristics. Appropriate instrumental analysis was used to examine the physico-mechanical properties of the binders. A few inexpensive building materials or components can be developed using these binders.

Limestone, waste materials such as phospho-gypsum from the Fertilizers & Chemicals industry, gypsum from the fertilizer industry, and bauxite from the cement industry were used (**Figure 4**). These raw resources were obtained from various regions in the Indian subcontinent. Before being used in the laboratory, these raw materials were carefully dried in an oven to a constant mass after being collected. In a high-temperature furnace (M/s. Carbonlite HTF-1800; Carbonlite-Zero Ltd., Hope Valley, UK), the mixture was prepared for cement development. The heating cycle involved gradually increasing the temperature from 27 to 1130 °C at a rate of 8 °C/min. After 60 min at 1130 °C, the clinker was quickly cooled to room temperature with compressed air cooling. **Figure 5** depicts the synthesis technique for the CSAB clinker before and after sintering. After grinding the clinker the CSAB cement was mixed with sand in a 1:3 ratio and a water-to-cement ratio of 0.50 to cast the cube for compressive strength test as shown in **Figure 6**.

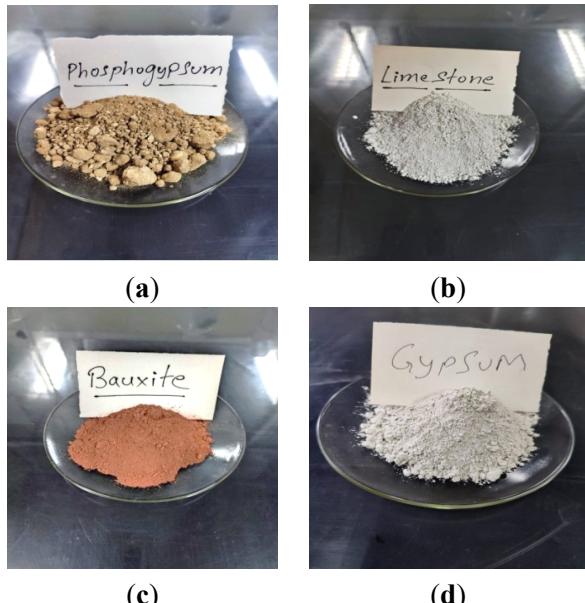


Figure 4. Raw materials: (a) Phosphogypsum; (b) Limestone; (c) Bauxite; (d) Gypsum.

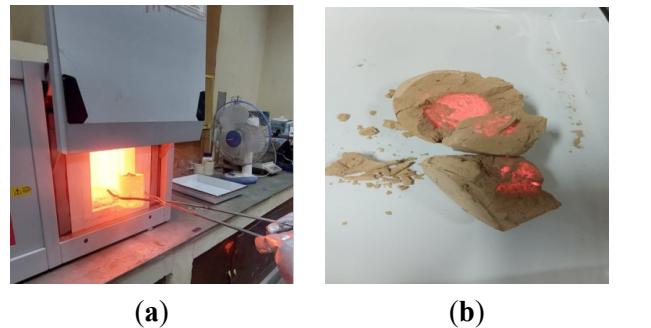


Figure 5. (a) Before sintering; (b) Quenching of CSAB clinker.



Figure 6. Casting and compressive strength testing of cube at 28 days.

The global market for calcium sulfoaluminate belite cement is still relatively small compared to that for traditional Portland cement, but it is steadily growing. The market is driven by the increasing demand for sustainable and eco-friendly construction materials and the superior performance of cement in certain applications. In China, which is one of the largest producers and consumers of cement globally, the cost of calcium sulfoaluminate belite cement (nearly US\$104/Ton) is typically higher than that of ordinary Portland cement. However, price differences can vary depending on the region, production scale, and market conditions. China has been at the forefront of calcium sulfoaluminate-belite cement production and research. Several major cement companies in China have invested in the development and manufacture of cement. The manufacturing process involves the use of raw materials, such as limestone, bauxite, and gypsum, which are readily available in many regions of China.

The developed CSAB cement reduces CO₂ emissions by 25–35% compared to traditional OPC clinker^[9], reduces burning temperatures by 250–300 °C, reduces fuel usage by 20–25%, and reduces manufacturing electricity costs by 25–30%^[2].

5. Conclusions

CSAB cement is appropriate for a variety of time-sensitive building projects, ensuring faster completion times owing to its rapid setting and early strength growth. Additionally, due to low alkali content CSAB binder, concrete constructions are more long-lasting because alkali-silica interactions are less likely to occur. Due to their properties, CSAB cement has drawn interest in the production of precast concrete products.

The production of CSAB cement involves lower levels of calcium-containing raw materials, such as limestone, than Portland cement. As a result, the calcination process (heating raw materials) releases lower amounts of CO₂ emissions. The manufacturing process of CSAB cement requires lower kiln temperatures, typically around 1300 °C, compared to the higher temperatures required for Portland cement production (approximately 1500 °C). This lower temperature requirement results in lower energy consumption and associated emissions from fuel combustion.

Utilization of industrial by-products, one of the advantages of CSAB is its ability to incorporate industrial by-products as primary raw material. These by-products include fly ash from coal-fired power plants, ground granulated blast-furnace slag from steel production, and other industrial waste materials. Utilizing these by-products not only reduces the consumption of virgin raw materials but also helps in the sustainable management of industrial waste. Thus, using industrial by-products in the development of cement can be a sustainable solution for the development of alternative binders.

The large-scale production of CSAB cement experiences principal limitations because it requires alumina-rich materials including bauxite for its production. The manufacturing expense of Ordinary Portland Cement (OPC) using limestone remains lower than using bauxite because bauxite is both more expensive and less accessible compared to limestone. In the production of CSAB cement the natural raw material such as limestone, bauxite, gypsum were partially replaced by low grade limestone waste, red mud, fly ash as well as aluminum anodizing sludge, etc. Industrial waste poses challenges due to improper disposal, which can harm the environment. To increase the production of Calcium Sulfoaluminate (CSAB) cement on a large scale, utilizing these industrial by-products provides the dual benefits of reducing

operational costs compared to traditional binders while also promoting ecological sustainability. This creates opportunities to increase their use, aligning economic performance with environmental care.

Author Contributions

A.Y.: Conceptualization, Methodology, Writing—original draft, Editing, Validation; R.K.: Conceptualization, Methodology, Writing—original draft, Writing—review & editing, Funding acquisition, Project administration, Supervision; C.M.: Methodology, Writing—original draft, Editing; N.S.N.: Writing—original draft, Writing—review & editing, Validation, Methodology; S.N.B.: Writing—review & editing, Validation. All authors have read and agreed to the published version of the manuscript.

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Data will be made available by the authors upon request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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