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Opening Letter of RILEM TC CSA: Calcium sulfoaluminate-based cement and concrete – Critical review and open questions

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Abstract

Calcium sulfoaluminate (CSA)-based cements represent a promising alternative to traditional Portland cement, offering benefits such as rapid strength development, low shrinkage, and reduced carbon footprint. Despite their commercial availability and proven performance, the adoption of CSA cements remains hindered by gaps in standardization and understanding. This RILEM Technical Committee (TC) CSA aims to review current knowledge, identify research needs, and address challenges related to clinkering, hydration mechanisms, durability, applications, nomenclature, standardization, and testing of CSA-based cements. The outcomes will further the understanding of manufacturing, technical performance, use, and specification of CSA-based cements, ultimately leading to broader acceptance in concrete construction.

Keywords: Calcium sulfoaluminate cement; Ye'elimite; Belite; Ettringite; Low-CO_2 cement.

1 Introduction

In 2024, 4.0 billion metric tons of Portland cement (PC) were produced globally [1], and production is expected to increase due to population growth and the rehabilitation of existing infrastructure [2]. Over the past 200 years, PC has been the predominant binder used in concrete production worldwide. In most parts of the world, it remains irreplaceable due to its low cost, large production volumes and the availability of its primary raw materials, limestone and clays.

However, the production of PC is the cause of significant CO_2 emissions, primarily released during the calcination of limestone and other steps in the manufacturing process. Meanwhile, the Paris Agreement calls for a 45% reduction in emissions by 2030 to limit global warming to below 2 °C [3], and global cement and concrete associations have set ambitious targets to achieve net-zero CO_2 emissions in cement production by 2050 [4, 5]. From an applications perspective, the strength gain of PC during hydration is relatively slow, and the concrete is susceptible to dimensional instability, such as high drying shrinkage that can lead to cracking and substantial concrete design constraints. PC concrete and mortars are also susceptible to detrimental alkali-silica reactions, which are both durability and sustainability concerns. Therefore, alternative binders or accelerators for PC are needed to meet the demands of specialized applications, reduce the CO_2 footprint, and improve the sustainability of the industry.

Calcium sulfoaluminate (CSA) cements are distinct from PC due to their unique mineralogy, which features ye'elimite (idealized formula $Ca_4(AlO_2)_6SO_4$) as the characteristic reactive phase, as reviewed in [6-12]. CSA clinkers are generally manufactured from mixtures of limestone, bauxite and calcium sulfate in a rotary kiln at temperatures of around

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1250°C; optional suitable waste materials can be used. CSA cement is produced from the clinker by intergrinding calcium sulfate and optionally further components, i.e. supplementary cementitious materials. Ye'elimite is known for its rapid hydration with calcium sulfates to form ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot26H_2O$), enabling CSA-based cements to achieve high early strength. This characteristic has positioned CSA cements as a viable solution for applications requiring rapid construction and repair [13]. Besides ye'elimite, other phases are present in the clinker. The most important one is belite (Ca_2SiO_4), and CSA cements with high belite contents are often named BCSA (belitic CSA) or BYF (belite-ye'elimite-ferrite cements) if they contain a substantial amount of ferrite ($Ca_2(Al,Fe)_2O_5$) [10]. Belite hydrates at later ages to produce first strätlingite ($Ca_2Al_2SiO_7\cdot8H_2O$), and then calcium silicate hydrates (C–S–H), especially when belite content is high (BCSA, BYF) [14]. Alite (Ca_3SiO_5) is generally not present (or only in traces) in conventional CSA. Alite calcium sulfoaluminate cements (ACSA) are a special class of CSA cements, where alite is made coexistent with ye'elimite using either mineralizers, a two-stage heating process or a thorough control of kiln atmosphere [15].

Besides high early strength, CSA-based binders exhibit additional advantages, such as reduced shrinkage [16, 17] and various other performance characteristics, for instance rapid setting [18-20] or high sulfate resistance [21-23], making them suitable for a wide range of construction needs. It has, however, to be considered, that the properties of CSA-based binders depend on various factors related to the formulation of the product, i.e. the mineralogical composition of the CSA clinker, the amount and kind of the calcium sulfate added, the presence of other binder components such as PC or supplementary cementitious materials, or the use of admixtures.

Furthermore, CSA-based binders provide environmental benefits, with studies indicating a reduction in global warming potential (GWP) of up to 30% compared to PC [24].

The history of CSA-based binders traces back to the work of Alexander Klein on expansive and shrinkage-compensating cements in the late 1950s [25]. Later, Klein's work was adapted in China under the name "third cement series" [26] and in the USA in part due to Ost's development of belitic calcium sulfoaluminate (BCSA) cements [27]. CSA cements have been commercially produced and used for decades in North America [28], China [29], and more recently in Europe [30-33].

The primary industry motivation for using CSA cements lies in their ability to significantly reduce construction times compared to PC. This unique advantage, combined with their potential to serve as a low-carbon binder, represents an important environmental opportunity, because an environmental benefit is intrinsically built into the economic benefit or rapid construction.

Applications of CSA-based cements range from pavements, rapid repair works and shrinkage-compensating concrete to dry-mix mortars. They are also used as accelerating additives and as binder component in ternary systems PC-CSA-calcium sulfate [28, 34, 35]. However, despite their technical advantages and commercial presence, the adoption of CSA cements in concrete has been slow, primarily due their high costs associated mainly to the availability of the alumina source (i.e. bauxite) and to a lack of standardization. In dry mix mortars, however, where the standards are performance-based and not descriptive and cost of the binder does not play such a role as for concrete, CSA clinkers and cements are rather well established as binder components.

2 State-of-the-art and knowledge gaps

Within the scope of TC CSA five different areas of work were identified, which are shortly summarized below.

2.1 Nomenclature, standardization and testing

The lack of a universal nomenclature for CSA cement is a unifying challenge across all working groups of TC CSA, and one that hinders progress in research and practice alike. A taxonomy is needed to clarify what "CSA cement" refers to because there is no one CSA cement—rather a family of CSA-based cements with different chemistries and properties. Still, technical literature is often unclear about what type of CSA cement is discussed or if the discussion is relevant to all CSA cements. This can lead to uncertainty among potential users about the type(s) of CSA cement that may be appropriate for their project. A few authors have recommended classification schemes for CSA cements [11, 12, 28]. The American Concrete Institute (ACI) Committee 242 on Alternative Cements [36] has been working on a report on CSA cements since 2018 that will include some form of disambiguation. China is the only known jurisdiction with a formal classification for CSA cements [37]. This classification limits the CSA clinker composition to more than 30% by mass of Al_2O_3 and the SiO_2 to less than 10.5% by mass. This means that belitic calcium sulfoaluminate is not officially classified in China. This technical committee aims to recommend a universal nomenclature for CSA cements that will be a model for organizations worldwide. The TC developed a draft framework for CSA cement nomenclature, shown in Figure 1, which we will continue to refine. As a next step, the TC will attempt to catalog the full breadth of CSA-based materials available in global markets.

Meanwhile, inadequate consideration of CSA cements in standards and specifications also presents a barrier to research progress and practical adoption. As "alternative" or "special" cements, CSA-based cements often fall outside of established norms, creating challenges in regulatory and industry adoption. In Europe, some agencies have provisions allowing the use of CSA-based cements. For example, in Germany CSA-type cements have received technical approvals to conform to European specifications (EN 197-1 [38]) with some differences in classification, setting time and sulfate content [39-42]. It is worth noting that these European Technical Approvals (ETA) are not necessarily based on the same European Assessment Document (EAD) and, therefore, do not reflect a consistent set of properties [43]. Furthermore, manufacturers can omit some properties from the published ETA. Switzerland extended the EN 197-1 European Standard for Portland cement with National

Standard SIA 215/1 [44] to allow “specially selected inorganic inert or reactive substances” as main constituents, effectively enabling the use of CSA cements and blends of CSA with PC. In the Americas, some CSA cements meet performance-based specifications such as ASTM C1600 [45] for rapid-hardening hydraulic cement or ASTM C845 [46] for shrinkage-compensating additives. CSA-based cements are regularly used in the USA, but such approvals are granted state by state and have significant regional variations [28]. The American Concrete Institute (ACI) 318 Building Code Requirements for Structural Concrete [47] has allowed the use of “alternative” cements for structural concrete since 2019, but states that they are only permitted if “approved by the licensed design professional and building official.” Standardization is much more advanced in China, which has a series of national and industrial standards for CSA cements. This TC aims to develop a draft specification for CSA cements that will be a model for global standards organizations. As a first step, they will systematically review international standards and specifications to understand how CSA cements are treated globally.

Finally, the chemistry and performance of CSA cements can be incompatible with testing methods written with PC in mind [48]. In some cases, tests may be wholly unsuitable (e.g., the accelerated mortar bar test can fundamentally alter the hydrate assemblage in CSA cement mortars [49]). In other cases, testing ages may need modification (e.g., corrosion test results for BCSA cement concrete are extremely sensitive to age [50]). Even if the methods are appropriate, test results may not be comparable between CSA cement and PC systems (e.g., electrical properties are highly sensitive to changes in pore solution chemistry). The TC aims to produce a set of recommendations for testing CSA cements. To that end, the TC will identify the most common test methods used for CSA cement, mortar, and concrete. Using evidence from the literature, they will critically assess the suitability of each method for use with CSA cements, recommend appropriate modifications, and identify gaps in knowledge.

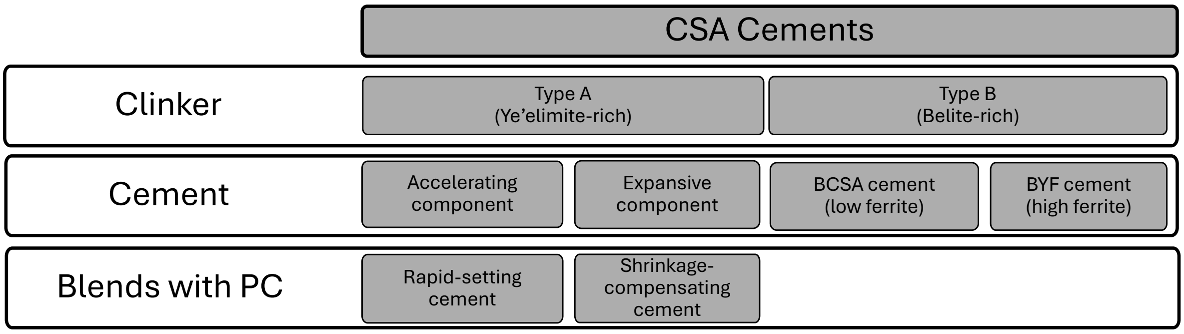

Figure 1. Draft framework of a simplified taxonomy for CSA-based cements.

2.2 Clinkering

CSA-based clinkers are generally produced by burning raw materials like limestone, marl, clay, bauxite and a sulfate source within a temperature range between 1250° and 1350 °C [51, 52]. There is a wide range of compositions possible within the frame of belite-sulfoaluminate clinkers. The main mineral phase is sodalite-type ye'elimite, also called Klein´s compound; belite, ferrite, alite and ternesite can occur in different types of CSA cements [9, 15, 53]. Among minor phases, periclase, gehlenite, mayenite, perovskite, arcanite, akermanite, free lime, magnetite and anhydrite are most commonly reported for CSA clinkers [54-59]. Since mass production of high alumina clinkers faces economic and sustainability challenges - mainly due to the cost of alumina sources - current research is increasingly focused on iron-rich BCSA clinkers, i.e., belite–ye’elimite-ferrite (BYF) systems [9, 60], as iron-containing alumina sources are cheaper and do not compete with aluminium metal production. The limited availability of alumina can also be addressed by using alumina-bearing waste materials such as anodization mud, steel slag or bottom ash [58, 61-63] - this has been used in the United States since the mid-90s. The potential of other secondary raw materials such as ashes and metallurgical by-products (slags) for CSA-type clinker production has also been demonstrated [58, 63-65].

Both $CaO–SiO_2–Al_2O_3–SO_3$ and $CaO–SiO_2–Al_2O_3–Fe_2O_3–SO_3$ systems are characterized by a high complexity, and a wide range of factors affecting the properties of the resulting products, such as the composition of raw materials and raw mix, as well as the clinkering conditions in terms of temperature and time [66]. Besides phase composition, e.g. the ratio between belite and ye'elimite, the clinker microstructure, including phase grain size, morphology, distribution, and incorporation of foreign ions, is the main parameter influencing the reactivity of CSA clinker [67]. Although the targeted amounts of the main clinker phases can be well-predicted, the formation of minor phases strongly depends on the minor elements present in the raw materials [68]; these foreign elements can also enter the main clinker phases, altering their hydraulic properties [54, 58].

The major phases of CSA clinkers have a high tendency to form solid solutions. Ye'elimite belongs to the sodalite family of compounds with the general formula $M_4[T_6O_{12}]X$, where T occupies tetrahedral sites and is often Si or Al, M is a low-charge cation (e.g., Na^+, Ca^{2+}, Sr^{2+}), and X is a charge-balancing anion (e.g., Cl^-, SO_4^{2-}, WO_4^{2-}, CrO_4^{2-}). In CSA clinkers two ye'elimite polymorphs are common, orthorhombic and pseudocubic [57]. The orthorhombic form [69] develops between 1100–1200 °C, while higher temperatures favour cubic forms with variable iron content. Ye'elimite is orthorhombic at ambient temperature, but substitution of Ca^{2+} with Na^+ and Al^{3+} with B^{3+}, Si^{4+}, and Fe^{3+} shifts symmetry to cubic [57, 70]. Iron content affects the phase's reactivity and grain morphology, with higher iron accelerating ye'elimite formation [10, 51, 52, 71, 72]. Belite, whose natural analogue is larnite, is recognised as a slowly reactive phase that exhibits temperature-dependent polymorphism [57, 73]. In the CSA clinkers, belite predominantly occurs as the ß-polymorph, which is less reactive than the α-polymorphs (α'_L and α'_H) that form at higher clinkering temperatures [52]. Slow cooling transforms β-C_2S to hydraulically inactive γ-C_2S, which is stable at room temperature [74]. The ferrite phase is an orthorhombic solid solution of the endmembers $Ca_4Fe_4O_{10}$ and $Ca_4FeAl_3O_{10}$ [75].

In general, the microstructure of CSA clinkers, see Figure 2, is formed by the reaction from solid-solid to liquid-solid state [67]. Belite typically forms irregularly shaped crystals with well-defined edges, ye'elimite develops as angular hexagonal crystals, and ferrite most commonly appears as an interstitial phase [67, 76]. The cooling regime significantly influences the crystal size and morphology of the main phases, while also affecting the formation of certain minor phases—for example, rapid cooling promotes the formation of highly hydraulic mayenite, whereas slow cooling favours the development of the less hydraulic gehlenite [77].

Minor components may have marked influence on clinkering reactions and clinker properties [78]. The impurities also exert a strong influence over which of the numerous polymorphs are obtained - the effects on chemical-stabilising ions on the stability of ß-phase belite have been extensively investigated [79].

Thermodynamic studies can accelerate the development and understanding of clinkering in novel systems; however, coupling thermodynamic modelling with experimental work is essential, and thermodynamic data for the relevant clinker phases such as ye'elimite, belite and ferrite are needed [80-82]. The raw mix composition and clinkering parameters, including atmosphere in the kiln and type of fuel, strongly influence the phase composition and polymorphism of CSA clinker as demonstrated in the case of a novel production process using elemental sulfur both as fuel and source of SO_3 for ye'elimite formation [83, 84].

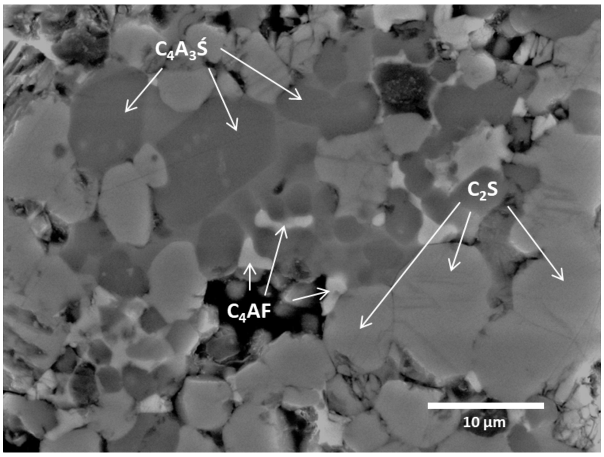

Figure 2. Main phases of BCSA clinker (scanning electron microscopy, polished section): C_2S – belite, $C_4A_3\acute{S}$ – calcium sulfoaluminate, C_4AF – ferrite. Image courtesy of Lea Žibret (Slovenian National Building and Civil Engineering Institute), published in [85] on page 107.

2.3 Hydration

Generally, the hydration of CSA-based cements with respect to ye'elimite and the role of calcium sulfate are well understood as underlined by multiple studies during the last decades and supported by thermodynamic modelling [10, 14, 55, 81, 86-90]. Ye'elimite reacts with calcium sulfate to form ettringite and aluminum hydroxide, $Al(OH)_3$, of low crystallinity. The amount of calcium sulfate, i.e. the molar ratio of $CaSO_4$ to ye'elimite which is known as "M-ratio" [91] as well as its reactivity (generally hemihydrate > gypsum > anhydrite) strongly influence early hydration kinetics [92-101]. When the calcium sulfate is depleted, monosulfate forms instead of ettringite. However, this reaction scheme is rather idealized as, especially at early age, other phases might occur, such as $CaAl_2O_4{\cdot}10H_2O$ [14, 102], nanocrystalline AFm-phases [103] and $Al(OH)_3$-gels with higher water contents and/or containing Ca [104, 105], which are also suggested to adsorb sulfate [106]. In general, a high amount of X-ray amorphous hydrates occurs [107]; however, it cannot be excluded that crystalline/amorphous content determined in experiments is often biased by various experimental issues such as hydration stoppage or poor description of single crystal structures of e.g. AFm-solid solutions.

Belite is the most relevant of the other clinker constituents and plays a major role in BCSA and BYF cements. Belite starts to hydrate significantly after ye'elimite has been largely dissolved and primarily forms strätlingite, $Ca_2Al_2SiO_7{\cdot}8H_2O$, under consumption of $Al(OH)_3$ [14, 86, 98, 99, 108]. C–S–H forms only at high belite reaction degrees [14]. Figure 3 shows the hydrates formed in BCSA cement depending on time as derived by thermodynamic modelling. At an early age, ettringite is the dominant hydration phase. At later ages, i.e. years, strätlingite, monosulfate and C–S–H are the major hydrates predicted to be stable, while ettringite content decreases. Investigations of aged (B)CSA samples would be needed to confirm this change in phase assemblage experimentally. These experiments could prove if, after long hydration times, the thermodynamic prediction is fulfilled or if the amount of ettringite initially formed is still present after years, and the transformation of ettringite to other hydrate phases is kinetically hindered due to missing water or low reactivity of parts of belite.

Among other phases, ferrite, mayenite ($Ca_{12}Al_{14}O_{33}$) and ternesite ($Ca_5(SO_4)(SiO_4)_2$), are the most important ones. The iron of the ferrite phase goes predominantly into the very stable Fe-containing siliceous hydrogarnet [109], while mayenite takes part in the very early hydration reactions [110], and ternesite reacts in the presence of aluminium hydroxide to strätlingite [88].

The pore solutions of CSA-based cements, see e.g. [32, 86, 89, 111-114], are characterized by a low pH of ≈ 11 at early ages, but reach values close to 13 after 28 days and later, which should be sufficient to protect steel rebars from corrosion. The ionic composition differs from that one of PC, e.g. the Al concentrations are significantly higher. Some work has been done to link pore solution composition to phase stability [86, 89, 113, 114], however, a critical evaluation of the pore solution data available in literature would be needed for a further understanding of the underlying mechanisms.

Supplementary cementitious materials (SCMs) can react in CSA cements; much less information is available for BCSA cements. Limestone can participate in the hydration reactions of ye'elimite in case the molar ratio of calcium sulfate to ye'elimite is below 2, forming hemi- or monocarbonate [115-118]. Blast furnace slag is activated by the alkaline medium of the pore solution, however the reaction degree seems generally lower than in PC [119]. As portlandite is generally not present in CSA cements, aluminosilicates do not exhibit a pozzolanic reaction in the true sense of the term. Nevertheless, a reaction of siliceous fly ash [120], calcined clay [121] or silica fume [122] is reported, which leads to the formation of strätlingite and possibly C-S-H. However, a systematic overview of the action of different SCMs is currently missing in literature.

Admixtures are often needed to retard the early setting of CSA cements, and a wide range of materials are used, mostly citrate, but also borate, tartrate or gluconate [123]. To accelerate early hardening, Li-salts can be used [124], especially in combination with set retarders [125]. Superplasticizers used for PC also seem to work for CSA [126]. A detailed overview of the action of the various types of admixtures and their fields of use is currently still lacking.

Ternary blends CSA-PC-calcium sulfate are in use as fast-setting, rapid hardening or shrinkage-compensated binders which exhibit rather complex hydration mechanisms [34, 35, 127, 128]. The mix designs are quite complicated as the raw materials and the blending ratio need to be thoroughly controlled, and specially-designed admixtures systems are needed to achieve the desired properties and to avoid deleterious expansion. Especially in the case of admixtures, there is significant proprietary knowledge in the mortar and concrete industry, which is generally not shared in open literature.

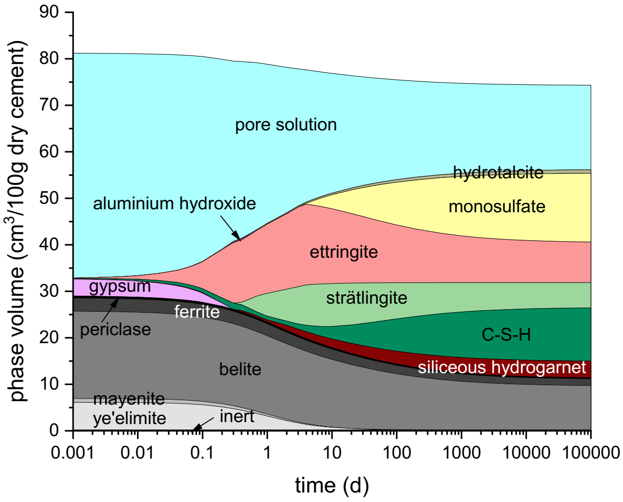

Figure 3. Hydrates formed in a BCSA cement as a function of time by thermodynamic calculations at 20 °C and a water/cement ratio of 0.50. Hydration kinetics is based on dissolution kinetics of the clinker phases derived from QXRD. Redrawn from [99].

2.4 Physical properties of fresh and hardened mortar/concrete

The physical properties of CSA cements represent an important area for characterization since these properties will define the specifications, potential applications, and design of these materials. While many properties of CSA cements may be similar to PC, there are key differences, especially in terms of setting time, strength gain, and durability, which must be clearly understood to use CSA-based cements for infrastructure and buildings [18, 129, 130]. To enable broader use of CSA cements, (i) properties that differ substantially from PC should be clearly identified; (ii) existing design relationships must be recalibrated; (iii) the influence of practical factors—ambient weather, curing, and compaction—should be established; and (iv) standards and procedures should be updated. Finally, the goal is to design mortar/concrete that meets performance requirements with an optimized balance of safety and conservatism, thereby realizing the performance and CO_2 benefits of these binders. Concrete mix design procedures for BCSA cement are similar to PC [129], but a retarder (e.g. citric acid or borax) is generally a requirement [18, 19]. The workability must often be enhanced with water reducers [131] due to the short setting times. There is some guidance on mix proportioning and fresh properties of CSA-based cements [129, 132], but relationships between mix proportions and entrained air content, w/c and strength, and the effects of mixture design parameters on workability are fields of future research. Also, gathering the effects of practical field factors—placement method, curing, and compaction—from previous field experiences and research is critical for application-specific mix design across different weather conditions, helping to avoid unnecessary conservatism. Additionally, the rheology of CSA cements is a potential future focus area, particularly the dynamic yield stress and viscosity, which are particularly relevant for pumping or 3D printing.

The effect of curing and ambient temperature on CSA mixtures has been studied [133, 134], but there is no consensus on field and laboratory curing procedures. There is some published information on strength development, particularly compressive strength [18, 129, 135-137], but the relationships between modulus of elasticity [18], tensile strength [18, 138-140], flexural strength [138, 141, 142], and Poisson's ratio are relatively unexplored.

Dimensional stability is an important topic for CSA cements, as some of these materials exhibit early-age expansion, and they may be chosen specifically for their low-shrinkage or expansive behavior. The expansion and shrinkage behaviour have been studied on paste [23, 112, 143-145], mortar [146], and concrete [16, 17, 139, 147]. However, one downside of many of these studies is the variety of CSA formulations (some of which may be blended in varying quantities or made at a laboratory scale), which limits the ability to produce practicable shrinkage models applicable in field applications. Consequently, there are no existing shrinkage models for use in the design of structures. Creep is even less well-studied than shrinkage [16, 142, 148, 149], and likewise, the development of creep models and characterization of commonly available CSA formulations and their creep properties is an area of future study.

A growing body of research has sought to connect the evolving microstructure of CSA cements with their physical properties, particularly compressive strength and expansion. Studies have shown that the degree of hydration strongly governs strength development. Porosity and pore structure have also been identified as critical parameters controlling strength gain and durability [150-153]. Expansion and dimensional stability, by contrast, are closely tied to the quantity and morphology of ettringite [143, 145, 154], with additional influences from overall strength, pore structure [155] and pore solution chemistry [112, 144]. Morphological changes in ettringite have been shown to directly impact expansive behaviour [143, 154], reinforcing the need to couple phase assemblage with physical performance. Other studies have extended this microstructure–property link to fresh-state performance, with hydration kinetics, admixtures, and additives shown to significantly influence the early workability and setting behaviour [18, 156]. Together, these findings highlight the critical role of microstructural parameters in governing both the mechanical and dimensional stability of CSA-based systems. Again, a weakness of the existing work is the variety of CSA cement chemistries present and the corresponding difficulty in extrapolating the results onto commercially available or widespread formulations which may be applied in practice.

In reinforced concrete, the flexural capacity [131], shear capacity [157], and flexural stress block parameters [158] have been validated for BCSA cement compared to existing international building code equations. There is little information about the long-term behaviour under load, bond and anchorage to rebar, shear transfer after cracking, behaviour under dynamic loading, and fatigue performance. In general, the behaviour under extreme loading (blast, seismic, etc.) is an area of future research.

2.5 Durability and applications

Durability is one of the key aspects of concrete due to its influence on the serviceability of concrete structures. Major durability indicators include permeability, sulfate attack, carbonation, chloride ingress, leaching, freeze-thaw, corrosion, acid attack, dimensional stability (cracking/shrinkage/expansion) and ASR. Although CSA/BCSA cements have been presented as an attractive alternative to PC, investigations on their durability indices are limited.

CSA-based cements exhibit a high resistance toward freeze-thaw and chemical attack in a wide range of aggressive environments [7]. They outperform PC in citric acid environment due to the absence of portlandite, while they seem to be less resistant to sulfuric acid attack [159, 160] PC-CSA composites show improved corrosion resistance to sulfuric acid when compared to PC alone [161]. The deterioration of CSA cement was reported to be inversely proportional to the pH of the exposure solution, irrespective of chemical or biogenic sulfuric acid attack [162]. Additionally, CSA-based cements are good candidates for ASR mitigation [49, 163]. This has been related to the low generation of portlandite as well as to the presence of aluminate-rich phases such as ettringite that potentially get adsorbed in the silicate gel, thus reducing the dissolution of amorphous silica in the aggregate [163, 164]. Pore solution and alkalinity play a role as the pH of CSA is even at late ages often still lower (approx. 0.5 pH units) than for PC [86, 126, 165]. CSA-based cements have shown very good resistance to sulphate attack, compared to PC [21-23]. Long-term investigations indicate that they remained essentially unaffected by a 3-year exposure to highly-sulfated environments [21]. Their stability was superior to that of a Type V (0.5% C_3A) Portland cement classified as 'sulfate-resistant' per ASTM standards.

The carbonation of CSA-based cements results in ettringite decomposition and potential strength loss [7]. The carbonation resistance of CSA cements increases with decreasing water-to-cement ratio as well as with increasing calcium sulfate content in most cases [166]. The type and content of SCMs also influence the carbonation rate of CSA cements [167]. For instance, the use of fly ash as SCM has been shown to reduce the carbonation depth in concrete mixtures over time (105 days), whereas combinations with limestone presented mixed effects [168]. There is disagreement in the literature regarding the carbonation rate of CSA cements vs PC, and contradictory findings have been reported among the researchers [169]. The chemical buffer capacity [170] of CSA-based cements towards carbonation, however, is lower compared to the one of PC due to their lower content of reactive CaO [166].

Contradictory results are also published on the corrosion resistance of CSA-based cements [139, 171-173] which is highly time-dependent [50]. Weak corrosion resistance of CSA blends compared to pure CSA, due to the decomposition of ettringite and reduction of the alkalinity of the pore solution which is not sufficient to promote the formation of the passivation layer around steel fibres, is reported [139]. On the contrary, there was no evidence of corrosion on the surface of steel bars embedded in CSA concrete after 14 years

[172] which was ascribed to lower permeability and self-desiccation of the concrete.

The inconsistent data outlined above emphasize the need for further research. A deep understanding of the link between durability indicators - microstructure - pathway of hydration and pore solution would be needed. As emphasized in section 2.4, the variability of CSA cement chemistries makes the extrapolation of these links challenging. Most and foremost, the durability of CSA-based binders in the long term and in field conditions must be investigated in detail to ensure a maximum service life of future structures.

In terms of applications, CSA-based cements are gaining traction, particularly for expedited rehabilitation of roads, bridges, and airport pavements, and they have been used in large-scale reinforced and prestressed concrete applications as has been demonstrated recently [149, 174, 175]. BCSA cement-based concrete has demonstrated considerable promise in high-impact infrastructure applications, including pavement rehabilitation [176], bridge deck and structural repairs [177], precast and prestressed elements [149], and emergency interventions such as utility trench restoration and temporary structural components. These applications share a common requirement: rapid return to service. However, they are often designed using conventional concrete specifications, which may not fully consider the unique properties of BCSA.

Proposed innovative uses of BCSA concrete include bonded concrete overlays over asphalt (BCOA) [178], large-format airfield pavement slabs [179], or rapid-strength ultra-high-performance concrete (UHPC) [180], capable of achieving compressive strengths up to 145 MPa within days and opening strength within 4 hours. Integration into emerging technologies such as 3D concrete printing has also been proposed.

Finally, the method of concrete production, whether through volumetric mixing or ready-mix batching, can significantly influence the performance, logistics, and cost of CSA-based concrete. A comprehensive understanding of the advantages, limitations, and practical challenges associated with each method is essential for developing standardized guidelines that support efficient and reliable implementation across various infrastructure applications.

3 Objective of the TC and expected impact

While a number of RILEM technical committees have focused on alternative cements such as alkali-activated cements (TC 224-AAM [181], TC 247-DTA [182], TC-283-CAM [183], TC 294-MPA [184]) and magnesium-based cements (TC 311-MBC [185]), calcium sulfoaluminate-based cements have not yet received similar attention. The main objective of the TC-CSA is to advance the scientific understanding and practical applications of CSA cements by addressing key gaps in knowledge and technology. It will also be a basis upon which specific topics related to CSA can be developed further, e.g. in future TCs.

Despite their potential, CSA-based cements face several challenges that must be addressed to facilitate their broader adoption. One of the primary challenges is the limited understanding of hydration mechanisms, particularly in systems that include blends with SCMs and admixtures. The interactions of these materials during hydration remain poorly characterized, which complicates efforts to optimize their performance. Another significant challenge is the lack of comprehensive data on the durability of CSA-based materials, especially under aggressive environmental conditions. This knowledge gap raises concerns about their long-term performance in real-world applications. An additional challenge is the confusion among end users with other technologies, such as calcium aluminate cement. Additionally, the absence of unified testing methods and standards for CSA cements creates regulatory and technical barriers, limiting their acceptance by industry and agencies.

To address these challenges, the TC will adopt a multifaceted approach structured by asking separate working groups to focus on the topics presented in sections 2.1-2.5 and compile a comprehensive overview of the state of the art, mineralogical characteristics and hydration behaviour of CSA cement. The TC will also evaluate the physical and mechanical properties of CSA-based materials and their long-term durability under various environmental conditions. Additionally, the committee will work toward developing recommendations for the nomenclature and standardization of CSA cements to facilitate their broader acceptance in the construction industry. Collaborative interlaboratory studies are to be defined and planned for the 2nd half of the TC lifetime to validate testing methods (e.g. phase analyses or mechanical properties) and generate reliable datasets, enabling the development of standardized procedures. We are aware that this TC will not be able to cover a wide range of testing methods, and that some activities might be shifted to future TCs on CSA-based cements and concrete. Experiences from field studies will also play a crucial role in documenting the performance of CSA-based materials both in long-term phase assemblage and in practical applications, offering insights into their durability and suitability for various conditions. Finally, the TC will foster collaboration between academia and industry through symposia, workshops, and publications, creating a platform for the exchange of knowledge and ideas. Synchronization with the activities of ACI (American Concrete Institute) committee 242 on Alternative Cements [36], which is dedicated to develop and report information on alternate cements for use in concrete, will be an important part of this work.

Achieving these objectives could have significant implications for both the construction industry and society at large. By reviewing and promoting the use of CSA cements, the TC aims to reduce carbon emissions associated with cement production and accelerate construction processes, thereby addressing urgent sustainability challenges. While CSA cements may not embody the universal solution to the sustainability challenges of the construction industry, they may be a stepping stone or an intermediate step in the process. For example, most low-carbon cement alternatives are still at the concept or laboratory benchtop stages. No large production volumes of low-carbon cements are currently operational or commercial. CSA cements are the only low-carbon alternative already produced in millions of tons worldwide. The knowledge generated by this TC has the potential to drive innovation in material science, expand the range of applications for CSA cements, and create new opportunities for industry collaboration and research. Furthermore, the outcomes of this work will contribute to the development of sustainable construction practices globally, supporting the transition to low-carbon infrastructure. By tackling these challenges, the TC aims to position CSA cements as a mainstream, rather than niche option in sustainable construction, bridging the gap between research and practice and paving the way for future innovations. In this context, it is important to note that among the different available cementitious binders the material should be selected which fits best to a certain application in terms of performance and sustainability.

The establishment of the TC CSA marks an important step toward advancing the understanding and application of CSA cements. By addressing critical knowledge gaps, fostering collaboration, and promoting standardization, the committee aims to unlock the full potential of CSA technologies. The outcomes of this work will provide a foundation for more sustainable construction practices, support the development of low-carbon infrastructure, and contribute to the global transition toward more environmentally friendly and net-zero building materials.

Authorship statement (CRediT)

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