



# Performance characteristics of concrete based on a ternary calcium sulfoaluminate–anhydrite–fly ash cement



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## ABSTRACT

This paper reports an assessment of the performance of concrete based on a calcium sulfoaluminate–anhydrite–fly ash cement combination. Concretes were prepared at three different w/c ratios and the properties were compared to those of Portland cement and blast-furnace cement concretes. The assessment involved determination of mechanical and durability properties. The results suggest that an advantageous synergistic effect between ettringite and fly ash (Ioannou et al., 2014) was reflected in the concrete's low water absorption rates, high sulfate resistance, and low chloride diffusion coefficients. However, carbonation depths, considering the dense ettringite-rich microstructure developed, were higher than those observed in Portland cement concretes at a given w/c ratio. It was concluded that the amount of alkali hydroxides present in the pore solution is as important factor as the w/c ratio when performance of this type of concrete is addressed.

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## 1. Introduction

Due to a combination of an energy-intensive process and calcination of raw materials during manufacture of Portland cement (PC), the embodied CO<sub>2</sub> emissions (eCO<sub>2</sub>) of concrete are mainly affected by the cement content rather than any of the other constituents. Due to increasing pressure to reduce the eCO<sub>2</sub> of concrete [2,3], industries across the globe are focusing on alternative approaches for the production of more sustainable cement combinations. Among these approaches, replacement of PC with non-Portland cement based materials is a feasible scenario. Among the most promising non-Portland cements, possessing potentiality for commercial-scale production, are the calcium sulfoaluminate cements. Calcium sulfoaluminate cement (CSAC) is obtained by burning a mixture of limestone, bauxite (or an aluminous clay) and gypsum at 1300–1350 °C in rotary kilns [4]. As this is 100–150 °C lower than that involved in PC production, the energy input requirement is therefore lower. Since the manufacturing process is similar to that of PC, energy consumption savings reach approximately 15–30 kW h [5]. Based on the eCO<sub>2</sub> emissions associated with the individual mineralogical cement compounds [6,

and given that a typical CSAC consists of predominantly ye'elimite, belite and smaller amounts of aluminoferrite, then the eCO<sub>2</sub> of CSAC can be estimated at approximately 600 kg/t, which is up to 35% lower than that associated with PC.

There is a considerable body of research available on the hydration and microstructural aspects of CSAC-based cements [1,4,5,7]. The main hydration product is ettringite, which is formed at early stages upon reaction between ye'elimite and calcium sulfate (added externally if not interground during manufacturing) in the presence of water. The phase is fundamental for the properties of the concrete, such as high early strengths, dense matrix and durability. When ye'elimite reacts with an insufficient amounts of calcium sulfate, then monosulfoaluminate is formed, whereas in the case of reaction with excess calcium sulfate, then the system is likely to be dimensionally unstable. Therefore one of the important factors underpinning performance and durability of CSAC/anhydrite combinations is the relationship between ye'elimite content and calcium sulfate content.

Although the hydration mechanisms of CSAC/anhydrite cements have been extensively studied over the past decades [7], there has been, however, little consideration of the long term durability of CSAC/anhydrite-based concretes, at least towards assessing their applicability for commercial scale use under standardized procedures. In this regard, there is a need to evaluate

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the true potentiality of the combination prior to introducing them to current design frameworks.

Concretes based on a CSAC/anhydrite cement have been determined to have relatively high early strengths, in the range of 40–50 N/mm<sup>2</sup> at 7 days at typical w/c ratios. The high early strength is primarily due to the formation of ettringite during hydration [8–10] and thereafter strength gain is slower than in Portland cement concretes to equivalent 28-day strengths.

Quillin [9] found that CSAC/anhydrite concrete exhibited excellent sulfate resistance although carbonation depths were higher than those of Portland cements and chloride diffusion coefficients were relatively high. Kalogris et al. [10] studied the influence of synthesized non-expansive CSAC/anhydrite cement on the steel reinforcement corrosion. They found reducing pH values in the pore solution, falling from 8.5 to 6 within 2 to 3 weeks of exposure to NaCl solution or tap water. When CSAC/anhydrite concrete was exposed to intermittent exposure to 3.5% NaCl solution they observed a high averaged corrosion rate of reinforcement and increasing Cl<sup>-</sup> ion concentrations. Carbonation depths of CSAC/anhydrite concretes removed from service were determined using infrared spectroscopy [11]. It was found that the carbonation of normal CSAC/anhydrite concrete averaged at about 0.5 mm/year and that the concrete sample removed from the high strength pile carbonated at a rate of 60 μm/year. The high resistance was attributed to self-desiccation of the matrix. Zhang [12] investigated the chloride resistance of a 16-year in-service concrete pipe using Electron probe Micro analysis and Quantab chloride titrator strips. He concluded that the chloride resistance of the concrete was very high and observed that the embedded steel reinforcement in the pipe was smooth and intact. Dachtar [13] studied the chloride permeability through electrical conductivity of CSAC/anhydrite concretes. Compared to PC concretes they exhibited less electrical resistivity due to their low alkali content and lower pH values.

An aspect to be addressed is that of the availability of the raw materials in a CSAC/anhydrite cement for potential commercial-scale production. Bauxite deposits are unevenly distributed and, compared to limestone, the resources are not as abundant [14]. Impure alumina and anhydrite resources are nonetheless fairly widespread. This might increase the potential for large-scale production of CSAC should the manufacture be based on impure alumina resources, as is the case in China [14].

A further aspect to be considered is the eCO<sub>2</sub> emissions of the cement. A CSAC with no additional gypsum appears to be associated with eCO<sub>2</sub> values that may not seem low enough to make substantial reductions when considering such a cement combination for commercialization. In fact, the approximate value of 600 kg/t as determined for CSAC is even higher than the average values of conventional blastfurnace cements. Therefore, to strengthen the potential to offer substantial eCO<sub>2</sub> reductions for achieving equivalent concrete performance there is a definite need to develop a

chemically stable and dense CSAC/anhydrite combination that makes maximal use of additions.

In this paper, an experimental study was carried out to assess the long term performance of concrete using a novel calcium sulfoaluminate/anhydrite/fly ash combination that has been proven in earlier work to have suitable cementitious characteristics [1]. The concrete is compared with reference Portland cement-based concretes. The assessment involved determination of fresh, mechanical, permeation and durability properties and a discussion on the applicability of the concretes to current design codes is provided.

## 2. Materials and methods

The experimental programme included a comparison of concretes based on three cement types: (i) a Portland cement (CEM I), (ii) a blastfurnace cement combination (III/A) and (iii) a calcium sulfoaluminate–anhydrite–fly ash cement combination that was developed in previous work [1]. Characterization and mix proportioning of the combinations are shown in Table 1. For the preparation of concrete mixes, crushed limestone aggregates were used as the coarse aggregate of sizes 4/10 mm and 10/20 mm. A combination of Marlborough grit and fine alluvial sand at a 1:1 ratio to achieve a medium grading requirement (MP), as in BS EN 206:2013 [15] was used as the fine aggregate in the concrete mixes. PSD of all aggregates are given in Fig. 1 and description is given in Table 2.

All concretes were prepared at w/c ratios of 0.35, 0.50 and 0.65. CEM I concretes were proportioned according to the BRE method for designing normal concrete mixes [16] for achieving a consistency conforming to the S2 slump as in BS EN 206:2013. In all mixes, a polycarboxylate based superplasticizer was added in the mix at 2% by mass. To maintain validity in comparison, the remaining concrete mix proportions were obtained by: (i) maintaining the same water, cement/combination and coarse aggregate content (kg/m<sup>3</sup>) for all concretes and (ii) adjusting the fine aggregate content (kg/m<sup>3</sup>) to maintain the volumetric yield based on the known densities of the constituents used [1].

Concrete mix proportions are shown in Table 3.

Mixing of concrete was carried out in accordance with BS 1881-125:2013 [17]. Samples were demoulded after 24 h and water-cured at 20 °C until specified ages of testing.

Consistence of fresh concrete was determined as a slump according to BS EN 12350-2:2009 [18], and the compressive strength development of 100 mm cubes was measured in accordance with BS EN 12390-3 [19].

The static elastic modulus of concrete was determined in accordance to BS 1881-121:2013 [20] using 300 mm long by 150 mm diameter cylinders. The test was performed on a load-control basis

**Table 1**  
Constituent properties and combination proportioning.

Constituent description	CEM I conforming to BS EN 197-1:2000	Ground granulated Blast furnace slag to BS EN 6699:1992	Calcium sulfoaluminate cement	Commercially available anhydrite	Fly ash category N conforming to BS EN 450-1:2012
Constituent notation	CEM I	Ggbs	CSAC	ANH	FA
Particle density	3140	2900	2790	2950	2290
Mean diameter size	19.6	18.6	25.3	24.5	34.5
Particle size distribution					
d <sub>10</sub>	1.7	1.6	2.2	2.3	2.4
d <sub>90</sub>	38.3	40.2	64.8	42.1	81.6
Cement notation	Mix proportions (% by mass)				
CEM I	100	0	0	0	0
III/A	50	50	0	0	0
GAF15	0	0	55	30	15

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