



Enhancing the performance of calcium sulfoaluminate blended cements with shrinkage reducing admixture or lightweight sand

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ABSTRACT

This study investigates the effect of using shrinkage reducing admixture (SRA) or lightweight sand (LWS) on enhancing the performance of calcium sulfoaluminate (CSA) cement in combination with ordinary Portland cement (OPC). Of special interest is the efficacy of the SRA or LWS in modifying the expansion/shrinkage and compressive strength characteristics of OPC-CSA systems in the absence of adequate duration of water curing, which is critical for the expansive reaction of CSA cement and its ability to mitigate shrinkage. Hydration kinetics, autogenous and drying deformation, thermogravimetry, and scanning electron microscopy (SEM) are used to evaluate the effect of SRA or LWS on the performance of the OPC-CSA systems. Test results indicate that the OPC-CSA system can exhibit similar drying shrinkage to that of the plain OPC mixture when no moist curing is applied. In the presence of LWS or SRA, the OPC-CSA systems exhibited lower shrinkage or higher extent of expansion compared to the corresponding OPC-CSA mixture alone. This is attributed to delay of the drop in internal relative humidity and promoting hydration of the OPC-CSA system which can enhance the ettringite-generating potential of CSA cement. The use of LWS was found to be highly effective in enhancing compressive strength of OPC-CSA system. SEM results at 91 days confirm the higher density and lower porosity for the paste surrounding LWS particles compared to the corresponding mixture made without LWS. In the case of inadequate moist curing, the presence of LWS or SRA is shown to enhance the overall performance of OPC-CSA system. For a given overall desirability value of 0.65 determined by multi-objective optimization, the incorporation of 1% SRA or 10% LWS was found to enable the reduction the required period of moist curing from 6 days to 5 and 3 days, respectively.

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1. Introduction

Cement-based materials typically exhibit autogenous and drying shrinkage due to self-desiccation and water evaporation. Under restrained conditions, the shrinkage of such materials can result in early-age cracking, which can lead to premature deterioration and shortening the service life of the concrete structure. Reduction of shrinkage is of practical importance in concrete infrastructures. A number of shrinkage mitigating materials can be employed to mitigate shrinkage and enhance shrinkage cracking resistance of cement-based materials. These materials include: (i) expansive-based cement/admixture (EX) to counteract shrinkage through

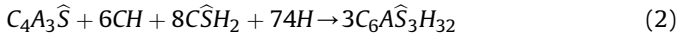
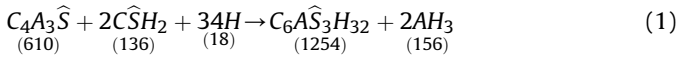
the expansion-induced stress [1,2]; (ii) lightweight sand (LWS) to provide internal curing and mitigate autogenous shrinkage [3,4]; (iii) shrinkage reducing admixture (SRA) to reduce autogenous and drying shrinkage [5,6] as well as restrained shrinkage cracking [7,8] due to the decreased surface tension of pore solution; and (iv) fibers to enhance shrinkage-induced cracking resistance and reduce crack width [9,10] due to the improved tensile strength and tensile creep behavior.

Among the various types of EXs, the use of calcium sulfoaluminate (CSA) cement is receiving increasing attention given its shrinkage compensation and environmentally friendly features associated with manufacturing process [11–14]. The latter involves a lower embodied energy and CO₂ emissions in the production of CSA cement compared to the ordinary Portland cement (OPC). CSA cement is mainly composed of ye'elimeite (C₄A₃S̄), belite (C₂S), calcium sulfate (CS̄), and aluminoferrite (C₄AF) [15]. The hydration of ye'elimeite in presence of calcium sulfate and water forms ettringite

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($C_6\hat{A}\hat{S}_3H_{32}$) and aluminium hydroxide (AH_3) [16–18], which contribute to the expansion and early-age properties development in CSA cement according to the following reactions [16]:



Number in parenthesis under the compound formula refers to its molecular weight.

A number of parameters can influence the early-age expansion induced by CSA cements, such as the degree of hydration of the ye'elimite [19], sulfate content [16–18], presence of lime [1,20], particle size distribution [21,22], pore structure [23,24], curing condition [25], and curing temperature [19]. The effectiveness of incorporating CSA cement to fully form ettringite crystals and compensate shrinkage of cement-based materials is significantly affected by the availability of water provided through the mixture design water-to-binder ratio (w/b), external moist curing, and/or internal curing provided by water-saturated porous materials. The complete hydration of the CSA-based EX for ettringite formation requires relatively high w/b of about 0.80 [26,27]. For instance, Collepari et al. [28] found that the reaction of CSA-based EX with water needs higher moist curing for 5–7 days to complete its hydration and develop its ettringite-generating potential. Cheung and Leung [29] investigated the effect of CSA-based EX on the drying shrinkage of high-strength fiber-reinforced cementitious composites formulated with various values of w/b, and concluded that the incorporation of CSA is more effective in compensating shrinkage for mixtures with higher w/b. The w/b affects the amount of space (porosity) available for hydration product formation and the amount of water available to hydrate the cement phases, both of which can alter expansion in CSA cements. Chen [21] studied the effect of w/b on expansion mechanism of calcium sulfoaluminate–belite cement and found that as the w/b decreases, there is less space for the formation of hydration products, including ettringite and amorphous phases. Given the lower water available for the hydration reaction, fewer hydration products can form prior to self-desiccation. This can lead to expansion at later-age in the hardened paste matrix when external water from the environment is supplied, since unhydrated phases can react to form secondary ettringite [30]. The formation of secondary ettringite in the hardened cementing systems may increase the risk of expansion-induced cracking, thus leading to cracking at later ages [24].

Based on the aforementioned review, the efficiency of CSA-based EX in terms of generating ettringite ability may not fully achieve when insufficient water is provided. The synergy between shrinkage mitigating materials (or hybrid curing systems) can promote the efficiency of such materials [28,31–33]. However, limited studies have been undertaken to evaluate the performance of expansive cements in combination with other shrinkage mitigating materials [28,31]. For instance, Collepari et al. [28] reported that there is a synergistic effect in the combined use of SRA and calcium oxide-based EX (CaO-based EX) in terms of generating expansion when no moist curing was applied. Therefore, a more comprehensive understanding of the synergy between CSA cement and other shrinkage mitigating materials, such as SRA and LWS, is required to magnify the beneficial effect of CSA cement at compensating shrinkage, especially in the absence of adequate moist curing.

Therefore, the subject of this study is to evaluate the effect of using SRA or LWS to enhance the performance of OPC-CSA systems subjected to different durations of initial moist curing to examine

the ettringite-generating expansion of the CSA cement. The investigation uses the results of hydration kinetics, autogenous and drying deformation, thermogravimetry, and scanning electron microscopy (SEM) to evaluate the interaction between OPC-CSA system and other shrinkage mitigating materials. A statistical factorial design was applied to assess the level of significance of the investigated shrinkage mitigating materials and their interaction on the modeled responses of OPC-CSA mortar mixtures.

2. Experimental program

2.1. Materials

A Type I/II OPC conforming to ASTM C150 [34] and a commercial CSA-based EX were used. The oxide composition of the OPC and CSA-based EX are presented in Table 1. The phase composition of the cementitious materials was determined using quantitative X-ray diffraction (QXRD) analysis. The OPC is composed of 61.8% C_3S , 13.5% C_2S , 8.2% C_3A , and 6.2% C_4AF (mass fraction). The CSA-based EX has 31.6% C_2S , 23.2% $C_4\hat{A}_3\hat{S}$, 17.5% $C\hat{S}H_2$ (gypsum), 19.4% $C\hat{S}$ (anhydrite), and 6.6% $C\hat{S}H_{0.5}$ (hemihydrate). The Blaine fineness values for OPC and CSA-based EX were 350 and 400 m^2/kg , respectively.

A commercially available SRA made of propylene glycol ethers was incorporated. A polycarboxylate-ether (PCE) based high-range water reducer (HRWR) with a solid content of 23% and a density of 1.05 was employed. The dosage of HRWR was adjusted to achieve a target fluidity of 220 ± 20 mm in all mortar mixtures.

Continuously graded siliceous river sand with nominal maximum size of 5 mm, density of 2.50, bulk density of 1.80 (using rodding method in accordance with ASTM C29 [34]), and water absorption of 0.6% was employed. An expanded clay LWS with 6 mm nominal maximum size and density of 1.65 was used to provide internal curing in OPC-CSA systems. The mineralogical composition of sand and LWS is primarily composed of quartz (SiO_2) determined using XRD. The sand and LWS had approximately 93% and 95% quartz (SiO_2), respectively, determined by QXRD. The LWS had a 72 h water absorption of 13% and a desorption capacity of 90% at 94% relative humidity (RH) in accordance with ASTM C1761 [34]. The LWS was pre-saturated to secure a saturated surface-dry (SSD) condition 72 h before mortar batching and kept in a sealed bags to maintain the SSD conditions. The saturation degree of LWS was measured before mixing, and accordingly the mixing water was adjusted based on the difference between water absorption and bulk moisture content of the LWS before batching. The degree of saturation of pre-saturated LWS before batching ranged between 0.98 and 1.0.

2.2. Experimental design and mixture proportions

All experimental evaluations were carried out on concrete equivalent mortar (subsequently abbreviated as mortar) [35]. The

Table 1
Oxide composition of OPC and CSA-based EX (wt.%).

Component (%)	OPC	CSA-based EX
SiO_2	19.32	8.22
Al_2O_3	4.38	7.41
Fe_2O_3	3.17	1.25
CaO	62.73	53.21
MgO	2.63	0.11
SO_3	3.31	28.23
$CaCO_3$	3.21	–
LOI	1.25	1.57

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