Mitigating of drying shrinkage in alkali-activated slag composites

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Abstract. Alkali activated slag composites are promising alternatives to be used as a replacement of Portland cement composites for different construction applications. However, despite the evolution of these composites over the years, its high drying shrinkage still poses a limitation on its application. The increasing interest in alkali-activated slag composites by the research community has resulted in the use of various methods and materials to mitigate the drying shrinkage. This current paper explores the different major types of mitigation techniques that can be used to reduce the drying shrinkage in alkali-activated composites. The mitigation techniques explored are in terms of the use of various materials and curing methods. Discussions presented in this paper showed that a significant reduction in the drying shrinkage can be achieved by partially replacing slag with mineral admixtures or incorporating chemical admixtures specifically made to reduce shrinkage. The use of appropriate internal or external curing method for alkali-activated slag was also found to reduce drying shrinkage effectively. However, it is recommended to carry out further research in order to fully understand the mechanism of drying shrinkage in alkali-activated slag composites in order to develop effective ways to mitigate it.

1. Introduction

Alkali activated slag (AAS) is one of the most common types of alkali-activated binders used as a substitute for the Portland cement to produce various types of building composites such as concrete and mortar. AAS are obtained by activating slag with alkali. However, depending on the type of activator used, the products obtained differs. It is worth mentioning that slags also have varying physical and chemical properties. Hence, these properties of the slag also influence the activation products achieved. Nevertheless, the primary product of alkali activation of slag is calcium aluminate silicate hydrate which is similar to the calcium silicate hydrate formed during the cement hydration but more amorphous [1]. AAS composites have been found to exhibit similar or higher performance compared to Portland cement composites (PCC) [2–4].
Despite the promising advantages with the use of AAS composites, its high drying shrinkage have posed a threat to its overall durability and its corresponding applications. Generally, the drying shrinkage in AAS has been reported to be more than five times that of Portland cement [5–7]. However, there is no comprehensive understanding of the drying shrinkage mechanism in AAS composites. Nonetheless, the higher drying shrinkage of AAS composites has been found to be primarily caused as a result of refined pores present in the matrix which creates higher capillary stresses [8,9]. The calcium aluminate silicate hydrate also has a huge influence on the drying shrinkage of AAS composites. The major parameters that affect the drying shrinkage of AAS composites have been found to be the type and concentration of activators, curing conditions, and the chemical and physical properties of slag. Hence, before AAS composites are used for various construction purposes, it is pertinent to put in place a mitigation process in order to ensure the higher performance of the composites.

The drying shrinkage in AAS composites can by using several methods such as the use of alternative activators, chemical admixtures, mineral admixtures, internal curing, etc. [10]. This review paper presents an overview of various ways in which the drying shrinkage in AAS composites can be mitigated. The AAS composites discussed in this paper are in the form of concrete, mortar and paste. It is anticipated that the discussion in this paper will encourage more application of AAS composites. It is also hoped that this overview would be a good reference material for researchers, engineers, contractors, etc., looking for ways to mitigate drying shrinkage in AAS composites.

2. Drying shrinkage mitigation in AAS composites

2.1 Alternative activators

The conventional types of activators used for AAS are Sodium silicate (SS) and/or sodium hydroxide (SH). The choice of these conventional activators is as a result of the promising high strength achieved when these activators are used. However, the utilization of these activators especially the use of SS has a negative effect on the fresh and shrinkage properties of AAS [11]. Hence, using an alternative activator with less alkalinity will result in lower drying shrinkage of AAS composites. Of such promising alternative activators that can be used to activated slag is sodium carbonate (SC). SC is more environmentally friendly, cheaper and less corrosive compared to SS and SH [12–16]. The use of SC has also be reported to yield equivalent strength at later ages as those activated with the SS and SH [17]. Atis et al. [18] explored the use of SS, SH and SC for activating slag and the corresponding effect on the performance was evaluated. Findings from the study concluded that the use of SC resulted in lower drying shrinkage followed by the use of SH as shown in Figure 1.

![Figure 1. Effect of activator type drying shrinkage of AAS mortar (adapted from Atis et al. 2009)](image-url)
2.2 Lower activator concentration

The drying shrinkage of AAS composites can also be reduced by reducing the concentration of the activators used even when the common activators are used (i.e. SH and SS). Atis et al. [18] investigated the effect of the concentration of three different types of activator on the drying shrinkage of AAS mortar. The results from the study indicated that a reduction in the concentration of the activators caused a corresponding reduction in the drying shrinkage of the composites as presented in **Figure 2**. However, it is worth mentioning that reducing the concentration of these activators will result in a corresponding reduction in strength. Hence, it is critical to ensure that acceptable strength performance is still achieved when the concentration of the activators is decreased.

![Figure 2. Influence of activator concentration on drying shrinkage of AAS mortar (adapted from Atis et al. 2009)](image)

2.3 Fibres

Another effective way to reduce the drying shrinkage in AAS is by incorporating short fibres as reinforcement within the matrix [19,20]. There exist various types of short fibres such as basalt, steel, carbon, etc., that can be used to reduce shrinkage in AAS composites. However, the influence of these fibres on the drying shrinkage of AAS is based on the mechanical and physical properties of the fibres coupled with the dosages used. Aydin and Baradan [21] reported that for AAS composites reinforced with steel fibres, there is more effect of fibre dosage on the drying shrinkage compared to the fibre lengths. Nonetheless, the drying shrinkage reduces with increasing steel fibre dosage and length. AAS mortars incorporating steel fibres with a length of 6mm and at a dosage of 2% the volume of the mixture was found to exhibit a 22% reduction in drying shrinkage compared to the unreinforced mortars [21],[42-44]. Similar observations were also reported by Vilaplana et al. [22] where carbon fibres were used to reinforce AAS pastes.

2.4 Mineral admixture

Fly ash (FA) and silica fume (SF) which are also an aluminosilicate precursor can also be incorporated as replacement of slag in AAS composites in order to mitigate the drying shrinkage [34-36]. Aydin [23] investigated the effect of FA and/or SF on the drying shrinkage of AAS mortars activated with combined SH and SS as an activator. The study reported that the use of the mineral admixture alone or combined decreased the drying shrinkage as shown in **Figure 3**. Findings from the study also indicated AAS mortars made with SF as replacement 20% of SL as the precursor exhibited the lowest drying shrinkage. Hence, the use of SF is deemed more effective compared to that of FA. Nonetheless, the drying shrinkage was reduced by approximately 70% when FA and SF were used to replace 40%
of SL at equal amounts [37-41]. The reduction in the drying shrinkage with the use of FA was ascribed to the enhancement of the stability of the aluminosilicate hydrates [24].

![Figure 3](image-url)

**Figure 3.** Effect of mineral admixture on 120 days drying shrinkage of AAS mortar (adapted from Aydin, 2013)

2.5 Chemical admixtures and additives

Chemical admixtures such as shrinkage reducing admixtures (SRA) and expanding agents (EA) can be incorporated into AAS mixtures to mitigate drying shrinkage. Bilim et al. [25] explored the influence of SRA and set-retarding admixture (SA) on the drying shrinkage of AAS mortars. The study showed that the use of SRA and SA at a dosage of 1% the binder content resulted in 10.2% and 40.8%, respectively for moist cured samples. However, the drying shrinkage of samples cured in dry conditions was reduced by 11.7% and 22.8% for SRA and SA, respectively. The reduction in the drying shrinkage with the use of SRA was as a result of the reduction in the surface tension of water in the voids coupled with the modification of the pore structure. Due to the reduction in the surface tension of the water, there is a lower occurrence of shrinkage in the composites when the water evaporates from the voids [26,27].

Similarly, Jie at el. [28] investigated the effect of two EA on the performance of AAS mortars. It was found from the study that the incorporation of EA up to 12% of the mass of the mortar resulted in lower drying shrinkage. However, it was reported that the use of calcium oxide-based EA resulted in more reduction in the drying shrinkage compared to that based on calcium sulfoaluminate. The higher elastic modulus of the calcium hydroxide and lower water consumption of the calcium oxide in the samples made with calcium oxide-based EA was found to result in more reduction in the drying shrinkage.

Chemical additives such as magnesium oxide and calcium hydroxide have also been found to yield lower drying shrinkage [29,30]. The reduction in the drying shrinkage with these chemical additives is a result of the acceleration of the activation reaction which results in the formation of products to fill the voids and act as restraints within the matrix.

2.6 Incorporation of coarse aggregates

The drying shrinkage in AAS can also be reduced with the incorporation of coarse aggregate or higher content of coarse aggregates. The incorporation of coarse aggregate into the AAS composite will proffer a restraint within the matrix. However, this technique might not be useful in applications where coarse aggregate is not desired as it will increase the brittleness of the composites. Hence, in such cases; other mitigation techniques should be considered.
2.7 Internal curing

Similar to the use of internal curing in PC composites, internal curing can also be employed to reduce the drying shrinkage in AAS composites. Internal curing can be achieved with the use of materials such as lightweight aggregates and superabsorbent polymers (SAPs). Internal curing reduces drying shrinkage by providing additional water during the chemical reaction in the composites and also decreasing the self-desiccation in the composites. SAPs are used as internal curing agents due to their ability to store water that is more than thirty times their dry weight [31]. SAPs have been used successfully to mitigate autogenous shrinkage in AAS composites [32,33]. However, it can also be used to mitigate the drying shrinkage in these composites.

2.8 Curing condition

The environment condition in which AAS composites are cured plays a huge role in the drying shrinkage. Hence, there is a need to control the environment temperature and relative humidity in which AAS composites are cured if possible. The study by Bilim et al. [25] reported that the use of moist curing (i.e. higher relative humidity) resulted in a decrease in the drying shrinkage of AAS mortars compared to those cured in dry conditions. However, the use of heat curing for AAS mortars was found to result in more reduction in the drying shrinkage. The lower drying shrinkage observed when moist curing was used was attributed to the lower loss of moisture from the samples. More reduction in the drying shrinkage exhibited with the use of heat curing was ascribed to the enhancement of the dimensional stability of the mortar matrix and lower water content of the calcium silicate hydrate [27].

3 Conclusions and recommendations

This current paper has explored the current methods used to mitigate drying shrinkage in alkali-activated slag (AAS) composites. Drying shrinkage in AAS composites cannot be avoided. Hence, it is paramount to take initiatives to mitigate this detrimental effect. Discussions presented in the overview showed that with proper use of certain materials or curing methods, the drying shrinkage in AAS composites can be reduced. However, it is recommended that more research needed in this area to fully understand the mechanism of drying shrinkage in alkali-activated slag composites.

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