



## SHRINKAGE IN ALKALI-ACTIVATED SLAG CONCRETE: MITIGATION TECHNIQUES

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**Abstract:** Despite the current knowledge about shrinkage of alkali-activated slag concrete and mitigation techniques, shrinkage is still one of the main problems that impedes its in-situ applications. It seems that there is a clear gap between the measured performance inside the lab and actual performance in-situ of alkali-activated materials. Shrinkage cracking can dramatically reduce the durability of any concrete member. Hence, a comprehensive understanding of the mechanism of the shrinkage in AAS, and effectiveness of different mitigation techniques are essential to prevent these damages in future. In this paper, an overview is given on the mitigation strategies and their effectiveness in reducing AAS shrinkage. This would allow engineers to select the suitable mitigation technique for different applications

### 1 INTRODUCTION

Alkali-activated slag (AAS) is a sustainable alternative binder for ordinary Portland cement (OPC). AAS is an environmentally friendly binder as it has around 40% less carbon emission than that of OPC production (Mellado *et al.*, 2014; Yang *et al.*, 2013). This reduction in carbon emission is due to the reuse/recycle of industrial by-products (i.e. blast-furnace slag from steel manufacturing) which is activated by an alkaline solution. There are many advantages of AAS system as lower heat of hydration, have good resistance to sulfate, freeze–thaw cycles, fire resistance, higher reduction in chloride diffusion, and stronger aggregate-matrix interface. Despite of superior performance and durability over OPC, AAS experiences some problems which hinder its acceptance as a construction material. Volumetric instability is the most significant challenge delaying its widely implementations. It is well documented in the literature that AAS exhibits autogenous and drying shrinkage significantly higher than that of the OPC (Cartwright *et al.*, 2015).

#### 1.1 Shrinkage in Alkali Activated Slag

Several studies have proposed that AAS exhibits large chemical, autogenous, and drying shrinkage, which leads to cracks formation and loss of durability and serviceability in restrained concrete elements (Ye and Radlińska, 2017). Chemical shrinkage results from the reduction in the absolute volume of solids and liquids in the paste, where the reaction products occupy less volume than the initial reacting materials, and it is directly proportional to the degree of reaction of slag. The autogenous shrinkage is closely related to chemical shrinkage, its resulted of the self desiccation of some of the pores, leading to the formation of menisci causing tensile stress. On another hand, drying shrinkage happens due to the loss of internal water to the external environment through evaporation. Generally, shrinkage strain resulting from the pressure on the wall of the pores which is caused by the formation of menisci in the pores, and can exert force to pull adjacent solids closer (Sakulich and Bentz, 2012; Thomas *et al.*, 2016). However, shrinkage behavior of AAS is not described and explained comprehensively. There are considerable differences between

shrinkage mechanisms for AAS and OPC, these differences are most probably related to pore structure and the viscoelastic/ viscoplastic of mechanical properties (inelasticity) (Ye and Radlińska, 2017).

## **2 MITIGATION TECHNIQUES OF AAS**

Different strategies are presented to reduce and compensate the shrinkage of alkali activated slag, whereas the mechanisms and effectiveness of each strategies are summarized in the following sections.

### **2.1 Shrinkage Reducing Admixture (SRA)**

Shrinkage reducing admixture significantly reduced the shrinkage of AASC, which was lower than that in OPC concrete. However, SRA is insoluble in alkaline solution, so it can reduce the shrinkage with different percentages (Bakharev *et al.*, 2000). The effect of 2% of shrinkage-reducing admixture, based on polypropylenglycol, on AAS mortars, activated by water glass, decreased the autogenous and drying shrinkage by 85% (cured at 99% RH) and 50% (cured at 50% RH) respectively. This is attributed to the reduction in the surface tension of the pore water which conducts smaller internal stress upon evaporation process, and the SRA causes increment in the proportion of pores diameters ranging from 1.0 to 0.1  $\mu\text{m}$ , which promotes a less capillary stress than that in mortars without admixture. Furthermore, a decrement in the liquid/solid ratio was noticed, whereas adding 2% SRA decreased the ratio by 14%, which decreased the average pore diameter, and enhanced the mechanical properties. According to Bilim *et al.*, (2013), 1% SRA reduced the drying shrinkage particularly of AAS mortars, activated by liquid sodium silicate(LSS), but still higher than those in OPC, so more investigations should be conducted to specify the appropriate contents of SRA, to compensate the shrinkage sufficiently.

### **2.2 Internal Curing**

Internal curing is simply to provide extra water to reduce self-desiccation and leading to alower tensile stresses inside pores of AAS paste. This can obviously mitigate autogenous shrinkage. Internal curing agent is added during mixing and could be absorbent lightweight aggregate (LWA) (e.g. pumice or expanded clay) or an superabsorbent polymer which acts as a water reservoir (Trtik *et al.*, 2011). The mechanism behind this process is throughout curing. Initially liquid desorbed by the internal curing agent, the internal humidity of the system drops, water enters the binder paste pores, so the self-desiccation process is inhabited, thus the extensive tensile stresses are avoided which that head to drop in autogenous shrinkage (Sakulich and Bentz, 2012).

Superabsorbent polymers (SAPs) can reduce self-desiccation and autogenous shrinkage of alkali-activated slag materials. Song *et al.* (2016) stated that increasing the dosage of SAP would increase the internal relative humidity, then more effective internal curing taken place. The compensating factor for AAS mortars, activated by water glass /NaOH and  $\text{Na}_2\text{CO}_3$ , with 0.6% SAP was 78% and 86% respectively. Hence more dosage is needed to completely mitigate the shrinkage. Furthermore, it is concluded that the content of SAP that is needed in AAS mortars is greater than that in OPC mortars, around 0.3% SAP was found more than enough in OPC, to 100% of autogenous shrinkage.

### **2.3 Expansive Reaction**

Use of expansive agents (e.g. gypsum, CaO-type, and MgO-type) can reduce the drying shrinkage through the formation of voluminous AFt, portlandite, and hydrotalcite in AAS.

#### **2.3.1 Gypsum**

Gypsum with appropriate percentage was proven to be effective admixture in reducing the autogenous and drying shrinkage considerably. Bakharev *et al.*, (2000), reported that 6% of gypsum can significantly lower drying shrinkage for the AAS concretes, activated by liquid sodium silicate, (i.e. At 50% RH). At age 56 days, the drying shrinkage was beneath 150 microstrain, while the autogenous one was around 500 microstrain. The 6% gypsum was indicated as the most suitable value, due to the higher formation of AFt and AFm phases. However, at (8-10%), gypsum reacted and combined with a low-Ca C-S-H that formed in this system, and AFt or AFm type phases were lower.

### 2.3.2 Quicklime (CAO)

Calcium oxide (CaO) enrichment was found insufficient in reducing drying shrinkage in AAS, it was observed that, incorporation of CaO with different dosages in AAS mortars (i.e. Exposed to 50 and 70% RH), leads to absence of the early-age expansion in AAS. Moreover, it resulted in refinement of pore structure. The chemical shrinkage of AAS was unchanged though the portlandite is formed, thus, the drying shrinkage increased, despite of decrement of moisture loss. This supports that the dominant mechanism of shrinkage at high RH (> ~50% RH) is the capillary stress.

### 2.3.3 Reactive MgO

Magnesium oxide (MgO), was used as a shrinkage reducing mineral additive, it has high efficiency in controlling the shrinkage of Portland cement. The dead burned MgO naturally present in slags. There are two types of MgO that are usually using, reactive MgO (calcined under 1000 C°) or hard burned MgO (calcined at 1000–1400 C°), while the characteristics of reactive MgOs may vary considerably, depending on their calcination history.

The effect of the inclusion of burnt magnesia on drying shrinkage and other properties of Waterglass activated AAS with various dosages (0%, 2%, 4%, 6% and 8 wt%), and at different temperatures of MgO (800, 850, 900, 950 C°) for 2 h were investigated by Fang *et al.*, (2011). The MgO burnt temperature has adverse effect on drying shrinkage. At temperature (850–950 C°), MgO could reduce the AAS shrinkage, while the drying shrinkage decreased as the MgO content increased, furthermore the authors recommended to use up to 8% of MgO, else it may affect negatively the other properties of AAS (e.g. setting time, compressive and flexural strengths). The shrinkage reduction happened as a result of the expansion of the hydration and carbonation of MgO.

## 2.4 Elevated temperature curing

Heat-curing and aging have been proven to be considered as effective mitigation technique of the drying shrinkage and promoting high early strength. Bakharev *et al.*, (1999) explained that the curing at elevated temperature caused changes in pore structure, and condensation of C-A-S-H resulted in coarser porosity (reduced effective capillary stress), with reaction products localized near slag particles and relatively open interstitial spaces, since the rate of the reaction was so much faster than the rate of diffusion which is agree with the great reduction in water loss. As satisfied by Thomas *et al.*, (2016) the magnitude of AAS drying shrinkage is about one quarter of that at early age. In other words, heat curing reduced the drying shrinkage of AAS concrete by around 75% and the resulting damage. Bilim *et al.* (2015) achieved a significant reduction particularly in early age shrinkage of AAS mortars when cured at 65°C in water for 5 h. This is ascribed to the fact that elevated temperature curing made concrete dimensionally stable. However, at elevated temperature the reaction in AAS is accelerated, consequently refinement of the microstructure is taken place.

### 2.5 Internal Restraint (Passive)

Adding high stiffness inclusion such as aggregate in AAS concrete is effective in decreasing the drying shrinkage. It has been noticed that AAS concrete has less shrinkage than AAS mortar, since the passive role of the inclusion that can serve as internal restraint which reducing the drying shrinkage. the key characteristics of the aggregate that influence the shrinkage are its volume fraction and its drying shrinkage (Bentz and Jensen, 2005).

## 3 EFFECT OF ADMIXTURES ON SHRINKAGE OF ALKALI-ACTIVATED SLAG

Shrinkage can be mitigated and limited by using the appropriate additives type and dosages, whereas recently, the alkali activated slag with admixtures inclusion has been widely investigated. Table 1 below shows the effects of different types of admixtures and fibres.

### 3.1 Chemical Admixtures

Despite the benefits of using chemical admixtures in solving a number of AAS binder's problems likewise in OPC, their effects have received less attention. Applying water-reducing and -retarding admixtures, based on lignosulphonates, in AAS concrete mixture with dosage 1% (10 ml/kg slag) decreased the autogenous and drying shrinkage slightly. Superplasticizer based on modified naphthalene polymers was found to be not suitable admixture for using in AAS concrete (AASC), however, results showed significant shrinkage increment in AASC, accelerating set, and impairing the later strength. At 28 days, there was about 25% compressive strength loss, and an increment in the shrinkage about 1.5 times the values without using it. Furthermore, researchers considered air entraining admixture (AEA) as the most appropriate admixture in AAS concrete, whilst using AEA admixture with 6 ml/kg slag in AAS concrete, activated by liquid sodium silicate, reduced the shrinkage significantly. The drying shrinkage value at 112 days was 390 microstrain, which is less than the shrinkage value in OPC concrete which was 800 microstrain, at the same age. Moreover, it enhanced the workability, and didn't affect the later strength (Bakharev *et al.* 2000). According to *Billim et al. (2013)*, 1% of set-retarding admixture (SSR), based on modified polymer liquid, decreased the drying shrinkage of AAS mortars, activated by LSS, but these shrinkage values were still higher than those of OPC.

### 3.2 Mineral Admixtures

Fly ash can be used as a mineral admixture in AAS, as proved by researchers, inclusion of FA reduced the setting time and improved the workability. The main advantage of FA is decreasing the drying shrinkage of AAS system. Chi and Huang (2013) stated that as the content of FA increases, the drying shrinkage of AAS mortars decreases. However, replacing slag with portland cement was studied at different ratios (0%, 10%, 20%, 30%), activated with  $\text{Na}_2\text{SiO}_3$ , 10% was the optimal dosage to reduce the drying shrinkage, which was similar to the shrinkage in PC (Fu-Sheng *et al.*, 2005). Furthermore, the effects of inclusion silica fume on the mechanical properties of AAS have been studied by Aydın (2013) with different replacement ratios (0%, 10%, 20%), the drying shrinkage of the steam cured slag mortars (activated with NaOH and sodium silicate) was lowest at 20% SF, while the 10% SF exhibited a shrinkage value similar to OPC which was 0.067% at 120 days. Moreover, the influence of limestone powder (LP) on the drying and autogenous shrinkage of sodium carbonate activated AAS has been studied. The result showed that adding LP > 30% would increase the pore volume of the pore size below 50 nm, whereas high LP resulted in slower reaction, due to the dilution effect, consequently, the autogenous shrinkage will decrease. Furthermore, as the LP percentage increases, the drying shrinkage also increases. This observation may be attributed to the fact that higher amount of free water is available in LP system, due to the dilution effect. Moreover, water comes from the decomposition of crystalline structures (e.g. gaylussitand Natron) which are unstable phases and converted to other phases after 28 days of curing (Yuan *et al.*, 2017).

## 4 EFFECT OF FIBRES ON SHRINKAGE OF ALKALI-ACTIVATED SLAG

The addition of fibers can be useful for reducing the drying shrinkage of AAS, however few researchers investigated the effect of fibers on the shrinkage behavior of AAS. Aydın and Baradan (2013) studied the effects of contents and length of steel fibres on drying shrinkage of AAS/ silica fume (SF), with composite ratio 80/20, various content of steel fibres and two different lengths. The results showed that, the drying shrinkage values of AASS decreased as the dosage increased, while the length of the steel fibres didn't affect the drying shrinkage. On another hand, using 1% Polypropylene fibres reduced the drying shrinkage of the specimens cured at 21°C and 50% RH by 25%, conversely the drying shrinkage for samples cured at 95% RH was increased (Puertas *et al.*, 2003). Moreover, the drying shrinkage of AAS mortars successfully reduced by 20%, by adding glass fibres, and without compromising its mechanical properties (Puertas *et al.*, 2006). Furthermore, Alcaide *et al.*, (2007), stated that carbon fibres in AAS decreased the drying shrinkage.

## 5 EFFECT OF OTHER ADDITIVES ON SHRINKAGE OF ALKALI-ACTIVATED SLAG

Utilizing nano materials in civil engineering field has been applied to improve the properties, such as mechanical strength, abrasion resistance, and impermeability, of Portland cement concrete. Yang et al. (2014), investigated the influence of nano TiO<sub>2</sub> on AAS system. The result showed that the addition of nano-TiO<sub>2</sub> into the AAS accelerates its hydration process, resulting in more hydration products and denser structure, which enhances the mechanical strength, and decreases the shrinkage of AAS.

Inclusion of phosphoric acid increased the drying shrinkage of AAS pastes with a dosage of 0.85 M, decreased the compressive strength and had retarding effect, on another hand, combining the phosphoric acid and gypsum (0%, 2%, 4%) showed that the setting time decreased, the compressive strength and the drying shrinkage still the same as before, even though it is proven that using only gypsum increased the compressive strength, and decreased the drying shrinkage (Chang et al., 2005).

Table 1. Effect of Admixtures and Fibres on AAS shrinkage

	Type	Influence on shrinkage	Reference
Chemical Admixture	Shrinkage reducing admixture (SRA) based on polypropylenglycol	2% reduced the drying and autogenous by 85% and 50% respectively	(Bakharev <i>et al.</i> , 2000)
	Water-reducing and retarding admixtures (WRRe) based on lignosulphonates	Dosage 1% WRRe decreased the autogenous and drying shrinkage slightly (still higher than that in OPC)	(Bakharev <i>et al.</i> , 2000)
	Air entraining agent (AEA)	The drying shrinkage value at 112 days is 390 microstrain AEA is the most appropriate admixture in AAS concrete	(Bakharev <i>et al.</i> , 2000).
	Superplasticizer admixture based on modified naphthalene polymers	Increased the shrinkage about 1.5 times the values without using it.	(Bakharev <i>et al.</i> , 2000).
	Set-retarding admixtures (SSR) based on modified polymer liquid	1% SSR decreased the shrinkage slightly (still higher than that in OPC)	(Bilim <i>et al.</i> , 2013)
Mineral Admixtures	Fly Ash	Decreasing the drying shrinkage with increasing FA content	[Chi and Huang, 2013; Aydın, 2013]
	Silica Fume	Reduced the drying shrinkage, 20% SF is recommended	(Aydın, 2013)
	Portland cement	10% was the optimal dosage in reducing the drying shrinkage (shrinkage value similar to PC value)	(Fu-Sheng <i>et al.</i> , 2005)
	Lime Powder	LP percentage increases, the drying shrinkage also increases	(Jin and Al-Tabbaa, 2014)
Other additives	5.1.1 <b>Phosphoric acid</b> 5.1.2	Increased the drying shrinkage	(Chang <i>et al.</i> , 2005).

	Nano TiO <sub>2</sub>	Decreased the shrinkage of AAS	Yang et al. (2014)
	5.1.3		
Fibres	Steel fibres	The drying shrinkage values of AASS decreased as the dosage increased	(Aydın and Baradan, 2013)
	Polypropylene fibres	1% fibre reduced the drying shrinkage by 25%	(Puertas <i>et al.</i> , 2003)
	Glass fibres	Reduced the drying shrinkage by 20%	(Puertas <i>et al.</i> , 2006)
	Carbon fibres	Decreased the drying shrinkage	(Alcaide <i>et al.</i> , 2007)

## 6 CONCLUSION

From the literature review the shrinkage can be compensated by using different techniques, each technique has its own unique effect and behaviour on the AAS matrix, researchers need to be aware of the suitable methods with appropriate content that should be used. Practically (in- situ) implementation of those techniques should be considered, such as heat curing is very effective method, but it is impractical and unfeasible. Although the autogenous shrinkage can be easily addressed with internal curing, the mitigation of drying shrinkage will require the development of shrinkage-reducing admixtures that performs well in AAS to compensate the drying shrinkage. Moreover, implementation of conventional expansive agents does not seem to be effective and successful in AAS systems. Furthermore, more investigations should be conducted on the chemical admixtures and their suitable dosages to mitigate the shrinkage satisfactorily. It is recommended to study the influence of other mineral admixtures on the shrinkage behaviour of alkali activated slag such as metakoline, quartz powder and rice husk ash (ternary or quaternary blending with slag) combined with chemical admixtures or fibres to reach the main goal that is AAS concrete with lowest shrinkage values and broader application of these sustainable alternative binder

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