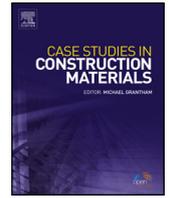




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## Case study

## A critical review on application of alkali activated slag as a sustainable composite binder

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## ABSTRACT

A state-of-the-art review of advances in alkali activated slag (AAS) with respect to its behaviour is presented. The need for sustainable development of AAS, and factors that affect the fresh and hardened properties of AAS based composites were discussed. The fresh properties of AAS reviewed include flow, setting times and heat of hydration. While the hardened properties considered were compressive strength, shrinkage, and microstructure. Major limitation of using AAS and possible solutions were also highlighted. Overall, various studies showed that large scale application and commercialization of AAS is imminent in the coming years, as AAS is capable of exhibiting similar/higher properties compared to that of Ordinary Portland Cement (OPC). In addition, the viewpoint of this review will be useful for contractors and researchers to have more understanding about AAS. Grey areas for possible research exploit were also identified.

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## 1. Introduction

Global increase in population and quest for urbanization are some of the contributing factors to challenges experienced in the construction sector [1,2]. There is an exponential increase in the demand for concrete and its constituent materials, based on the expanding infrastructural development, which is yet causative to depletion of the material sources [3]. Many natural deposits of aggregates such as, rivers and mountains, have been over exploited and consequently results to pollution and degradation of biodiversity. Also, the production of Ordinary Portland Cement (OPC), a main binder of conventional concrete, contributes about 7% to the world's human induced carbon dioxide (CO<sub>2</sub>) emission [4,5]. But, the emission associated with cement production is due to the high temperature required for calcination of raw materials, and additional CO<sub>2</sub> produced during the production.

As the demand for concrete is increasing yearly, so also more pollution and emissions are anticipated. However, numerous research efforts are focused on optimizing the production process of OPC to reduce the energy usage and CO<sub>2</sub> emission. But, only about 17% reduction of the later have been achieved. Such attempts include the partial replacement of OPC with supplementary cementitious materials (SCMs) [3], and production of specialty cements (calcium aluminate cements, super sulfated cements, calcium sulfoaluminate cements, and slag cement [6]. However, reduction in embodied carbon and energy is still low due to the fact that SCMs are produced in a similar way as the OPC.

Alkali activated materials (AAMs) are alternative green materials that can be used in place of OPC. The AAMs are produced by activating a high calcium aluminosilicate precursor with an alkali source [6–11]. The aluminosilicate sources used for

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AAMs are mostly by-products of industrial processes such as metal production [12–14]. The use of AAMs is more sustainable compared to OPC, because in OPC production high embodied energy and carbon are generated [15]. In addition, aluminosilicate precursors are considered as waste product, hence, using it for concrete production can reduce its negative impact on the environment or cost of landfilling the material [14,16]. Studies have also shown that up to 75% of CO<sub>2</sub> could be reduced by using AAMs as binder [17]. Slag and fly ash the most generated aluminosilicate precursors [12]. Annual global production of slag has been estimated to about 320 Mt [18].

It is noteworthy to mention that alkali activated materials and geopolymer materials are not the same. Though the two have similar chemistry, but the major difference is in the type of aluminosilicate precursor used in their production and their separate reaction products. Geopolymer materials contain low and high calcium binders such as class F fly ash and generally require high temperature for dissolution of monomers to occur (activation). However, alkali activated materials are binders with high calcium content, and can be activated at ambient temperature. Also, the main product formed in an alkali activated materials is calcium-aluminosilicate hydrate C-A-S-H [13,19,20]. While the main reaction product formed in geopolymer materials sodium-aluminosilicate hydrate N-A-S-H [21–24]. High temperature curing required for geopolymer materials only limits its practical application to precast industry where high heat is used for curing [25,26]. However, such limits do not affect the alkali activated concrete. Therefore, there's high feasibility of practical application of alkali activated material compared to geopolymer materials. That is, in terms of lower cost, reduced energy consumption, and minimal emission, incurred during the production of alkali activated materials.

Alkali activated slag (AAS) is the most renowned type of alkali activated material (AAM) due to its ability to consume less energy when used to replace OPC as binder [27]. Also, the production of 1 ton of slag requires about 1300 MJ of energy and produce only 0.07 ton of CO<sub>2</sub>. While the production of equivalent amount of OPC requires 5000 MJ of energy and emits 1 ton of CO<sub>2</sub> into the environment [28]. In addition, AAS composites have been reported to enhance the mechanical and durability properties of concrete [29–31]. However, major limiting factors to the use of AAS are high shrinkage [32,33], and quick setting [34].

Despite the advances in the studies relating to alkali activated materials in the open literatures, the use of alkali activated slag has not been overly explored. Therefore, this review aims to explore how alkali activated slag has evolved over time, and also portray the current limitations and development prospects. It is anticipated that this review will contribute towards having a deep understanding of AAS, which would open pathways for extensive studies on how the current challenges can be overcome. In addition, this review will provide useful information to contractors and scientists on different factors that may affect the fresh and hardened properties of AAS.

## 2. General overview and history of alkali activated slag composites

Since 1983, slag has been used in OPC concrete to improve its strength and durability properties [35]. However, it was also used as binder for AAM as early as 1957 in USSR by Kiev Institute of Civil Engineering, Ukraine [36]. And there has been over a 100 patents and certificates of invention issued in the field of AAS [37], with the first patent documented to be in 1908 [38]. Now, several investigations are performed in the field of AAS. In the United States of America, researchers have made attempts since 1987 to produce alkali activated slag cement, comprising of dry mix of slag and alkali activator [39,40].

Despite the discovery of alkali activated slag (AAS) for almost a century, its general acceptance in the construction industry is still obscured as a result of its several limitations. These limitations are observed in both the fresh and hardened properties of the alkali activated slag. Common fresh properties challenges are its low flowability and rapid setting, which makes the mixing and placing of the AAS impossible in hot weather condition and congested reinforced sections. Also, high drying shrinkage of the AAS compared to other alkali activated material also plays a big role in the non-acceptance of AAS in the construction industry [41–43].

### 2.1. Sustainability of alkali activated slag

The world is paying huge attention on global warming and possible ways of remedy. Several deliberate actions have been ensued by various industries to reduce their carbon emission to the minimum. The construction industry is not left out, especially the cement industry which is responsible for about 7% of the world's man-made carbon emission [44]. It should however be noted that compared to other building materials, concrete is more sustainable. But due to high annual concrete demand, the production of more cement, which is the main binder in OPC concrete, leads to higher amount of emissions. For the production of 1 t of cement, an approximate one tonne of carbon dioxide is produced [45,46]. Also, approximately 50% of the carbon emission that emanates from cement product is as a result of the calcination of the raw materials, and the remaining 50% from energy usage [44,47].

Therefore, a total replacement of cement with AAS in concrete can be a sustainable concreting technique. Another fact is that AAS composite, unlike geopolymers, can be cured at ambient temperature, which makes it a good choice for green concrete production. However, a wrong choice of activators may negate the sustainable use of AAS, as the production of the activators induce high carbon emission [48]. Sodium hydroxide and sodium silicate, which are the common activators, contribute higher embodied energy and carbon than other components in alkali activated concrete [49]. Therefore, it is essential to use alternative greener medium to activate slag to achieve a greener concrete. Some of the alternative green activators that can be used are sodium carbonate [11], sodium sulphate [50], bayer liquor [51], sodium aluminate [52], lime [53,54], rice husk ash [55], and glass [56]. Also, sodium carbonate was reported by Yuan et al. [57], as a good alkaline slag activator in which carbon emission reduction

and energy savings could be as high as 97%. Živica [58] reported that silica fume could be utilized as an activator to replace the sodium silicate. Thus, the possibility to use alkali waste solution from industrial processes such as aluminium production might be a way to make alkali activated concrete production more sustainable.

The use of AAS as binder in concrete can help, not only to achieve a greener concrete, but also takes off the strain on exploration of natural resources used for cement production. Also, the approach can prevent environmental degradation emanating from mining of new raw materials. In addition, use of AAS can prevent contamination that follows the disposal of slag.

### 3. Slag as binder for AAM

Slag is waste products of the production of different types of metals. The main components of slag are alumina, silicates, calcium and magnesium. Most of the slag used in concrete and as binder as AAM are produced from the steel and iron industry, and these types of slag are called blast-furnace slag [37]. These types of slag are formed by quick cooling of molten slag by immersion in water. The quick cooling of the molten slag changes the molten slag into small sized particles of less than 4 mm. The small size particles formed are mostly non-crystalline material, as a result of minimum crystallization that occurs during quick cooling [59]. This occurs because, due to the high composition of alumina and silica in slag, it exhibits binding and pozzolanic properties in the presence of an alkali medium.

However, it should be noted that the composition of slag varies depending on the raw materials used by the metallurgical industry to produce metals. These differences in raw materials lead to differences in how different slag responds to the alkali activation [32,60,61]. Therefore it is essential to do trial mixtures before any large-scale application to observe how the slag behaves during and after activation. AAS referred to in this text covered all types of possible composite of AAS (AAS as binder, AAS mortar/grout and AAS concrete).

#### 3.1. Activators used to activate AAS

Activators used in alkali activated materials are capable of liberating the aluminate and silicate monomers in the aluminosilicate material, which further dissolves and form an aluminosilicate gel [62]. Some common examples of alkali activators are sodium hydroxide (NaOH), potassium hydroxide (KOH), potassium silicate ( $K_2SiO_3$ ) and sodium silicate ( $Na_2SiO_3$ ). Theoretically, the higher the level of alkalinity, the higher the amount of dissolution. However, in case of sodium hydroxide and potassium hydroxide, it has been shown that sodium hydroxide can liberate more silicate and aluminate monomers than potassium hydroxide [62]. The reason is that, there are sodium cations which are smaller than that of the potassium cations, and this enables them to move easily in the paste matrix, thereby resulting in more zeolitization. Sodium silicate has been reported to provide more activation influence (higher strength) when compared to sodium hydroxide and sodium carbonate [62]. Other activators that have been tried for slag activation are: quick lime (CaO) [63], sodium sulphate ( $Na_2SO_4$ ) [64], calcium hydroxide ( $Ca(OH)_2$ ) [65], magnesium oxide (MgO) [66], barium hydroxide ( $Ba(OH)_2$ ), and strontium hydroxide ( $Sr(OH)_2$ ) [39]. Activators can be used individually or combined with one or more activator. Combined activators have been found to be more beneficial than being used individually, especially, when improvement of mechanical properties of the alkali activated concrete is desired [67]. The most common examples being the combined use of sodium silicate and sodium hydroxide. Other combinations such as sodium silicate with sodium sulphate and/or sodium carbonate have been explored in different study [68].

A common type of activator used during the early years of AAS in Scandinavian countries is called the F-activator [61]. F-activator is comprised of sodium hydroxide, sodium carbonate, sodium gluconate, tributyl phosphate, and lignosulphonate. However, all attempts to use this F-activator in later years did not produce AAS with good strength [69]. However, the type of activator used affects the fresh and hardened properties of the produced concrete. Table 1 presents selected AAS activators and mineral products developed. It is clear from the studies reviewed that parameters such as activator type and curing medium for AAS composite production, strongly contribute to the mineralogical or mechanical nature of AAS composite. However, it remains unclear whether the aforementioned properties are also influenced by the specific surface area and oxide composition of slag that is being used.

**Table 1**  
Selected AAS activators and products development.

S/N	Specific surface area ( $m^2/kg$ )	$Al_2O_3 + SiO_2 + Fe_2O_3$ (%)	Activator (s)	Curing method	Mineral Products	Source
1	440	50.58	Sodium silicate (Water glass) and NaOH	Heat at 60 °C	Aluminosilicate gels	[71]
2	360	39.053	sodium silicate	hydrothermal at $135 \pm 5$ °C	–	[72]
3	424	50.4	$Na_2CO_3$ and NaOH	Constant room temperature ( $20 \pm 2$ °C) and relative humidity ( $50 \pm 5$ %)	Hydrotalcite	[73]
4	400	46.95	$Ca(OH)_2$ and $Na_2CO_3$	–	Calcite-type compounds	[54]
5	383	54.96	Sodium silicate and NaOH	Room temperature ( $27 \pm 3$ °C) with 65% RH	C-A-S-H and/or C-S-H gel	[74]
6	–	47.94	Sodium silicate and NaOH	Heat between 30 °C and 60 °C		[75]

In addition to the high embodied energy and carbon as a result of some of these activators, their use is responsible for quick setting time, high shrinkage, potential alkali silica reaction (ASR) of AAS [11]. Also, most of these activators are corrosive chemicals, and non - economical [70]. Thus, there is imminent need to evaluate the sustainability of common AAS activators, so as to validate their potential application.

### 3.2. Alkali activation of slag

Despite the existence of AAS for a very long time, there has been no consensus yet on the chemistry of alkali activation of the slag. The alkali activation of slag has been referred to as “a complex process of structural disruption of slag and polycondensation of hydrate products” [20]. Krizan and Zivanovic [76] stated that the activation of slag started with the breaking down of the slag bonds, accompanied by the formation of silicate-alumina gel. Also, Krizan and Zivanovic reported that there was production of hydration products. Alkali activation can also be simplified as the breaking down of slag particles into inert components, followed by the interaction between the components to form compact structures [77–79]. However, there is variation in the types of products formed based on the type of activators used. But, most research findings have identified hydrotalcite (Ht) and C-S-H as the main hydration products [80–83]. A further investigation showed that Ht plays a major role in strength development of the resulting AAS [82].

## 4. Fresh properties of alkali activated slag

### 4.1. Flow properties

Workability is a function of the ease of placing and compacting concrete/mortar without segregation. The main factor that affects the rheology of the alkali activated slag is the type of activator used. Flow of AAS is also an indication of its workability. Several other factors such as the concentration of the activator, amount of water present, type of aluminosilicate materials, chemical admixtures, among others, affects how the alkali activated slag flows [84]. The effects of some of these factors are further explained as follows:

#### 4.1.1. Effect of the type and concentration of activators

Use of sodium silicate has also been attributed to high loss of fluidity of the AAS compared to those activated with sodium hydroxide only [8]. This loss of fluidity of the AAS led to lower workability [19]. Low flowability of AAS activated with sodium silicate has been associated with the high fluidity loss, which results in poor workability [34]. The slump of AAS activated with sodium silicate are higher when compared to that of OPC and AAS activated with sodium hydroxide [85]. The reduction in the flow of AAS occurs when there was increase in the concentration of the activator. It may be due to quick formation of reaction products, especially when there is high amount of alkali available in the system.

#### 4.1.2. Effect of water and chemical admixture

In analogous with OPC composites, the flow of AAS increases with increase in the amount of water introduced into the system. Water reducing admixtures used for OPC concrete shows similar results when used in AAS. Also, air entrainer has also been found to increase the flow of AAS without any significant decrease in compressive strength [86].

### 4.2. Setting time

With the presence of alkali medium and absence of  $C_3S$  and  $C_3A$  in AAS, it is expected that it would have a different setting mechanism compared to OPC composites. However, the setting time of AAS depends mainly on the type and concentration of activators and water to solid ratio [87].

#### 4.2.1. Effect of type and concentration of activator

The activation of slag with sodium silicate is well known to results in fast setting of the AAS. As such, this rapid setting has been attributed to the formation of initial calcium silicate hydrate [88]. The effects of different activators on the setting time of AAS is presented in Fig. 1. As can be seen, out of all the activators considered, the proportions (4, 6, and 8%) of slag - sodium carbonate (Slag SC) exhibit setting times that are somewhat close to the that of OPC. It is obvious from here that the rate of activation is enhanced by dosage of slag SC. However, further check is required to evaluate the possible means of energizing the slag - liquid sodium silicate (Slag LSS) and slag - sodium hydroxide (Slag SH) mixtures. AAS activated with sodium carbonate exhibits longer setting time which was as a result of the reaction being delayed as a result of the initial formation of sodium calcium carbonate [88]. Also, AAS activated with sodium hydroxide set very quickly, however, it is slower than those activated with sodium silicate [87]. And it was also reported that AAS activated with sodium carbonate have similar setting time compared to OPC paste. Similar studies also showed that AAS activated with sodium hydroxide was more workable than those activated with sodium silicate [56].

The final setting time of AAS activated with sodium silicate was found to reduce with increase in  $SiO_2/Na_2O$  ratio and increases with increase in sodium concentration [89].

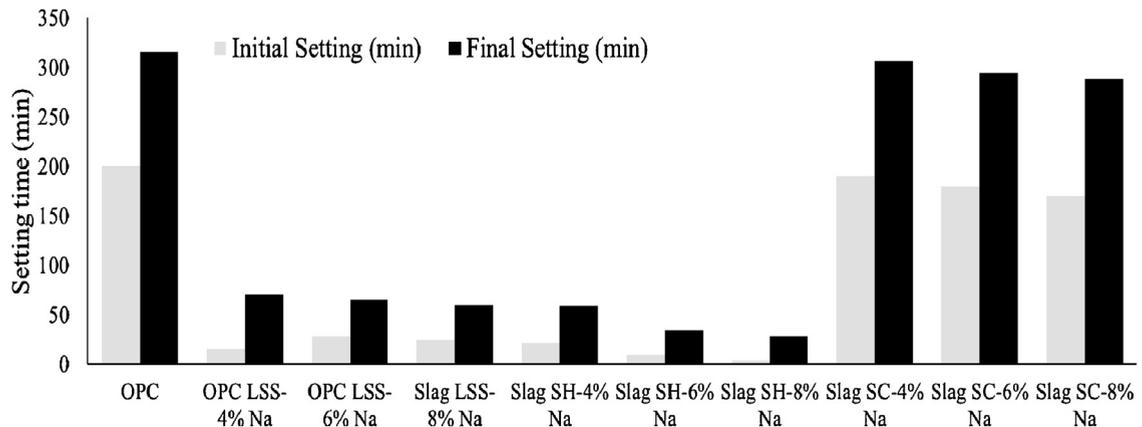


Fig. 1. Setting time of slag activated with different activators [89].

#### 4.2.2. Effect of chemical admixtures

Early studies have shown that the use of phosphate and borate within the range of 1–2% by mass of the slag can be used to retard the setting time of AAS with medium strength. However, these chemical admixtures are not effective for high strength AAS, even at higher dosages [90]. The addition of slaked lime at 2–5% by mass of the slag to sodium silicate to activate slag has been found to also retard the setting time of the resulting slag [91]. However, another study reported that slaked lime, compared to sodium silicate leads to decrease in the early and latter ages of the AAS [92].

The use of a concentrated solution of ethanol sulphate such as sodium alkylsilicone was reported to extend the setting time of high strength AAS to up to 30 min, without any significant decrease in strength [61]. However, the use of this solution is not consistent in all situations. On the other hand, Palacios et al. [93], reported that the setting time of AAS can be extended for up to 3 h with the use of naphthalene-based admixture. Therefore, more research on how to extend the setting time of AAS would help to bridge this knowledge gap and extend the application of AAS.

#### 4.2.3. Effect of mixing time

The time used to mix AAS has also been found to affect the setting time of AAS. Mixing of AAS for 3–10 min extended the initial and final setting time to approximately 40 min and 4 h respectively [94], and the study also showed that mixing for 30 min also exhibited retarded initial and final setting time. However, irrespective of the mixing times, as reported in those studies, factors such as temperature, relative humidity and other environmental factors may contribute to the acceleration or retardation of the initial and final setting times of AAS.

#### 4.3. Heat of hydration

The heat of hydration of AAS is generally lower than that of OPC [32], which has been approximated to be about one-third of that of OPC [95]. However, the heat of hydration of AAS has been found to increase with increasing dosage and modulus of sodium silicate [76]. Despite the increasing heat of hydration observed by increasing dosage and modulus of sodium silicate, lower heat of hydration of AAS to that of OPC was still observed. The effects of different types of activator on the heat of hydration of AAS is shown in Fig. 2. As shown, the heat of hydration measured for AAS binder are lower than that of OPC, low heat and high heat cements. This lower heat of hydration of AAS is as a result of the hydration products formed which differs from that of OPC. The hydration products of AAS have lower Ca/Si ratio, therefore low hydration energy is needed compared to that of OPC [96].

Slag activated with lime showed lower heat of hydration compared to those activated with lime and gypsum [97]. From the study, high heat of hydration of slag activated with lime and gypsum was attributed to the formation of ettringite, and its evolution to monosulfoaluminate. However, the heat of hydration of AAS was lower than that of OPC [97].

NB: OPC- ordinary Portland cement, HAC-high aluminate Portland cement, LHC-low heat Portland cement. AAS (SH), AAS (SC), AAS (SS)- alkali activated slag activated with sodium hydroxide, sodium carbonate and sodium silicate respectively.

### 5. Hardened properties of alkali activated slag

#### 5.1. Mechanical properties

Compared to OPC composites, where the strength is mostly controlled by the amount of binder and water, AAS composites are much complicated as its strength is being controlled by its composition and the interactions between them. The effect of different factors that affect the compressive strength of the AAS are further discussed as follows. It is necessary to note that, most of the other mechanical properties can also be related to the compressive strength of the composite.

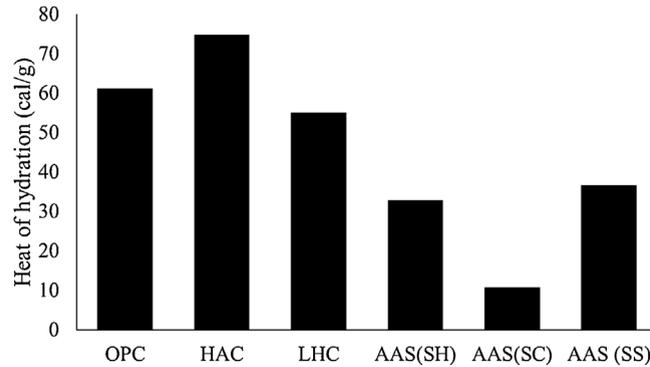


Fig. 2. Heat of hydration of different binders (data from [20]).

Key: OPC – Ordinary Portland Cement, HAC - High Alumina Cement, LHC – Low Heat Cement, AAS (SH) – AAS (Sodium Hydroxide), AAS (SC) – AAS (Sodium carbonate), AAS (SS) – AAS (Sodium Silicate).

### 5.1.1. Effect of type of activator

Bakharev et al. [37] found out in series of studies they carried out that activating slag with sodium silicate gave the best compressive strength compared to sodium carbonate and sodium hydroxide. Similar results were also observed by Krizan and Zivanovic [76] where the compressive strength of AAS activated with sodium silicate was higher than even that of OPC mortar. The effects of different slag activators on the compressive strength of composite is presented in Fig. 3. On that figure, Cengiz et al. [89], concluded that sodium silicate gave best compressive strength, followed by sodium carbonate and sodium hydroxide. Slag activated with calcium hydroxide was found to have strength 30% higher than those activated with magnesium oxide at 28 days for activator level between 5%–10% [66]. However, at activator levels above 10% and below 20%, the strength of slag activated with magnesium oxide showed higher strength about four times that of slag activated with calcium hydroxide. It should however be noted that the composition of magnesium oxide may differ greatly, depending on their sources. Therefore, it is expected that different magnesium oxide would behave differently depending on its production conditions and impurities present [98,99].

Sodium carbonate has been used to activate slag in the quest to achieve a more sustainable AAS. Compared to conventional activators, sodium carbonate resulted in lower early age. This low early age has been attributed to the low alkalinity of sodium carbonate [61]. The higher strength at later ages was as a result of the formation of carbonated compounds, which led to an enhanced strength [100]. This observation was also made in a study by Li and Sun [101], in which the strength of slag activated with sodium silicate increase from 0 MPa at 3 days to 60 MPa at 28 days.

Therefore, as mentioned earlier; trial experiments must be done to determine the best activators to use as different types of slag behave differently during activation [102]. However, more consideration has to be done to carefully select the best activators, as they affect other fresh and hardened properties of the concrete

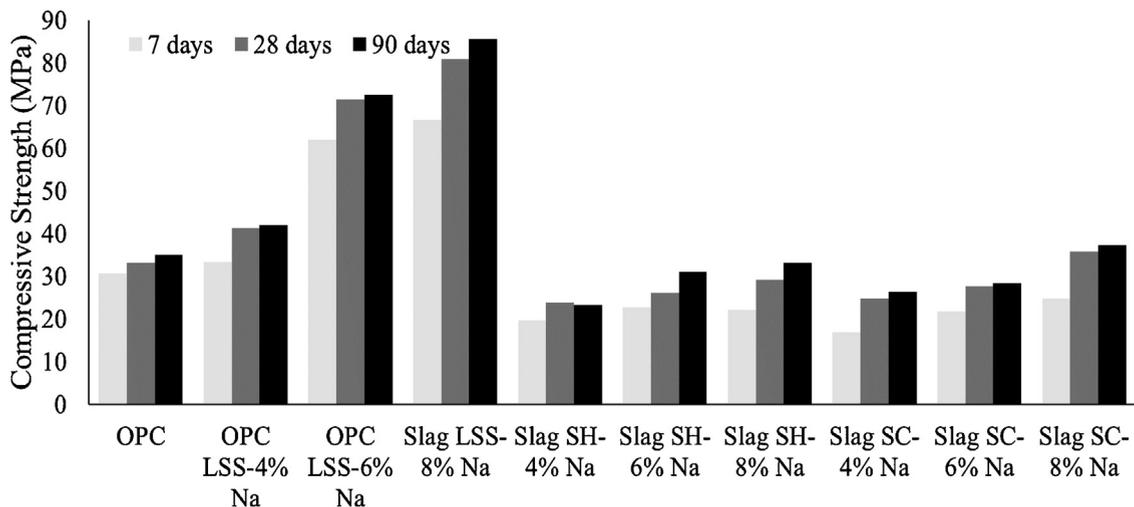


Fig. 3. Compressive strength of slag activated with different activators (data from [89]).

### 5.1.2. Effect of concentration of activators

Cengiz et al. [89] observed that increasing the concentration of the sodium increases the compressive strength of the AAS. Abdalqader et al. [12] also observed increase in the strength of AAS when the activator dosage was increased from 5% to 10%. Increase in the strength of the AAS could be attributed to higher content of  $\text{Na}_2\text{O}$  in the mixture, which also affect the alkali content of the system. Therefore, it can be deduced that increasing the concentration of the activator would increase the alkalinity of the pore solution thereby increasing the reaction and dissolution rates. However, another factor to be considered maybe, increase in the concentration of the alkali, as it has been reported that it can lead to formation of a more densified interfacial transition zone which consequently improves the strength [103].

### 5.1.3. Effect of mineral admixtures

Mineral admixtures are used to either supplement or targeted towards improving the mechanical characteristics of AAS. The use of mineral admixtures such as silica fume has been found to improve the strength of AAS [104]. Also, replacement of slag with silica fume in the range of 10%–15% has been found to improve the 28 days compressive strength of AAS by 13%, 24% and 27%, respectively. Similar results were also reported in related studies [33,105,106]. Therefore, more research efforts are required in the area of finding sustainable admixtures for AAS production.

### 5.1.4. Effect of curing conditions

The curing process selected for a cementitious mix has major role on the strength and durability performance of the material. The common curing methods include water immersion, water sprinkling, polythene wrapping, and heat curing of composite. However, one of the advantage of using slag as a binder for AAM is the ability to cure it at room temperature compared to its counterpart such as fly ash that needs elevated temperature for curing. Bakharev et al. [37] carried out a study to observe the effect of heat curing on AAS. The study showed that elevated temperature curing of AAS led to rapid strength development of the AAS. However, the strength at later ages was similar to those cured at ambient temperature. But curing AAS at elevated temperature reduces the drying shrinkage of the AAS significantly, compared to OPC concrete. Gu et al. [107] observed that curing AAS at elevated temperature could aid an increase in its early strength. However, this was not the case at later ages, as elevated temperature was detrimental to the latter age strength, compared to those cured at ambient conditions.

Sealed curing was found to result in higher compressive strength compared to curing inside water [12]. The lower strength of AAS cured inside water has been attributed to the leaching of alkali ions into the water which reduces the amount of activator available for activation.

## 6. Shrinkage of alkali activated slag

Generally, shrinkage mechanism in AAS can be classified into three groups; autogenous shrinkage, drying shrinkage, and carbonation shrinkage. Autogenous shrinkage can results from the macroscopic process of self-desiccation and chemical shrinkage [97]. While drying shrinkage occurs as a result of disjoining pressure and capillary suction [108]). Disjoining pressure mechanism occurs mostly when the AAS has a very fine porosity, but capillary suction mechanism dominates when the pore diameters are above 10 nm.

Shrinkage in AAS has been found to be higher than that of OPC [33,41,109], and this was reported to be due to finer pore structure and lower stiffness in AAS. In addition, according to Collins and Sanjayan [33], higher amount of mesopore coupled with high capillary stress as a result of the pore distribution in AAS compared to OPC could also contribute greatly to its high shrinkage. Other studies [89,97] also agreed to the responsibility of pore distribution, lower stiffness and high capillary stress causing high shrinkage in AAS. However, the distinct makeup of the reaction product (C-S-A-H and C-S-H) was also reported as a major factor to AAS higher shrinkage [76]. Though the mechanism of shrinkage in AAS is not fully understood till date, however, various studies have explored the possibility to reduce the effect of shrinkage on AAS. Some of the suggested methods are; heat curing [60,110], internal curing [111], use of mineral admixtures [25]. Also, use of fibres [29,56], and expanding admixtures [112] can be used to reduce shrinkage of AAS.

Overall, the factors affecting the shrinkage of AAS are the type of activator used, the ratio of activator to binder, fineness of slag, concentration of activator and the curing conditions employed. And from all treatment methods, the use of heat curing is not encouraged as this would lead to higher energy consumption and high volume change. Drying shrinkage of AAS can be curb to an extent by optimizing the design mix

### 6.1. Effect of type of activator

The shrinkage of AAS activated with sodium hydroxide and sodium silicate was 3 and 6 times higher than that of OPC respectively [89]. Fig. 4 shows that effects of different activators on the drying shrinkage of AAS. It can be seen that the shrinkage of AAS activated with sodium carbonate have lower or similar shrinkage compared to OPC mortar. Similar results were also observed by Ye and Radllinska [109]. The higher shrinkage caused by activating AAS with sodium silicate is as a result of the formation of rich silica gel during hydration [113]. Due to high water content of the silica gel, its water dries out during drying thereby causing micro-cracks in the concrete.

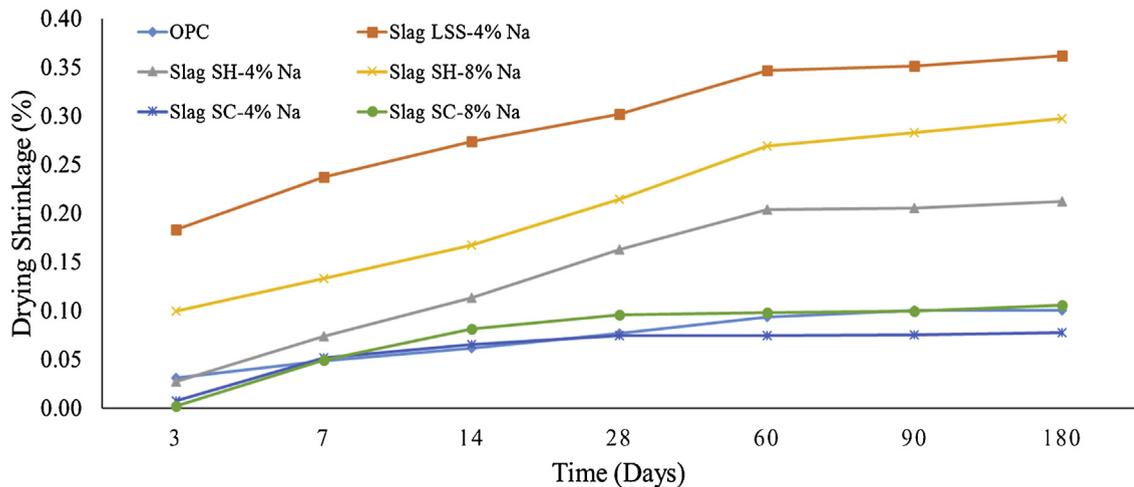


Fig. 4. Drying shrinkage of slag activated with different activators (data from [89]).

The use of 9% sodium silicate and 10% OPC has been observed to reduce the drying shrinkage of AAS to values similar to that of OPC [114]. Slag activated with only lime has been found to have higher shrinkage compared to those activated with lime and gypsum [97]. This high shrinkage of lime activated slag has been attributed to the presence of more refined pores in lime activated slag compared to lime-gypsum activated slag. In addition, the presence of large amount of calcium silicate hydrate and the nature of the hydrated products are also responsible for this high shrinkage.

## 6.2. Effect of chemical admixtures

The use of shrinkage reducing admixture (SRA), air entrainer and gypsum has been found to reduce drying shrinkage of AAS [86]. Similarly, it was found out that shrinkage reducing admixture (SRA), air entrainers and gypsum can be used to reduce the drying shrinkage of AAS concrete.

### 6.2.1. Effect of exposed moisture

The Effect of relative humidity on shrinkage of AAS at 70 days is presented in Fig. 5. AAS undergo higher shrinkage when exposed to higher relative humidity compared to lower ones [109]. OPC have a strong relationship between moisture loss and drying shrinkage [115]. However, this is not the case in AAS. Shrinkage can increase in AAS even without loss of any moisture from the samples. Therefore, the shrinkage in AAS is due more to the reorganization of the microstructure than the moisture loss. This higher shrinkage at higher relative humidity greater than 50% has been attributed to packing of the nanoparticles. The packing creates a more densified microstructure which results in pore refinement and collapse of the gel pores. The refinement of the pore microstructure is an irreversible process which leads to permanent shrinkage of AAS.

In addition, when OPC samples are soaked in water for a short period, they absorb back most of the lost water, and shrinkage reduce by half [109]. However, AAS samples soaked in the same limited time, was only partially saturated, and most of the shrinkage was reversible.

## 6.3. Effect of curing method

Mode of curing AAS is another factor that influences drying shrinkage in the matrix. Elevated temperature curing of AAS has been found to reduce the drying shrinkage of AAS compared to OPC mortar/concrete [37]. In other words, the early accelerated curing using elevated temperature reduces drying shrinkage of the AAS by transforming the silica gel formed to calcium silicate hydrates. However, the absence of moist curing increases the drying shrinkage of AAS [33]. This increased drying shrinkage results in formation of more micro cracks, and thereby reducing the overall strength compared to those moist cured. Krizan and Zivanovic [76] also observed higher drying shrinkage in AAS when compared to OPC composites.

## 7. Problems to be addressed in AAS

Despite the promising advantage of using AAS over other conventional binders, its production and use is being hindered by several challenges. Some of the main challenges are highlighted as follows

- **Quick setting time and poor workability:** Quick setting and low workability have made the large scale application possible. However, this limitation is associated with the common types of activators. Therefore, the search or development of

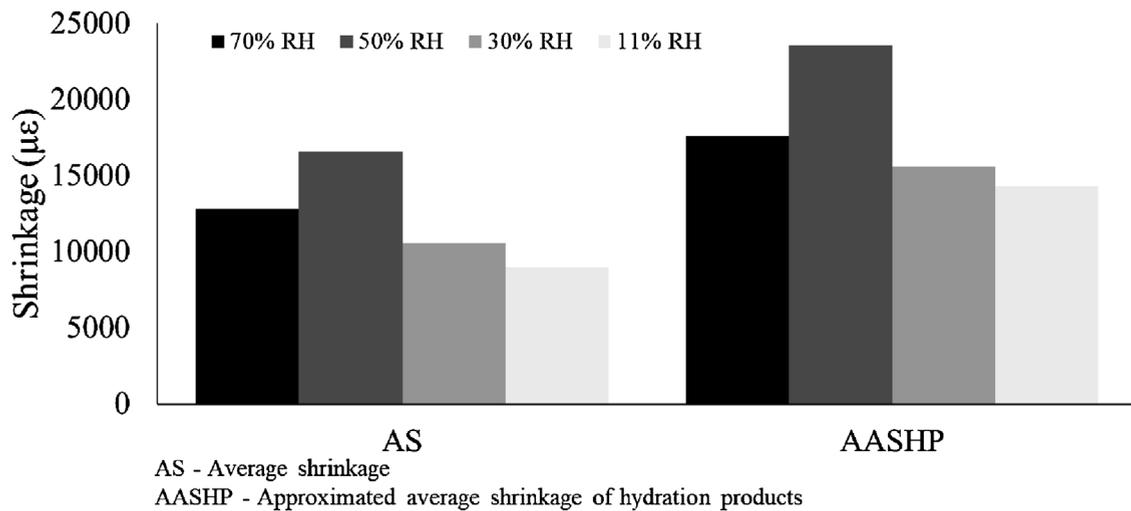


Fig. 5. Effect of relative humidity on shrinkage of AAS at 70 days (data from [109]).

alternative activators that would give AAS excellent fresh and hardened properties would propagate its large scale application

- Not-user friendly activators: Most of the activators currently available are viscous, corrosive and expensive which possess a threat to the workers during mixing and placing of AAS. Consequently, the high cost of these activators which increased the overall cost of the AAS has made contractors opt for OPC as a cheaper alternative. In order to promote more application of AAS, it is essential to search for green activators that would produce similar/higher strength compared to conventional one, while being safe to use.
- High shrinkage: Several ways to mitigate high shrinkage in AAS is available in open literature. However, all these mitigation process only reduce the shrinkage to a certain threshold. In addition, some of these mitigation method increase the overall embodied energy and carbon of AAS. Therefore, alternative green methods have to be developed to reduce the shrinkage in AAS to the possible minimum
- Complicated chemistry: The chemistry of alkali activation is not fully yet understood and has been confused with geopolymerization in most cases. Several studies in literature have also contributed to this misconception due to published data. Therefore, extensive study is still required to understand the alkali activation process, and the product of the reaction.
- Varying slag composition: The composition of slag varies depending on the raw material and metal production process employed. This varying composition makes the response of slag to activation differs from one source to another. Therefore, small scale test is advised to be carried out first to determine the best way to activate different type of slag, and no general assumption should be made about all slag.
- Lack of standard: There exist limited available standards that can be used for AAS. Though some of the standards available for OPC are currently used for AAS, some limitation in some of the standards such as minimum OPC content inhibits their use. This limitation prevents asset managers, contractors and engineers to accept AAS due to possible unexpected liability they might encounter. The current available standards currently available are secluded to certain part of the world (i.e. Europe and Australia). Therefore, sensitization of government officials and contractors about AAS would be a step in the right direction to have more regulation and standards on production of AAS. Also, the development of a performance standard system instead of the current prescriptive ones used for OPC would ensure that the standard covers a wide range of binders.
- AAS specific admixtures: Most of the admixtures currently used were produced based on the understanding of OPC chemistry. As AAS have a different chemistry, it is paramount to develop admixtures specifically made for AAS. This would prevent conflicting results observed in AAS with the use of the conventional activators. Availability of AAS specific admixtures would also promote AAS to a level where it can successfully compete against the modern available Portland cement composites.
- Supply chain deficit: Compared to OPC, AAS raw material which is slag is not readily available while limestone is available everywhere. This deficit would limit its worldwide use, and also affects its distribution as there exist no local market currently established for slag.
- Limited large-scale applications: OPC has been used for several centuries for large scale application; its excellent track record has made it a top choice for a concrete work. Very limited large-scale application of AAS has been done in recent years. Though some early large-scale application of AAS was done in the USSR, the data are not available for the wider audience. As a result, limited record of AAS used for large scale application, concrete makers have little to know trust in the advantage of AAS over conventional OPC binder

## 8. Conclusions

Based on this review of alkali activated slag composites, the following conclusions can be drawn;

- Though the current corrosive activators result in high strength of concrete, its detrimental effects limits its large scale use. Therefore, development of a less corrosive, cheap activator specifically for AAS would help to eliminate most of the challenges currently faced. In addition, this would reduce the overall embodied energy of AAS.
- The main product of alkali activation of slag is C-S-H and Ht. However, other products are formed depending on the activator used.
- Currently, the use of sodium carbonate as activator can be deemed to be most appropriate as it results in similar strength with those activated with sodium hydroxide and sodium silicate. Also, it produces excellent fresh properties which would make its large scale application possible. In addition, it is considered a greener alternative as it has a very low embodied energy and carbon.
- More studies are still required in terms of microstructure of AAS as there exist limited data in these areas. In addition, there has been contradictions in the observations made by different researchers. Therefore, exploring these areas would boost the confidence of the society to trust this green material.
- Overcoming the major challenges faced by AAS would lead to a wider acceptance of the material, and also its commercialization and large scale applications

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**Update**

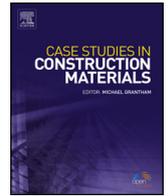
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### Erratum regarding missing Declaration of Competing Interest statements in previously published articles



Declaration of Competing Interest statements were not included in published version of the articles that appeared in previous volumes of Case Studies in Construction Materials. Hence, the authors of the below articles were contacted after publication to request a Declaration of Interest statement:

1. Effects of calcined halloysite nano-clay on the mechanical properties and microstructure of low-clinker cement mortar2018S2214-5095(18)30278-X10.1016/j.cscm.2018.e0021310C
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