Factors Affecting Compressive Strength Development in Alkali-activated Slag Concrete

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Abstract. Studies show that the production and use of ordinary Portland cement (OPC) is responsible for more than 5% of the global CO₂ emission. Alkali-activated slag (AAS) has been studied for decades as potential alternative to OPC. Engineers are interested in understanding and quantifying the fresh properties, mechanical properties, and durability of concrete made used AAS as sole binder. This paper reviews some of the literature highlighting the factors affecting compressive strength development in AAS slag. These include water-binder-ratio, temperature, humidity, and amount of Na₂O, molarity of the alkaline activator solution, and type of alkaline activator. For instance, certain studies reported that AAS concrete activated using sodium silicate solution (water-glass) produce higher 7-day and 28-day compressive strength compared to similar concrete that use 100% OPC, concrete activated using sodium hydroxide (NaOH), or concrete activated using potassium hydroxide (KOH). When NaOH is used as activator, mechanical properties of concrete improved with increase in molarity of the alkaline activator solution. Compressive strength of concrete cubes increases with increase in the amount of Na₂O supplied by the activator solution but to an optimum beyond which further increase in Na₂O results in decrease in compressive strength. However, the optimum amount of Na₂O, often reported as percentage of total slag content, varied from one study to another, probably dependent on the type of activator used as well as the water-to-binder (w/b) ratio.

1. Introduction

The most commonly used construction material is reinforced concrete, which uses ordinary Portland cement (OPC) as primary binder. However, the production and use of OPC reportedly contributes to more than 5% of the global CO₂ emission, not to mention the significant energy used during the manufacturing process. It is therefore essential to consider alternative binders that cost less energy to produce and produces less CO₂ into the atmosphere. A promising alternative to OPC is to use industrial by-products such as ground granulated blast furnace slag (GGBS), silica fume, or fly ash. Partial replacement of OPC with GGBS increases the 28-day compressive strength up to an optimum replacement percentage, but compressive strength decreases with further increase in replacement percentage. Mohamed [1] demonstrated that 35% is the optimum replacement percentage of OPC with GGBS in self-consolidating concrete (SCC) to obtain the maximum 28-day cube compressive strength at water-to-binder ratio (w/b) of 0.36. In the case of partial replacement of OPC with high volume GGBS, OPC acts as the activator for GGBS. The goal of this paper is to review the factors affecting the compressive strength of concrete and mortars produced using GGBS as sole binder.

Replacement of cement with alternative industrial by-products characterized with high percentages of alumina and silica (alumina-silicates), such as GGBS, activated with alkalis has been researched for
decades, but is gaining popularity at the present time due to increased interest in reducing environmental footprint of cement production. For the most part, GGBS can be used as sole binder in production of concrete if activated by alkaline solution of higher pH alumina-silicates, the most commonly used source materials as alternatives to OPC, contain relatively large amounts of silicon oxide (SiO$_2$) and aluminium oxide (Al$_2$O$_3$) [2]. Despite certain shortcomings in comparison to OPC concrete, such as high carbonation and shrinkage, AAS concrete offers many opportunities to the construction industry in terms of durability and high early strength development. In the following sections, factors affecting compressive strength in terms of increase or decrease are discussed, with the exception of the well-known water-to-binder (w/b) ratio.

2. Effect of type of alkaline activator and molar concentration on compressive strength

High pH alkaline activator solution promote dissolution of GGBS, while those with pH lower than 9.5 do not support dissolution of GGBS and don not speed up the hydration of GGBS [3]. Regardless of the activator type, the main hydration product of AAS is calcium-aluminate-silicate-hydrate (C-A-S-H) and/or calcium-silicate-hydrate (C-S-H), along with sodium-aluminate-silicate-hydrate (N-A-S-H). Unlike C-S-H formed due to hydration of OPC, calcium-silicate-hydrate formed during hydration of AAS is characterized by low molar ratio of calcium/silicate (C/S) that is close to 1.0. Formation of calcium-silicate-hydrate (C-S-H) in AAS concrete/mortar occurs through precipitation reaction that is much faster than the “topotactic” reaction that characterizes OPC [4]. Increasing the molar concentration of the alkaline activator solution increases compressive strength as well as splitting tensile strength [5]. Compressive strength tests on 16 mm x 16 mm x 160 mm mortar samples conducted by Brough and Atkinson [6] demonstrated that AAS activated using sodium silicate (Na$_2$O.r.SiO$_2$), also known as water glass, produces concrete with higher compressive strength than AAS activated using potassium hydroxide (KOH) at all times after 1-day of curing, as shown in figure 1. The reason is possibly that water glass contains silica that is an essential part of the C-S-H gel, the key structure contributing to concrete strength.

![Figure 1](image-url) Compressive strength concrete where AAS activated using water-glass compared to potassium hydroxide [6].

Reactive magnesium oxide (MgO) is capable of activating GGBS and producing hydration including C-S-H as well as hydrotalcite-like phases. Calcined MgO often contains relatively small amounts CaO and SiO$_2$ as impurities originating from the source rocks. Experiments conducted by Jin et al. [7] demonstrated that the higher the reactivity of MgO and content of CaO, the higher the compressive strength. Higher contents of CaO increases the pH of the alkaline activator solution, which in turns increase the dissolution reaction of GGBS. The reaction product hydrotalcite is more voluminous than C-S-H resulting in lower porosity paste.
Experiments on 100 mm cubic samples conducted by Puertas et al. [8] show lower porosity in AAS concrete activated using sodium silicates compared to AAS activated using NaOH, which is consistent with the higher compressive strength of AAS concrete/mortar activated using sodium silicate compared to NaOH. Therefore, compressive strength of samples activated using sodium silicate was higher than sodium hydroxide for the same Na$_2$O of 5%. The higher mortar/concrete strength when water-glass is used to activate GGBS compared to NaOH is attributed to the silicon in water-glass which is also the reason for the lower porosity of the water glass activated samples.

3. Effect of sodium oxide (Na$_2$O) content and silicate modulus on compressive strength

In AAS concretes/mortars where GGBS is activated using combination of water-glass and sodium hydroxide, the content of Na$_2$O is often expressed as a percentage of the total slag content. Mechanical properties of AAS concrete/mortar are reportedly related to the content of Na$_2$O. Al-Otaibi [9] concluded that at a water-to-binder (w/b) ratio of 0.48 increasing the Na$_2$O content from 4% to 6% increases the 28-day compressive strength. However, the increase after 28-days is very slow and essentially ceases after 180 days, as shown in figure 2.

Rashad et al. [10] tested 20 mm cubic mortar samples prepared from various AAS mixes where the alkaline activator solutions had Na$_2$O concentrations of 3.5%, 5.5%, 6.5%, and 10.5%. 7-day and 28-day Compressive strength of mortar samples increased with increase in Na$_2$O concentration up to 6.5% by weight of slag, then dropped slightly when Na$_2$O was increased to 10.5%. This identifies 6.5% as the optimum sodium oxide concentration. The investigators used commercial water glass with silicate modulus SiO$_2$/Na$_2$O = 1.7. However, Tran and Kown [11] conducted experiments using silicate modulus SiO$_2$/Na$_2$O = 1.0 and noted that increasing Na$_2$O from 4% to 10% (in increments of 2%) increased the compressive strength continuously but at slower rate when Na$_2$O is higher than 6%. The highest increase in compressive strength occurred when Na$_2$O was increased from 4% to 6%. The slowdown in compressive strength gain as Na$_2$O content increases beyond 6% may be attributed, in part, to the increase in shrinkage deformations associated with increase in the content of sodium. The investigators tested compressive strength on 40 x 40 x 160 mm$^3$ mortar samples, which is different from size used by other investigators as indicated in this section. This indicates the optimum sodium oxide ratio doesn’t depend on mortar sample size but depends on silicate modulus.

When AAS mortar experiences carbonation, increase in activator dosage also increases compressive strength and decreases porosity, therefore, decreases loss of compressive due to carbonation [12].
Increasing the silicate modulus in water-glass activated AAS concretes/mortars decreases the porosity and average pore sizes. Shi et al. [13] tested 40 mm cubic mortar samples and demonstrated that increasing the silicate modulus (SiO$_2$/Na$_2$O) of sodium silicate (water-glass) activator solution (from 0.5 to 2.0 in increments of 0.5) increases the compressive strength. Similarly, increasing the silicate modulus decreases the drop in compressive strength of mortar under carbonation test when the activator of GGBS is water-glass.

4. Effect of chemical physical characteristics of GGBS on compressive strength of AAS mortars/concretes

Activation of GGBS is often necessary to produce hydration products that will impart the necessary strength on concrete and mortar. When GGBS is hydrated without activator, strength development is very slow, reportedly due to formation of a thin protective film around GGBS particles. However, GGBS containing anhydrite calcium sulphate (CaSO$_4$) or gypsum (CaSO$_4$.H$_2$O) possess self-activation properties, depending on calcium sulphate content [14]. Calcium sulphate may be added to GGBS during the manufacturing process of GGBS. Experimental studies by Park et al. [14] showed that, in comparison to OPC, significant compressive strength may develop 50 mm cubic un-activated GGBS samples prepared at w/b = 0.4. In addition to the content of calcium sulphate, other factors affecting strength development of GGBS without activators include the basicity ((CaO+MgO+Al$_2$O$_3$)/SiO$_2$), chemical modulus ((CaO+MgO)/SiO$_2$), and the content of (Ca+Na+K+Mg), known as network-modifying elements of the glass phase. The higher the basicity, chemical modulus, and network-modifying elements percentage, the greater hydraulic reactivity of GGBS, without alkaline activator [14].

ASTM C989 [15] uses a more direct approach to classify GGBS based on activity. The value of the slag activity index given by Equation (1) is used to classify slag in Grade 80, Grade 100, and Grade 120, with the latter being the most active slag.

\[
\text{Slag activity index (\%) = } \frac{\text{SP}}{\text{P}} \times 100
\]  
(1)

Where,

\[ \text{SP} = \text{average compressive strength of slag-reference cement mortar cubes at designated ages, MPa (psi). This mortar contains 50\% of the tested slag + 50\% OPM, and } \text{P} = \text{average compressive strength of reference cement mortar cubes at designated age, MPa (psi).} \]

Compared to OPC, GGBS contains higher amounts of silicon oxide (SiO$_2$) and aluminium oxide (Al$_2$O$_3$), and calcium oxide (CaO). The chemical constituents of GGBS including contents the aforementioned oxides affect fresh properties as well as strength development of AAS mortars. In addition, the silicate modulus of activator solution SiO$_2$/Na$_2$O also affects the fresh and mechanical properties. Therefore, Yang and Song [2] proposed an alkaline quality coefficient as in indicator of the performance AAS mortars and concretes. The higher the value of the alkaline quality coefficient the higher the 28-day compressive strength. However, the proposed coefficient appears to be directly proportional to the ratio of Na$_2$O/SiO$_2$ while studies outlined later in this article will indicate compressive strength is directly proportional to the silicate modulus (Ms = SiO$_2$/ Na$_2$O).

5. Effect of curing method and temperature on compressive strength of activated GGBS

Similar to traditional OPC concrete, strength of AAS concrete is also affected by curing method. El-hassan et al. [16] examined the 28-day compressive strength of 150 mm x 300 mm cylinders under air-curing (A), intermittent water (IW) curing, and continuous water (CW) curing. IW curing produced the highest 28-day compressive strength compared to air curing and CW curing. In IW curing, concrete cylinders were water cured for 7-days, then placed in air under ambient temperature for 21-days when the compression test was conducted. This is consistent with the findings of Mohamed and Najm [17].
confirming IW curing produces higher 28-day compressive strength of 150 mm x 150 mm x 150 mm cubes compared to CW curing. However, in that study, IW curing was done by submerging the cubes under water for 3 days, followed 25 of air curing under ambient temperature.

Rostami and Behfarnia [18] tested the compressive strength of 100 mm cubic AAS samples cured using two methods, 1) plastic cover, 2) submerging under water. Samples cured under water exhibited higher compressive strength after 28-days and after 90-days compared to samples cured under plastic cover. The difference in compressive strength between water curing and curing under plastic cover is more pronounced after 90 days of curing than after 28-days.

Compressive strength of AAS mortars and concrete is affected by the curing temperature and by exposure temperature simulating fire. Tran and Kown [11] noted that the compressive strength of 40 x 40 x 160 mm$^3$ samples increased significantly after being subjected to 200°C temperature when the content of Na$_2$O = 4%. The samples were prepared with sodium oxide content Na$_2$O ranging from 4% to 10% and cured for 28-days at ambient laboratory temperature prior to being subjected to the elevated temperature (from 200°C to 1000°C) for 2 hours. The increase in compressive strength when Na$_2$O = 4% is likely caused by the increased hydration rate at elevated temperature of 200°C. However, for samples prepared at Na$_2$O = 6%, the strength gain was modest when temperature was increased to 200°C. Samples prepared using alkaline activator contents of 8% and 10% experienced continuous drop in compressive strength with increase in temperature up to 1000°C. Therefore, the effect of heating temperature after 28-days of curing of AAS samples depends on the content of Na$_2$O. The decrease in strength at higher temperature may be related to greater shrinkage and/or cracks associated with high thermal stresses along with high content of Na$_2$O, as shown in Figure 3.

![Figure 3. Compressive strength at different curing temperature [11].](image)

6. Effect of silica fume and nano-silica on compressive strength of activated GGBS
AAS concrete and mortar are less porous and develop better durability and higher strength when up to 15% of GGBS is replaced by silica fume [18]. Rostami and Behfarnia [18] reported that compressive strength of 100 mm cubic AAS concrete samples increased with increase in silica fume from 5% to 15%, compared to AAS concrete samples that didn’t contain silica fume. The higher compressive strength with increase of silica fume up to 15% continued from 28-days of curing to 90-days of curing. Aydin [19] reported that steam-cured 40 mm x 40 mm x 160 mm AAS mortar samples developed higher compressive strength when 10% of GGBS was replaced with silica fume, compared to 100% OPC mortar samples or 100% GGBS samples. Aydin [19] reported a drop in compressive strength when 20%
of GGBS was replaced with silica fume, compared to mortar samples activated using 100% GGPS. Interestingly, even in traditional concrete, 15% is also the optimum percentage of silica fume to partially replace OPC replacement and produce the highest 28-day compressive strength. Mohamed and Najm [20] reported that in binary OPC-silica fume, replacement of OPC with 15% silica fume produced the highest 28-day compressive strength on 150 mm x 150 mm x 150 mm water cured concrete cubes.

Experiments by Shahrajabian and Behfarnia [21] showed that adding nano-silica to AAS in the range of 1% to 3% by weight slag increases compressive strength of 100 cubic samples compared to the control AAS mix that doesn’t contain nano-silica. The investigators used nan-silica containing more than 99% SiO₂ with particles ranging from 11 to 13 nm. Adding 1% nano-silica to AAS concrete increased strength significantly but adding 2% and 3% had smaller impact on increasing compressing strength.

7. Effect of carbonation, shrinkage, and sulphate attack on compressive strength of AAS

AAS is known to be more vulnerable to carbonation compared to OPC paste/concrete. Carbonation affects OPC paste and AAS paste differently. In OPC pastes, carbonation is the reaction of CO₂ with C-S-H and with Ca(OH)₂ resulting in formation of CaCO₃ that fills the pores, decreases porosity, and increases compressive strength. In AAS mortars where the alkaline solution was activated using sodium silicate (water-glass), carbonation leads to decalcification of C-S-H and extensive formation of CaCO₃ compared to OPC mortars [12]. However, unlike OPC mortar, carbonation of AAS mortar activated using water-glass (WG) results in reduction in compressive strength due to loss of cohesion in the matrix and increase in porosity [22]. Based on experiments by Shi et al. [13] when the activator is NaOH, carbonation of concrete/mortar increases compressive strength. Figure 4 shows that without carbonation, increasing the silicate modulus of the water glass activator results in increase in compressive strength compared to OPC mortars. However, when subjected to carbonation, compressive strength is lower for each value of water glass silicate modulus.

![Figure 4](image_url)

**Figure 4.** Compressive Strength of AAS and PC mortars before and after Carbonation [24].

Experiments by Shi et al. [13] shows rapid decrease in compressive strength of 40 mm cubic AAS mortar samples activated using water-glass over 28-days of exposure to CO₂, as a result of carbonation. Despite decrease in compressive strength due to carbonation, increase in silicate modulus (Ms = SiO₂/Na₂O) of water-glass activated sample increases compressive strength. As shown in figure 5, samples prepared with NaOH didn’t experience decrease in compressive strength when subjected to the same carbonation level as the water-glass activated samples. Figure 5a shows the compressive strength of mortars when the alkaline activator contains 6% Na₂O while figure 5b is for alkaline activator...
containing 8% Na₂O. Compressive strength at all curing ages, with or without carbonation, is higher when activator contains 8% Na₂O compared to 6%. When the alkaline activator is NaOH, mortar continued to develop higher compressive strength as curing age increases.

![Figure 5](image)

**Figure 5.** Effect of carbonation on evolution of compressive strengths of the alkali-activated mortars with different alkali dosage, (a) 6% and (b) 8% [13].

Sulphates in various forms, such as magnesium sulphates migrating into concrete from a source, such as ground water, binds with calcium in Ca(OH)₂ (if available) or C-S-H and forms ettringite and later gypsum. This leads to expansion, cracking, and loss of bond between cement paste and aggregates. As a result, sulphate attacks are known to cause loss of compressive strength in OPC concrete. However, sulphate attack has limited or no impact on compressive strength of AAS concrete. This is attributed to lack of Ca(OH)₂ in AAS concrete [23]. Experimental research by Komljenovic et al. [23] showed that AAS mortar prisms continue to gain strength while immersed in 5% Na₂SO₄ solution for 90 days, while similar mortar samples made of OPC lost strength under the same conditions. It is possible that the gain in strength of AAS samples was caused by formation of more reaction products through activation due to high pH of the Na₂SO₄ medium. The reaction products in turn reduce porosity of the AAS prims and increase compressive strength.

8. Summary
Several factors affect the strength of alkali-activated concretes and mortars. This article explored some of these factors:

- Increasing the content of sodium oxide (Na₂O) increases the compressive strength more rapidly with increase from 4% to 6%. Increase in content of Na₂O beyond 6% increases the compressive strength at a much slower rate, with some studies reporting a drop in compressive strength at higher contents of Na₂O.
- In sodium silicate activated slag concrete, increasing the silicate modulus (SiO₂/Na₂O) up to 1.5 2.0 increases the compressive strength. The silicate modulus beyond which compressive strength decreases requires further research.
- Compressive strength is dependent on the type of alkaline used to activate slag. Sodium silicate produces compressive strength in mortars/concretes that is higher than similar samples prepared using potassium oxide (KOH) or sodium hydroxide (NaOH).
- Carbonation of alkali-activated slag concrete decreases the compressive strength when the activator was is sodium silicate. However, carbonation of sodium hydroxide activated mortars/concretes doesn’t lead to loss of compressive strength.
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