Review Article

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Influence of various additives on the early age compressive strength of sodium carbonate activated slag composites: An overview

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Abstract: The use of sodium carbonate as an alkali activator for slag to produce alkali-activated slag is promising due to its sustainable, economic and user-friendly properties. However, the lower early age performance of composites made with such binder has limited its use especially in applications where higher early age is required. Hence, in order to propel the application of this sustainable binder, it is imperative to find ways in which the early age performance can be enhanced without having a detrimental effect on later age performance. One of the effective and sustainable ways to enhance the early age strength of sodium carbonate activated slag is by incorporation of various additives as partial replacement of sodium carbonate on/and slag. In order to propel more application of sodium carbonate slag for various applications, this current study was undertaken. In this paper, an overview of the types of various additives that can be used to enhance the early age compressive strength of sodium carbonate activated slag composites was discussed. The mechanism and dosage of each of the additives were briefly discussed alongside the limitation and advantages of the additives. Findings from this overview showed that the early age compressive strength of sodium carbonate activated slag can be enhanced with the use of additives such as calcium oxide, calcium hydroxide, Portland cement, sodium hydroxide and sodium silicate.

Keywords: alkali-activated materials, compressive strength, slag, sodium carbonate, additives

Abbreviations

AAS alkali-activated slag
LM hydrated lime
PC Portland cement
QLM quick lime
SC sodium carbonate
SH sodium hydroxide
SL slag
SS sodium silicate

1 Introduction

Alkali activated slag (AAS) is gaining huge attention in the construction industry due to its viability to serve as a sustainable alternative binder to Portland cement (PC) [1–6]. Though AAS was developed in 1957 in USSR [7], rapid research, development and application have ensued in the last two decades. AAS is obtained by using an alkali to dissolve the aluminate and silicate monomers to produce a binder similar to that of PC. AAS has been found to possess outstanding mechanical and durability performance similar or higher compared to that of PC [8–11]. The advantage of AAS compared to other alkali-activated binders is due to the ability to cure it at ambient temperature coupled with a huge amount of different slags produced as waste materials all over the world [12].

However, despite the sustainable advantage of AAS, the high cost and corrosiveness of the sodium silicate and sodium hydroxides which are the primary alkali activator have limited the practicality of producing and using AAS [13, 14]. The production of sodium silicate (SS) and sodium hydroxide (SH) is energy-intensive and requires a complex production system as these activators are not available naturally in the environment [15]. On the other hand, sodium carbonate (SC) which is present naturally in the environment, cheaper and less corrosive can be used as an alkali activator for slag systems [16, 17]. The use of

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SC as slag activator has also been found to exhibit similar strength as those activated with the conventional activators at later ages [18]. However, due to the lower alkalinity of SC compared to the conventional activators, its use results in lower early age strength. Several studies have shown that the 1-day compressive strength of SC activated slag is negligible (i.e. approximately zero) which prevents the removal of formworks/moulds [19]. In order to overcome this challenge, elevated curing can be employed to accelerate the dissolution of the monomers. However, the use of elevated curing is energy intensive and eliminates the sustainable and cost advantage of AAS over PC. Hence, there is need to find ways to improve the early age strength of sodium carbonate activated slag at ambient conditions.

The incorporation of additives that can increase the alkalinity of the pore solution is one of the effective and sustainable ways to improve the early age of sodium carbonate activated slag. These additives can be used as either partial replacement of the SC or slag. Hence, in order to propel more application of SC activated slag composites for various construction purposes, this study was undertaken. The main aim of this paper is to explore various studies in which additives have been incorporated in order to enhance the early age compressive strength of SC activated slag. The effect of these additives on the early age compressive strength was classified in terms of the types of additives. In this paper, focused was made only to compressive strength as it is a good indication of the overall performance of composites. Also, as sodium carbonate activated slag is known to exhibit outstanding strength at later ages (i.e. 28 days). Hence, the focus was placed only on early age (i.e. up to 7 days) in this study. It is worth mentioning that all SC activated slag composites discussed in this paper are cured at ambient temperatures.

3 Additives to enhance early age compressive strength

3.1 Calcium oxide

Calcium oxide which is also referred to as quicklime (QLM) can be incorporated into SC activated slag to improve its early age compressive strength. Wang et al. [25] utilized calcium oxide at different contents to partially replace SC as an activator in order to improve the compressive strength. The results from the findings showed that the use of calcium oxide as a 33% replacement of the SC resulted in the highest compressive strength of the AAS as shown in Figure 1. The increase in the early age compressive strength with the introduction of QLM was attributed to the increase in the alkalinity of the pore solution as a result of the generation of SH from the reaction between SC and QLM. This increase in alkalinity accelerates the dissolution of monomers at an early age. Eq. (1) presents the reaction between SC and QLM. The calcium carbonate generated
Table 1: Advantages and limitations of additives

| Additive Replacement of | Pros | Cons |
|-------------------------|------|------|
| Limestone powder Slag   | • cheap  
• locally available  
• sustainable | • no significant increase in strength |
| Magnesium oxide Slag    | • can be used at a relatively low amount | • Requires calcination  
• High variability depending on source and calcination |
| Calcium oxide Slag      | • can be used at a relatively low amount  
• cheap | • High embodied energy and carbon |
| Calcium hydroxide Slag  | • can be used at a relatively low amount  
• cheap | • High embodied energy and carbon |
| Sodium silicate SC      | • results in significant enhancement | • High embodied energy and carbon  
• Corrosive  
• Expensive |
| Sodium hydroxide SC     | • results in significant enhancement | • High embodied energy and carbon  
• Corrosive  
• Expensive |
| Portland cement Slag    | • results in significant enhancement | • High embodied energy and carbon |

during the reaction acting as a filler in the matrix might also contribute to the enhancement of the compressive strength [26, 27]. The lower early age compressive strength of slag activated with SC partial replaced with 67% QLM was attributed to the lower generation of calcium carbonate and SC in the matrix compared to that when 33% QLM was used to partially replace SC [25]

\[
\text{CaO} + \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + 2\text{NaOH} \quad (1)
\]

3.2 Calcium hydroxide

Calcium hydroxide also referred to as hydrated lime or slaked lime (LM) is one of the additives that can be incorporated into SC activated slag to reduce the carbonate ions and increase the alkalinity of the system [23]. The study by Akturk et al. [28] showed that the use of LM as a 3% replacement of the slag in SC activated slag resulted in significant enhancement of the early age compressive strength as presented in Figure 2. The presence of LM in the system also increases the rate and amount of calcium aluminate silicate hydrate formation which is a reaction that contributes to the strength capacity of the composite [24]. The significant increase in the early age compressive strength was attributed to the increase in the alkalinity of the system as a result of the generation of SH from the reaction of SC and LM as shown in Eq. (2). This production of SH results in the acceleration of the dissolution of the monomers in slag. Similarly to the effect of QLM, the calcium carbonate formed during the reaction process acts as a filler within the matrix resulting in the densification of the microstructure and improvement of the compressive strength [25].

\[
\text{Na}_2\text{CO}_3 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + 2\text{NaOH} \quad (2)
\]
3.3 Magnesium oxide

One of the additives that can also be used to improve the early age compressive strength of SC activated slag is magnesium oxide. Magnesium oxide is obtained from the thermal treatment of magnesium carbonate [29]. Jin and Al-Tabbaa [30] investigated the effect of various content of magnesium oxide on the performance of SC activated slag paste activated. Results from the study showed that the use of magnesium oxide to replace 5% slag is optimum to enhance the early age compressive strength as seen in Figure 3. It can also be seen from Figure 3 that the 1-day compressive strength of SC activated slag without magnesium oxide was 0 MPa. However, the incorporation of various content of magnesium oxide as partial replacement of the slag resulted in an enhancement in the compressive strength. The increase in the compressive strength with the incorporation of magnesium oxide can be associated with the formation of hydrotalcite which refines the microstructure of the paste and result in higher compressive strength [31]. The reaction of the dissolved monomers from slag with the magnesium oxide to form magnesium silicate hydrate gel which contributes to the strength capacity of the paste [32].

![Figure 3: Effect of magnesium oxide content on compressive strength (adapted from [30])](image)

3.5 Portland cement

Portland cement (PC) which is the primary binder used in cementitious composites is the highest contributor to the embodied energy and carbon of the composites due to its use in high volume. However, when it is used at a very low volume, these detrimental impacts are insignificant. Kovtun et al. [34] used PC to as partial replacement of slag in the range of 3% to 5% in SC activated slag. It was found out from the study that replacing 3%, 4% and 5% slag with PC increased the 1-day compressive strength by 5 MPa, 14 MPa, and 17 MPa, respectively. The enhancement of the compressive strength with the introduction of PC was attributed to the presence of belite and alite in the PC which results in an acceleration in the activation of the slag [35]. The effect of PC content on the 1-day compressive strength of SC activated slag is shown in Figure 5.

![Figure 4: Effect of limestone powder content on 7 days compressive strength (adapted from [24])](image)
3.6 Sodium hydroxide

Sodium hydroxide (SH) which is one of the conventional alkali activators for AAS can be used at lower dosages to partially replace SC in order to improve the early age compressive strength. Yongde and Yao [36] investigated the effect of partial replacement of SC with SH on the compressive strength of slag. The findings from the study showed that the 3-day compressive strength of slag activated with only SC is 0 MPa. However, the replacement of 50% SC with SH to activate the slag resulted in approximately 30 MPa at 3 days. The effect of the combined use of SH and SC as an activator for slag is presented in Figure 6. This observation corresponds to that of Fernandez-Jimenez and Puertas [37] where the use of SS as a 20% replacement of the SC resulted in a 35 MPa increase in the 7 days compressive strength. Kevtun et al. [34] also reported approximately 8 MPa and 23 MPa increase when SH was used as 20% and 50% replacement of the SC. The study by Akturk et al. [28] where SH was used up to 40% replacement of SC also showed an enhancement in the early age compressive strength. The effect of various replacement levels of SC with SH on the 7 days compressive strength of SC activated slag from various studies is presented in Figure 7.

Similarly, Jiao et al. [38] investigated the effect of SH concentration on the compressive strength of SC activated slag incorporating SH as a 40% replacement of the SC. It was found out from the study that using SH with a concentration of 6M compared to 4M and 8M resulted in the highest compressive strength at early ages as shown in Figure 8. The increase in early age strength up to 6M SH was attributed to an increase in the hydroxyl ions in the composites which increase the alkalinity of the pore solution. However, as activation of slag occurs at an optimum alkali concentration, introducing higher concentration will result in the inability of the surplus alkali to react with slag particles [39].
3.7 Sodium silicate

Sodium silicate (SS) which is also one of the conventional activators for AAS can be incorporated as partial replacement of SC in AAS. Bernal et al. [40] investigated the effect of the use of sodium silicate (SS) as a replacement of 50% SC to activate slag used as a binder for mortar. Findings from the study showed that the 1 day and 7 days compressive strength of slag activated with the binary activator increased by 19 MPa and 44 MPa, respectively compared to that activated with only SC. The increase in the compressive strength with the introduction of SS was attributed to the reduction in the content of carbonate ions and the higher alkalinity of SS which results in an increase in the rate of dissolution of the silicate and aluminate monomers in the slag. The effect of the activator composition on the compressive strength is presented in Figure 9. This observation is in agreement with that of Fernandez-Jimenez and Puertas [37] where the use of SS as a 20% replacement of the SC resulted in 53.4% increase in the 7 days compressive strength.

3.8 Calcined layered double hydroxides

As the name implies, calcined layered double hydroxides (CLDHs) are obtained from the thermal treatment of layered double hydroxides minerals [41, 42]. Due to the ability of CLDHs to permit the interchange of anions, they can be incorporated into cementitious composites to enhance the performance [43, 44]. CLDHs are also capable of reducing the carbonate ions in SC activated slag resulting in an increase in the alkalinity of the pore solution and a corresponding increase in early age compressive strength. Ke et al. [45] incorporated 5% CLDH by mass of slag into SC activated slag mortar. Results from the study showed the incorporation of CLDH into the mixture resulted in a 23% increase in the 7 days compressive strength compared to the SC activated slag mixture without CLDH. The increase in the compressive strength was associated with the resulting lower porosity as a result of the incorporation of CLDH coupled with the increase in the formation of hydration products.

3.9 Hybrid additives

Hybrid additives are additives composed of more than one the additives that can be used to enhance the early age compressive strength. Kovtun et al. [46] incorporated a hybrid additive composed of an equal amount of silica fume and calcium hydroxide (LM) to partially replace slag activated with SC. The findings from the study showed that the 1-day compressive strength increases with increasing content of silica fume and slaked lime as shown in Figure 10. The increase in the 1-day compressive strength with the introduction of the hybrid additives was attributed to the increase in the alkalinity in the pore solution as a result of the dissolution of the calcium hydroxide. The reaction accelerated formation of calcium silicate hydrate as a result of the reaction between the calcium hydroxide and sodium silicate was also found to result in the enhancement of the early age compressive strength. The possible reaction of SC with calcium hydroxide similar to that of calcium oxide mentioned early might also have contributed to the enhanced 1-day compressive strength observed.

Figure 9: Effect of activator composition on early age compressive strength (adapted from [40])

Figure 10: Effect of hybrid additives on 1-day compressive strength (adapted from [46])

Akturk et al. [28] also investigated the effect of the combined use of SH and LM on the strength development of SC
activated slag. The SH was used as partial replacement of SC up to 40% while the LM was used as a 3% replacement of the slag. Results from the study showed that the use of this hybrid additive resulted in a significant enhancement in the early age compressive strength as presented in Figure 11. The increase with the incorporation of this hybrid additive can be associated with the increase in the alkalinity of the pore solution as a result of the presence of the SH and generation of additional SH due to the reaction of the LM with SC.

![Figure 11: Effect of hybrid additive on compressive strength (adapted from [28])](image)

### 4 Conclusions and recommendations

This overview explored different additives that can be incorporated into sodium carbonate activated slag to improve its early age strength. The need to improve early strength is important as this helps to demould formworks/moulds as soon as possible and also makes the composite suitable for applications where higher early strength is desired. Discussion in this paper shows that the early age compressive strength of sodium carbonate activated slag can be improved with the incorporation of additives as partial replacement of the sodium carbonate or slag. The additives incorporated into the sodium carbonate activated slag increases the alkalinity of the pore solution thereby resulting in the higher dissolution of the monomers from the slag. The increase in the dissolution of these monomers results in a corresponding product formation and enhancement of the early age compressive strength of the composites.

Though these additives are used at a very low dosage compared to the volume of the composites, some of the additives are expensive and have a high carbon footprint. Hence, there is a need for more research and development to be carried out on cheaper and sustainable materials that can be used as alternatives to improve the early age properties of the composites. Chemical admixtures used for enhancing the early age of Portland cement are capable of increasing the rate of hydration and shortening the setting time by increasing the formation of calcium hydroxide. Hence, it is recommended that these accelerators can be explored for improving the early age compressive strength of sodium carbonate activated slag composites.

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