



## A comprehensive overview about the influence of different additives on the properties of alkali-activated slag – A guide for Civil Engineer



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### H I G H L I G H T S

- Water absorption and permeability porous were markedly improved with the addition of steel fibres.
- Superplasticizer (naphthalene-based) improved workability and compressive.
- SF in AAS matrix decreased workability and increased compressive strength.
- 10% PC in AAS gave higher compressive strength and the lowest drying shrinkage.
- Gypsum in AAS reduced drying shrinkage, setting time and increased compressive strength.

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### A B S T R A C T

The development of new binders, as an alternative to Portland cement (PC), by alkaline activation, is a current researchers interest. Alkali-activated slag (AAS) binder is obtained by a manufacturing process less energy-intensive than PC and involves lower greenhouse gasses emission. AAS belongs to prospective materials in the field of Civil Engineering. Researchers have employed fibres, chemical admixtures, mineral admixtures and other materials as additives in AAS system aiming to modify some properties of this system. This paper presents a comprehensive overview of the previous works carried out on using different additives in AAS system.

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### 1. Introduction

Practices in the delivery of build infrastructure, there are specific concerns over atmospheric CO<sub>2</sub> concentrations which at 390 ppm reached record breaking levels (U. N. Intergovernmental Panel on Climate Change) [1]. Major CO<sub>2</sub> producing sectors, such as power generation, transportation, oil refining and manufacturing of steel and concrete are under pressure to adopt measures that would drastically reduce the global CO<sub>2</sub> emission rate by 2030. Within the concrete industry, cement manufacturing is the main culprit [2]. Each year, the concrete industry produces approximately 12 billion tonnes of concrete and uses about 1.6 billion tonnes of PC worldwide [3]. The production of cement is increasing about 3% annually [4]. Indeed, with the manufacture of 1 tonne of cement approximately 0.94 tonnes of CO<sub>2</sub> are launched into the atmosphere [5]. The IEA (International Energy Authority) holds the cement industry responsible for emitting between 6% and 7% of

all the CO<sub>2</sub> emission into the atmosphere [6]. The projections for the global demand of PC show that in the next 40 years it will have a twofold increase reaching 6 Gt/year [7]. Among the green house gases, CO<sub>2</sub> contributes about 65% of global warming. Additionally, cement production and resulting emissions are expected to increase by 100% from the current level by 2020 [8]. On the same line with this, global demand will have increased almost 200% by 2050 from 2010 [7]. Beside the emission of CO<sub>2</sub>, cement industry launches SO<sub>3</sub> and NO<sub>x</sub> which can cause the greenhouse effect and acid rain [9,10]. This is particularly serious in the current context of climate change caused by CO<sub>2</sub> emissions worldwide, causing a rise in sea level and the occurrence of natural disasters and being responsible for future meltdown in the world economy [11].

In many countries around the world cement production consumes huge amounts of energy, in particular, arising from the calcination of raw materials at around 1500 °C and the grinding of raw materials, cement clinker and gypsum [12]. The energy demand associated with PC production is about 1700–1800 MJ/tonne clinker [13–15], which is the third largest use of energy, after aluminium and steel manufacturing industries [6,13]. The cement

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production account about 5% of worldwide industrial energy consumption [16,17]. In addition, cement production consumes considerable amounts of virgin materials (limestone and sand), producing each tonne of PC of which about 1.5 tonnes of raw material is needed [14]. Further, concrete made of PC is subject to certain durability problems that are difficult to solve. In the light of these problems, the scientific community has undertaken to seek new processes, technologies and materials to provide the construction industry with alternative binders. One avenue that is expected to significantly reduce cement use is of blended cement [18–25]. The second alternative is to recycling in cement industry [26–34] which has become indispensable processes in some countries. The third alternative is the use alkali-activation of slag, fly ash (FA), burned clay and other aluminosilicate materials. The new binder materials that can replace PC, by alkali activation, can generate about 80–90% less carbon dioxide than PC [35]. Comparison to PC concrete, the global warming potential of alkali-activated concrete is 70% lower [36]. In addition, there are numerous advantages of this system as lower heat of hydration [37], the development of earlier and higher mechanical properties [38,39], low heat release [40], better resistance of chemical attack [41,42], freeze–thaw resistance [43], fire resistance [44,45], higher reduction in chloride diffusion [46] and stronger aggregate–matrix interface formation [47,48]. On the contrary, the AAS system presents some problems such as rapid setting periods [49], higher shrinkage values [50], higher formation of salt efflorescences [39], higher carbonation [51] and tendency to crack during curing [52,53]. However, these advantages and disadvantages are depended on the types of PC and blended cement, and AAS and not always in the case. For specific problems, adequate solutions have been established. Researchers have been tried to solve some of these problems by using different additives in AAS system.

The most commonly used activators are sodium silicate, sodium hydroxide, sodium carbonate or a mixture of sodium - potassium hydroxide (NaOH, KOH) with sodium silicate - potassium silicate, the mixture of sodium hydroxide with sodium silicate has been generally agreed to be the most effective activator and provides the best formulation for high strength and other advantageous properties. However, both the sodium hydroxide and sodium silicate do not exist naturally and they are obtained from energy intensive manufacturing processes. This is particularly the case for sodium silicate, which is produced by melting sand and sodium carbonate at 1350–1450 °C, followed by dissolving in an autoclave at 140–160 °C under suitable steam pressure [54]. As a result, even though AAS could potentially be considered as a low energy and low carbon cement system. Other uncommon activator as Na<sub>2</sub>SO<sub>4</sub> can be obtained either from natural occurring sodium-sulfate-bearing brines, crystalline evaporate deposits or as a by-product during the manufacture of various products such as viscose rayon, hydrochloric acid and silica pigments [13]. However, in general the energy consumption of alkali activation system is calculated to be approximately 60% less than that of PC [55].

Ground granulated blast furnace slag (denoted as slag) is a by-product obtained in the manufacturing of iron in a blast furnace where iron ore, limestone and coke are heated between 1400 °C and 1600 °C. Quenching process of molten slag by water is converting it into a fine (no larger than 5 mm diameter), granulated slag of whitish colour. The rapid cooling prevents the formation of larger crystals. The resulting granular material comprises some 85–95% non-crystalline calcium-aluminosilicates (glassy materials) that higher in energy than the crystalline material [56]. Slag is commonly utilized in the cement industry for preparation of blended cement CEM II, CEM IV and CEM V where cement clinker substitution by slag range from 6 to 95 wt% [57]. This may be a partially solution to the disposal problem. Despite this use, the vast majority of this slag is still disposed in landfills [58]. One option to eliminate

this disposal of the slag in an ecologically sensitive manner is to reuse it as cementing material by alkali activation.

The alkali activation system is a chemical process that transforms partially or wholly vitreous structures into cementitious skeletons. In this context, the idea of applying alkali activation was put forward in the researchers priorities. Thus, AAS cement and concrete were invented in the USSR in 1957 by Glukhowsk of the Kiev Institute of Civil Engineering, Ukraine [59], although the possibility of using alkaline activation of slag can be traced back to the 1940s [60]. In recent years AAS cement and concrete have received great attention worldwide, with applications in the Far East [61,62] and Europe [63–65]. A variation of AAS cement has been used in the USA since 1987 [66,67]. Today the focus is no longer on obtaining new binders, but on developing materials with sustainably high mechanical strength and other characteristics. One option to improve some special properties of AAS system is to add one or more additives into this system. Already the literature has abundant of review papers in alkali activation system [68–78]. In addition, the previous authors reviewed the opportunities and challenges of AAS system [58]; historical background, terminology, reaction mechanisms, hydration products and materials and binders manufacture [79,80]; reinforced geopolymer composites [81]; durability [82]; geopolymers with recycled aggregate [83]; effect of various chemical activators on pozzolanic reactivity [84] and the pursuit of an alternative of PC [85]. Indeed, there is no published literature review paper which reviewed the previous works carried out on AAS modified with different types of additives. However, in this investigation, the author conducted a comprehensive literature review focused on the effect of different additives on some properties of AAS system. A review on fibres, chemical admixtures, mineral admixtures and other additive materials that were added into slag in alkali activation system is presented.

## 2. Fibres

In the literature, there are few references concerning the influence of fibres on the mechanical properties of alkali-activated cements. However, the available references can be summarized as following: Bernal et al. [86] activated slag concretes with waterglass. They added steel fibres in amounts of 40 kg/m<sup>3</sup> and 120 kg/m<sup>3</sup> into the AAS concrete mixtures. They reported that the water absorption and permeable porous quantity were markedly improved with the addition of the fibres. Both splitting tensile and flexural strengths were largely improved with increasing fibre volume. On the other hand, a reduction in compressive strength with fibre incorporations was observed. Aydin and Baradan [87] studied the effects of length and volume fraction of steel fibres on the mechanical and drying shrinkage behaviour of steel fibre reinforced alkali-activated slag/silica fume (SF) mortars. Steel fibres with two different lengths of 6 mm and 13 mm, and four different volume fractions of 0.5%, 1.0%, 1.5% and 2.0% were used. The composite ratio of slag/SF was 80/20. This composite was activated with waterglass and NaOH solution. The results showed a reduction in the workability and drying shrinkage with the inclusion of fibres. As fibres content increased as the workability and drying shrinkage decreased. Compressive strength (Fig. 1) and flexural strength as well as toughness increased with the increase in fibres contents and fibres lengths (Fig. 2). Bernal et al. [88] modified AAS concretes by steel fibres. The steel fibres contents were 0%, 0.1% and 0.3%, by weight. Waterglass was used as alkaline activator. They reported that the inclusion of fibre increased the splitting tensile strength, flexural strength and toughness, at ages of 7, 14 and 28 days. Water absorption was reduced with the inclusion of fibre, at ages of 7, 14 and 28 days. 0.3% fibre content showed better performance than 0.1%.

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