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# Study of alkali activated slag as alternative pavement binder

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## HIGHLIGHTS

- An alkali activated slag (AAS) was developed as alternative pavement binder.
- The AAS has similar compressive strength with cement but higher flexible strength.
- The AAS achieved comparable after-polishing skid resistance.
- The AAS mortar reduces $CO_2$ emission to around 40% of cement counterpart.

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## ABSTRACT

The sustainable development of the building sector is an important concern of the public, industry and governments. One way to reduce the ecological footprint is to use building materials with less energy consumption and lower $CO_2$ emissions. In this study, a clinker-free cementitious binder was synthesized through an alkali activation of ground granulated blast furnace slag. Flexural and compressive strength of the resulting alkali activated slag (AAS) were measured and compared with ordinary Portland cement (OPC). The Aachen Polishing Machine (APM) equipped with real vehicle tires and a British pendulum tester was applied to assess the skid resistance of AAS and OPC after polishing. Reaction products were documented using the X-ray Diffraction (XRD) technique to explore the reaction mechanism. In addition, the equivalent $CO_2$ emission of AAS production was calculated to evaluate its environmental impact. Results show that the AAS possesses comparable after polishing skid resistance to OPC, but higher flexural strength and lower equivalent $CO_2$ emission. All these demonstrate that AAS can be used as an environmentally friendly alternative binder for concrete pavement construction.



## 1. Introduction

Roads play a crucial role in modern civilization and will continue to be a driving force in socio-economic growth by providing increased mobility for people, goods and services [19]. Though possessing several shortcomings, such as high initial costs, higher tendency to crack and more serious noise pollution than asphalt pavement, cementitious concrete is one of the most frequently used pavement binders [44]. This is partially attributed to the high stiffness and load bearing capacity, low maintenance costs as well as a long service life of concrete pavement [7]. However, the production of cement clinker is an energy-intensive process with high $CO_2$ emissions, and therefore concrete pavements are associated with a high global warming potential [17,48]. Over the years, efforts have been made to reduce the greenhouse gas emissions to promote a sustainable development of road construction. Limestone blended cement has been used in Europe for decades. Pavements using cement containing up to 10% limestone have been constructed in several states in the US [47]. According to Taylor [43], demand of ordinary Portland cement (OPC) binder can be reduced by adopting optimized aggregate gradation without sacrificing mechanical properties of the resulting concrete, but the low workability of this kind of concrete leads to a higher demand of superplasticizers. Furthermore, these concretes are less robust and the processing at varying climate conditions may be problematic [4,30]. In spite of this, work has been ongoing in

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looking for clinker-free cementitious binders, of which alkali activated slag (AAS) is a robust candidate.

AAS has received greater attention from both the academic and industrial field since the 1940s for both its comparable performance to cement binders and significant reduction of $CO_2$ emissions [39]. Metallurgical slags, particularly blast furnace slag, have long been used for AAS production [33]. The most frequently used alkaline activators are ROH, $R_2CO_3$ and $R_2O{\cdot}(n)SiO_2$, where R is an alkali metal ion such as Na or K. The reaction processes of AAS are summarized by the destruction of the precursor, and the gelation of the dissolved ions leading to a coagulation and condensation of gels [32]. Numerous researches have discussed the superior engineering properties of AAS in detail, including rapid hardening, superior strength, resistance to chemical attack and freeze-thaw, low stringent requirements on aggregate quality, etc. [50,39,32].

Benefiting from the avoidance of high temperature sintering of carbonate precursors, which is the basic process of cement manufacturing, AAS is attributed to a small environmental footprint [15,32]. Compared with OPC, the estimated $CO_2$ saving property of AAS ranges from 7% to 97%, depending on the choice of mix design, curing conditions, the OPC reference and the material supply and transport [32]. Because of the aforementioned advantageous properties, AAS is among the most mature commercially applied alternative binders for high-volume infrastructure construction [11,39,32,34].

Since the 1970s, masonry blocks, workshops, retail buildings, storehouses and drainage systems have been built in the Former Soviet, China, Belgium, Finland, etc [39,33]. Particularly in Russia, several over 20 floors' residential buildings have been constructed. An inspection of these buildings conducted in 2000 revealed that the AAS based structures were in a good condition, showing no cracks or deterioration on the surface [39]. Aside from these, there are some practices of AAS in pavement construction. A 6 km trial section of high duty road was built in Russia using the blend of OPC and $Na_2CO_3$ activated ground granulated blast furnace slag (GGBS). After 15 years in service, the trial section exhibited very good working conditions, while those built only using OPC concrete had seriously deteriorated [39,33]. According to Mithun et al. [25,26], the AAS possess better workability, higher strength and better fatigue resistance than OPC concrete. Wu [59] and Karahan [21] investigated the polishing resistance of AAS using the ball bearing method and horizontal Böhme grinding method, respectively. Both demonstrated that the AAS retains better polishing resistance than OPC. These reported practices focused on strength development and stimulated polishing resistance of AAS binders. Studies about the skid resistance of AAS under real vehicle tires are more essential in promoting the field application of AAS in pavement construction. However, to the author's best knowledge, studies about this have not yet been reported.

Skid resistance of roads, which refers to the friction between wheels and pavement surface is essential in ensuring traffic safety because it reduces the possibility of skidding and hydroplaning of vehicles [23,18,19]. The skid resistance is intrinsically a function of material mix design and surface properties ([54,55]. Studies have shown that fine aggregate containing over 25% siliceous particles is important to withstand polishing and wearing effects over a long period of time [58]. The surface texture characteristics are known as microtexture and macrotexture [23,52]. The former refers to intrinsic fine irregularities on the surface of the aggregate particles, which contain surface asperities of less than 0.5 mm in height, while the latter involves the greater asperities that are associated with the void area among aggregates [18,53,56]). In comparison with the microtexture, macrotexture is more easily handled and can directly contribute to the dispersion of accumulated water on the road surface and the prevention of hydroplaning of vehicles [23]. Methods, such as grooving, or dragging with burlap or brooms, which improve the surface texture of concrete pavement, are frequently used to enhance the skid resistance [3].

In this work, a clinker-free AAS was synthesized via alkali activation of GGBS. The workability was tested by measuring the setting time. Effects of activator concentration and liquid-to-solid ratio on flexural and compressive strength of the resulting AAS were studied and the reaction process was analyzed by X-ray powder diffraction (XRD). Since the AAS binder is developed as an alternative to OPC, a comparison with conventional OPC was made in the test program. The British pendulum tester and the Aachen Polishing Machine (APM) equipped with real vehicle tires were applied to assess the skid resistance of AAS. Considering the sustainable development of pavement, the equivalent $CO_2$ emission of AAS based paving material was calculated and compared with OPC paving. The performance with respect to mechanical properties, polishing and skid resistance, and equivalent $CO_2$ emission, was determined in a first test of the applicability of AAS binder from engineering and an environmental point of view. The XRD study is aimed to investigate the reaction property of AAS binder, which can offer insights into further optimizing the synthesized material. The findings of this work will contribute to the further optimization and application of AAS and other alkali activated materials in road construction.

## 2. Materials and methods

### 2.1. Materials

The GGBS and OPC used in this study are commercially available materials. The particle fineness was measured and represented by the Blaine specific surface area value, which was 4224 $cm^2/g$ for GGBS and 4290 $cm^2/g$ for OPC. The chemical compositions of solid precursors were measured using an X-ray fluorescence spectrometer (XRF) and are shown in Table 1. As expected, the GGBS has a higher content of $SiO_2$ and $Al_2O_3$ but a lower content of CaO than OPC. The mineral composition of the solid precursors was measured by powder XRD, quantitatively analyzed using Rietveld refinement and the Partial Or No Known Crystal Structure (PONKCS) method (details about the measurement and quantification are given in Section 2.2). As shown in Fig. 1 and Table 2, the OPC comprises the typical crystalline phases, alite, belite, tricalcium aluminate ($C_3A$) and brownmillerite. The GGBS is mainly composed of glassy structure, which is characterized by the broad hump centering at ca. 25–35 ° 2θ. Quantitative results reveal that the GGBS contains 5.1 wt% of Akermanite-Gehlenite ($Al_{0.92}Ca_2Mg_{0.54}O_7Si_{1.54}$) and 94.9 wt% of amorphous phase.

Analytical grade sodium hydroxides and deionized water were used to prepare the activation solution. The concentration of NaOH solution prepared was of 6 and 9 mol/L. Solutions were initially

**Table 1**
Chemical composition of GGBS and OPC given in % by weight.

| Parameter/Compound | OPC | GGBS |
|---|---|---|
| Loss on ignition | 1.94 | 0.47* |
| $Al_2O_3$ | 3.41 | 10.53 |
| $SiO_2$ | 19.91 | 40.28 |
| CaO | 61.29 | 34.54 |
| $Fe_2O_3$ | 4.80 | 0.39 |
| MgO | 3.72 | 8.63 |
| $P_2O_5$ | 0.19 | 0.15 |
| $TiO_2$ | 0.24 | 0.40 |
| MnO | 0.05 | 1.14 |
| $Na_2O$ | 0.15 | 0.59 |
| $K_2O$ | 0.43 | 1.62 |
| $Na_2O$-equivalent | 0.43 | 1.66 |

* Tested in protective gas atmosphere.