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# Fracture properties of alkali-activated slag and ordinary Portland cement concrete and mortar

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## HIGHLIGHTS

- Three-point bending tests were conducted on notched AAS and OPC concrete beams.
- Given the same strength, AAS concrete was found to exhibit higher fracture energy than OPC concrete.
- The ITZ of AAS concrete was found to be denser than that of OPC concrete.
- Given the same strength, AAS mortar was found to exhibit a lower fracture energy than OPC mortar.
- AAS concrete and mortar were found to have a lower elastic modulus than their OPC counterpart.

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## ABSTRACT

Three-point bending (TPB) tests were conducted on notched beams to compare the fracture properties of alkali-activated slag (AAS) concrete and ordinary Portland cement (OPC) concrete at three different compressive strength levels (30, 50 and 70 MPa). Parallel comparisons were also conducted between AAS mortar (AASM) and OPC mortar (OPCM). Load vs. mid-span deflection ($P$-$\delta$) curves, load vs. crack mouth opening displacement ($P$-CMOD) curves and load vs. crack tip opening displacement ($P$-CTOD) curves of the tested beams were obtained. The fracture energy $G_F$ and the characteristic length ($l_{ch}$) of the AAS and OPC concrete and mortar were calculated and analyzed. It was found that the $G_F$ of AAS concrete was always higher than that of OPC concrete given the same compressive strength, due to their denser and stronger interfacial transition zones (ITZs). At a compressive strength of 30 MPa, the $G_F$ of AASM was also larger than its OPC counterparts. However, the $G_F$ of AASM became lower than that of OPCM when the compressive strengths were 50 and 70 MPa, as more initial micro-cracks were formed in the AASM matrix with strength increase. In addition, the $l_{ch}$ values of AAS concrete and mortar were all smaller than those of OPC, implying that the formers were more brittle given the same compressive strengths. The elastic modulus of AAS concrete and mortar were found to be always lower than those of OPC. Microstructural observations were carried out to explain the above phenomena.



## 1. Introduction

Alkali-activated slag (AAS) cement has been widely regarded as a potential alternative to ordinary Portland cement (OPC) for two main reasons: (1) through alkali activation, industry waste such as ground granulated blast furnace slag (GGBFS), which is a byproduct of the iron industry, can be reused in an efficient way [38,28,33]; (2) the carbon footprint of AAS cement is significantly lower than that of OPC, making it a more environmentally-friendly choice [15,16,40]. AAS cement was first studied by Purdon [27], and extensive research since then has demonstrated that AAS cement exhibits similar mechanical strength to OPC [14], and even performs better in many aspects such as early strength development, durability, high resistance to chemical attack, low hydration heat and good resistance to freeze-thaw cycles [33].

Despite its many advantages, the AAS cement has a brittle nature, similar to that of OPC. Thus, an in-depth understanding of its fracture properties, such as the fracture energy and characteristic length [20,21] is a prerequisite for the safe application of AAS cement in practical structural applications. The fracture properties of concrete are generally believed to be governed by the size and angularity of the coarse aggregates, the microstructure of the paste, and the interfacial transition zone (ITZ) between the aggre-

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gates and the paste [44,39,45,13,35]. Cracks are prone to happen along the porous ITZ which is generally perceived as the weakest region in normal concrete. Hence, denser and stronger ITZ may contribute to the higher fracture consumption during crack propagation [44,19]. Many studies have been conducted on OPC concrete and mortar [20,5,6,23,42,43], but very few on the fracture properties of AAS concrete and mortar. There are only a few on alkali-activated fly ash (AAFA) systems, which might be useful for the understanding of AAS systems. Pan et al. [26] studied the fracture properties of AAFA concrete using the three-point bending (TPB) test and found that their characteristic length, elastic modulus and fracture energy were all smaller than those of OPC concrete, which had a similar compressive strength, indicating that the former was more brittle than the latter. The same results were found for AAFA paste. Sarker et al. [31] also studied the fracture behavior of heat cured AAFA concrete using the TPB test. It was found that the post-peak portions of the load-deflection curves of AAFA concrete beams were steeper than those of OPC beams. The fracture planes of AAFA concrete beams were found to be smoother than those of OPC beams. Li et al. [25] studied the fracture toughness of AAS concrete under freeze-thaw cycles and found that the fracture toughness decreased with the increase of freeze-thaw cycles.

However, AAFA systems could not completely reflect the fracture properties of AAS systems because the hydration products of AAFA are mainly N-A-S-H gel with a three-dimensional spatial structure [17], while those of AAS are C-S-H gel with lower Ca/Si ratio compared to OPC [32]. if Thus, it remains unclear AAFA and AAS concrete/mortar exhibit similar fracture behavior. To fill in this knowledge gap, a systematic comparative study is conducted on the fracture properties of AAS and OPC (both concrete and mortar) at three compressive strength levels, i.e., 30, 50 and 70 MPa. The above three strength levels were selected to represent a transition of normal to high strength concrete/mortar. TPB tests were conducted following the [29] recommendation. The fracture energy $G_F$ and the characteristic length ($l_{ch}$) were analyzed to see how the fracture properties of AAS concrete and mortar (AASM) are different from OPC concrete and mortar (OPCM). Microstructural analyses were also conducted to interpret the mechanism responsible for the observed differences.

## 2. Experiment program

### 2.1. Raw materials

#### 2.1.1. GGBFS

GGBFS used in this study was produced by Meibao New Building Materials Co. in Nanjing, China. Its chemical compositions were obtained from the X-ray fluorescence (XRF) analysis and are listed in Table 1. Fig. 1 shows the particle size distribution of the GGBFS, which is mainly in the range of 0.4–100 μm. The morphology of GGBFS particles observed by the scanning electron microscope (SEM) is shown in Fig. 2, which illustrates that the particles are predominately of anomalous shape with clear edges and angles.

#### 2.1.2. Alkali activator

The alkali activator liquid used was a combination of sodium silicate solution and sodium hydroxide. The sodium silicate solution was a commercially available product with a water content of 59% (by mass) and a modulus (the mole ratio of $SiO_2$ to $Na_2O$) of 3.7. The modulus of the alkali activator was further adjusted to the designed values by adding sodium hydroxide (NaOH) flakes with 99% purity, which was purchased from the Tianjin Bohai Chemical Industry, China.

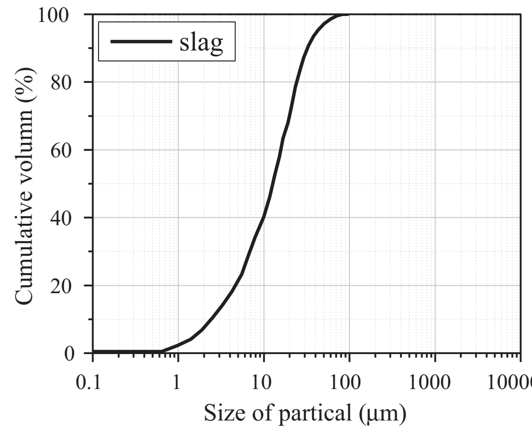


**Fig. 1.** Particle size distribution of GGBFS.

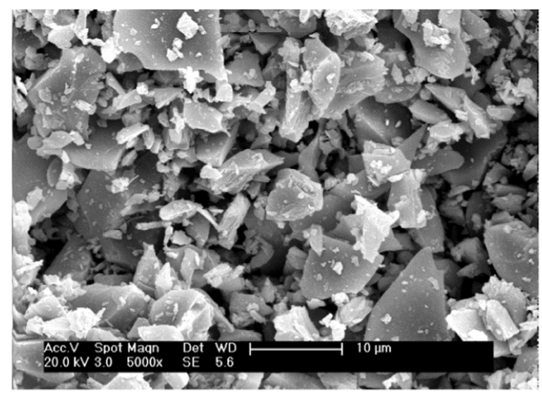


**Fig. 2.** Morphology of GGBFS particles.

#### 2.1.3. Portland cement

OPC produced by the Anhui Conch Cement Company, China with a specific surface area of 336 $m^2/kg$ and loss on ignition of 1.62% was used in this research. Its chemical compositions are also indicated in Table 1.

#### 2.1.4. Fine aggregate and coarse aggregate

Gravel from local river were used as the coarse aggregate whose bulk specific density was 2530 $kg/m^3$ with a maximum size of 10 mm. The water absorption of the coarse aggregate was 1.83%. The fine aggregate used was natural, uncrushed river sand. Its specific density, absorption, and fineness modulus were 2340 $kg/m^3$, 2.75% and 2.47, respectively.

**Table 1**
Chemical composition of GGBFS and OPC (% by mass).

| | CaO | $Al_2O_3$ | $SiO_2$ | $SO_3$ | $P_2O_5$ | MgO | $Na_2O$ | $K_2O$ | LOI* |
|---|---|---|---|---|---|---|---|---|---|
| Slag | 33.3 | 16.9 | 33.4 | 2.35 | 3.77 | 7.0 | 2.0 | 0.16 | 1.05 |
| Cement | 65.1 | 4.81 | 21.9 | 0.51 | – | – | 0.65 | – | 1.62 |

* Loss on ignition.