

# Effect of Blain Fineness of Slag on the Compressive Strength Development of Alkali-Activated Slag Mortars

Keun-Hyeok Yang<sup>1</sup>, Seung-Jin Oh<sup>2</sup>, and Jin-Kyu Song<sup>3</sup>

<sup>1-2</sup>Mokpo National University, Chonnam, South Korea

<sup>3</sup>Chonnam National University, Gwangju, South Korea

**ABSTRACT:** Ten cementless slag-based mortars activated by combination of sodium silicate and sodium hydroxide powders were mixed and tested. The main variables were the mixing ratio of sodium oxide ( $\text{Na}_2\text{O}$ ) of the activators to GGBS by weight, and the blain fineness of the GGBS. The hydration products and microstructural characteristics of the mortars tested were also investigated using X-ray diffraction (XRD) analysis, energy-dispersive X-ray (EDX) analysis, and scanning electron microscope (SEM) image. Test results showed that the compressive strength of alkali-activated mortars increased with the increase of blain fineness of GGBS. From the XRD and EDX analyses, a calcium silicate hydrates (CSH) gel was detected as the main hydration product showing that the molar Si/Ca ratio in the CSH gels is independent of the fineness of GGBS.

**Keywords:** alkali-activated mortar, slag, blain fineness, compressive strength.

## 1. INTRODUCTION

The reduction of greenhouse gas (GHS) emissions is one of the hottest issues all over the world. The Kyoto Protocol has aimed for a 5.2% lower emission amount of GHS between 2008 and 2012 compared with that in 1990. It is generally estimated that the amount of GHS emitted from the worldwide production of ordinary Portland cement (OPC) corresponds to approximately 7% of the total GHS emissions into the Earth's atmosphere [1]. A large proportion of the concrete industry is very interested in reducing GHS emissions. In an effort to minimize carbon dioxide emissions, the concrete industry has invested considerable expense and labor to develop concrete and mortar partially replaced with by-product materials, such as fly-ash (FA), and ground granulated blast-furnace slag (GGBS).

Another active effort is development of cementless paste synthesized from FA or

GGBS as a source material and an alkaline inorganic material as an activator. There has been a significant increase in the number of studies into GGBS-based alkali-activated binders [2-3]. Although there are several important questions remained on the mechanism of alkali activation process, sodium hydroxide solution or sodium silicate solution is generally said to be a good application as an activator [2-3].

This paper reports the results of tests on the ten alkali-activated cementless mortars and a control OPC mortar to explore the significance and shortcomings of a binder using a powder typed activator. GGBS was used as the source material, and sodium silicate powder and sodium hydroxide powder were selected as the alkaline activator. The main variables investigated were the mixing ratio of sodium oxide ( $\text{Na}_2\text{O}$ ) of the activators to source material by weight, and the Blain fineness of the GGBS. The flow loss and compressive

strength development of the mortars tested were evaluated according to the alkali quality coefficient combining the amounts of the main compositions in the source materials and the molar silicate oxide ( $\text{SiO}_2$ ) to sodium oxide ( $\text{Na}_2\text{O}$ ) ratio of the activator used. The hydration products and microstructural characteristics of the alkali-activated pastes sampled from the mortars tested are also presented to determine the effect of the fineness of the source material on the compressive strength of the alkali-activated mortar.

## 2. EXPERIMENTAL DETAILS

### 2.1 Materials

Ground granulated blast-furnace slag (GGBS) was used as the source material. The Blain fineness of the GGBS that is locally and commercially available was 4000  $\text{cm}^2/\text{g}$ , 6000  $\text{cm}^2/\text{g}$ , and 8000  $\text{cm}^2/\text{g}$  classes. The measured actual Blain fineness of the GGBS was 4204, 6150, and 8167  $\text{cm}^2/\text{g}$ . The particle distribution and the specific gravity of the GGBS were also tested. The maximum and average sizes of the source materials used decreased with the increase of Blain fineness as shown in Fig. 1. The maximum and average sizes of the GGBS with a Blain fineness of 4204, 6150 and 8167  $\text{cm}^2/\text{g}$  were 76.3  $\mu\text{m}$  and 15.5  $\mu\text{m}$ , 51.6  $\mu\text{m}$  and 8.5  $\mu\text{m}$ , and 23.6  $\mu\text{m}$  and 5.1  $\mu\text{m}$ , respectively. The specific gravities of the GGBS with a Blain fineness of 4204, 6150, and 8167  $\text{cm}^2/\text{g}$  were 2.93, 2.98, and 2.94, respectively, which indicates that the specific gravity of GGBS is independent of its Blain fineness.

Table 1 gives the chemical composition

of the source materials measured from X-ray fluorescence (XRF) analysis, and Table 2 shows the molar ratios of the major element in the source materials used determined by energy-dispersive X-ray (EDX) analysis. The GGBS was composed mainly of calcium, silicon, alumina and magnesium oxides, which indicates that the chemical composition of GGBS is independent on its Blain fineness. The molar silica-to-alumina, calcium-to-alumina and silica-to-calcium ratios of the used GGBS were approximately 2.35, 4.46, and 0.52, respectively.

Sodium silicate powder and sodium hydroxide powder, which are commercially available in South Korea, were used as the activator. The sodium silicate powder was a compound of 50.2 % sodium oxide ( $\text{Na}_2\text{O}$ ) and 45 % silicon oxide ( $\text{SiO}_2$ ), producing a molar ratio of 0.9.

Locally available sand was used as the fine aggregate in saturated surface-dried condition. The specific gravity, grading and maximum size of the sand used were 2.54, 2.97 and 5mm, respectively.

### 2.2 Mixing Design

Table 3 refers to the mixing details of

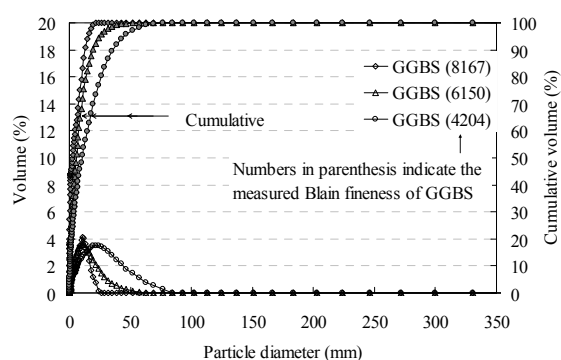


**Figure 1:** Particle distribution of GGBS.

**Table I:** Chemical composition of GGBS

| Materials | Blain fineness ( $\text{g}/\text{cm}^2$ ) | $\text{SiO}_2$ | $\text{Al}_2\text{O}_3$ | $\text{Fe}_2\text{O}_3$ | $\text{CaO}$ | $\text{MgO}$ | $\text{K}_2\text{O}$ | $\text{TiO}_2$ | $\text{SO}_3$ | LOI* |
|-----------|-------------------------------------------|----------------|-------------------------|-------------------------|--------------|--------------|----------------------|----------------|---------------|------|
| GGBS      | 4204                                      | 34.70          | 13.80                   | 0.11                    | 44.60        | 4.38         | 0.48                 | 0.74           | 0.95          | 0.24 |
|           | 6150                                      | 33.80          | 12.90                   | 0.03                    | 45.60        | 4.70         | 0.42                 | 1.50           | 0.69          | 0.36 |
|           | 8167                                      | 33.10          | 13.60                   | 0.11                    | 46.30        | 3.86         | 0.57                 | 1.02           | 1.10          | 0.34 |

\* Loss on ignition.

the different designed mortars. The compressive strength of the GGBS-based alkali-activated mortar was greatly influenced by the ratio of sodium oxide ( $\text{Na}_2\text{O}$ ) of the activator to the source material (SM) by weight, and the type and fineness of the GGBS as showed by Wang et al.[3]. The amount of sodium silicate powder mixed was selected to have a  $\text{Na}_2\text{O}$  of sodium silicate to SM ratio of either 0.038 or 0.09. Sodium hydroxide powder was added to control the molar ratio ( $\text{SiO}_2/\text{Na}_2\text{O}$ ) of the sodium silicate. The designed  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio was 0.55, 0.75 and 0.85. Considering the molecular weight for both sodium oxide and sodium hydroxide, 1.0 mole of sodium hydroxide can be converted into 0.5 moles of sodium oxide. As a result, the ratios of  $\text{Na}_2\text{O}$  obtained from combination of sodium silicate and sodium hydroxide powders added to the SM by weight ranged from 0.023 to 0.079 as given in Table 3.

The designed initial flow and 28-day mortar were 150 mm and 40 MPa, respectively. A water-binder ratio (W/B) of

50% and fine aggregate-binder ratio (S/B) of 3.0 were used for all mortar mixes tested. No water-reducing admixture was added to the mortar mixes.

### 2.3 Casting and Testing

The source material, sodium silicate, sodium hydroxide and fine aggregate were dry-mixed in a mixer pan for 30 seconds, and water was then added and mixed for a further 30 seconds. After testing for the initial flow, each mix was poured in various steel moulds to measure the compressive strength. Immediately after casting, all the specimens were cured at a constant temperature and relative humidity of  $23 \pm 2^\circ\text{C}$  and  $70 \pm 5\%$ , respectively, until they were tested at a specified age.

The flow of different mortars was measured at 0 (initial), 30, 60, 90 and 120 minutes after mixing to determine the flow loss against the elapse of time. Cubes of 50 mm in size were used to evaluate the compressive strength of the different mortar specimens in a Universal Testing Machine (UTM) with a capacity of 200 kN. The

**Table II:** Molar ratios of the major element of GGBS

| Materials | Blain fineness (g/cm <sup>2</sup> ) | Si/Al | Ca/Al | Si/Ca | Mg/Al | Mg/Ca | Mg/Si |
|-----------|-------------------------------------|-------|-------|-------|-------|-------|-------|
| GGBS      | 4204                                | 2.3   | 4.52  | 0.51  | 0.25  | 0.05  | 0.11  |
|           | 6150                                | 2.38  | 4.65  | 0.51  | 0.19  | 0.04  | 0.08  |
|           | 8167                                | 2.37  | 4.22  | 0.56  | 0.16  | 0.04  | 0.07  |

**Table III:** Details of the mortar mixes tested.

| Specimen No. | S.M.* | $\text{Na}_2\text{O}/\text{S.M.}$ | Blain fineness (cm <sup>2</sup> /g) | $Q_A^\#$ | Unit weight (kg/m <sup>3</sup> ) |                 |                  |       |      |
|--------------|-------|-----------------------------------|-------------------------------------|----------|----------------------------------|-----------------|------------------|-------|------|
|              |       |                                   |                                     |          | Binder                           |                 |                  | Water | Sand |
|              |       |                                   |                                     |          | S.M.                             | Sodium Silicate | Sodium hydroxide |       |      |
| 1            | OPC   | -                                 | -                                   | -        | 500.4                            | -               | -                | 250.2 | 1501 |
| 2            | GGBS  | 0.023                             | 4204                                | 0.01035  | 479.1                            | 14.1            | 4.9              | 244.1 | 1465 |
| 3            |       | 0.027                             | 4204                                | 0.01169  | 460.4                            | 20.7            | 2.6              | 243.7 | 1462 |
| 4            |       | 0.027                             | 6150                                | 0.01175  | 460.4                            | 20.7            | 2.6              | 243.7 | 1462 |
| 5            |       | 0.027                             | 8167                                | 0.01308  | 460.4                            | 20.7            | 2.6              | 243.7 | 1462 |
| 6            |       | 0.031                             | 4204                                | 0.01294  | 450.7                            | 27.6            | 0.4              | 243.3 | 1460 |
| 7            |       | 0.054                             | 4204                                | 0.02130  | 451.9                            | 31.8            | 11.1             | 240.6 | 1444 |
| 8            |       | 0.066                             | 4204                                | 0.02304  | 429.7                            | 47.6            | 5.9              | 239.8 | 1439 |
| 9            |       | 0.066                             | 6150                                | 0.02306  | 429.7                            | 47.6            | 5.9              | 239.8 | 1439 |
| 10           |       | 0.066                             | 8167                                | 0.02559  | 429.7                            | 47.6            | 5.9              | 239.8 | 1439 |
| 11           |       | 0.079                             | 4204                                | 0.02433  | 407.6                            | 63.3            | 0.8              | 238.9 | 1433 |

\* In source material (S.M.) column, OPC, FA and GGBS refer to ordinary portland cement, fly ash, and ground granulated blast-furnace slag, respectively.

compressive strengths of the mortars were measured at 1, 3, 7, 28, 56 and 91 days so that the gain in strength with age could be investigated. The test procedures of the flow and compressive strength were carried out according to the specifications of the Korean Industrial Standard [4] for testing OPC mortar.

### 3. TEST RESULTS AND DISCUSSION

Although the evidence for the alkali activation mechanism is still unclear and several important questions remain unanswered, Yang et al. [5] ascertained that an alkali quality coefficient  $Q_A$  can be a more effective index for evaluating the properties of mortar activated by sodium silicate powder. In the present study, flow loss and compressive strength gain are examined according to  $Q_A$ .

#### 3.1 Flow Loss

The flow of the different mortars tested was decreased linearly with time, regardless of  $\text{Na}_2\text{O}$ -to-SM ratio. The flow  $F$  of specimens having a  $Q_A \geq 0.0231$  and a fineness of the source material  $\geq 6000 \text{ cm}^2/\text{g}$ , after 60 minutes could not be measured due to the rapid setting. The relative flow of the fresh mortars against the elapsed time can be expressed approximately as follows:

$$\frac{F}{F_i} = kT + 1 \quad (1)$$

where  $F_i$  is the initial flow,  $T$  is the elapsed time in minute, and  $k$  is the rate of flow loss, which can be determined from a least-square regression analysis of the test results. Fig. 2 shows the effect of the alkali quality coefficient  $Q_A$  on the rate of flow loss  $k$  of the different mortar mixes tested. The rate of flow loss increased with the increase of  $Q_A$ , indicating that a larger amount of both  $\text{Na}_2\text{O}$  in the alkaline activators and calcium content in the source materials can significantly reduce the workability of fresh mortars with time.

Therefore, increasing the amount of sodium silicate and sodium hydroxide powders would result in AA mortars with poor workability. In addition, for the GGBS-based AA mortar with the same  $\text{Na}_2\text{O}$ -to-SM ratio, the decreasing rate of flow accelerated significantly with the increase of the fineness of the source material. The rate of flow loss of the AA mortar with  $Q_A \geq 0.00213$  was higher than that of the control OPC mortar.

#### 3.2 Compressive Strength at 28-days

The relative compressive strength at 28 days of the AA mortars  $f'_c / (f'_c)_c$  commonly increased with the increase of  $Q_A$  as shown in Fig. 3, where  $(f'_c)_c$  is the 28-day compressive strength of the control OPC mortar. The  $f'_c$  of the alkali-activated mortars with a  $Q_A$  of 0.023 was comparable to that of the control OPC mortar. In addition, for the GGBS-based AA mortars with the same  $\text{Na}_2\text{O}$ -to-SM ratio, increasing the GGBS fineness from  $4204 \text{ cm}^2/\text{g}$  to  $8167 \text{ cm}^2/\text{g}$  led an increase in compressive strength by 41 % and 16 % for a  $\text{Na}_2\text{O}$ -SM ratio of 0.027 and 0.066, respectively. This study clearly showed that the optimum fineness to enhance the compressive strength of the GGBS-based mortars activated by the sodium silicate and sodium hydroxide powders would be at least  $8167 \text{ g/cm}^2$ , even though a higher GGBS fineness leads to sharp loss of workability of the mortars.

#### 3.3 Hydration Products

The hydration products of AA pastes can be generally traced using X-ray diffraction (XRD) and EDX analysis combined with scanning electron microscope (SEM) image. Figures 4 and 5 show the XRD patterns and microstructural characteristics, respectively, of the AA pastes according to the fineness of the source material at a  $\text{Na}_2\text{O}$ -to-SM ratio of 0.066. The AA pastes were sampled from the mixed AA mortars and examined by SEM. In the GGBS-based pastes activated

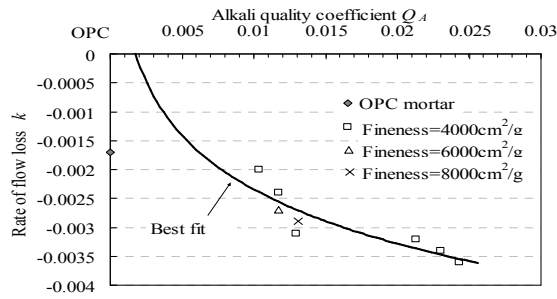


**Figure 2:** Influence of  $Q_A$  on  $k$

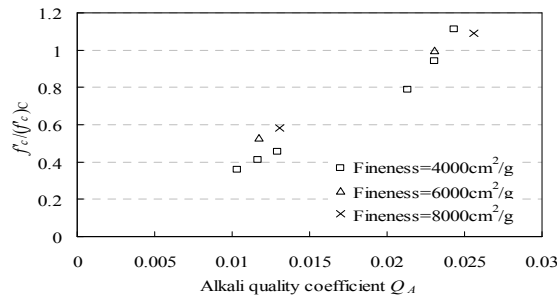


**Figure 3:** Influence of  $Q_A$  on relative strength of AA mortars tested.

by a combination of sodium silicate and sodium hydroxide, a calcium silicate hydrates (CSH) gel was detected as the main hydration product, regardless of the fineness of the GGBS as shown in Fig. 4. The microstructural characteristics of the GGBS-based AA pastes tested were influenced significantly by the fineness of the GGBS. Most voids between the slag particles were filled with coagulated products, indicating that the AA pastes using GGBS with a higher fineness had a lower porosity and fewer unhydrated particles as shown in Fig. 5, which in turn affects the strength development of the AA mortar. In the CSH gels produced from the alkali-activated GGBS, EDX analysis showed that molar Si/Ca ratios for the GGBS fineness of 4204, 6105, and 8167  $\text{cm}^2/\text{g}$  were 0.76, 0.79, and 0.75, respectively, which indicates that the molar Si/Ca ratio in the CSH gels is independent of the fineness of GGBS.

### 3.4 Compressive Strength Development

Fig. 6 shows the typical compressive strength development of an AA mortar tested against age according to the main variables. The rates of compressive strength development of the GGBS-based mortar

activated by combination of sodium silicate and sodium hydroxide powders at both early and long-term ages increase with the increase of  $Q_A$ , whereas a higher fineness of the source material increased the rate of compressive strength development at an early age but reduced the rate of compressive strength development at the long-term age. In particular, much higher strength at the early age was developed in GGBS-based AA mortars than in OPC mortar, indicating that increasing  $Q_A$  and the fineness of GGBS improves the strength of the AA mortars at an early age.

## 4. CONCLUSION

1) The decreasing rate of flow against the elapsed time was increases with the increase of alkali quality coefficient.

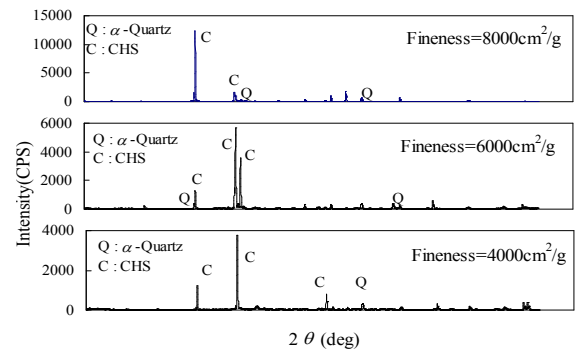
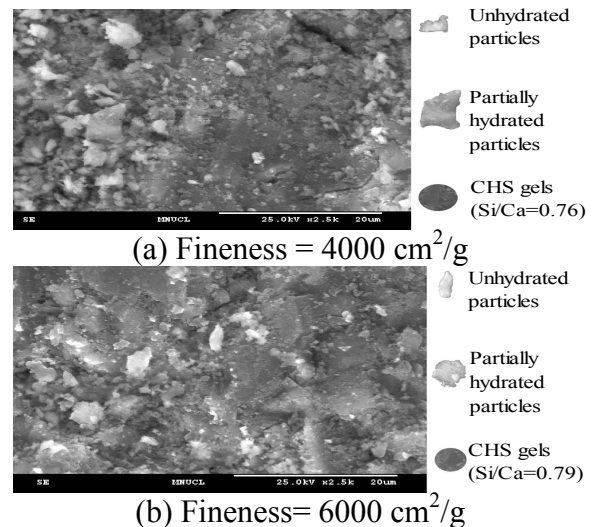


**Figure 4:** XRD patterns of the AA pastes with a  $\text{Na}_2\text{O}$ -to-SM ratio of 0.066.



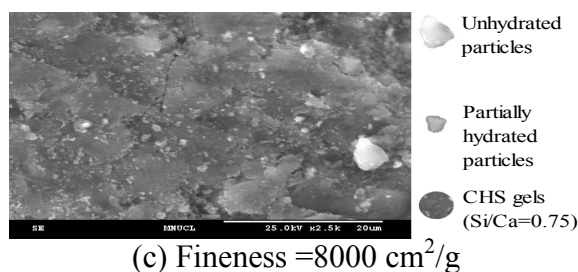
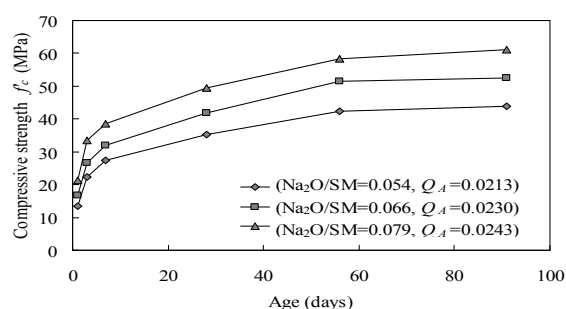
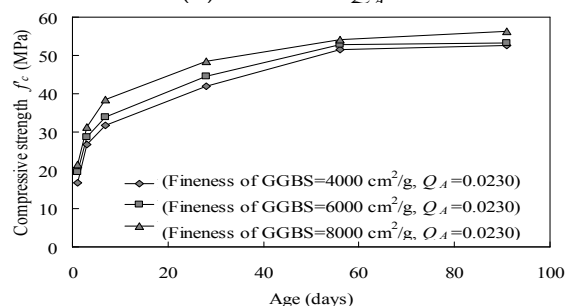


**Figure 5:** Microstructure of AA pastes with a  $\text{Na}_2\text{O}/\text{SM}$  ratio of 0.066.



(a) Effect of  $Q_A$



(b) Effect of fineness of GGBS

**Figure 6:** Compressive strength development of AA mortars tested.

2) The relative compressive strength at 28 days of the AA mortars tested commonly increased with the increase of alkali quality coefficient and the fineness of GGBS. The 28-day compressive strength of the AA mortars having an alkali quality coefficient of 0.023 was comparable to that of the control OPC mortar.

3) The optimum fineness to enhance the compressive strength of the GGBS-based mortars activated by sodium silicate and sodium hydroxide powders was at least  $8167 \text{ g/cm}^2$ , even though a higher GGBS fineness leads to sharp decrease in the workability of the mortars.

4) The main hydration product in the GGBS-based AA pastes tested was calcium

silicate hydrates (CSH) gel with a molar silica-to-calcium (Si/Ca) ratio of approximately 0.76, regardless of the fineness of the GGBS.

5) A higher fineness of the GGBS increased the rate of compressive strength development at an early age but reduced the rate of compressive strength development at the long-term age.

## ACKNOWLEDGEMENT

This work was supported by the National Research Institute of Cultural Heritage and the Regional Research Centers Program (Bio-housing Research Institute), granted by the Korean Ministry of Education & Human Resources Development. The authors wish to express their gratitude for financial support.

## REFERENCES

- [1] Malhotra, V.M. 2002. Introduction: sustainable development and concrete technology. Concrete International. Vol 24. No 7. 22 pp.
- [2] Pchecho-Torgal, F, Castro-Gomes, J, & Jalali, S. 2007. Alkali-activated binders: A review. Part 2. About materials and binder manufacture. Construction and Building Materials. Doi:10.1016/j.conbuildmat.2007.03.019.
- [3] Wang, S.D, Pu, X.C, Scrivener, K.L & Pratt, P.L. 1995. Alkali-activated slag cement and concrete: a review of properties and problems. Advances in Cement Research. Vol 27. pp.93-102.
- [4] Korean Standards Information Center. 2006. Korean industrial standard. South Korea.
- [5] Yang, K.H, Song, J.K, Ashour, A.F, & Lee, E.T. 2007. Properties of cementless mortar activated by sodium silicate, Construction and Building Materials. doi:10.1016 /j.conbuildmat.2007.07.003.