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# Analysis of geometric characteristics of GGBS particles and their influences on cement properties

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**Abstract**

This paper presents an investigation into the geometric characteristics of different ground granulated blast furnace slag (GGBS), including particle size distribution (PSD), shape and their influences on cement properties. Samples of GGBS with different PSDs are prepared using in three processing approaches, a ball mill, an airflow mill and a vibromill. The morphology of GGBS and the PSD is studied, respectively, with scanning electron microscope (SEM) and laser particle analyzer (LPA). The results indicate that the PSD of GGBS processed by an airflow mill is concentrated on a narrow range, whereas the size of GGBS made by a ball mill are distributed in a large range. The morphology of GGBS processed by a vibromill is mostly spherical and its surface is very smooth. The results also show that when GGBS has a similar surface area, the strengths of cement mortar, in which 50% cement is replaced by GGBS, are related to PSD of the GGBS. The early strength of sample containing GGBS processed by a ball mill is higher than that by an airflow mill, whereas the long-term strength of this mix is lower. When 0.05% ZS grinding assistant agent is added into the ball mill, the output of the ball mill increases by 18%, the fluidity of mortar containing GGBS is greatly improved and the fluidity ratio reaches to 106. Strengths of the mortars, consisting of 50% cement and 50% GGBS with and without grinding assistant agent, are similar.


*Keywords:* Grinding; Particle size distribution; SEM; Compressive strength

## 1. Introduction

It is known that granulated blast furnace slag (GBS) possesses a latent hydraulic property. The performance and application of ground granulated blast furnace slag (GGBS) have been studied for many years [1–3]. As an active additive, GGBS is widely applied in cement and concrete, especially in high-performance concrete (HPC). The main reason is that it possesses active, shape and microaggregate effects [4]. At the same composition of GBS, grinding techniques are a chief factor that affects particle geometric characteristics of GGBS.

For a long time, ball mills have commonly been used as the grinding equipment. But their energy efficiency is only about 2–5%, and most energy is converted into heat and dissipates into air [5]. Since the last decade, grinding techniques have been developed rapidly and made delightful achievements. Many types of mills have been invented, such as vertical roller mills, squeezing mills, roller mills, airflow mills and so on. These mills greatly decrease the energy consumption and remarkably improve the grinding efficiency [6]. However, the particles geometric characteristics of ground products, such as particle size distribution (PSD), gradation and shape change accordingly. Hence, GGBS with a same surface area but made by different grinding techniques can have different performance when it is used as cement additives.

This research aims at investigating the effects of morphology, PSD of GGBS on the fluidity and the strength of cement mortar. For this purpose, different grinding procedures are designed and performed, and the morphology and PSD are analyzed with scanning electron microscope (SEM) and laser particle analyzer (LPA), respectively.

## 2. Experiments

### 2.1. Raw materials

The chemical compositions of the clinker, gypsum and GGBS are listed in Table 1. Portland cement is composed

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Table 1
The chemical compositions of clinker, gypsum and GGBS (wt.%)

| | $SiO_2$ | CaO | $Fe_2O_3$ | $Al_2O_3$ | MgO | f-CaO | $SO_3$ | $TiO_2$ | MnO | LOI | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GGBS | 34.70 | 36.81 | 1.02 | 14.95 | 10.45 | / | 0.07 | 0.38 | 0.39 | 0.61 | 99.38 |
| Clinker | 22.15 | 64.74 | 4.48 | 5.47 | 1.03 | 0.86 | 0.52 | / | / | 0.41 | 99.66 |
| Gypsum | 4.08 | 30.26 | 0.46 | 1.65 | 1.50 | / | 40.17 | / | / | 21.05 | 99.17 |

of 96% clinker and 4% gypsum and its surface area is 320 $m^2$/kg.

### 2.2. Preparation of GGBS

All samples of GGBS come from the same batch of GBS. Sample A is prepared by a $\phi 2.2 \times 6.5$ m industrial ball mill with open circuit, using steel balls as grinding medium. Sample B is made by a laboratory vibromill, which is composed of a driving device and a round steel vessel of filled samples. In the vessel of filled samples, there is a steel cylinder and a steel ring for crushing materials. Sample C is processed by an industrial airflow mill made by Alpine, Germany. Sample D comes from an identical ball mill that is used to process Sample A. In order to improve the output of a ball mill, 0.05% ZS grinding assistant agent is added into it.

### 2.3. Methods

The surface areas of GGBS are determined by the Blaine air permeability method, the PSD of GGBS is analyzed with LPA (Malvern Mastersiszer 2000) and the morphology of GGBS is observed with SEM. The activity index is measured by the compressive and/or flexural strength ratio of the tested samples to the reference sample. The fluidity ratio is determined by the fluidity ratio of the tested samples to the reference sample. The weight proportion of a tested sample is Portland cement/GGBS/standard sand/water = 270:270: 1350:238. The weight proportion of the reference sample is Portland cement/standard sand/water = 540:1350:238. GGBS and Portland cement are premixed for 8 h in an automatic mixer. The strength and fluidity of cement mortar are determined in accordance with Chinese Standard GB177 and GB 2419, respectively.

## 3. Results and discussions

### 3.1. The morphological characteristics of GGBS

SEM images of samples A–D are shown in Figs. 1–4, respectively. It is seen that the shape of GGBS is not really spherical; it varies according to different grinding techniques. It is known that GBS is mainly composed of glassy phases, which are in a continuous network structure, and there is no stress concentration in the interfacial area; thus, grinding GBS leads to the disconnection of bonds between molecules and atoms. When slag particles are broken, the shape of the broken surface is not fixed. Figs. 1 and 4 are the appearance of GGBS processed by a ball mill, which is predominately in anomalous shape with clear edges and angles. This is due to interimpacting and interrubbing between steel balls in the ball mill. The purpose of adding 0.05% ZS grinding assistant agent into the ball mill is to disperse particles of GGBS packed on the steel balls, to avoid an overgrinding phenomenon and thus to improve grinding efficiency. The experimental results indicate that the output of a ball mill is increased by 18% at the same surface area of GGBS after the addition of the grinding assistant agent. Fig. 2 shows that the shape of GGBS is mostly in sphericity and its surface is relatively smooth. The

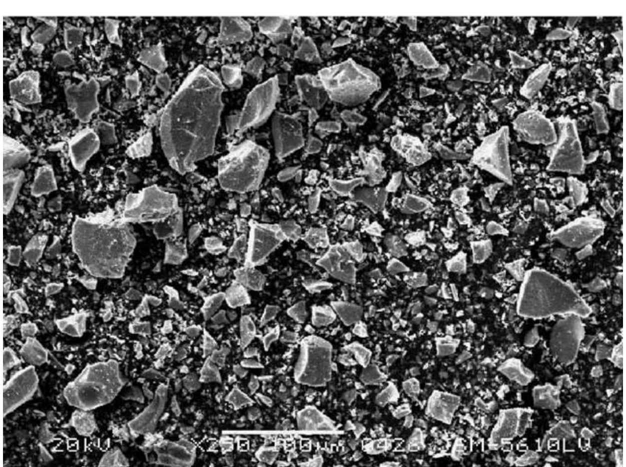


Fig. 1. SEM photograph of sample A.


Fig. 2. SEM photograph of sample B.

Fig. 3. SEM photograph of sample C.

reason for this phenomenon is that GBS is crushed by the interaction between a steel cylinder and a steel ring and that between a steel ring and a vessel wall; in addition, this increases the probability of interrubbing between particles and leads to smooth edges and angles of particles. Fig. 3 shows that the GGBS sample has the most uniform particle size, and the particle appearance is similar to sample A. This has much to do with the working mechanism of airflow mills. When an airflow mill is working with a high-speed air current, particles collide severely with fixed manganese-steel boards, and this leads to pulverization and thus decreases the probability of contacts between particles.

### 3.2. The PSD of GGBS

In the powder engineering, the PSD can be expressed by a normal distribution function, a logarithmic distribution function and a Rosin–Rammler–Bennett distribution function (i.e., RRB equation). For small grains and wide distribution, RRB is generally preferred because PSD is the most reasonable and the error is the least one for analyzing experimental results [3,7]. RRB equation is expressed as follows:

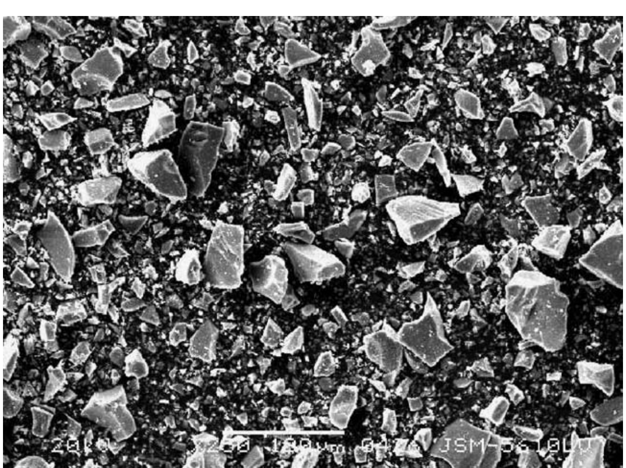

Fig. 4. SEM photograph of sample D.

Table 2
The surface areas ($m^2$/kg) and average diameter (μm) of GGBS

| | A | B | C | D |
|---|---|---|---|---|
| S($m^2$/kg) | 510 | 685 | 515 | 512 |
| D (μm) | 13.69 | 9.12 | 11.72 | 13.15 |

$$R = 100e^{-\left(\frac{x}{x_0}\right)^n} \quad (1)$$

where $R$ is a cumulative percentage retained on an $x$-μm mesh (%); $x_0$ is called the characteristic grain size. It corresponds to the grain size of cumulative percentage retained on 100/e (μm); $x$ is the size of a mesh (μm); $e$ is the base of a natural logarithm (2.718); $n$ is an index. It is called the uniformity coefficient.

After double natural logarithms at both sides of Eq. (1) are taken simultaneously, Eq. (1) is converted into the following form:

$$\ln\left(\ln\frac{100}{R}\right) = n \ln x - n \ln x_0 \quad (2)$$

Let:

$$Y = \ln\left(\ln\frac{100}{R}\right) \quad X = \ln x \quad b = -n \ln x_0$$

Then, Eq. (2) can be turned into the following linear equation:

$$Y = nX + b \quad (3)$$

where the value of $n$ is a linear slope. It expresses a uniformity coefficient. The larger it is, the more uniform PSD is, i.e., the particles distribute in a small size range. In Eq. (1), the larger the value of $x_0$ is, the higher the proportion of a coarse particle is.

The surface areas, the average sizes and PSDs of GGBS are shown in Tables 2 and 3, respectively. To judge directly PSD of GGBS by means of the above method, the results in Table 3 can be schematically shown in Fig. 5. From Fig. 5, it is seen that the slope of sample C, the value of $n$, 1.38, is the largest and that of sample A, 0.72, is the smallest. This means that the PSD of sample C processed by an airflow

Table 3
The PSDs of GGBS (%)

| Sample | Range of particle size/μm | | | | | | |
|---|---|---|---|---|---|---|---|
| | < 3.0 | 3.0–5.0 | 5.0–10.0 | 10.0–20.0 | 20.0–40.0 | 40.0–60.0 | >60.0 |
| A | 5.26 | 3.80 | 14.35 | 25.03 | 32.52 | 18.11 | 0.93 |
| B | 8.35 | 6.14 | 28.44 | 36.80 | 18.69 | 1.58 | 0 |
| C | 3.56 | 3.04 | 23.02 | 48.36 | 18.02 | 0 | 0 |
| D | 3.18 | 2.96 | 15.78 | 27.24 | 35.45 | 15.39 | 0 |

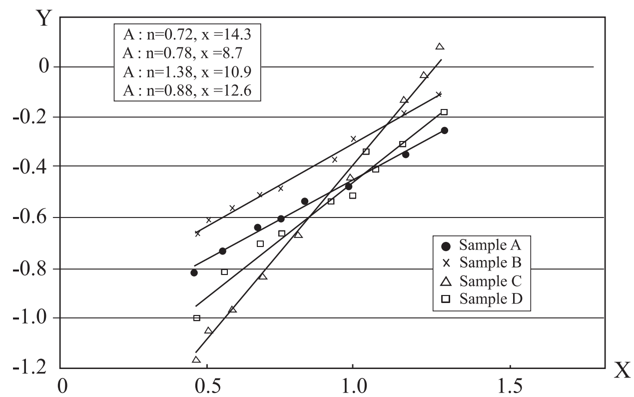


Fig. 5. The PSDs of particles.

mill is very uniform. PSD of sample A processed by a ball mill exhibits a wide PSD. The characteristic grain size of sample A, the value of $x_0$, 14.3, is the largest and that of sample B, 8.7, is the smallest. This indicates that the proportion of coarse grains of sample A is high, while that of sample B is low.

### *3.3. Activity of GGBS*

The activity of GGBS is evaluated by determining the compressive strength of hydrated mortar of cement containing GGBS. Although the cementitiousness of GGBS is much weaker than that of Portland cement, GGBS may take a micro-crystal-core effect for a cement hydration system. GGBS is activated in an alkaline environment; this is of great advantage to decrease hydration products of cement, $Ca(OH)_2$, which furthers accelerating the process of cement hydration reaction. At the same time, GGBS may provide enough space for hydration products to be distributed uniformly [4]. The results in Table 4 indicate that the flexural and the compressive strengths increase with the increase of the surface area of GGBS. Previous research work [4,5,7] shows that GGBS with a particle diameter of less 3 μm just contributes to early strengths of mortar, GGBS with a particle diameter of 3–20 μm is advantage for long-term strengths of mortar and GGBS with other particle diameters only have a microaggregate effect. The results in Tables 2 and 4 show that samples A and C share nearly the same surface area. But a 7-day compressive strength of sample A is just 0.4 MPa higher than that of sample C, while a 28-day compressive strength is 3 MPa lower because their PSDs are different. Sample A has more fine particles. The strengths of samples A and D are approximately equal.

### *3.4. Influence of GGBS on the fluidity of mortar*

At an initial stage of cement hydration, GGBS particles are packed uniformly on surface of cement particles, which retard and decrease mutual combination of early hydration products, and this is somewhat similar to the effect of water reducer and increases the fluidity of mortar [4].

The influence of GGBS on the fluidity of mortar is shown in Table 4. The fluidity of sample D is much better than that of sample A. It is the same as that of sample B. This is because that sample D is added with a grinding assistant agent, which is of great advantage to improving the fluidity of mortar. It has been discussed that the fluidity of mortar increases with the increase of the surface areas of GGBS [8]. The fluidity of mortar is related with the PSD of GGBS. At the same surface area of GGBS, the narrower is PSD of GGBS, the larger is the fluidity of mortar. For example, sample A is different from sample C. Apart from the surface area of GGBS, theoretically, the fluidity of mortar is associated with the morphological characteristics of the GGBS particles. The smoother the surface of particles is, the better the fluidity of mortar is. But the results in Table 4 show that the influence of shape of GGBS on the fluidity of mortar is not remarkable. The reason is that all particle size of GGBS is too small. This trend is in agreement with that of previous investigators such as Olorunsogo [9] and Jiang [4].

## 4. Conclusions

1. Even though the surface areas of GGBS are the same, both the geometric characteristics and the PDS can be different due to different grinding techniques. The PDS of GGBS processed by a ball mill is the widest, while that by an airflow mill is the narrowest. The shape of GGBS processed by a vibromill is predominately spherical with a smooth surface, while that by a ball mill and an airflow mill appears to have similar edges.

Table 4
Test results of activity index and fluidity ratio

| Sample | $F_{tm}$(MPa) | | Activity index of flexural strength (%) | | $F_c$(MPa) | | Activity index of compressive strength (%) | | Fluidity ratio (%) |
|---|---|---|---|---|---|---|---|---|---|
| | 7 days | 28 days | 7 days | 28 days | 7 days | 28 days | 7 days | 28 days | |
| Reference | 6.42 | 7.10 | | | 43.4 | 54.3 | | | |
| A | 6.04 | 9.11 | 94 | 128 | 35.6 | 55.4 | 82 | 102 | 102 |
| B | 6.60 | 9.78 | 103 | 138 | 42.5 | 63.0 | 98 | 116 | 106 |
| C | 6.01 | 9.42 | 93 | 133 | 35.2 | 58.4 | 81 | 108 | 103 |
| D | 5.98 | 9.02 | 93 | 127 | 34.9 | 56.5 | 80 | 104 | 106 |

2. The fluidity of mortar containing GGBS is associated with PSD of GGBS. The narrower is the PSD of GGBS, the larger is the fluidity of mortar. The influence of morphological characteristics of GGBS on the fluidity of mortar is not remarkable. After a 0.05% ZS grinding assistant agent is added in a ball mill, apart from the output of the mill increases by 18%, the fluidity of mortar incorporating the GGBS is also greatly improved.
3. The strength of mortar incorporating GGBS is both related to the surface area and PSD of GGBS. When GGBS has the same surface area, the more mortar contains fine particles ( < 3 μm) of GGBS, the higher its early strength is. The more mortar contains 3–20 μm particles of GGBS, the higher is its long-term strength.

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