Effect of particle size distribution of slag on the strength and pore structure of low-temperature concrete

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Abstract. In order to study the effect of particle size distribution of slag on strength and pore structure of the concrete at low temperature, the particle sizes of slag were divided into four grades, namely, 5~10 μm, 10~15 μm, 15~20 μm and 20~26 μm. The influence of particle size distribution of slag on the compressive strength and pore structure of low temperature concrete cured for 3 days, 7 days and 14 days were analyzed. The results show that different particle size distribution of slag leads to different pore structure and strength of concrete. When the slag with the size is of 10~15μm, the concrete obtains the best performance, regardless of curing temperature. In addition, the decreasing granularity of slag improves the pore structure and increases the density of concrete.

1. Introduction
In the cold region of China, the winter lasts for a long time, which is unfavourable to concrete construction and curing. In general, there are ways to solve this problem, such as the curing equipments was used to improve its insulation performance, or mixed with admixtures as silica fume, slag powder, fly ash and so on.

Ground granulate blast furnace slag is a by-product from the iron and steel manufacturing industry. Its main ingredients are SiO2, CaO and Al2O3. Generally, volume fraction of the three ingredients can reach more than 90%[3-4]. Slag is a normal mineral admixture, due to the higher activity as compared to fly ash.

2. Experimental materials and methods
The cement used in this test is P O 42.5 grade ordinary Portland cement produced by Anshan Jidong cement co., LTD. The properties of the Portland cement are shown in Table 1. Granulated blast furnace slag powder was produced by Anshan iron and steel co., LTD. The chemical composition is shown in table 2. The sand is medium sand with sand rate of 0.3. Polycarboxylic acid superplasticizer
was mixed with a content of 1.0% of the cementing material, and the performance index met the requirements of GB 8076-2008. Sodium nitrite was selected as antifreeze agent, and the content was 3.0% of the cementing material.

Table 1. Properties of the Portland cement

| label   | stability | Initial set | Final set | 3 d | 28 d | 3 d | 28 d |
|---------|-----------|-------------|-----------|-----|------|-----|------|
| P. O 42.5 qualified | 3:18 | 4:24 | 23.6 | 52.3 | 5.7 | 9.6 |

Table 2. Chemical composition of slag /%

| Composition   | CaO  | SiO2 | Fe2O3 | Al2O3 | MgO  |
|---------------|------|------|-------|-------|------|
| Content       | 32.56| 42.56| 3.65  | 14.70 | 7.45 |

Based on our preliminary test, when the slag content is 20%, the concrete strength reaches the optimal value. The slag dosage in this work was thus fixed as 20%, and the mix design is shown in table 3.

Table 3. Mix design/ (kg/m³)

| Water | Cement | Slag  | Sand    | Crushed stone | Water-reducing agent | Antifreeze |
|-------|--------|-------|---------|---------------|----------------------|------------|
| 128   | 328.2  | 82.05 | 585.52  | 1244.23       | 4.1                  | 12.3       |

Slag was screened by standard sieve with different mesh size, and the mesh size corresponding to pore size was shown in Table 4. The particle size of the slag passed through screen sieves to obtain particle sizes of 20~26μm, 15~20 μm, 10~15μm and 5~10μm.

Table 4. Screen mesh number and corresponding aperture

| Mesh | The aperture/μm |
|------|-----------------|
| 2300 | 5               |
| 1800 | 10              |
| 1000 | 15              |
| 900  | 20              |
| 600  | 26              |

The concrete specimen (100 mm * 100 mm * 100 mm) were cured at 10 °C, -10 ~10 °C  and -10 °C, and was taken out for compressive strength test after cured to 3 d, 7 d and 14 d curing. In order to characterize the meso-pore structure of concrete, samples after the compressive strength were crushed and analyzed by mercury intrusion method.

3. Experimental results and analysis

3.1. Influence of slag size and curing temperature on compressive strength of concrete

The slag with particle size of 5 ~ 10μm, 10 ~ 15μm, 15 ~ 20μm and 20 ~ 26μm were added to the concrete respectively, and its compressive strength was tested after curing for 3d, 7d and 14d. The results are shown in Fig. 1.
(a) Curing temperature is 10 °C
(b) Curing temperature is -10 °C~10 °C
(c) Curing temperature is -10 °C

**Figure 1.** Compressive strength of concrete with different slag particle size distribution

As seen in Fig. 1, at 10 °C temperature curing temperature slag granularity for 10 ~ 15 µm of 3 d, 7 d, 28 d compressive strength is the largest, the biggest compressive strength stronger than 5 ~ 10 µm large 1.9%, the biggest compressive strength stronger than 15 ~ 20 µm large 13.93%, stronger than 20 ~ 26 µm large 28.7%. The compressive strength increases with the curing age. In -10 ~ 10 °C temperature curing, the slag particle size for 10 ~ 15 µm of 3 d, 7 d, 28 d compressive strength is the largest, the biggest compressive strength stronger than 5 ~ 10 µm large 12.5%, stronger than 15 ~ 20 µm large 22.87%, stronger than 20 ~ 26 µm large 55.17%. The compressive strength increases with the curing age. In -10 °C temperature curing environment, slag granularity for 10 ~ 15 µm of 3 d, 7 d, 28 d compressive strength is the largest, the biggest compressive strength stronger than 5 ~ 10 µm large 12%, stronger than 15 ~ 20 µm large 20.17%, more than 20 ~ 26 µm large 26.13%. The compressive strength increases with the curing age, because of the filling effect of slag in concrete, the fine slag powder particles are filled in the void between clinker particles, which increases the bulk density of powder and enhances the density of cement slurry, thus leading to the increase of cement strength. So the size of the slag will affect the strength of concrete, therefore 10 ~ 15 µm slag is the most suitable for concrete void.

When slag in concrete size for 5 ~ 10 µm, curing temperature at 10 °C temperature, the compressive strength of concrete is the largest, the largest stronger than in -10 ~ 10 °C under variable temperature curing strength increased by 27.8%, stronger than -10 °C under the constant temperature curing strength increased by 55.17%. When slag in concrete size for 10 ~ 15 µm, curing temperature at
10 °C temperature, the compressive strength of concrete is the largest, the largest more than in -10 ~ 10 °C under variable temperature curing strength increased by 15.83%, more than -10 °C under the constant temperature curing strength increased by 48.93%. When slag in concrete size for 15 ~ 20µm, curing temperature at 10 °C temperature, the compressive strength of concrete is the largest, the largest more than in -10 ~ 10 °C under variable temperature curing strength increased by 24.9%, more than -10 °C under the constant temperature curing strength increased by 57.08%. When slag in concrete size of 20 ~ 26µm, curing temperature at 10 °C temperature curing, the compressive strength of concrete is the largest, the largest more than in -10 ~ 10 °C under variable temperature curing strength increased by 39.65%, more than -10 °C under the constant temperature curing strength increased by 45.95%.

In four groups of slag particle size distribution range, three kinds of curing system under different curing ages relations of concrete compressive strength is 10 °C > -10 ~ 10 °C > -10 °C. The growth rate of concrete strength increases with age, and the lower the temperature is, the higher the growth rate of concrete strength is.

3.2. Influence of slag particle size on concrete pore structure
In curing temperature 10 °C, the mixed with different granularity of slag 10 ~ 15µm, 15 ~ 20µm of the total pore volume, total of concrete hydration 7 d control area, average pore diameter and porosity were measured, as shown in Fig. 2. The percentage of concrete aperture is shown in Fig. 3.

(a) Slag size and total pore volume  
(b) Slag size and total pore area  
(c) Slag size and average pore size  
(d) Slag size and porosity

Figure 2. characteristic parameters of slag size and void
According to Fig. 2 (a), the total pore volume of concrete increases with the increase of slag particle size; It can be seen from Fig. 2 (b) that the total pore area of concrete decreases with the
The larger particle size of concrete mineral admixtures is, the more distribution of 15 μm>200nm accounted for 18.84%, and more than 200nm accounted for 49.28%. Therefore, the use of smaller slag particle size, so that the concrete pore structure has been significantly improved, slurry structure more dense, lower porosity, strength has been improved.

4. Conclusions
(1) The compressive strength of concrete varies in the order of 10–15μm>5–10μm>15–20μm>20–26μm for all the curing ages. Consequently, there is an optimal value of particle size distribution (10–15μm) at which the highest compressive strength of concrete can be obtained.

(2) The higher the curing temperature, the lager the compressive strength of concrete is. The compressive strength of concrete varies in the order of 10 °C > - 10 ~ 10°C > - 10°C for all the particle size distribution of slag.

(3) Total pore volume, average pore diameter and porosity increases with increase in the particle size of slag for all the curing temperature, when the total pore area decreases.

(4) The features of the pore structure of concrete are few big harmful pores, more harmless pores, when the particle size of slag was 10-15μm which is beneficial to improve concrete strength.
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