Effect of Ground Slag on Mechanical Properties of Concrete under Low Temperature

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Abstract: Through using cube resisting compression test, fracture properties and micro-structure, the mechanical properties of high volume ground slag concrete under low temperature are studied in this paper. The results show that low temperature can improve the compressive strength of high volume ground slag concrete. And strength increased with the decreased of temperature. Low temperature can also improve the fracture energy and fracture toughness. Not only can ground slag reduce the content of calcium hydroxide in hardened cement paste, but ground slag can improve the compactness of hardened cement paste, reduce porosity and improve the strength of the interface.

1. Introduction
The northern coastal areas of China are cold in winter, and the lowest temperature can be below -20°C. The winter construction in the three eastern provinces lasts for 3~6 months[1], accounting for 30% of the project. Therefore, people pay more and more attention to the construction safety of concrete buildings in cold areas[2]. Concrete is the most widely used material in construction, bridge, tunnel, hydraulic engineering and other engineering fields. When the temperature drops to below 4°C, the water in the concrete expands and the free water in the pores freezes. The concrete strength will increase with the reduction of unfrozen pores and the solid-state transformation of liquid phase, and the concrete with low strength will be damaged. At present, the mechanical properties of concrete under low temperature are mainly manifested in the following four characteristics[3-8]: (1) Low temperature will increase the elastic modulus and strength of concrete; (2) The increase of strength is linear with water content. The higher the water content of concrete at low temperature, the greater the increase of compressive strength; (3) Free water freezing is helpful to improve the strength, but the research shows that at -120°C, the structure of ice changes. If the temperature continues to drop, the strength change of concrete appears discrete; (4) Repeated freezing and thawing will reduce the strength of concrete at low temperature.

Scholars at home and abroad have reported on the low-temperature performance of high-volume ground slag concrete. Xianmin Xu and Dechen Cao [9-10] showed that the performance of high-strength concrete can be improved by adding admixtures such as fly ash and silica fume under the condition of low-temperature seawater, and analyzed the main causes of damage under this condition. Zhiqing Cheng [11] of Central South University published the research on the early strength of concrete under low temperature curing conditions. The addition of early strength agent and slag helps to improve the early strength of concrete. At the same time, the method of double mixing ground slag and ultra-fine
fly ash can not only effectively improve the early strength but also improve the workability. Jun Liu et al.\cite{12} studied the strength development of concrete with different mineral admixtures under low temperature and its influence on the critical strength against freezing. However, few scholars study the coupling between low-temperature environment and high-volume ground slag concrete. This paper systematically studies the mechanical properties of high-volume ground slag concrete under low-temperature conditions, and explores its change law of mechanical properties, so as to provide reference basis for the engineering design of high-volume ground slag concrete under low-temperature environment.

2. Experiment

2.1 Materials

The cement used in the test is 42.5 ordinary portland cement produced by conch company. The coarse aggregate used in the test is 10~20mm small stone and 20~40mm medium stone with a ratio of 3:7, which meet the requirements of GB/T14685-2001, belonging to class II gravel. The fine aggregate sand used in the test is river sand, with a fineness modulus of 2.3, which meets the requirements of GB/T14684-2001, belonging to class II river sand in zone II. The test uses ground slag as the mineral admixture, which meets the requirements of grade S105 in the standard of GB/T18046-2000. The admixture used in the test is HLC superplasticizer produced by Sobute new materials Co.,Ltd., which meets the requirements of GB8076-2008.

2.2 Mix proportion

In this paper, the mechanical properties of high content ground slag concrete at low temperature are studied by taking the mix proportion (content of ground slag) and test temperature as variables. The test samples are divided into four groups: KZ0, KZ55, KZ65 and KZ75. The temperature groups are t20 (normal temperature 20℃), t-5 (-5℃), t-20 (-20℃) and t-40(-40℃). The mix proportion is shown in Table 1.

| No.  | Water binder ratio | Ground slag | Cement | Sand  | Small stone | Medium stone | Water reducing agent | Water  |
|------|--------------------|-------------|--------|-------|-------------|--------------|---------------------|--------|
| KZ0  | 0.38               | 0           | 410    | 606   | 353         | 824           | 4.1                 | 156    |
| KZ55 | 0.38               | 225         | 185    | 606   | 353         | 824           | 4.1                 | 156    |
| KZ65 | 0.38               | 266         | 144    | 606   | 353         | 824           | 4.1                 | 156    |
| KZ75 | 0.38               | 307         | 103    | 606   | 353         | 824           | 4.1                 | 156    |

2.3 Experimental method

In this paper, the mechanical property test is carried out according to the requirements of SL352-2006. The sample size is 100mm × 100mm × 100mm non-standard test piece with size factor 0.95. The microstructure was analyzed by Japanese Hitachi S3400-N scanning electron microscope.

The fracture performance test is carried out by KZ65. Like the compressive strength test, it is manually mixed by secondary mixing method and loaded into a 100mm × 100mm × 400mm mould. 40mm crack shall be reserved for fracture energy test, which is realized by placing a L-shaped steel sheet inside the mold during forming, and the size of the steel sheet is 40mm × 100mm, perpendicular to concrete sides. In this test, the three-point bending method is used to test the fracture performance. The specimen size and loading mode are shown in Figure 1.
3. Results and Discussion

3.1 Effect of temperature on mechanical properties with different content of slag powder

The 3d, 7d, 28d and 56d compressive strength test results of concrete with different slag powder content at different temperatures are shown in Figure 2. The results show that the compressive strength increases with the decrease of temperature. The compressive strength increases with the increase of age, but the early strength (3d and 7d) of KZ0 is significantly higher than that of the other three groups mixed with slag. For example, at 3d and -20°C, the strengths of KZ0, KZ55, KZ65 and KZ75 are 35MPa> 34.2MPa> 34MPa> 33.3MPa. With the development of age, the intensity of the latter three groups catch up with or even higher than KZ0 at 28d. At 56d, strengths of almost all samples mixed with slag are higher than KZ0. For example, at 56d and -20°C, strengths of KZ0, KZ55, KZ65 and KZ75 are 59.6MPa< 61.5MPa< 63.5MPa< 64.7MPa. Taking the compressive strength of KZ65 at 28d as an example, the strength increase range of -5°C, -20°C and -40°C is 24.3%< 27.3%< 35.8%. The lower the temperature, the greater the strength increase range. This is due to the micro cracks in concrete have different pore sizes and continuous distribution with a wide range. Under the influence of capillarity, the smaller pores are saturated with water first, and then transition to macropores. Due to the influence of curved liquid surface, the critical temperature of liquid-solid transition of pore water decreases with the decrease of pore size. Therefore, at low temperature, the larger pore water freezes first. When the temperature decreases to the critical temperature of the smaller pore, the smaller pore water begins to freeze. Therefore, when the temperature drops to below zero, the water in the larger pores begins to freeze, which helps improving the compressive strength. If the temperature drops lower, the smaller pore water also begins to freeze, which further improving the strength.
3.2 Effect of temperature on fracture properties of concrete

Figure 3 shows the displacement-load curve of concrete sample at different temperatures when the slag content is 65% (KZ65). In the rising section of the curve, the load peak value of t20 is lower than that of the other three groups, and the displacement corresponding to the peak value is smaller. With the decrease of temperature, the peak value and corresponding displacement of the other three groups gradually increase. It can be seen that the lower the temperature, the more the strength is improved, the better the toughness, and can maintain greater deformation without damage. The three groups of low temperature curves t-5, t-20 and t-40 are consistent at the beginning of curve rise, and the change of load with displacement is not obvious. When the displacement increases to a certain extent, the load suddenly increases sharply. At this time, the slopes of the three groups of curves are almost the same, but the peaks are different.

In the descending section of the curve, after t20 reaches the peak value, the internal cracks of the concrete develop rapidly. From the appearance, it can be observed that the obvious cracks begin to spread upward from the reserved joints, and the curve decreases almost vertically, while the decline speed of the other three groups is obviously much slower. It can be seen that the crack growth speed at low temperature is lower than that of at normal temperature. Thus, the crack resistance of concrete is stronger. After a stage of rapid decline, the curve will begin to decline gently until the concrete is completely destroyed. Considering that the temperature of concrete has lost a lot at this stage, the three curves at low temperature almost coincide at this stage. At the end of the curve, the maximum displacement increases with the decrease of temperature. It can be seen that the lower the temperature, the better the toughness and the stronger the crack resistance.
Fig. 4 shows the development trend of maximum load, maximum displacement, fracture energy and fracture toughness of KZ65 at different temperatures.

The results show that the maximum load, maximum displacement, fracture energy and fracture toughness increase with the decrease of temperature. Low temperature can significantly improve the fracture energy and fracture toughness. Concrete fracture energy refers to the energy required to produce cracks per unit area. The higher the fracture energy, the stronger the crack resistance of concrete. Fracture toughness refers to that when the stress of concrete reaches a value, even if the external stress does not continue to increase, the cracks will expand and increase rapidly and destroy. This stress value is called fracture toughness. The test results show that the lower the temperature, the higher the fracture toughness, and the higher the maximum stress required for the rapid expansion of internal cracks.

Concrete does not become more brittle at low temperature, but is more strong and tough, and is not easy to crack and damage. Observing the damaged concrete surface, it is found that the matrix and coarse aggregate surface account for a large proportion of the fracture surface. According to the literature, the crack development in the concrete extends along the coarse aggregate interface. Therefore, the ability of concrete to resist crack development, that is, the fracture energy and fracture toughness, are directly related to the interface strength. According to the conclusion of the previous chapter, low temperature can improve the compressive strength of concrete. After the pore water of various pore sizes at the interface is frozen, it can improve the compactness and bonding strength at the interface, which also improves the crack resistance of concrete.

![Fig. 4 Fracture performance of KZ65](image)

3.3 Microstructure of concrete with different slag powder content

![Fig. 5 SEM of 500 times hardened paste](image)

(a)SN  (b)KZ

Fig. 5 SEM of 500 times hardened paste
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(a) SN (b) KZ
Fig. 6 SEM of 500 times hardened paste at the hole

From the comparison of SEM images, it can be seen that there is no great difference between the pure cement slurry without ground slag and the cement slurry with slag at 500 times magnification. The addition of slag does not play an obvious role in the large pores in the hardened slurry.

(a) SN (b) KZ
Fig. 7 SEM of 5000 times hardened paste

At 5000 times, the hardened cement paste with slag is denser than the pure one. The cementation between hydration products is closer, and there is no loose flake crystal structure. Fewer small pores reduce internal stress defects and improve the strength of hardened slurry. At the same time, after the pure cement paste is hardened, there are a large number of ettringite needle crystals in the hole, while the hole of the paste mixed with slag is relatively dense and flat, and Ettringite can hardly be found. Therefore, the addition of slag greatly reduces the content of ettringite, makes the hardened slurry denser, the hydration more complete and obtains higher strength.

The role of slag is to have secondary hydration reaction with Ca(OH)$_2$, so as to consume most of Ca(OH)$_2$ and finally reduce the formation of ettringite. Therefore, ettringite can hardly be found in the hardened cement paste mixed with slag, and the effect of slag is obvious.

4. Conclusion
In this paper, the mechanical properties of ground slag concrete at low temperature are studied through concrete cube compression test, microstructure SEM test and fracture performance test. The conclusions are as follows:

(1) Low temperature can improve the compressive performance of concrete. The pore water in concrete is frozen at low temperature to fill the pores and cracks, which plays a role in supporting and bonding the pores and cracks, delaying the expansion and development of cracks and improving the
compressive strength of concrete.

(2) Low temperature can obviously improve the fracture energy and fracture toughness of concrete. Low temperature improves the tensile strength at the concrete interface, which can effectively prevent the fracture.

(3) The addition of slag can not only decrease the content of Ca(OH)$_2$ effectively, but also reduce the size of Ca(OH)$_2$ grains, which can greatly decrease the formation of ettringite, make the loose acicular ettringite crystals almost disappear, improve the compactness of the hardened cement slurry, reduce the porosity and improve the interfacial strength.

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References
[1] Zhu Y, Hu X P. Experimental study on pore structure of early frozen concrete paste [J]. Journal of Dalian Jiaotong University, 2020, 41 (03): 84-88.
[2] Hu X P, Peng G, Niu D T, Yang C. Effect of early freezing environment on service life performance of concrete [J]. Journal of building materials, 2020, 23 (05): 73-82.
[3] Yang L H, Zhu H, Li C F. Strengths and flexural strain of CRC specimens at low temperature[J]. Construction and Building Materials, 2011, 25(2):906-910.
[4] Liu J H, Wang D M, Song S M, et al. Study on properties and microstructure of reactive powder concrete with large amount of mineral powder [J]. Journal of Wuhan University of technology, 2008 (11): 54-57.
[5] Wang P, Du Y J. Study on impermeability and frost resistance durability of high content fly ash concrete [J]. Concrete, 2011 (12): 76-78.
[6] Nie H B, Gu S C, Gao P K, et al. Experimental study on frost resistance of carbon fiber reinforced concrete in cold regions [J]. Concrete and cement products, 2020, No. 289 (05): 51-55.
[7] Lu H L, Dong Y W, He L, et al. Effect of mixing basalt fiber and air entraining agent on frost resistance and mechanical properties of concrete [J]. Concrete and cement products, 2020 (7): 51-54.
[8] Gong J, Zhang W. The effects of pozzolanic powder on foam concrete pore structure and frost resistance[J]. Construction and Building Materials, 2019, 208:135-143.
[9] Xu X M, Cao D C. Performance of high strength concrete at low temperature [J]. Fujian building materials, 2003 (4): 7-10.
[10] Jiang L H, Qu G S, Li S W, Chu H Q, Du Y. Experimental study on mass high performance concrete for bridge bearing platform [J]. Concrete, 2010 (1): 121-123.
[11] Cheng Z Q, Liu B J, Yang Y X, He Z H, Liang H. Study on early strength of fly ash concrete under low temperature curing [J]. Fly ash, 2006:5:7-10.
[12] Liu J, Li Z G, Tian Y. Effect of mineral admixtures on strength development and frost resistance critical strength of concrete under low temperature [J]. Journal of Shenyang Architecture and Architecture University, 2006.5 (22): 415-427.