Effect of Mineral Admixture and Fiber on the Frost Resistance of Concrete in Cold Region

Zhonghua Li1,4*, Wei Gao1, Keke Li1, Qing Wang2, Jinliang Yang3 and Chao Su3

1 College of Mechanics and Materials, Hohai University, Nanjing, Jiangsu Province, 210098, China
2 Infrastructure Management Department, Hohai University, Nanjing, Jiangsu Province, 210098, China
3 College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, Jiangsu Province, 210098, China
4 Changjiang River Scientific Research Institute of Changjiang Water Resources Commission, Wuhan, Hubei Province, 430012, China

*Corresponding author’s e-mail: lizhonghua77@126.com

Abstract. Frost resistance performance of concrete is very important to hydraulic structures in cold regions. In this paper, the effects of mineral admixtures, fiber and the slag content on the frost resistance performance of concrete were studied by testing the weight loss and relative dynamic elasticity modulus. At the same time, the microstructure of high frost resistance concrete was analyzed. Results show that the weight loss rate of high performance concrete with mineral admixtures and fiber is reduced by 65% and the relative dynamic elasticity modulus retention rate is increased by 12% after 300 freeze-thaw cycles comparing to single mineral admixture concrete. A decrease in weight loss rate and an increase in relative dynamic elasticity modulus retention rate with increased slag content are observed in the double-mixture and triple-mixture concrete. The concrete with the excellent freeze-thaw cycle resistance performance can be prepared by air entraining agent, fly ash, slag, silica fume and polypropylene fiber. The maximum amount of the admixture can reach 51%, which can reduce the cost and meet the demand for concrete in cold regions.

1. Introduction

The hydraulic structural concrete in cold regions is in a harsh environment, and often subjected to freeze-thaw cycles, salt and other factors. These result in cracking, denudation, steel corrosion and bearing capacity degradation, and even loss of function. The problems seriously shorten the service life and increase maintenance costs. So this paper researched the damage rule of concrete in cold regions, analyzed the reasons for short lifetime of concrete, revealed the method and mechanism of improving hydraulic concrete durability.

2. Materials and test methods

2.1. Materials

P·O 42.5 Portland cement was used. Its chemical compositions are given in table 1. Fly ash used in this experiment was Class I with a specific surface area of 660 m²/kg. The silica fume has an average
particle diameter of 0.12 μm and a specific surface area of 1.45 × 10^4 m^2/kg. Ground slag specific surface area is 550 m^2/kg. The chemical compositions of admixtures are given in table 1. Polypropylene staple fiber used in the experiment was produced by Sobute New Materials Co., Ltd., and its physical properties are given in table 2. The water reducing agent is a My-1 type superplasticizer, and the recommended amount is 0.5~1.5% of the mass of the binder. The air entraining agent is type M-A, and the recommended amount is 0.012% of the mass of the binder. Gray-green gravel with maximum size of 20mm and continuous grading was used as coarse aggregates. River sand with the fineness modulus of 2.8 and reasonable grading was used as fine aggregates.

| Table 1. Chemical compositions of mineral admixtures. (wt %) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SiO₂            | Al₂O₃           | Fe₂O₃           | CaO             | MgO             | SO₃             | R₂O             |
| Cement          | 21.1            | 5.5             | 3.9             | 62.3            | 1.7             | 2.6             | 0.8             |
| Fly ash         | 64.7            | 21.6            | 4.6             | 2.9             | 2.4             | 0.3             | 0.6             |
| Slag            | 38.6            | 7.2             | 0.4             | 42.5            | 6.7             | 0.9             | 0.7             |
| Silica fume     | 93.7            | 0.3             | 0.8             | 0.2             | 0.2             | 0.5             | 0.3             |

| Table 2. Properties of polypropylene fibers. |
|---------------------------------------------|
| Test item | Breaking strength | Initial modulus | Elongation at break | Alkali-resistance |
|------------|--------------------|-----------------|---------------------|-------------------|
|            | MP             | MP            | %                   | %                 |
| Test result| 425             | 4600          | 21                  | 96                |

2.2. Mixing proportion of concrete
The components of the concrete in the experiment include air entraining agent, ground slag, fly ash, silicon fume, and polypropylene fiber, as shown in table 3. The water-binder ratio of concrete is 0.32, and the water consumption is 154 kg/m^3. The amount of water reducing agent and air entraining agent is 1.6% and 0.11% of the mass of the cementitious material respectively.

| Table 3. Mixing proportion of concrete. |
|----------------------------------------|
| NO.          | Raw material/(kg/m³) | Cement | Slag | Fly ash | Silica fume | Fiber | Sand | Gravel |
|--------------|----------------------|-------|------|--------|------------|-------|------|--------|
| A11          | 361                  | 120   | 0    | 0      | 0          | 663   | 1036 |
| A21          | 313                  | 96    | 72   | 0      | 0          | 650   | 1018 |
| A22          | 289                  | 120   | 72   | 0      | 0          | 653   | 1022 |
| A23          | 265                  | 144   | 72   | 0      | 0          | 652   | 1021 |
| A31          | 284                  | 96    | 72   | 29     | 0          | 650   | 1018 |
| A32          | 260                  | 120   | 72   | 29     | 0          | 649   | 1016 |
| A33          | 236                  | 144   | 72   | 29     | 0          | 649   | 1016 |
| A41          | 260                  | 120   | 72   | 29     | 1.44       | 648   | 1014 |

2.3. Experimental program
The test method in this experiment was according to rapid freezing-thawing cycle method (GBT50082-2009). The specimens with size of 100×100×400 mm were tested for each mix. After demoulded, specimens were cured in the standard curing room (20 °C, 98% RH) until 28 days. Then the specimens were tested by the freezing-thawing cycle method. The change in the mass and the relative dynamic modulus of elasticity retention rate were used as a determined index of the frost-resistance performance of concrete. In addition, the microstructure of concrete was analyzed by
3. Results and discussion

3.1. Effect of admixture and fiber on frost resistance performance of concrete

The effect of admixtures and fiber on the frost resistance performance after 300 freeze-thaw cycles is shown in figure 1. A decrease in the mass and relative dynamic elasticity modulus of concrete with the number of freeze-thaw cycles is observed. After 300 freeze-thaw cycles, the relative dynamic elasticity modulus of A22 with 15% fly ash is 87%, which is higher than the relative dynamic elasticity modulus of A11. The weight loss rate of A22 is 1.2% which is less than the weight loss rate of A11. It can be seen that the frost resistance performance of concrete with double mineral admixtures is better than that of concrete with single mineral admixture in the range of this test. The relative dynamic elastic modulus of A32 with 6% silica fume is 92%, which is higher than the relative dynamic elastic modulus of A22. The weight loss rate of A32 is 0.7%, which is less than the weight loss rate of A22. It can be seen that silica fume improves the frost resistance performance of concrete[1,2]. The relative dynamic elasticity modulus of A41 with 0.3% polypropylene fibers is 93%, which is higher than the relative dynamic elastic modulus of A32. The weight loss rate of A41 is 0.6%, which is less than the weight loss rate of A32. It shows the polypropylene fiber can further improve the frost resistance performance of concrete[3].

![Figure 1. Effect of admixture and fiber on the frost resistance performance of concrete.](image)

3.2. Effect of slag content on frost resistance of concrete mixed with two admixtures

Figure 2 shows the effect of slag content on the frost performance resistance. A decrease in the mass and relative dynamic elasticity modulus of the concrete added two admixtures with number of freeze-thaw cycles is observed, especially after 200 freeze-thaw cycles. After 300 freeze-thaw cycles, the weight loss rate of concrete decreases and the relative dynamic elasticity modulus retention rate increases with the increase of the amount of slag. The amount of the added mineral admixture has reached to 45%, which improves the frost resistance performance of the concrete and saves the cost of concrete[4].

![Figure 2. Effect of slag content on frost resistance of concrete mixed with two admixtures.](image)
3.3. Effect of slag content on frost resistance performance of concrete with three admixtures

Figure 3 shows the effect of slag content on frost resistance performance of the concrete with three admixtures. The weight loss rate of concrete gradually decreases as the amount of slag increases from 20% to 30%. The relative dynamic elasticity modulus retention rates of A31, A32 and A33 are 92.2%, 91.6% and 91.1%. The total amount of admixture reaches 51%, which greatly reduces the cost of concrete.

3.4. Formation mechanism of high frost resistance concrete

As shown in figure 4(a), there are a few cracks inside the concrete with the only slag. The microstructure of the concrete is more compact after adding the fly ash replacing the same cement as shown in figure 4(b). The secondary hydration product appears on the surface of the fly ash particles. The hydration product causes the fly ash particles and the cement hydration product to integrate. It fills the micro-cracks of the cement stone and improves the compactness of the cement stone[5]. As
shown in figure 4(c), after replacing the cement with fly ash, slag and silica fume, the microstructure of the cement stone is more compact. No obvious cracks appear and the hydration product is uniform. As shown in figure 4(d), the distribution of polypropylene fibers in cement stone can prevent cracks from occurring or further cracking.

Figure 4. Effect of mineral admixture and fiber on microstructure of concrete.

Figure 5(a), 4(b), and 5(b) show the microstructure of concrete when the slag content is increased from 96 kg/m³ to 120 kg/m³ and 144 kg/m³. It can be seen from figure 5(a) that the degree of fly ash hydration in the concrete is relatively low when the amount of ground slag is 96kg/m³. The cement stone has significant cracks and the compactness is poor. As the content increases, the degree of hydration of fly ash particles gradually increases, as shown in figure 5(b). When the amount of slag is increased to 144 kg/m³, the fly ash particles inside the cement stone have been completely hydrated and can fully fill the pores and cracks in the cement stone. Therefore, the concrete has better frost resistance performance. Figure 5(c), 4(c), and 5(d) show the microstructure of concrete when the amount of slag is increased from 96 kg/m³ to 120 kg/m³ and 144 kg/m³ in the concrete with three admixtures. The microstructure changes of cement stone are similar to the concrete with two admixtures.
It is well known that cement is calcined from calcareous raw materials and clay raw materials at a high temperature of 500 °C, 800 °C or even 1450 °C. A series of solid phase reactions occur to form cement clinker with C₃S, C₂S, C₃A and C₄AF. Gypsum and limestone are added during the grinding process to produce Portland cement. C-S-H gel, AFT, AFM, Ca(OH)₂ and excess free water are formed during the hydration process. The durability of concrete is largely determined by the structure of cement stone, such as pore size, bubble spacing, bubble number, amount of capillary water, properties of hydrated gel, and adsorbed water. In addition, since the cement particles are hydrated, the shrinkage and restraint of the cement stone can also cause looseness and micro-cracks. These can provide access to water, salt, acid in cold regions. Three admixtures are used in this paper, including fly ash, ground slag, and silica fume. These mineral powders have some main effects such as filling effect, crystal nucleation effect and activity effect.

In hardened cement stone, these mineral powder can fill the pores of concrete, reduce the number of harmful pores, and enhance the interface structure between cement paste and aggregate. The relative dynamic elasticity modulus retention rate of A32 is higher than A22, and the mass loss rate of A22 is higher than A32. It shows that the frost resistance performance of A32 is better than that of the double-adding concrete. The silicon fume can improve the frost resistance performance of the concrete. Firstly, the fine particles of silica fume fill the tiny pores inside the concrete. Furthermore, the reaction of silica fume with Ca(OH)₂ reduces the orientation of Ca(OH)₂ and the width of the interface between cement stone and aggregate. Finally, the hydrated product of silica fume blocks the capillary pores in the cement stone, reduces the volume of the capillary pores, increases the number of gelled pores, and improves the freeze-thaw cycle resistance of the concrete. Polypropylene fiber has obvious crack resistance performance, which improves the energy consumption of concrete during the freeze-thaw damage, inhibits the frost-cracking of concrete, and improves the frost resistance of fiber-reinforced concrete.
concrete[6].

Slag is the mineral admixture mainly used in hydraulic structural concrete. Therefore, this paper studies the effect of the amount of slag on the frost-resistance performance and microstructure of hydraulic structural concrete. The hydration speed of fly ash is slow and the slag hydration speed is relatively fast, and the effect is reflected in the early hydration of cement[7]. The silica fume particles are finer and require a large amount of water, but the SiO$_2$ content is higher, reaching more than 90%, and the hydration rate is the fastest. The above admixtures can all improve the frost resistance performance of concrete.

4. Conclusion

(1) The frost resistance of concrete with the two mineral admixtures (slag and fly ash) is better than concrete mixed with single mineral admixture (slag). The frost resistance of concrete added three mineral admixtures (slag and fly ash and silica fume) is better than the concrete with two admixtures (slag and fly ash). The frost resistance of concrete mixed with four materials (slag, fly ash, silica fume and polypropylene fiber) is best among the all concrete.

(2) In the series of concretes with 15% fly ash and slag, the frost resistance of the concrete gradually increases with the increase of the slag content from 20% to 30% after 300 freeze-thaw cycles. In the triple-mixture concretes (fly ash, slag and silicon fume) the frost resistance of the concrete decreases slightly with the increase of slag content from 20% to 30%.

(3) The maximum weight loss rate of high performance concrete is 1.64%, and the dynamic elasticity modulus retention rate is 83.3%. The frost resistance of the concrete meets the requirements of F300. The high-content admixture concrete with excellent freeze-thaw resistance performance can be prepared by adding air entraining agent, fly ash, slag, silica fume and polypropylene fiber. The maximum amount of admixture can reach 51%, and meet the demand for concrete in cold areas.

References

[1] Sun, W., Chen, H.S., Luo, X., Qian, H.P. (2001) The effect of hybrid fibers and expansive agent on the shrinkage and permeability of high—performance concrete. Cement and Concrete Research, 31: 595–601.
[2] Sabir, B.B. (1997) Mechanical Properties and Frost Resistance of Silica Fume Concrete. Cement and Concrete Composites, 19: 285-294.
[3] Nam, J., Kim, G., Lee, B., Hasegawa, R., Hama, Y. (2016) Frost resistance of polyvinyl alcohol fiber and polypropylene fiber reinforced cementitious composites under freeze thaw cycling. Composites Part B: Engineering, 90: 241-250.
[4] Sheng, A.C., Yue, Z.Y., Sheng, T. D., Fei,F. (2012) Study on Frost Resistance of High Performance Concrete Resistance to Chloride Ion. Applied Mechanics and Materials, 174-177: 1312-1316.
[5] Wang, D.H., Shi, C.J., Wu, Z.M., Xiao, J.F., Huang, Z.Y., Fang, Z. (2015) A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. Construction and Building Materials, 96: 368-377.
[6] Ding, X.Q., Zhou, R.T., Wang, Y. (2017) Effect of silica fume on the frost resistance and pore structure of concrete. Concrete, 2: 53-55.
[7] Liu, R.J., Ding, Q.J., Chen, P., Yang, G.Y. (2012) Durability of concrete made with manganese slag as supplementary cementitious materials. Journal of shanghai jiaotong university, 17: 345-349.