Study on early basic mechanical properties of inorganic polymer-based fast-hardening concrete

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Abstract. In order to predict the application effects of inorganic polymer-based fast-hardening concrete (IPFC) in pavement emergency repair, the slag, fly ash and silica fume were used as solid cementitious materials, and sodium hydroxide and sodium silicate were used as alkali-activators to prepare IPFC specimens. The change rules of the basic mechanical properties of the specimens with different slag, fly ash and silica fume contents in early stage were studied by experiments. The results show that, the early compressive strength of each group of specimens is more than 20 MPa and that of slag-based fast-hardening concrete (SFC) specimens is the highest. SFC specimens have the highest bending strength when they are cured for 2 h, while the silica fume/slag-based fast-hardening concrete (SSFC) specimens have the highest bending strength when the curing time is up to 3 h.

1. Introduction

Roads and bridges are important ties to connect each other, which is very important to ensure the normal implementation of various social and economic activities. However, in recent decades, under the actual use of environmental conditions, due to natural disasters and man-made reasons, the cases of damage to roads and bridges and other structures are gradually increasing. Therefore, it is urgent to carry out more in-depth research on the rapid repair and reinforcement of road and bridge engineering.

In general, the development of high-strength rapid repair materials is of great significance for timely repair of pavement damage. In 1940s, American scientist Purdon [1] first tested the clinker-free cement composed of industrial waste residue and alkali, and put forward the theory of “alkali activation”. After that, the French scientist Davivodits [2] first proposed the new term “inorganic polymer”, which has attracted wide attention from scholars and in-depth research [3-8]. Inorganic polymer has excellent physical, mechanical properties and rapid curing characteristics, which shows better performance than cement in many application environments. Moreover, the production energy consumption of inorganic polymer is extremely low, which is of great significance for energy conservation and environmental protection. During scores of year’s development, inorganic polymers have been widely used in rush repair and construction projects due to their “fast hardening and early strength” properties. In addition, the raw materials of inorganic polymers are generally slag, silica fume, fly ash and other industrial wastes. On the one hand, these raw materials are cheap and easy to obtain. On the other hand, their physical properties are extremely stable, and they are not easy to deteriorate in the process of transportation and storage, thus ensuring the quality of raw materials. Based on this, the slag, fly ash
and silica fume were used as solid cementitious materials, and sodium hydroxide and sodium silicate were used as alkali activators to prepare five groups of inorganic polymer-based fast-hardening concrete (IPFC). The early basic mechanical properties of IPFC were studied in this paper.

2. Test

2.1. Raw materials

The slag powder used in the test was S95 slag, with density of 2.89 g/cm³, specific surface area of 478 m²/kg, fluidity ratio of 101%, 7-day activity index of 89%, 28-day activity index of 105%. The components of the fly ash are 58.2% SiO₂, 29.8% Al₂O₃, 4.3% Fe₃O₄, 1.5% CaO, 2.8% MgO and 3.2% Na₂O. The Semi densified silica fume with density of 350 kg/m³, loss on ignition of 2.7%, silica content of 98.2%, alkali content of 0.54%, moisture content of 0.04%. The modulus of the sodium silicate is 3.2~3.4, and the mass fraction of the sodium silicate is about 34%. The sodium hydroxide was produced by Wuhai Xinye Chemical Co., Ltd., with purity of 99%. And the sand was natural medium sand from Bahe River.

2.2. Mixture ratio design

Three kinds of IPFC were prepared: slag-based fast-hardening concrete (SFC), fly ash/slag-based fast-hardening concrete (FSFC) and silica fume/slag-based fast-harde ning concrete (SSFC). The specific mix proportion design of the specimens is shown in table 1, in which FSFC1 group and FSFC2 group indicate that the fly ash content is 5% and 15% respectively; SSFC1 group and SSFC2 group indicate that the silica fume content is 5% and 15% respectively.

In this study, the influence of curing methods on early strength was comprehensively considered, and different curing methods were adopted for concrete curing, including standard curing and curing in water. The method of standard curing: Pour the new mixture into the cube or cuboid test mold, after vibration compaction and plastering, let it stand for 1 h. After the specimen has certain strength, it should be demoulded. The demoulded specimen is put into the standard curing box for curing (the temperature is (20±2) ℃, and the humidity is 95%). The method of curing in water: After demoulding, the specimen is completely immersed in water for curing, and the water temperature is controlled at about 20 ℃.

The mechanical properties of IPPC were tested according to GB/T50081—2002 Standard for test method of mechanical properties of ordinary concrete. The size of the specimen used for compressive strength test is 150 mm×150 mm×150 mm, and that for bending strength test is 100 mm×100 mm×400 mm.

Table 1. Mix proportions of SFC, FSFC, SSFC (kg/m³)

| Specimen number | Slag | First grade fly ash | Semi densified silica fume | Sodium silicate | Sodium hydroxide | Water | Medium sand | Crushed limestone |
|-----------------|------|---------------------|---------------------------|----------------|-----------------|-------|-------------|------------------|
| SFC             | 497.4|--                  | --                        | 159.5          | 39.0            | 79.2  | 551.3       | 1073.7           |
| FSFC1           | 465.2|24.5                | --                        | 157.0          | 38.4            | 77.9  | 555.4       | 1081.6           |
| FSFC2           | 407.5|71.9                | --                        | 153.7          | 37.6            | 76.3  | 560.8       | 1092.2           |
| SSFC1           | 454.6|--                  | 23.9                      | 153.4          | 37.5            | 76.1  | 561.3       | 1093.2           |
| SSFC2           | 393.8|--                  | 69.5                      | 148.6          | 36.3            | 73.7  | 569.3       | 1108.8           |

3. Results and Analysis

3.1. Compressive strength

Affected by the paste, the specimen after curing mainly show dark green, and the specimen with larger amount of silica fume presents dark green, which is obviously different from ordinary concrete in appearance. Before the test, it is found that there are no obvious cracks on the surface of each group of specimens, and they are basically in good condition. According to the failure mode after testing, most of the specimens show “hoop effect” in the process of compression failure.
Figure 1 shows the test results of compressive strength of each group of specimens. It can be seen from the figure that the concrete specimens prepared in this test generally have good early compressive strength, most of which exceed 20 MPa. Under different curing conditions, the compressive strength of SFC group is always the highest, and the compressive strength of SFC exceeds 40 MPa after curing for 3 h. The addition of fly ash and silica fume both reduces the compressive strength of the specimens, and the compressive strength of the specimens cured by immersion in water is lower than that of the standard curing specimens under the same proportion.

3.2. Bending strength
During the bending strength test, the main crack appears in the middle of the specimen, and then the fracture occurs suddenly. The bending strength test results of concrete specimens are shown in figure 2. It can be seen from the figure that the bending strength of SFC group is the highest when curing for 2 h under two different conditions, and the bending strength of SSFC2 group is higher when curing for 3 h. The bending strength of the standard curing specimens at 2 h is slightly higher than that of the immersion curing specimens on the whole, but the bending strength of the immersion curing specimens increases significantly after curing for 3 h, which is obviously higher than that of the standard curing specimens in the same period.

4. Discussion
From the point of view of reaction characteristics, the reaction of slag-based inorganic polymer cementitious materials is divided into two stages in some literatures. Since this paper mainly studies the early performance of slag-based fast-hardening concrete (SFC), it mainly analyzes the first stage of its reaction.

In the first stage of SFC reaction, C-S-H (the main source of early strength of SFC) is mainly formed.
In addition, some polymerization products of silicon tetrahedron and alumina tetrahedron are also formed. The effect of strong alkali will lead to the release of a large number of calcium ions and silicon oxygen ions, and alkali activator also provides a part of silicon oxygen ions, calcium ions and silicon oxygen ions combine to form a large number of C-S-H. In addition, slag has strong alkali excitability. In a short time, a large number of silica tetrahedron and aluminum oxide tetrahedron can be released into the solution. The tetrahedron reacts with the alkaline metal in the solution to form oligomeric polymers. The oligomeric polymers accumulate continuously and transform to high polymer, and finally form a stable three-dimensional network structure. But at the same time, the first stage of the reaction has the characteristics of “three high”, that is, the concentration of calcium ion and silicon oxygen ion is very high, the pH of the solution is very high, and the temperature of the solution is very high due to the heat of hydration. “Three high” results in a very rapid reaction in the first stage, and the initial fluidity of SFC mixture is completely lost in a very short time, which makes the SFC matrix and aggregate not well integrated, and there are many pores in the interfacial transition zone (ITZ).

Combined with the analysis of test results, SFC shows excellent early compressive strength no matter what curing method is adopted. This can be attributed to the formation of a large number of C-S-H in the reaction, and its stable three-dimensional network structure plays a major role. However, the bending strength of SFC is almost the worst, and the bending performance of SSFC is the best. It may be due to the influence of the pores caused by the “three highs” in the early reaction of slag based rapid hardening concrete, while the particle size of silica fume is very small, which makes the internal structure of SSFC relatively relatively dense, so that the bending performance of SSFC can be improved significantly.

5. Conclusion

Here, five groups of inorganic polymer-based fast-hardening concrete specimens were prepared, and their early basic mechanical properties were evaluated. In summary, combined with experimental research results and theoretical analysis, we observe that:

(1) Under the two curing conditions, the early compressive strength of each group of specimens is more than 20 MPa and that of SFC specimens is the highest. The addition of fly ash and silica fume has a certain weakening effect on the compressive strength of concrete.

(2) Under the two curing conditions, SFC specimens have the highest bending strength when they are cured for 2 h, while the SSFC specimens have the highest bending strength when the curing time is up to 3 h.

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