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

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Abstract. For the purpose of explore the early dynamic mechanical properties of inorganic polymer based fast hardening concrete (IPFC), two groups of IPFC specimens were prepared with slag and silica fume as the main raw materials, flake alkali and water glass as alkali activators: slag based fast-hardening concrete (SFC) and silica fume-slag based fast-hardening concrete (SSFC). The dynamic mechanical properties of specimens at the age of 3 hours were studied by Φ100 mm split Hopkinson pressure bar (SHPB) test device. The results show that, the dynamic compressive strength and peak toughness of SFC and SSFC both have obvious strain-rate sensitivity, and the peak stress of SSFC is higher than that of SFC, while the peak toughness is lower than that of SFC overall; The peak strain of SFC and SSFC shows no rate dependence, and the peak stress changes little with strain rate in the range of 30 to100 s⁻¹, the peak strain of SFC is generally higher than that of SSFC.

1. Introduction
Since the 21st century, the earth movement has entered an active period, earthquakes, tsunamis and other natural disasters occur from time to time. Meanwhile, under the modern background of complex and tense international relations, wars break out frequently. The recovery and support ability of traffic after the disaster is directly related to the efficiency of rescue and backup work.

Inorganic polymer was first proposed by French scientist Davidovits, but it did not cause strong response at that time, after the "alkali activation" theory proposed by Purdon [1] and the classical "glukhovsky" polymerization model [2] established by glukhovsky [3, 4] were put forward, the inorganic polymer have gradually caught widespread attention from domestic and international scholars [5-8]. After years of development, inorganic polymers have been widely used in emergency repair and construction projects because of its "rapid hardening high strength" properties. In addition, the raw materials of inorganic polymers are generally slag, silica fume, fly ash and other industrial wastes [9-11], they can be supplemented by zeolite powder, metakaolin and so on [12, 13]. These materials are not only price moderate and convenient to get, but also have very stable physical properties, they are not easy to deteriorate during transportation and storage, and ensures their quality.
For the emergency repair and construction, the dynamic loads such as wheel load, vibration load, or explosion impact load will be faced at the first time after the completion of cement concrete pavement. Based on this, this paper takes slag and silica fume as the main raw materials, and the flake alkali and sodium silicate are used as alkali activator to prepare inorganic polymer based fast hardening concrete (IPFC) specimens, the dynamic mechanical properties of specimens at the age of 3 hours were studied by $\Phi$ 100 mm split Hopkinson pressure bar (SHPB) test device, and analysis the application of pavement in repair and construction.

2. Experiment

2.1. Specimen preparation

Materials used for the preparation of IPFC mainly include: slag, silica fume, sodium silicate, flake alkali, crushed limestone, medium sand and water. Two types of IPFC were prepared in this experiment: slag based fast-hardening concrete (SFC) and silica fume-slag based fast-hardening concrete (SSFC). The specific mix proportion is shown in Table 1.

| Specimens number | Silica fume | Slag | Water | Flake alkali | Sodium silicate | Crushed limestone | Medium sand |
|------------------|-------------|------|-------|--------------|----------------|-------------------|-------------|
| SFC              | 0           | 500.4| 79.6  | 39.5         | 160.4          | 1037.3            | 583.5       |
| SSFC             | 74.3        | 420.6| 77.6  | 38.2         | 156.7          | 1037.3            | 583.6       |

In this paper, the dynamic characteristics of IPFC at the age of 3 hours are tested, the specimens are taken out after 2.5 hours of immersion curing, and then polished with a grinding machine to ensure that the two ends of the specimens are flat and smooth, and the surface roughness is less than 0.02 mm, the size of the specimens is designed as $\Phi$ 100 mm×50 mm, and the dimension error is controlled within ±0.2 mm. Reasonably control the grinding and testing time to ensure that the test is completed in about 3 hours after the specimens are poured.

2.2. Experiment technology

The dynamic mechanical property test is carried out with a $\Phi$ 100 mm SHPB test device, for the processing of test data, the "three wave method" [14] is used to express the strain $\varepsilon_s(t)$, strain rate $\dot{\varepsilon}_s(t)$ and stress $\sigma_s(t)$.

Based on the current research results [15], the relatively mature stress wave shaping technology is used to reshape waveform, the shaper is made of H62 round brass sheet which with the thickness of 1 mm and the diameters of 20, 22, 25, 27, 30 mm (Figure 1).

Figure 1. The shaper of H62 round brass sheet

It should be noted that there will be a friction effect on the two interfaces between the specimen and the bar during the test, which will have an impact on the propagation of stress pulse signal, therefore, a mixture of graphite and lubricating is paint on the surfaces of specimen and bars to minimize the influence of friction effect.

3. Experiment results
3.1. Dynamic compressive strength

In the impact compression test, the peak stress is generally taken as the dynamic compressive strength of the material, and the peak stress $f_p$ of two groups under different $\varepsilon_\dot{\varepsilon}$ is shown in Figure 2.

![Figure 2. Peak stress](image)

Figure 2 indicates that the $f_p$ of SFC and SSFC specimens shows a significant rate correlation, that is, it increases with the increase of the $\varepsilon_\dot{\varepsilon}$. Some studies have suggested that the dynamic compressive strength of concrete materials in SHPB test shows obvious rate dependence, which may be related to the lateral inertia effect. The one-dimensional stress assumption in SHPB test regards the specimen as an ideal slender bar, and the stress and strain only produced in longitudinal direction inside the specimen during loading. For the sake of approach the assumption, the section size of specimen should be as small as possible. However, unlike metal materials, concrete is the materials without regular and uniform lattice, and in order to ensure the uniformity, most SHPB tests of concrete have to prepare the relatively large specimens. In the process of high-speed loading, the specimen may be in the state of three-dimensional stress or one-dimensional strain, and resulting in the transverse inertial effect, which makes the dynamic compressive strength always higher than the static compressive strength.

3.2. Deformation characteristics

Based on the analysis of SHPB test, the peak strain $\varepsilon_p$ is often used to characterize the deformation capability of material [16]. The $\varepsilon_p$ is defined as the corresponding strain when the material reaches the $f_p$, and the larger the $\varepsilon_p$, the stronger the deformation capacity of the material. The data distribution characteristics of this test are shown in Figure 3, and the $\varepsilon_p$ shows no obvious rate correlation.

![Figure 3. Peak strain](image)

It can be seen from figure 3 that, the peak strain of SFC is higher than that of SSFC on the whole, which indicating that in early age, SFC has greater deformation capacity than SSFC, and this result can be analyzed from the perspective of density or internal pores of materials. Due to the addition of silica
fume, the internal structure of SSFC is relatively more dense, under the high-speed impact loading, the internal space that allowed to deform is relatively smaller, thus the deformation capacity has weakened. The stronger deformation capacity of SFC is related to the more internal pores, and further analysis is made below from the perspective of reaction characteristics. The reaction of slag based inorganic polymeric cementitious material is divided into two stages in reference [17], and the first stage reaction of SFC is analyzed since this paper studies the early performance of SFC.

The formation of C-S-H is the main reaction during the first stage of SFC, and some polymerization products of silicon oxygen tetrahedron and aluminum oxygen tetrahedron are also included. The strong alkali will help to release a lot of calcium ions and silicon oxygen ions from slag, in addition, alkali activator also provides part of silicon oxygen ions, and C-S-H is the main source of early strength of SFC which is formed by the combination of calcium and silicon oxygen. The first stage of the reaction has the characteristics of "three highs", that is, the concentration of calcium ion and silicon oxygen ion is very high, the pH of the solution is very high, and the hydration heat makes the temperature of the solution very high. The "three highs" make the actions in first stage complete quickly, and the initial fluidity of SFC mixture will be completely lost in a short time, which makes the matrix and aggregate of SFC cannot be integrated very well, and there are many pores in the transition phase. When the specimens subjected to impact load, these pores will play a buffer role, thus the SFC shows a relatively stronger deformation capability than SSFC at early age.

3.3. Impact toughness

At present, there are various evaluation indexes for impact toughness of concrete material, and the peak toughness $R_p$, or specific energy absorption $SEA$ are usually be used. Before the material reaches the $f_p$, the internal microcracks are in the stable growth stage, there was only minor damage to the material, the test data is more accurate at this time. After the stress reached the peak, the microcracks enter the stage of unstable growth, the damage evolution is intensified, and the whole specimen is in a state of instability, which increases the discreteness of test data. Therefore, $R_p$ was chosen to characterize the impact toughness of IPFC in this paper. The physical meaning of $R_p$ is the toughness before the material reaches the $f_p$, and the calculation method is shown in Equation (1):

$$ R_p = \int_0^T \sigma(t) \mathrm{d} \varepsilon(t) $$

Where $T$ is the time when the material reaches the peak strain.

The $R_p$ of SFC and SSFC specimens are obtained in Figure 4, and it can be seen from the figure that the $R_p$ of SFC is higher than that of SSFC generally, the $R_p$ of SFC specimens ranged from 0.186 to 0.468 MJ·m⁻³, and that of SSFC specimens ranged from 0.118 to 0.305 MJ·m⁻³. The $R_p$ of SFC and SSFC specimens both shows obvious rate sensitivity, the relationship between $R_p$ and $\dot{\varepsilon}$ can be obtained by linear fitting, and the result is shown in Equation (2):

![Figure 4. Peak toughness](image-url)
Toughness is determined by stress and strain, the results show that in most cases, the dynamic strength of SFC is lower than that of SSFC, and the SFC shows relatively stronger deformation capability than SSFC, according to the stress-strain curves in Figure 1, the stress wave peak section of SFC is relatively wider, and the work done by stress increases accordingly. Therefore, it can be considered that although the dynamic strength growth of SFC is relatively low, its good deformation capability makes its toughness higher.

4. Conclusions
In this paper, the SHPB test technology is used to analyze the dynamic properties of two kinds of IPFC specimens from the aspects of dynamic compressive strength, deformation characteristics and impact toughness. The dynamic compressive strength and $R_p$ of SFC and SSFC show obvious rate sensitivity, with the increase of $\bar{\varepsilon}$, both of them increase gradually; On the whole, the $f_p$ of SSFC is higher than that of SFC, while the $R_p$ is lower than that of SFC; The $\varepsilon_p$ of SFC and SSFC shows no rate dependence, and the $f_p$ changes little when the $\bar{\varepsilon}$ ranged from 30 to 100 s$^{-1}$, the $\varepsilon_p$ of SFC is generally higher than that of SSFC.

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