Experimental study on static and dynamic mechanical properties of slag concrete

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Abstract: The slag concrete with 15%, 30% and 45% admixtures was prepared by the equal displacement cement method. The quasi-static mechanical properties of slag concrete were studied using a TYE-2000B pressure testing machine, and the dynamic mechanical properties of slag concrete under different strain rates were studied using a Φ100mm split Hopkin, and compared with ordinary concrete. Studies have shown that under quasi-static loading conditions, the compressive strength of slag concrete increases with the increase of slag content. Under dynamic load conditions, the strain rate sensitivity of slag concrete is significant. As the strain rate increases, the peak stress, strength enhancement factor and peak strain of slag concrete are significantly improved. In addition, the amount of slag is in the range of 0% to 45%. As the amount of slag increases, the dynamic compressive strength of the slag concrete increases.

1. Introduction
Adding slag to the concrete can reduce the heat of hydration of the concrete; it can also increase the strength and durability of the concrete to the greatest extent. The improvement of these properties is mainly related to the amount of slag powder [1]. In this paper, the mechanical properties of concrete with different amounts of slag powder under different strain rate conditions are studied. It is hoped that it can provide a certain reference for the application of slag concrete.

2. Experiment Overview

2.1 Raw material and test specimen preparation
Raw materials: Nanfang brand P·042.5 grade cement; S95 grade slag powder produced by Henan Anyang Ironworks, with a specific surface area of not less than 355m²/kg, the specific indexes are shown in Table 1; Coarse sand with a fineness modulus of 3.3. The specific cooperation is shown in Table 2.

Table 1 Physical index of slag powder

| Density g/cm³ | Specific surface area m²/kg | Activity index 7d 28d | Loss on ignition % | Chloride % | Mobility ratio % | Water content % |
|---------------|-----------------------------|------------------------|--------------------|------------|------------------|-----------------|
| 2.89          | 425                         | 78 98                  | 0.60               | 0.036      | 102              | 0.28            |
Table 2 Proportion of slag concrete

| Test number | Admixture substitution rate /% | Dosage of admixture /kg | Water to glue ratio | Amount of concrete material per cubic meter /kg |
|-------------|-------------------------------|-------------------------|---------------------|-----------------------------------------------|
|             |                               |                         |                     | cement Sand Stone water                        |
| K0          | 0                             | 0                       | 0.6                 | 358 712 215 1114                               |
| K15         | 15                            | 53.7                    | 0.6                 | 304.3 712 215 1114                             |
| K30         | 30                            | 107.4                   | 0.6                 | 250.6 712 215 1114                             |
| K45         | 45                            | 161.1                   | 0.6                 | 196.9 712 215 1114                             |

Using the above raw materials, according to the mixing ratio shown in Table 2, to prepare concrete of strength class C30, there are mainly two types of test specimen specifications: the standard cubic test specimen (150mm × 150mm × 150mm) used under static compression first, and Cylindrical test piece (Φ100mm × 50mm) used under dynamic compression test conditions.

2.2 Test method
According to GBT50081-2002 "Standard for Test Methods for Mechanical Properties of General Concrete" [2], a quasi-static compression test was performed using a TYE-2000B pressure tester. When the concrete test pieces were cured under standard curing for 7d and 28d, the test pieces were removed for concrete resistance. Pressure test. The concrete test specimen was tested for dynamic compression using a 100mm SHPB test system (see Figure 1). The length of the bullet was 0.6m, and the length of the incident rod, transmission rod, and absorption rod were 5m, 3m, and 2m. The end of the test piece was greased with grease. Lubrication is used to eliminate the end friction effect. In order to improve the rising edge time and make the internal stress of the test specimen uniform, a rubber disc with a thickness of 2mm and a radius of 15mm is used as the wave shaper. Based on the one-dimensional stress wave propagation law, the following calculations are performed on the specimen strain rate, stress, and strain.

\[
\dot{\varepsilon}(t) = \frac{E}{L_s} \left[ \varepsilon_i(t) - \varepsilon_R(t) - \varepsilon_T(t) \right] \quad (1)
\]

\[
\varepsilon(t) = \frac{E}{L_s} \int_0^t \left[ \varepsilon_i(t) - \varepsilon_R(t) - \varepsilon_T(t) \right] dt \quad (2)
\]

\[
\sigma(t) = \frac{E_A}{2z} \left[ \varepsilon_i(t) + \varepsilon_R(t) + \varepsilon_T(t) \right] \quad (3)
\]

3. Static test results analysis

| Specimen number | Compressive strength /MPa |
|-----------------|---------------------------|
|                 | 7d | 28d  |
| K0              | 21.9 | 25.7 |
| K15             | 25.1 | 28.6 |
| K30             | 25.7 | 29.5 |
| K45             | 30.5 | 35.2 |

From Table 3 and Figure 2, it can be seen that when the test period is the same, the compressive strength displayed by the slag concrete at this time is greater than that of ordinary concrete, and through experiments, it can be seen that with the continuous increase of the amount, the compressive strength is also constantly rising. When the value of slag content is in the range of 30% to 45%, the strength increases fastest. When the cement is replaced by slag powder, the early strength is improved at this time. The reason for this is mainly due to the combined effect of the morphological effect of the slag powder and the micro-filling effect. Enrichment of Ca(OH)₂ crystals at the aggregate-cement interface, reducing the size of Ca(OH)₂ crystals, increasing the density of the interface, thereby effectively improving the aggregate-cement interface structure [3-4].
Figure 1 Effect of slag content on compressive strength of concrete

4. Analysis of dynamic test results
According to the scientific nature of the experimental method, the impact velocity of the bullet is stable between 0-10m/s for 3 to 4 specimens under each working condition. The peak stress, peak strain and specific energy of the slag concrete under the same pressure are averaged. The impact compression test results of the slag concrete are shown in Table 4.

| Specimen number | Air pressure (MPa) | Average strain rate (s⁻¹) | Peak stress (MPa) | Peak strain (10⁻³ε) | Specific energy (KJ/m³) | DIF | Damage situation |
|-----------------|--------------------|---------------------------|------------------|---------------------|-------------------------|-----|-----------------|
| K0-1            | 0.4                | 34.65                     | 33.86            | 5.29                | 301.3                   | 1.32| large pieces    |
| K0-2            | 0.6                | 67.44                     | 36.02            | 7.02                | 527.3                   | 1.40| Shatter         |
| K0-3            | 0.8                | 80.23                     | 39.46            | 8.96                | 699.3                   | 1.54| Shatter         |
| K0-4            | 1.0                | 105.10                    | 41.58            | 11.43               | 694.5                   | 1.62| Shatter         |
| K15-1           | 0.4                | 34.47                     | 33.86            | 4.08                | 306.4                   | 1.18| large pieces    |
| K15-2           | 0.6                | 60.73                     | 37.55            | 6.92                | 442.1                   | 1.31| Shatter         |
| K15-3           | 0.8                | 77.42                     | 45.09            | 8.54                | 609.4                   | 1.58| Shatter         |
| K15-4           | 1.0                | 99.01                     | 46.49            | 11.16               | 688.2                   | 1.63| Shatter         |
| K30-1           | 0.4                | 33.26                     | 36.07            | 5.69                | 311.6                   | 1.22| large pieces    |
| K30-2           | 0.6                | 58.22                     | 39.27            | 7.65                | 494.0                   | 1.33| Shatter         |
| K30-3           | 0.8                | 79.70                     | 45.69            | 11.07               | 581.7                   | 1.55| Shatter         |
| K30-4           | 1.0                | 99.81                     | 46.78            | 11.82               | 751.5                   | 1.59| Shatter         |
| K45-1           | 0.4                | 32.33                     | 35.93            | 5.90                | 295.9                   | 1.02| large pieces    |
| K45-2           | 0.6                | 51.76                     | 45.79            | 6.77                | 574.5                   | 1.30| Shatter         |
| K45-3           | 0.8                | 79.86                     | 47.50            | 8.21                | 784.3                   | 1.35| Shatter         |
| K45-4           | 1.0                | 94.23                     | 47.72            | 10.38               | 861.3                   | 1.36| Shatter         |

4.1 peak stress
According to the above SHPB device, impact compression tests with different strain rates on the same slag test specimen were obtained, and the dynamic stress-strain rate curve of the slag concrete was obtained as shown in FIG.
Fig. 2 Relationship between peak stress and strain rate

According to the results in Table 4 and Figure 2, when the replacement rate of slag powder is 0%, the peak stress of slag concrete increases by 32%, 40%, 54% and 62%, respectively, when the strain rate is 34.65s\(^{-1}\), 67.44s\(^{-1}\), 80.23s\(^{-1}\) and 105.10s\(^{-1}\), relative to the quasi-static compressive strength and strain rate of normal concrete on 28d. When the replacement rate of slag powder is 15%, the quasi-static compressive strength and strain rate of slag concrete are 34.47s\(^{-1}\), 60.73s\(^{-1}\), 77.42s\(^{-1}\) and 99.01s\(^{-1}\), respectively, the peak stress of slag concrete increases by 18%, 31%, 58% and 63%. When the slag powder replacement rate is 30%, the peak stress of slag concrete increases by 22%, 33%, 55% and 59% when the strain rate is 33.26s\(^{-1}\), 58.22s\(^{-1}\), 79.70s\(^{-1}\) and 99.81s\(^{-1}\), relative to the 28d pseudo-static compressive strength of slag powder replacement rate is 30%. When the replacement rate of slag powder is 45%, the peak stress of slag concrete increases by 2%, 30%, 35% and 36%, when the strain rate is 32.33s\(^{-1}\), 51.76s\(^{-1}\) and 79.86s\(^{-1}\), compared with the 28d quasi-static compressive strength and 94.23s\(^{-1}\) of slag powder replacement rate is 45%. Therefore, with the increase of strain rate, the peak stress of slag concrete is gradually increased and the bearing capacity is enhanced. Slag concrete is an obvious rate-related material, just like ordinary concrete. It can also be found from Figure 3 that under the condition of the same strain rate, the peak stress of ordinary coagulation is lower than that of slag concrete.

4.2 Intensity Enhancement Factor

Figure 3 shows the relationship between strength enhancement factor and strain rate. The analysis shows that the strength enhancement factor and the strain rate are positively correlated. When the strain rate is in the range of 30s\(^{-1}\) to 60s\(^{-1}\), the strength enhancement factor of slag concrete is smaller than that of ordinary concrete at the same strain rate. When the strain rate is in the range of 60s\(^{-1}\) to 100s\(^{-1}\), the strength enhancement factor of slag concrete with 0%, 15% and 30% of the same strain rate is close, and the strength growth factor of slag concrete with 45% is the smallest.
4.3 peak strain
The peak strain is the strain corresponding to the peak stress, which reflects the deformation capacity of the material. As can be seen from Table 4, when the replacement rate of slag powder is 0%, the peak strain of slag concrete increases by 32.70%, 69.38% and 116.07% respectively when the strain rate of slag powder replacement rate is 34.65s$^{-1}$, 67.44s$^{-1}$ and 105.10s$^{-1}$, when the strain rate of slag powder replacement rate is 0%. When the strain rate of slag powder replacement rate is 15%, the peak strain of slag concrete increases by 69.61%, 109.31% and 173.53%, respectively, when the strain rate of slag powder replacement rate is 34.47s$^{-1}$, the strain rate is 60.73s$^{-1}$, 77.42s$^{-1}$ and 99.01s$^{-1}$. When the replacement rate of slag powder is 30%, the peak strain of slag concrete increases by 34.45%, 94.55% and 107.73% respectively when the strain rate of slag powder replacement rate is 33.26s$^{-1}$, 58.22s$^{-1}$, 79.70s$^{-1}$ and 99.81s$^{-1}$. When the slag powder replacement rate is 45%, the peak strain of slag concrete increases by 14.75%, 39.15% and 75.93% respectively when the strain rate of slag powder replacement rate is 32.33s$^{-1}$, 51.76s$^{-1}$, 79.86s$^{-1}$ and 94.23s$^{-1}$. Thus, as the strain rate increases, the peak strain gradually increases.

4.4 Effect of Slag Content on Impact Properties of Slag Concrete
It can be seen from FIG. 2 that the peak stress of the concrete is also increasing due to the increasing amount of slag at the same strain rate. When the strain rate is in the range of 77.42s$^{-1}$ ~ 80.23s$^{-1}$, the K15, K30 and K45 specimens are 45.09MPa, 45.69MPa, 47.50MPa, respectively, which are 14.27%, 15.79% stronger than the peak stress of ordinary concrete 20.38%. According to the analysis in Table 4, it can be known that when the strain rate is kept within the same level range, the strength enhancement factor DIF of the slag concrete decreases with the increase of the slag content.

4.5 Effect of slag content and strain rate on morphology of slag concrete
In this experiment, under the action of impact load, the failure modes of the specimen are mainly broken into large pieces and crushed into two forms. Due to space limitations, this article only lists a group of test pieces with a substitution rate of 30% and a group of test pieces at a pressure of 0.4 MPa for analysis, as shown in Figures 6 and 7. When the slag content is the same, as the strain rate increases, the failure form of the test piece becomes more serious. Under the same air pressure, the failure shapes of slag concrete with different slag content are not much different.

5. Conclusion
In this paper, a TYE-2000B pressure tester and a Φ100mm separated Hopkinson pressure bar are used to study the quasi-static and dynamic mechanical properties of slag concrete under different strain rates. The main conclusions are as follows:
(1) Under quasi-static load, the compressive strength of slag concrete increases with the increase of slag content.

(2) When under dynamic loading, the strain rate sensitivity of slag concrete is significant. With the increase of strain rate, its own peak stress, strength enhancement factor and peak strain will also increase.

(3) When the strain rate is the same, the peak stress of slag concrete is positively correlated with the slag content.

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