Uniaxial Tensile Test of Waste Glass Powder Concrete at Different Loading Rates

Shirui Li¹, Yuanchu Gan¹ and Guojun Ke¹
¹School of Civil Engineering, University of South China, Hengyang 421001, China
2193963600@qq.com

Abstract: Test method by direct stretching. The failure modes and failure mechanisms of concrete specimens with 0%, 10% and 20% of waste glass powder at five different loading rates were studied. The uniaxial tensile view of waste glass powder concrete was established by using parallel-bar model PBS. The damage model is the modified parallel model, and the damage relationship is very similar to the stress-strain curve in the test. It shows that the concrete uniaxial tension meso-damage model can be used in this test. The ultimate tensile strength of waste glass powder concrete increases with the increase of loading rate. The relationship between dynamic tensile strength and loading rate is studied. The linear regression fit is applied to the influence of loading rate and dynamic tensile strength to obtain dynamic tensile strength. The increment is approximately related to the loading rate.

1. Introduction
Concrete is a commonly used building material in engineering and has been widely used for many years. Due to the growing demand for such materials, especially in complex working environments, such as offshore concrete rigs, high arch dams, prestressed concrete pressure vessels for nuclear power plants, and the emergence of large-span prestressed bridges [1], many Researchers are eager to understand the mechanism of concrete failure [2-3] and the effect of loading rate on the constitutive relationship of concrete [4-5].

Researchers have studied the effect of loading rate on the mechanical properties of concrete [6-8]. Futian Jiang [9] found that the loading rate had little effect on the tensile strength when the loading rate was between 0.2Mpa/min and 0.6Mpa/min. Korol Komlos et al. carried out a dynamic test on prismatic specimens. At loading rates of 1.5 MPa/min and 5 MPa/min, the higher the loading rate, the greater the tensile strength. Thuong Ngo [10] studied the effect of loading rate on crack propagation in ultra-high performance concrete, and there is a strong correlation between strain rate sensitivity and dynamic crack propagation characteristics of ultra-high performance concrete.

2. Materials and experimental details

2.1. Test piece raw materials and molding
The material used for waste glass concrete is P.O32.5 ordinary Portland cement, gravel with particle size of 5-20mm, Xiangjiang Zhongsha, window corner scrap, ball mill grinding about 300 mesh waste glass powder by ball mill, waste glass powder blending The mass ratio of the materials was 0%, 10%, and 20%, respectively. The mix ratio of waste glass concrete base is shown in Table 1.
Table 1. Waste glass concrete matrix mix ratio

| ingredient | cement | Fine aggregate | Coarse aggregate | water |
|------------|--------|----------------|-----------------|-------|
| Mass ratio | 1      | 1.16           | 2.05            | 0.46  |

The direct tensile test specimens were 100 mm × 100 mm × 300 mm prisms, and the test pieces of each group were 15 and a total of 3 sets. The split test and the base compressive strength test specimens are standard cubes with a side length of 150 mm, and each set of admixtures has 3 test pieces, a total of 9 sets.

2.2. Test method and device

The test was carried out by a 600KN microcomputer-controlled electro-hydraulic servo universal testing machine. The loading rates of the test were 0.4KN/s, 0.2KN/s, 0.1KN/s, 0.05KN/s, and 0.025KN/s. The strain gauge of RX120-50AA was attached to the surface of the test piece to measure the deformation of the waste glass powder concrete. The sticking position is shown in Figure 1. The strain information collected by the strain gauge is transmitted to the computer through the receiver. The test adopts the test method of direct stretching of the pre-embedded steel bars at the end of the concrete. The test device is shown in Figure 2.

Figure 1. Strain gauge measurement position

Figure 2. Test device

3. Analysis of test results

3.1. Form and mechanism of tensile failure of waste glass concrete

The test shows that under the uniaxial tensile stress, the basic feature of the tensile crack of the waste glass powder concrete is transverse pull-off. As the loading rate increases, the shape of the section of the concrete also changes. When the loading rate is low, the fracture section of the test piece is rough (see Fig. 3 and Fig. 4). The broken section is not flat and has a certain angle, indicating that the crack extends and bends around. When the loading rate increases, the broken section of the test piece is relatively flat, and the coarse aggregate on the broken section is mostly broken. At the moment of destruction, a crisp "beep" sound can be heard, which is manifested as brittle failure. From the macro level, when the strain rate is higher than the transition strain rate, the dependence of the fracture morphology on the variability is strong.

Figure 3. Fracture of concrete specimens at different loading rates
Concrete is formed by hydration of aggregate and cement slurry. Due to the large difference between the elastic modulus of aggregate and cement, temperature cracks or shrinkage cracks are easily generated inside the specimen after hardening process. The transition zone of the section is the interior of concrete. The weak link, and the destruction of waste glass powder concrete is closely related to the crack. According to the fracture mechanics, the development path of the crack is also related to the blockage of the aggregate. That is, if the development of the front section of the crack is greater than the strength of the cement colloid, the crack will detour. The destruction of waste glass powder concrete is a process including the generation, expansion, and polymerization of cracks until unstable expansion. Since the test piece is taken out from the curing room, the surface of the test piece is different from the internal dry environment. At the same time, the stress state of the surface and the internal part of the test piece is different when loading, the surface stress state is similar to the plane stress, and the internal force state is more like a plane. Strain, which causes the surface of the test piece to crack first and inside. As the load increases, the inside of the test piece enters the diffusion stage. The internal cracks are active and develop, and then further loaded. The inside of the test piece enters the centralized stage, and some cracks appear to penetrate.

Under the condition of high loading rate, the evolution of the damage of waste glass powder concrete will be transformed from single crack propagation under static conditions to multi-crack competition under dynamic action. Cracks of different sizes expand simultaneously, and the number of multiple cracks consumes more energy and crack propagation. The increase in total energy required increases the fracture toughness of crack propagation; multi-crack competition delays crack propagation, and the corresponding strain progression will be slow under low loading conditions. It can be seen that at high loading rates, the test piece breaks the crack close to a straight line, and at the same time, the fracture surface destroys the aggregate significantly.

3.2. Quaternary tensile microscopic statistical damage model of waste glass powder concrete
In this section, the parallel damage model PBS is used to establish a statistical damage constitutive model to simulate the process of uniaxial tension deformation of waste glass powder concrete, and reveal the mechanism of material damage and damage.

(1) constitutive model
Weifeng Bai [11] and other ideas based on the PBS model established a modified parallel bar model (IPBS), as shown in Figure 5, used to simulate the damage process of the fracture process area of waste glass powder concrete at the reference loading rate. The material volume unit is discretized into N(N→∞) mesoscopic parallel rods, and the spring, the sliding piece and the cementing rod respectively represent the elastic, plastic and brittle failure of the solid material.

![Figure 5. Correcting the parallel bar model](image)
In the uniaxial tension monotonic loading process, Bai Weifeng et al. derived the full curve equation corresponding to the monotonic tensile loading process. Assuming $\varepsilon_{ymin}=0$ ($\varepsilon_{ymin}$ is the minimum yield strain), the standard damage constitutive form is written. Since there is no steel frame auxiliary device in this test, the falling section curve cannot be obtained. Therefore, the damage stress $\sigma_N$ corresponding to the first two steps of the following is calculated.

1) Elastic stage ($0<\varepsilon \leq \varepsilon_0$): $\sigma_N=\sigma_R=\varepsilon_0\varepsilon$

2) Uniform damage stage ($0<\varepsilon \leq \varepsilon_{ymax}$): $\sigma_N=E_0(1-D)\varepsilon,D=1-(1-D_R)(1-D'_{ymax}),D'_{ymax}=\int_{\varepsilon_0}^{\varepsilon_{ymax}} p(\varepsilon_R)d\varepsilon_R$

3) Local destruction stage ($\varepsilon_{ymax} < \varepsilon \leq \varepsilon_{Rmax}$):

$$\sigma_N=1-(1-D_R)(1-D'_{ymax}),D=1-(1-D_R)(1-D'_{ymax}),D'_{ymax}=1-\int_{\varepsilon_0}^{\varepsilon_{ymax}} p(\varepsilon_R)d\varepsilon_R$$

The values of the damage variables $D'_{ymax}$ and $D_R$ are: $0 \leq D'_{ymax} \leq 1$, $0 \leq D_R \leq 1$. Where $D$ is the cumulative damage of the system and elastic modulus; $D'_{ymax}$ is the cumulative damage of the system's elastic modulus due to the yield of the member; $D_R$ is the cumulative damage of the system's elastic modulus due to the fracture of the member. It also represents the cumulative probability distribution corresponding to the fracture damage of the rod in the volume unit.

(2) Determination of mesoscopic damage parameters

The meso-strength intensity of concrete materials is in the form of Weibull distribution and positive distribution. It is assumed that the probability density distribution functions $P(\varepsilon_y)$ and $q(\varepsilon_R)$ of the two meso-damage modes have similar distribution patterns with Weibull distribution and Zhengtai distribution. To reduce the difficulty of analyzing problems, this paper uses a very simple form of probability density distribution (such as uniform distribution, triangular distribution, etc.). The simplified probability density form is shown in Figure 6. The eigenvalues to be determined include $\varepsilon_{ymin}, \varepsilon_{ymax}$. According to the test data, $E_0=3.0\times10^8$Pa was obtained.

\[\text{Figure 6. Simplified form of probability density functions } P(\varepsilon_y) \text{ and } q(\varepsilon_R)\]

According to the test data, the elastic modulus of the three waste glass powders is shown in Table 3-4. The values obtained by other parameters are shown in Table 2. Define the minimum yield strain $\varepsilon_{ymin}=0$.

\[\text{Table 2. Parameters of damage stress}\]

| WGP(%) | 1.5KN/min | 3KN/min | 6KN/min | 12KN/min | 24KN/min |
|--------|-----------|---------|---------|-----------|----------|
| 0      | 110       | 112     | 115     | 130       | 123      |
| 10     | 105.5     | 99      | 95      | 97.5      | 92.5     |
| 20     | 99        | 96.5    | 95      | 97        | 98.5     |

(3) Test analysis and verification

According to the data in Table 1, the stress $\sigma_N$ of the strain corresponding to the damage of the three kinds of waste glass powder at five different loading rates was calculated, and the damage constitutive relationship was obtained as shown in Figure 7. It can be seen from the figure that the
damage constitutive relation and the stress-strain curve in the test are very similar, indicating that the concrete uniaxial tension meso-damage model can be used in this test, and the damage curve is not monotonously increasing, and the elastic phase After that, there is a superposition effect of yield damage and fracture damage inside the test piece, so that the slope of the damage curve is reduced.

3.3. Relationship between loading rate and tensile strength
The uniaxial tensile strength of the waste glass powder concrete specimens at different loading rates is shown in Table 2. In order to study the relationship between dynamic tensile strength and loading rate, through the use of mathematical software and analysis and processing of a large number of experimental data, and draw on the existing empirical formula $f^d_i/f^s_i = 1.0 + \alpha \cdot \log(\varepsilon^d_i/\varepsilon^s_i)$, thereby linearly fitting the effect of loading rate and dynamic tensile strength. In Figure 9, (b)(d)(e)
shows the relationship between the average tensile strength and the loading rate at five different loading rates using \( f_t^d - \log_2 \sigma_t^d \) relationship. Through linear regression analysis, the approximate relationship between the dynamic tensile strength increment and the loading rate is shown in (b)(d)(e). Equations (1) to (3) correspond to the relationship between the mean point of compressive strength and the loading rate of 10% and 20% waste glass powder.

\[
\frac{f_t^d}{f_t^c} = 1.0 + 0.05159 \log_2 \frac{\sigma_t^d}{\sigma_t^c} \quad (R^2=0.97) \\
\frac{f_t^d}{f_t^c} = 1.0 + 0.03155 \log_2 \frac{\sigma_t^d}{\sigma_t^c} \quad (R^2=0.91) \\
\frac{f_t^d}{f_t^c} = 1.0 + 0.02144 \log_2 \frac{\sigma_t^d}{\sigma_t^c} \quad (R^2=0.92)
\]

Where: \( f_t^d \) represents the dynamic tensile strength, \( f_t^c \) represents the tensile strength at the loading rate \( \sigma_t^c=1.5\text{KN/min} \), and \( \sigma_t^d \) represents the dynamic loading rate.

**Table 3. Tensile strength of waste glass powder concrete at different loading rates**

| 0%/ (KN/Min) | 10%/ (KN/Min) | 20%/ (KN/Min) |
|---------------|---------------|---------------|
| 1.5 3 6 12 24 | 1.5 3 6 12 24 | 1.5 3 6 12 24 |
| 2.5 2.9 2.9 3.0 3.3 | 2.8 2.7 2.7 3.0 2.4 | 2.5 2.4 2.5 2.6 |
| 4 1 6 6 4 4 6 6 8 9 | 1 7 3 8 9 8 |  |
| 2.9 3.3 3.1 3.3 3.5 2.7 2.6 2.6 2.9 2.3 | 2.4 2.5 2.4 2.5 |  |
| 0 2 6 1 3 7 9 9 9 1 9 4 8 7 5 |  |
| 3.0 2.4 3.1 3.4 3.4 2.4 2.7 2.7 3.0 2.9 2.3 2.5 2.5 2.6 |  |
| 5 7 5 7 5 5 6 3 7 0 7 0 6 2 7 |  |
| average 2.8 2.9 3.0 3.2 3.4 2.6 2.7 2.8 2.8 2.9 2.4 2.4 2.5 2.5 2.6 |  |
| 3 0 9 8 4 2 7 0 5 4 1 9 4 6 0 |  |

It can be seen from Table 3 that the ultimate tensile strength of waste glass frit concrete increases with the increase of loading rate. When the dosage is 0%, the tensile strengths of loading rate 3KN/min, 6KN/min, 12KN/min and 24KN/min are increased by 2.5%, 9.2%, 16.9%, respectively, relative to the tensile strength of 1.5KN/min. And 21.6%; while the dosage is 10% and 20%, the tensile strength is increased by 5.7%, 6.9%, 8.8%, 12.2% and 3.3%, 5.14%, 6.2%, 7.9%, respectively. The tensile strength of the specimens without the blended waste glass powder is obviously higher than that of the specimens with the glass-filled powder, indicating that the blended waste glass powder material has a weakening effect on the tensile strength of the concrete, so the test results obtained are different.

(a) Different loading rates corresponding to the tensile strength increase of concrete at 0% dosing

(b) Relationship between tensile strength increase and loading rate of concrete at 0% content
(c) Different loading rates corresponding to tensile strength increment of concrete at 10% dosing

(d) Relationship between tensile strength increment and loading rate of concrete under 10% content

(e) Different loading rates corresponding to the tensile strength increase of concrete at 20% dosing

(f) Relationship between tensile strength increment and loading rate of concrete at 20%

**Figure 8.** Relationship between dynamic tensile strength and loading rate

It can be seen from the formulas (1)-(3) and Figure 8 that the model change trend of each test piece was consistent, and the tensile strength of the concrete increases as the loading rate increases. It is generally believed that the effect of dynamic loading on tensile strength is attributed to the inertia effect and the void water viscosity effect. Since the test is a dry concrete test piece, the strength effect is mainly caused by the microcrack inertia effect.

4. Conclusions

1. The destruction process of waste glass powder concrete is the process of crack generation, expansion and instability. As the loading rate increases, the failure mode of the test piece changes. When the loading rate is low, the fracture surface of the specimen is rough, and when the loading rate is high, the fracture section of the specimen is flat and the gravel is more on the section.

2. According to the idea of PBS model, the uniaxial tensile mesoscopic statistical damage model of waste glass powder concrete was established. It can be seen from Fig. 4-6 that the damage constitutive relation and the stress-strain curve in the test are very similar, indicating that the concrete uniaxially stretched. The observational damage model can be used in this experiment.

3. With the increase of loading rate, the energy absorption capacity of waste glass powder concrete is obviously improved; however, as the amount of waste glass powder increases, the energy absorption capacity of concrete decreases gradually.

4. The ultimate tensile strength of waste glass powder concrete increases with the increase of loading rate. At the macro level, it is mainly attributed to the influence of loading rate; based on the microscopic level, the mechanism of dynamic tensile strength enhancement of waste glass powder...
concrete is caused by the microcrack inertia effect.

**Fund Project**
National Natural Science Foundation of China (51378247); Hunan Provincial University Innovation Platform Open Fund Project (12K092).

About the author: Shirui Li (1992-), male, master student, research engaged in high performance concrete and structural safety research.

Corresponding author: Yuanchu Gan, male, associate professor.

**References**
[1] Yufei Sheng, Xudong Cheng, Hailong Wang. A review of the effects of free water on concrete strength under dynamic loading [J]. Concrete, 2018(09): 54-58.
[2] Yuhua Zhang. Study on the mechanism of FRP-concrete interface peeling under impact load [D]. Ningbo University, 2017.
[3] Guangyu Lei, Huanyuan Wang, Jianhong Sun, Dang Fanning. Research on the mechanism of concrete tensile and compressive failure based on CT test[J]. Building Structure, 2018, 48(S2): 644-650.
[4] Jie LI, Xiaodan REN. A Review of Research Progress on Static and Dynamic Damage Constitutive Models of Concrete[J]. Advances in Mechanics, 2010, 40(03): 284-297.
[5] Jie LI, Xiaohuan YAN, Xiaodan REN. Study on large-scale experimental study of concrete uniaxial compression performance under different loading rates[J]. Journal of Building Structures, 2016, 37(08): 66-75.
[6] Debin WANG, Hongnan LI, Guozhen FAN. Experimental study on the mechanical behavior of reinforced concrete columns under different loading rates[J]. Journal of Building Structures, 2016, 37(08): 76-81.
[7] Shiyun XIAO, Wenbo CAO, Haohao PAN. Experimental study on mechanical properties of reinforced concrete beams under different loading rates[J]. Journal of Building Structures, 2012, 33(12): 142-146.
[8] Feng Pan, Fanning Dang, Kai Jiao, Junping Shi. Study on the mechanism of dynamic bending strength improvement of uneven brittle materials under impact loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(S2): 3948-3955.
[9] Futian Jiang. Testing of mechanical properties of concrete. Beijing: China Railway Publishing House, 1989, 17-118.
[10] Tri Thuong Ngo, Jun Kil Park, Dong Joo Kim. Loading rate effect on crack velocity in ultra-high-performance fiber-reinforced concrete[J]. Construction and Building Materials 197(2019)548–558.
[11] Bai Weifeng, Guo Lei, Chen Shoukai, Cui Ying. Statistical damage mechanics of concrete [M]. Beijing: China Water Resources and Hydropower Press, 2015.