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ABSTRACT

The dynamic properties of concrete in two states (saturated and dry) were compared and analyzed through a series of dynamic biaxial tensile-compressive (T-C) experimentals. All specimens were subjected to constant biaxial T-C stress ratios (0.5:-1, 0.25:-1, 0.1:-1, 0.05:-1 and 1:0 respectively) at different strain rates ($10^{-5}s^{-1}$ to $10^{-2}s^{-1}$). It was found that the biaxial T-C ultimate strengths of both kinds concrete closely relate to the lateral pressure of the specimen, and the independent tensile and compressive strength increases with the increase of strain rate. In the case of exerting lateral pressure, the failure states of specimens show same manner as that of the uniaxial tensile specimens, which indicates that the specimens were completely fractured under tensile loading. The test results show that the biaxial T-C strength of saturated concrete is lower at strain rates of $10^{-5}s^{-1}$, whereas it is higher at the other three strain rates ($10^{-4}s^{-1}$, $10^{-3}s^{-1}$ and $10^{-2}s^{-1}$). This distinct difference indicates that saturated concrete is more rate sensitive under lateral pressure. Through mechanical analysis the article explains the reason of this phenomenon is mainly dued to the beneficial tensile stress of the pore water surface and the Stefan effect. Meanwhile, the strength prediction expression of saturated concrete was established under the condition of stress ratio and strain rate are considered simultaneously.

Keywords: saturated concrete; experiment; tensile strength; biaxial T-C; lateral pressures; strain rates; strength prediction expression;

1 Introduction

There are lots of concrete structures that are often eroded by rain, and many hydraulic structures and port engineering structures are in service in the water environment all year round. The free water will penetrate into the concrete through numerous pores and micro-cracks. These structures are not only often subjected to static loads, but also are subjected to dynamic loads such as explosion, shock, and earthquake. Wang et al (2016), Wu et al (2012) and Kaplan (1980) found that the properties of concrete have changed significantly because of pore water in microcracks. Bischoff and Perry (1991), Fu et al (1991), Malvarl and Ross (1998) thought the saturated concrete showed different mechanical properties under different strain rate load conditions. The research on saturated concrete is of great significance for the application of civil structural engineering.

Some related research results show that the rate-sensitivity of concrete is closely related to the free water in micro-cracks. Due to the internal defects of the concrete itself, free water can penetrate into the micro-cracks of the concrete. Xuan et al (2009), Liu et al (2011) and Zhang et al (2017) have shown that free water could reduce the static strength of concrete. Rossi et al (1992)and Cadoni et al (2001) have found that the dynamic strength of saturated concrete increased significantly. The study of Erzar and Forquin (2011) indicated that when the strain rate was 20-150 s^{-1}, the strength of wet concrete was 30% higher. Wang et al (2007, 2009) and Zhang et al (2015) found that wet concrete was more sensitive to strain rate. Based on Rossi (1991), Zheng et al (2004, 2005) and Yan and Lin (2006) previous studies, it is speculated that the water is the main factor for the increase of the dynamic strength of concrete. Bjerkei et al (1993) and Morley (1979) showed that there was no difference in strength between saturated concrete and dry concrete. Since the loading rate is too fast at the high strain rate of $1s^{-1}$, the effect of water in the microcracks can be ignored due to the high local stress intensity near the aggregates. However, some scholars had found that when hydraulic concrete structures were in service, the concrete was under multi-axial loading state due to water pressure, which should be considered in the design.

Ferrari and Granik (1995) considered that during the service of concrete structures, concrete materials was often in a state of multiaxial complex stress, especially the combination state of tensile-compressive loading is the most unfavorable to the concrete structure. The tensile strength of concrete is significantly reduced in the presence of lateral pressure, which will lead to susceptibility of concrete to cracking and thus steel corrosion and reduction of service life. The concrete studied in this paper is a common material for hydraulic structure and is submerged in water for a long time. Due to the special service environment, the hydraulic concrete structure is under complex stress state. At present, becasuce of the lack of equipment and the difficulty of multi-axial load test, only the experimental researches of uniaxial loading condition were carried out. Although there have been some relevant studies on saturated concrete (Wang et al (2016), Wu et al (2012), Xuan et al (2009), Liu et al (2011), Wang et al (2016), Zhao and Wen (2018), Sun et al (2020) and Huang et al (2020)), these researches are limited to uniaxial tensile, compressive, or impact loads. The evaluation of saturated concrete under biaxial T-C stress state is very scarce. The influence of free water in micro-cracks is not considered in the current design specifications. It is of great significance to study the properties of saturated concrete under the combined action of tensile and compressive loading. In this study, a large number of saturated concrete specimens were investigated by tensile tests under lateral pressure, and the prediction equation of biaxial T-C strength of saturated concrete was established.

2. Materials and Experimental Program

The concrete mixture ratio and specimen size used in this paper are shown in Table 1 and Fig. 1, and the multi-axis test system used in this test and the installation of the specimens are shown in Fig. 2. Concrete specimen production and test details, please refer to Supplementary Material.

Table 1 Mix Ratio of Specimen (unit: kg/m^3).

Sand	Cement	Fly ash	Water	Aggregate size (mm)			Water reducer
				3~20	21~40	41~80	
533	215	52	121	411.5	411.5	580	0.209

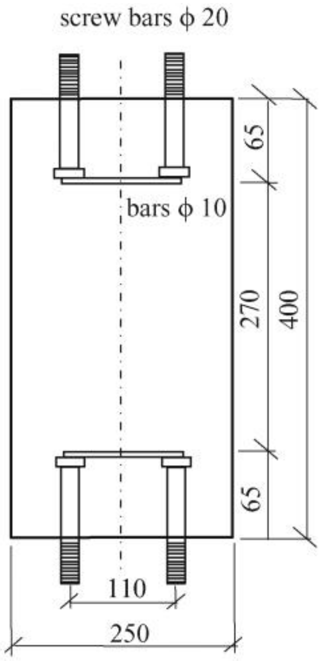


Fig. 1 Details of Specimen (unit: mm)

(a) Multi-axis Test Apparatus (b) Installation of Specimen

Fig. 2 Test Instrument and Specimen Installation

3 The Results Discussed

3.1 Tensile Strength of Concrete under Lateral Pressure

The test results were listed in Table 2 and 3 respectively. The difference in strength between the two types of concrete is remarkable, in which it can be seen that all the strengths in both directions increase with increasing strain rate. We can clearly see from the results that the increase strength of saturated concrete was even higher. According to the current results, it may be the effect of pore water.

Table 2 Dynamic Strengths of Saturated Concrete under Biaxial T-C Loading (MPa)

Stress ratio	Strain rate							
(σ_1 : $-\sigma_3$)	$10^{-5}s^{-1}$		$10^{-4}s^{-1}$		$10^{-3}s^{-1}$		$10^{-2}s^{-1}$	
1 : 0	1.63	0	2.22	0	2.55	0	2.91	0
0.05 : -1	0.42	8.4	0.76	15.2	0.91	18.2	1.19	23.8
0.1 : -1	0.59	5.9	0.98	9.8	1.21	12.1	1.63	16.3
0.25 : -1	0.97	3.88	1.48	5.92	1.77	7.08	2.03	8.12
0.5 : -1	1.24	2.48	1.73	3.46	2.07	4.14	2.43	4.86
0 : -1	0	-17.11	0	-26.16	0	-24.83	0	-27.82

Table 3 Dynamic Strengths of Dry Concrete under Biaxial T-C Loading (MPa)

Stress ratio	Strain rate							
(σ_1 : $-\sigma_3$)	$10^{-5}s^{-1}$		$10^{-4}s^{-1}$		$10^{-3}s^{-1}$		$10^{-2}s^{-1}$	
1 : 0	1.71	0	2.02	0	2.38	0	2.72	0
0.05 : -1	0.49	9.8	0.69	13.8	0.84	16.8	1	20
0.1 : -1	0.68	6.8	0.85	8.5	1.04	10.4	1.43	14.3
0.25 : -1	1.07	4.28	1.37	5.48	1.57	6.28	1.86	7.44
0.5 : -1	1.3	2.6	1.55	3.1	1.86	3.72	2.12	4.24
0 : -1	0	-20.34	0	-21.57	0	-23	0	-24.83

3.2 Failure Mode

From Fig. 3(a) and Fig. 3(b) we could see that, the failure patterns of concrete in the two states are similar, and the failure patterns of concrete specimens have little relationship with moisture content. The failures of both kind of specimens were very sudden and showed a loud crack. Figure 4 shows that there is an obvious fracture crack in the middle part of the concrete specimen, and the load direction of the specimen is perpendicular to the fracture surface of the specimen, which indicates that the specimen was completely fractured under tensile loading. The failure patterns of all concrete specimens with all stress ratios are the same, indicating that the lateral pressure has little affect on the damage modes of specimens. The failure of concrete specimens mainly occurs in the transition zone of mortar at low loading rate. The existence of pore water in micro-cracks of concrete weakens bonding force of mortar in transition zone. Therefore, the static properties of saturated concrete depend more on the effects of pore water between mortar and transitional zone. The number of aggregates fracture increases with the increasing strain rate.

Under dynamic biaxial T-C loading, both kinds of concrete specimens are accompanied by some fragments at the fracture section. A large number of micro-cracks form the fracture area, and finally fragments appear. The size of the macroscopic crack is determined by the lateral pressure, and the extension and development effect of micro crack is not obvious when the lateral pressure is less. On the contrary, there are several macroscopic cracks in the fracture surface of the concrete specimen.

(a) Saturated (b) Dry

Fig. 3 Failure Surfaces of Specimens

(a) Biaxial T-C (b) Tensile Load

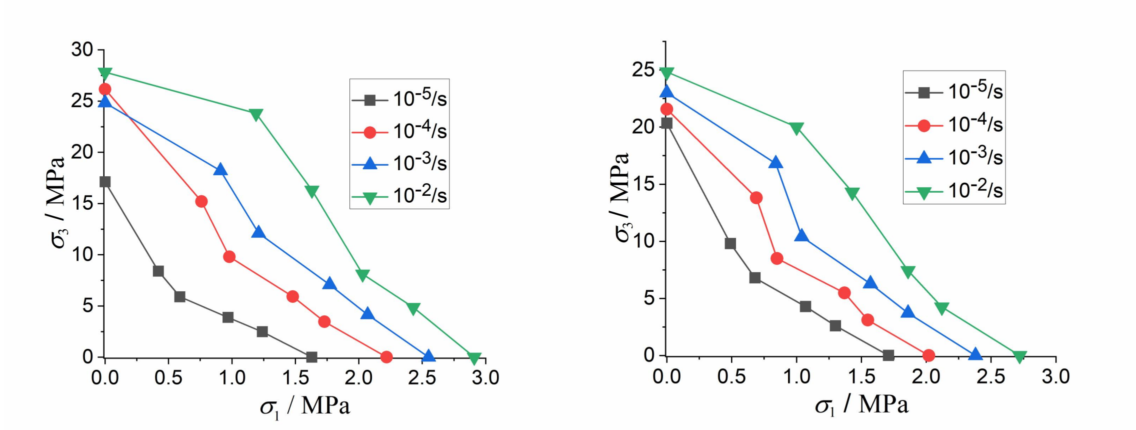
Fig. 4 Image of Specimen Failure

3.3 Effect of Strain Rate

From Table 2 and 3 we can see that the uniaxial strength is much higher than that of the biaxial T-C strength at all strain rate conditions. The lateral pressure strength (σ_3) and tensile strength (σ_1) of concrete in both directions increase with the increasing strain rate. The $10^{-5}s^{-1}$ was defind as static condition in this study, and at the static loading condition, both σ_1 and σ_3 of saturated concrete are lower at the same stress ratio. In contrast, the strength (σ_1, σ_3) of saturated concrete are higher. This may be caused by free water in the micro-cracks of saturated concrete specimen. Under the static loading conditions, the water pressure in the micro-crack promotes the crack expansion and reduces the strength of concrete. But due to the high loading rate and the viscous effect of water, the reverse tensile stress that inhibits the crack propagation is generated instantly, which lead to the strength increase.

3.4 The Influence of the Presence of Lateral Pressure

It is obvious that the uniaxial strength is much higher than that of the biaxial T-C strength at any strain rate condition. It could be found that the tensile strength decreases with the increase of lateral pressure from Fig. 5 for comparison. It is found that the failure strength are strongly influenced by the magnitude of lateral pressure from the test results. The variation law of lateral pressure and strain rate in Fig.5. The lateral pressure strength (σ_3) decreasing with the absolute value of stress ratios increasing, the strength of the combined loading (tensile loading and lateral pressure) is much lower than the uniaxial lateral pressure strength. It indicates that due to the greater lateral pressure, the concrete is more likely to be damaged under tensile load.



(a) Saturated (b) Dry

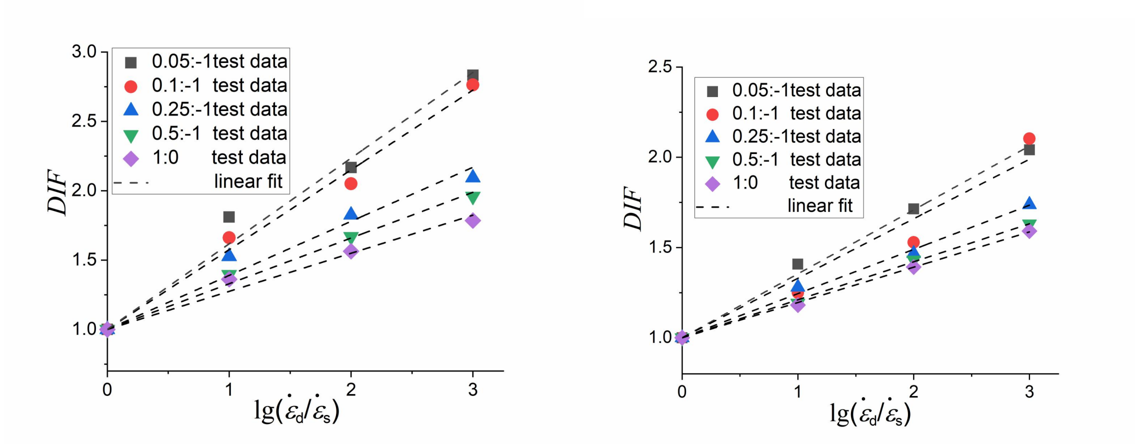
Fig. 5 Variation Law of Tensile Strength with Lateral Pressure

3.5 Dynamic Increase Factor (*DIF*)

In Fig. 6, the tensile strength changes with the increasing strain rate at different lateral pressure. However, the strength of concrete increases by different degrees at different stress combinations. Through fitting analysis of test data, the following formula can well describe the growth range of dynamic strength of concrete .

$$DIF = \frac{\sigma_t^d}{\sigma_t^s} = 1 + a\lg\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right) \quad (1)$$

where $\dot{\varepsilon}_s$ is defined as $10^{-5}s^{-1}$; $\dot{\varepsilon}_d$ is the current strain rate (In this paper, they are $10^{-5}s^{-1}$, $10^{-4}s^{-1}$, $10^{-3}s^{-1}$ and $10^{-2}s^{-1}$, respectively); σ_t^s and σ_t^d are static and dynamic tensile strengths respectively, and correlation coefficients *a* are shown in Table 4.



(a) Saturated (b) Dry

Fig. 6 *DIF* Versus Strain Rate for Saturated and Dry Concrete

Table 4 Test Regression Parameters and the Correlation Coefficient

Types of concrete	Fitting parameter	Stress ratio (σ_1 : $-\sigma_3$) 1:0	0.05:-1	0.1:-1	0.25:-1	0.5:-1
Saturated concrete	*a*	0.256	0.586	0.568	0.358	0.315
	R^2	0.9704	0.9707	0.9832	0.9577	0.9891
Dry concrete	*a*	0.339	0.168	0.244	0.257	0.277
	R^2	0.9988	0.9939	0.9339	0.9917	0.9975

3.6 Influence of Pore Water in Microcracks on Tensile Strength of Concrete

It's obvious that the failure patterns of concrete specimen are typical tensile failure, and the damage is mainly induced by the action of tensile loading, while implies that the lateral pressure accelerates the tensile failure of the specimen, and the ultimate tensile strength decreases obviously with the increase in lateral pressure. It is also found that the sensitivity of saturated concrete to strain rate may be caused by the viscous effect of water.

The spread of micro-cracks leads to the failure of concrete, so the free water in pores will play a significant role in the change of concrete strength. According to the Griffith Microcrack Theory, the fracture is not caused by the pulling of two parts of the body along the interface, but by the internal micro-cracks growth. The stress that makes the crack start to grow is regarded as the ultimate tensile strength of concrete is proposed by Bazant and Planas (1998).

$$\sigma = \sqrt{\frac{2E\gamma}{\pi c}} \tag{2}$$

where σ is the stress that causes the crack to spread, γ is the concrete surface energy of microcrack propagation, c is the semi-length of microcrack inside concrete, and E is elastic modulus of concrete. According to the microcrack theory, the surface energy of concrete material is the main factor which influences the ultimate tensile strength. Based on the surface physicochemical theory of Prutton (1983), the film pressure of solid surface immersed in water is lower than that is not immersed in water. In this case, the surface tension of saturated concrete is much lower. The specific formula is as follows,

$$\gamma' = \gamma - \gamma_0 \tag{3}$$

where γ' stands for the surface energy of saturated concrete, γ is the surface energy of dry concrete, γ_0 is the reduced surface energy.

Under the condition of dynamic loading, the micro-cracks in the concrete extend and expand rapidly, resulting in fracture and failure of the concrete specimen. The free water doesn't have enough time to reach the crack tip due to the rapid crack propagation, the direction of free water surface tension is opposite to the direction of crack propagation, which inhibits the crack development in a short time. The dynamic biaxial T-C strength of concrete is improved, and the free water surface tension which prevents crack propagation is expressed by Prutton (1983),

$$\sigma_c = \frac{2\gamma \cos\theta}{\rho} \tag{4}$$

where γ stands for the free water surface energy, θ is the wetting angle, and ρ is radius of curvature of liquid.

From the physical point of view according to Stefan effect, the improvement of concrete dynamic strength compared with quasi-static strength is given by Zheng and Li (2004) and Rossi (1991) ,

$$\sigma_v = \frac{3\eta r^2 v}{2h^3} \tag{5}$$

where η is the water viscosity coefficient, h is the width of the crack, and r is radius of plates. From the above formula, when concrete is subjected to dynamic load, the loading rate v increases and the cohesive force also increases, which prevents the expansion of cracks. Within a certain loading rate range, reverse cohesion that prevents crack propagation can be obtained by Eq. (5). The free water surface tension and the free water viscous stress is considered simultaneously, the following formula is obtained,

$$\sigma = \frac{2\gamma\cos\theta}{\rho} + \sigma_v \tag{6}$$

Under the condition of dynamic lateral pressure, the increasing mechanism of dynamic tensile strength can be explained by the following schematic diagram Fig. 7.

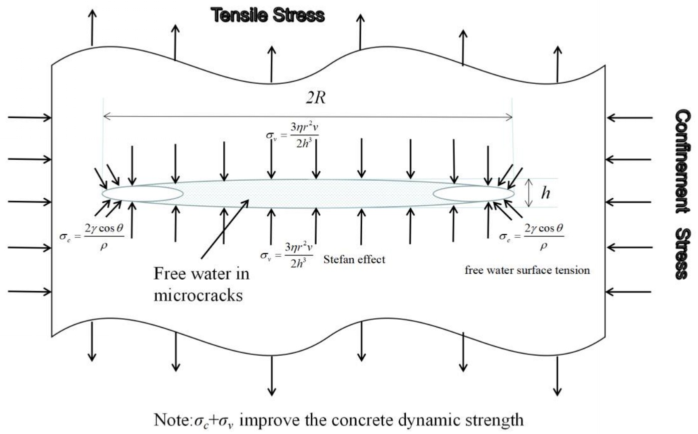


Fig.7. Schematic Diagram of Tensile Strength Increase of Saturated Concete

Based on the concept of wet weakening, Pihlajavaara(1974) found the following relation equation:

$$\frac{f_t^{sat}}{f_t^{dry}} = \sqrt{1 - cS_r} \tag{7}$$

where f_t^{sat} is the splitting tensile strength at saturation; f_t^{dry} is the splitting tensile strength at dry state; c is the correlation coefficient; and S_r is saturation ratio.

On the basis of considering saturation and strain rate factor, we establish the expression of biaxial T-C strength of concrete in principal stress space.

$$\frac{\sigma_1}{f_t} = \left[\frac{A\alpha}{1 + A\alpha} + B(1 - e^{-C\alpha}) \bullet \lg(\dot{\varepsilon}_d / \dot{\varepsilon}_s)\right] \bullet (1 - DS_r)^{1/2} \tag{8}$$

where f_t is uniaxial tensile strength; σ_1 is dynamic biaxial T-C strength of concrete; α is stress ratio, S_r is saturation ratio, and A, B, C, D are the correlation coefficient.

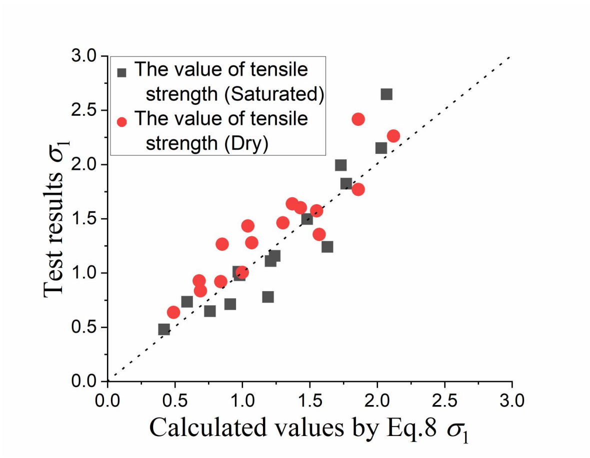


Fig. 8. Comparison of Test Results and Calculated Values

The factors of saturation, strain rate and lateral pressure was considered in the tensile strength criterion in this paper. It could be clearly seen that the calculated results were close to the test results in Fig. 8. However, due to the discrete nature of concrete, very few scattered data results could be ignored. The relative error range between the prediction results and the test results are from 1.3% to 20%. Therefore, the proposed strength relationship was considered reasonable.

4. **Strength Criteria in Octahedral Space**

Through the analysis of the test results of both kinds concrete under different strain rates, the triaxial principal stress is transformed into octahedral stress. The octahedral normal stress (σ_{oct}) and octahedral shear stress (τ_{oct}) are calculated by the following formula. In octahedral space, similarity θ represents the direction of shear stress (τ_{oct}).

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{9}$$

$$\tau_{oct} = \frac{1}{3}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]^{1/2} \tag{10}$$

$$\theta = \arccos\frac{2\sigma_1 - \sigma_2 - \sigma_3}{3\sqrt{2}\tau_{oct}} \tag{11}$$

The σ_{oct}/f_c and τ_{oct}/f_c are listed in Table 5 and 6.

Table 5 Octahedron Space Biaxial T-C Stress of Saturated Concrete

Stress ratio	Strain rate							
(σ_1 : -σ_3)	$10^{-5}s^{-1}$		$10^{-4}s^{-1}$		$10^{-3}s^{-1}$		$10^{-2}s^{-1}$	
0.05:-1	-0.16	0.24	-0.28	0.43	-0.34	0.51	-0.44	0.67
0.1:-1	-0.1	0.17	-0.17	0.28	-0.21	0.35	-0.29	0.47
0.25:-1	-0.06	0.12	-0.09	0.19	-0.1	0.22	-0.12	0.26
0.5:-1	-0.02	0.09	-0.03	0.13	-0.04	0.15	-0.05	0.18

Table 6 Octahedron Space Biaxial T-C Stress of Dry Concrete

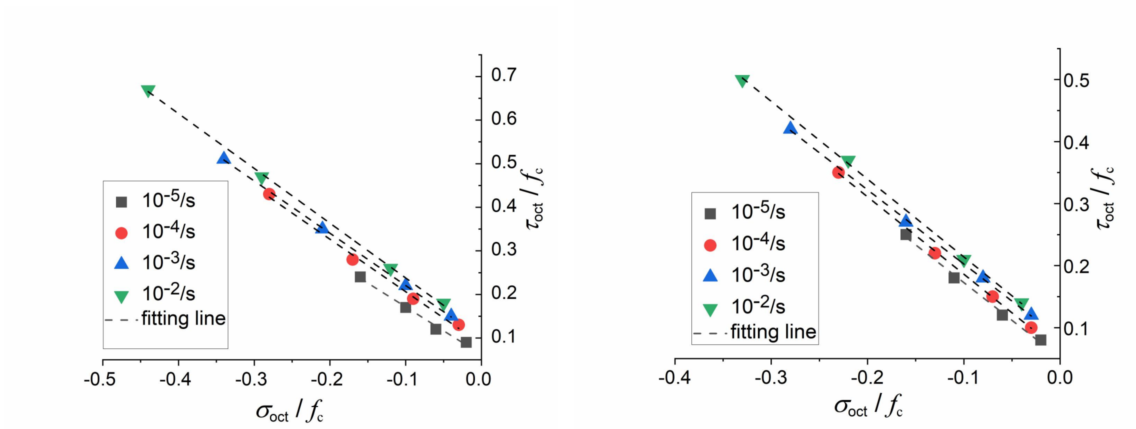
Stress ratio	Strain rate							
(σ_1 : -σ_3)	$10^{-5}s^{-1}$		$10^{-4}s^{-1}$		$10^{-3}s^{-1}$		$10^{-2}s^{-1}$	
0.05:-1	-0.16	0.25	-0.23	0.35	-0.28	0.42	-0.33	0.5
0.1:-1	-0.11	0.18	-0.13	0.22	-0.16	0.27	-0.22	0.37
0.25:-1	-0.06	0.12	-0.07	0.15	-0.08	0.18	-0.1	0.21
0.5:-1	-0.02	0.08	-0.03	0.1	-0.03	0.12	-0.04	0.14

By analyzing the dynamic strength of both concrete, the failure criterion of octahedral space are established:

$$\frac{\tau_{oct}^{d}}{f_c} = a + b\frac{\sigma_{oct}^{d}}{f_c} + c\lg(\dot{\varepsilon}_d \big/ \dot{\varepsilon}_s) \qquad (12)$$

where f_c stands for static uniaxial compressive strength, $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_d$ are the same values represented by Eq.(1) in this paper. ($\dot{\varepsilon}_d = \dot{\varepsilon}_s$, σ_{oct}^{d}、 τ_{oct}^{d} represents the static octahedral normal stress and shear stresses respectively, $\dot{\varepsilon}_d > \dot{\varepsilon}_s$, $\sigma_{oct}{}^{d}$、 $\tau_{oct}{}^{d}$ represents dynamic variable field). a, b and c are the regression parameters. For saturated concrete: a = 0.055, b = -1.224, c = 0.022 , R^2 = 0.997. For dry concrete: a = 0.049, b = -1.232, c = 0.014, R^2 = 0.999.

As can be seen from the value of R^2, it could be determined the Eq.(12) can be suitable for dynamic T-C failure criterion in octahedral space. Fig. 9 shows the fitting line of the biaxial T-C in octahedral space which is very close to the experimental results. It illustrates that Eq. (12) is more reasonable to express the failure criterion in octahedral space for two kinds of concrete.



(a) Saturated (b) Dry

Fig. 9 Biaxial T-C Failure Criterion in Octahedral Space of Concrete under Various Strain Rates

5. Conclusions

In this paper, the servo hydraulic multiaxial test system is used to carry out dynamic tensile test on saturated and dry concrete with five different variations of lateral pressure. The conclusions are obtained through the test of 120 concrete specimens.

(1) The uniaxial tensile strength of concrete is much higher than ultimate biaxial T-C

strength in the presence of lateral pressure in all strain rate ranges. Lateral pressure plays an decisive role in ultimate tensile strength.

(2) The factors of lateral pressure and strain rate are considered simultaneously, the failure criterion in octahedral space was proposed which are very suitable to express the biaxial T-C strength of both concrete.

(3) Although the failure modes of both concrete are the same as those of uniaxial tensile dynamic specimens, the ultimate biaxial T-C strength is lower, and concrete structures are more prone to failure under multi-axial complex stress states, especially under the combination of tensile and compressive loading. And the failure patterns of concrete specimens have little relationship with moisture content.

(4) In the current research, the dynamic strength of saturated concrete increases is even more dramatic. This indicates that the tensile strength of saturated concrete is more easily affected by strain rate in the presence of lateral pressure. The beneficial tensile stress of the free water surface and the Stefan effect are the main factors for inducing the enhancement of strength. In this study, the strength prediction expression (Eq.(8)) of saturated concrete was established which the stress ratio and strain rate are considered simultaneously, and the prediction expression is more reasonable by comparing with the test results.

Acknowledgments

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