

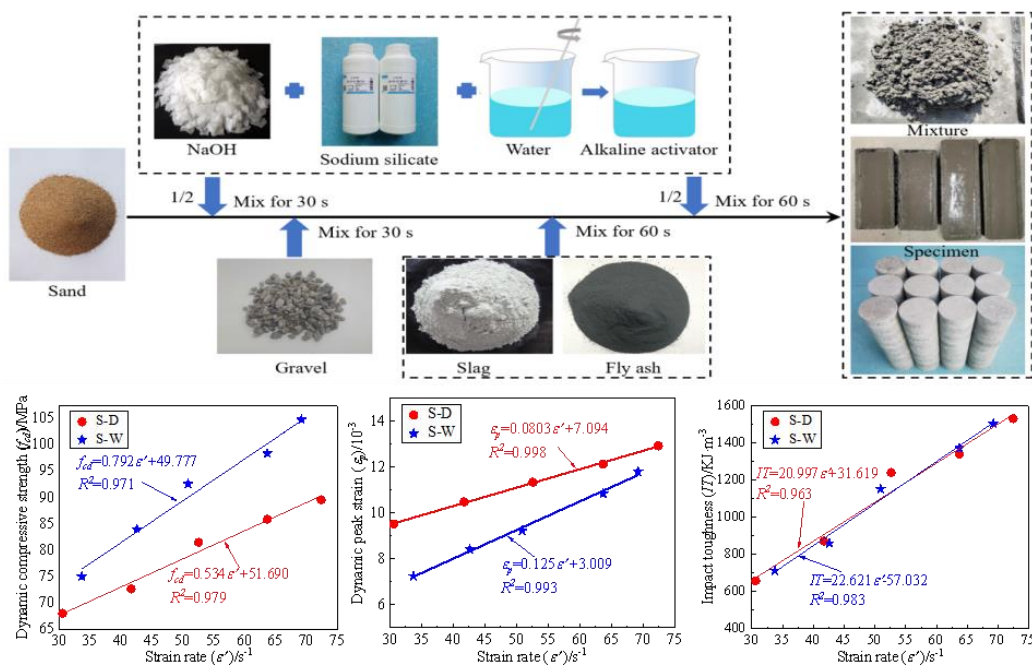
Original Research Report

Effects of water saturation and impact load on the mechanical properties of geopolymer concrete

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Graphical abstract



Abstract: In terms of quality test, ultrasonic wave velocity test, static mechanical test and dynamic compression test, the physical and static mechanical properties of geopolymer concrete after water immersion for 180 d were studied, and the effects of water saturation and impact load on the mechanical properties of geopolymer concrete were analyzed. The results show that the geopolymer concrete reaches the water saturated state after water immersion for 180 d, and the ultrasonic wave velocity of geopolymer increases after water saturation, while the compressive strength, splitting tensile strength and flexural strength decrease. Water saturation increases the strength and stiffness

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of geopolymer concrete under impact load, while reducing its deformation capacity, with no significant effect on its energy consumption characteristics. The dynamic compressive strength and dynamic elastic modulus of geopolymer concrete increase after water saturation, the dynamic peak strain and pre-peak toughness decrease, and the impact toughness exhibits no significant alteration. The dynamic compressive strength of geopolymer concrete after water saturation increases by 8.61%~19.01%, the dynamic elastic modulus shows an average increase of 52.20%, the dynamic peak strain shows a maximum reduction of 28.88%, and the pre-peak toughness decreases by 14.07%~43.26%. The dynamic increase factor (*DIF*) of geopolymer concrete increases significantly after water saturation, and the fractal dimension of fragments decreases. The Comité Euro-International du Béton (CEB) model can well predict the *DIF* of geopolymer concrete in dry state, but significantly underestimate the *DIF* value of geopolymer concrete in water saturated state. Based on the test results, a *DIF* fitting formula for geopolymer concrete in water saturated state is proposed.

Key words: geopolymer concrete; impact load; water saturation; mechanical properties; strain rate

1. Introduction

Geopolymer concrete is considered to be one of the best substitutes for ordinary Portland cement concrete, which not only has the advantages of environmental protection, solid waste recycling, low energy consumption, low carbon emission, but also has high strength, high temperature resistance and excellent durability [1,2]. Furthermore, geopolymer concrete exhibits exceptional corrosion resistance and superior erosion resistance, which is a highly promising material for hydraulic structures, and has been applied in marine engineering projects and bridge engineering construction [3,4]. Concrete contains numerous inherent voids and microcracks. When subjected to prolonged water exposure, water infiltration becomes inevitable, leading to a water saturated or near-water saturated state within the concrete. The moisture gradient, surface tension and pore water pressure caused by water saturation will change the stress state of concrete and affect the mechanical properties of concrete [5].

In addition, due to various natural disasters and human factors (such as earthquakes, underwater explosions, collisions, weapon strikes, etc.), many hydraulic structures will be subjected to impact loads during their service life [6,7]. Under impact load, the stress state, failure mode and damage evolution process within concrete differ significantly from those under static load [8]. Consequently, the effect and mechanism of water saturation on the mechanical properties of concrete under impact load will undergo further alterations. Li et al. studied the effect of water saturation on the static compressive strength and acoustic emission characteristics of concrete, and found that the static compressive strength and acoustic emission characteristics of concrete decreased after water saturation [9]. Wang et al. also confirmed that the static compressive strength of concrete decreased after water saturation, but found that the dynamic compressive strength of concrete in water saturated

state under impact load was larger than that in dry state [10]. Cui et al. studied the dynamic mechanical properties of concrete in water saturated state by the split hopkinson pressure bar (SHPB) test equipment, and found that concrete with different saturation levels exhibits strain rate sensitivity, and under dynamic compression load, free water in the pores reduced the strain rate effect [11]. Yan et al. found that the peak strain and specific energy absorption of concrete after water saturation under impact load decreased, and the degree of fragmentation of concrete decreased [12].

However, current research on the dynamic mechanical properties of concrete in water saturated state mainly focuses on ordinary Portland cement concrete, and less on geopolymer concrete. Therefore, understanding the dynamic response of geopolymer concrete under the coupling action of water saturation and impact load is of significant importance to promote the application of geopolymer concrete in hydraulic structures and ensure their safety and reliability. In view of this, this paper firstly conducts quality test, ultrasonic wave velocity test and static mechanical test on geopolymer concrete in dry and water saturated states, and studies the physical and static mechanical properties of geopolymer concrete after water saturation. Then the dynamic compression test of geopolymer concrete is carried out by SHPB test equipment, and the effect of water saturation and impact load on the mechanical properties of geopolymer concrete is analyzed.

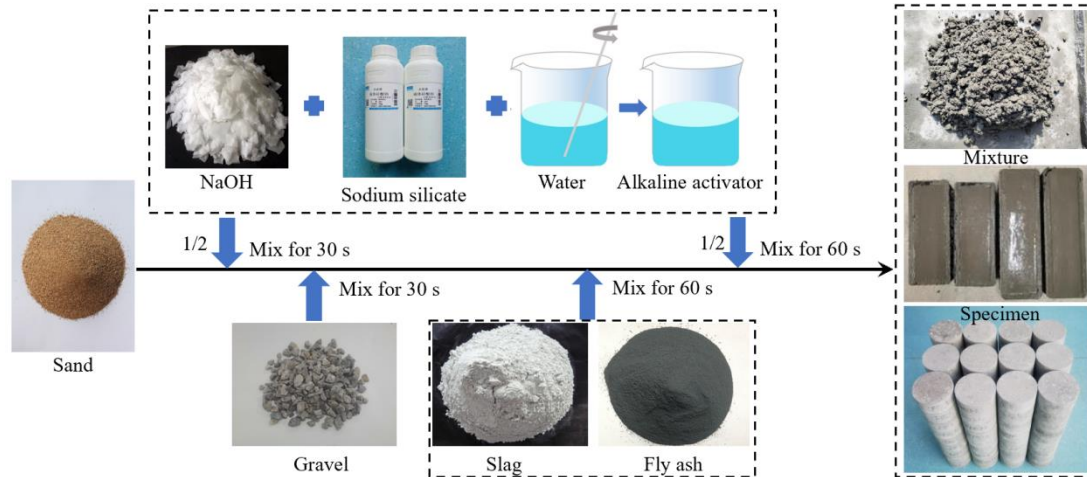
2. Experiment

2.1. Specimen preparation

The materials prepared geopolymer concrete include slag, fly ash, NaOH, sodium silicate, gravel, sand and water[13]. Slag: quenched blast furnace slag, produced by Hancheng Longmen Iron and Steel Co., LTD., with a density of $2.97 \text{ g}\cdot\text{cm}^{-3}$, a specific surface area of $491.6 \text{ m}^2\cdot\text{kg}^{-1}$ and an activity index of 95%. Fly ash: Grade I low calcium fly ash, produced by Hancheng No. 2 Power Plant, with a density of $2.05 \text{ g}\cdot\text{cm}^{-3}$. NaOH: flake solid, produced by Tianjin Kemie Ou Chemical Reagent Co., LTD., with a purity of 97%. Sodium silicate: analytically pure, produced by Nanjing Unity inorganic Chemical plant production, with a $\text{SiO}_2/\text{Na}_2\text{O}$ modulus of 3.1 ~ 3.4. Gravel: limestone gravel, with a density of $\text{g}\cdot\text{cm}^{-3}$ and a particle size of 5 ~ 20 mm. Sand: river sand, with a fineness modulus of 2.8 and a density of $2.63 \text{ g}\cdot\text{cm}^{-3}$. Water: clean tap water. The mix ratio of geopolymer concrete is shown in Table 1, geopolymer concrete is prepared according to it, and the specific preparation process is shown in Figure 1. Three sizes of specimens are prepared, which were $100\times100\times100 \text{ mm}^3$ (for mass test, ultrasonic wave velocity test, compressive strength test and splitting tensile strength test), $100\times100\times400 \text{ mm}^3$ (for flexural strength test), and $\Phi100 \text{ mm}\times50 \text{ mm}$ (for dynamic compression test).

Table 1. The mix ratio of geopolymer concrete ($\text{kg}\cdot\text{m}^{-3}$).

Slag	Fly ash	NaOH	Sodium silicate	Gravel	Sand	Water
250	110	25	90	1018	810	90

**Fig. 1.** Preparation process of specimen.

The specimens that were standard cured to 28 d are divided into two groups. One group (S-W) is immersed in tap water for 180 d to achieve a fully water saturated state, while the other group (S-D), as control group, is placed indoor (the standard concrete curing room) for 180 d to dry naturally [12,13].

It should be noted that the S-D specimens used as control group in the test are treated by indoor natural drying rather than oven drying for two main reasons. First, hydraulic structures in real-world environments are usually not subjected to oven drying treatment when dry, so the use of natural drying ensures that the test results better reflect actual conditions. Secondly, relevant studies have shown that oven drying treatment can alter the capillary pore structure and composition of concrete, thereby affecting its properties [14]. Therefore, to ensure the accuracy and comparability of the test results and avoid interference of other factors, the natural drying method is chosen. After drying and water saturation for 180 d, the specimen is taken out for test.

2.2. Experimental method

Quality and ultrasonic wave velocity test: precision electronic balance is used to test the mass of specimen, the ultrasonic wave velocity of specimen is tested by NM-4 non-metallic ultrasonic detection analyzer. Before measurement, the surface moisture of the specimen is wiped dry.

Mechanical tests: The electro-hydraulic servo material test system is used to test the compressive strength and splitting tensile strength of specimen, the flexural strength of strength is tested by the flexural testing machine, and the dynamic compression test is carried out by the $\Phi 100$ mm SHPB test equipment, as shown in Figure 2.

In dynamic compression test, the strains of incident wave, reflected wave and transmitted wave are measured by strain gauge, and then the "three-wave method" is used to process the test data. During the test, the aluminum wafers are used to correct the incident waveform to ensure the stress uniformity in the specimen. The time history curve of test waveform is shown in Figure 3. From this figure, the coincidence degree of incident wave + reflected wave and transmitted wave is high, indicating that the internal stress of the specimen reaches the uniform state [15,16].



Fig. 2. $\Phi 100$ mm SHPB test equipment.

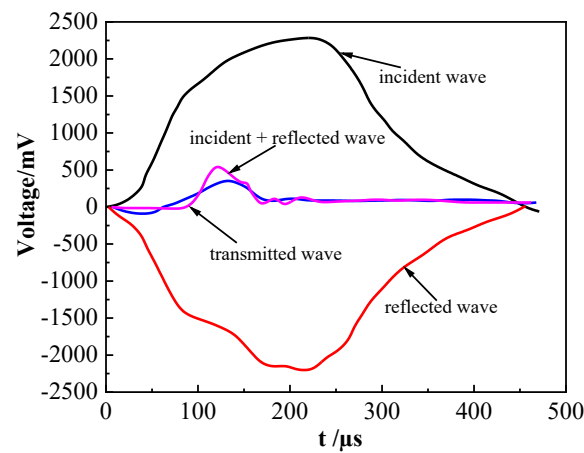


Fig. 3. Time history curve of the test waveform.

3. Results and discussion

3.1. Physical properties and static mechanical properties

The mass-time curve of geopolymer concrete after water immersion is shown in Figure 4, the mass and ultrasonic wave velocity after water saturation for 180 d are shown in Table 2 and Figure 5, and the static mechanical properties are shown in Table 3 and Figure 6. From Figure 4, with the increase of water immersion time, water continues to enter the specimen, and the mass of geopolymer concrete continues to increase. After water immersion for 180 d, the mass of specimen increases by

3.34%. The water absorption rate of specimen decreases with the increase of water immersion time, and the mass of specimen increases rapidly in the early stage of water immersion (within 7 d), and tends to be stable after water immersion for 28 d. After water immersion for 180 d, the mass of specimen has no change compared with that of water immersion for 28 d, so it can be considered that the geopolymer concrete has basically reaches the water saturated state after water immersion for 180 d. The variation of mass of geopolymer concrete with water immersion time is similar to that of ordinary Portland cement concrete [17,18]. It should be noted that although the mass of geopolymer concrete has not increased significantly after water immersion for 28 d, it is still chosen to extend its water immersion time to 180 d during this test. The primary purpose is to allow water to penetrate the specimens as thoroughly as possible, ensuring that the specimens reach full saturation and achieve internal humidity equilibrium. This avoids the formation of humidity gradients, which could otherwise affect the subsequent test results.

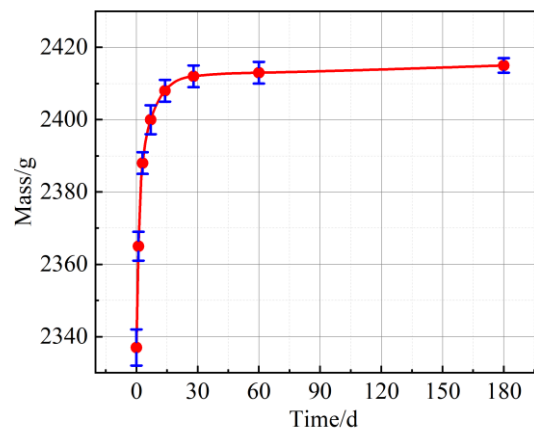


Fig. 4. Mass-time curve of geopolymer concrete after water immersion.

Table 2. Mass and ultrasonic wave velocity of geopolymer concrete after water immersion for 180 d.

Time	Mass /g		ultrasonic wave velocity /m·s ⁻¹	
	Test value	Average value	Test value	Average value
Before water immersion	2379		4216	
	2295	2337	4422	4322
	2336		4328	
After water immersion for 180 d	2447		5218	
	2394	2415	5171	5148
	2405		5056	

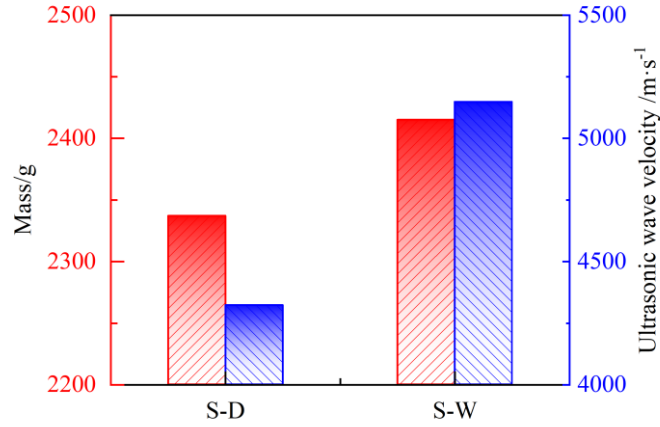
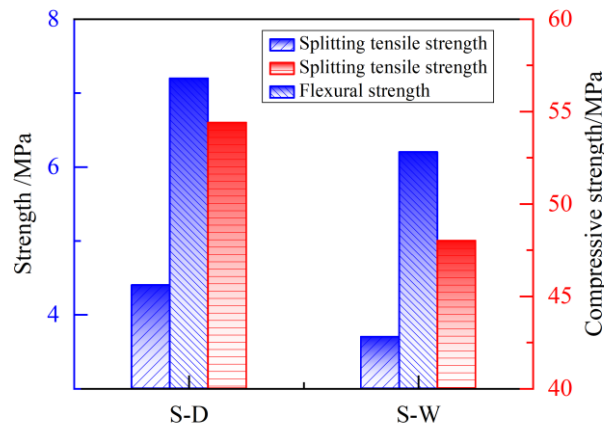


Fig. 5. Mass and ultrasonic wave velocity of geopolymer concrete after water immersion for 180 d.

From Table 2, Table 3, Figure 5 and Figure 6, compared with S-D, the acoustic characteristics of S-W improves, while the static mechanical properties decrease. Compared with S-D, the ultrasonic wave velocity of S-W increases by 19.11%, while the compressive strength, splitting tensile strength and flexural strength decrease by 11.76%, 15.91% and 13.89%, respectively. Ultrasonic wave velocity is an indirect reflection of the inner pore structure and density of concrete. In general, the less the pores and the larger the density of concrete, the larger the ultrasonic wave velocity [13]. After long-term water immersion, the non-closed pores inside S-W are filled with water to reach saturation, and the compactness increases. The ultrasonic wave propagates faster in water than in air, so the ultrasonic wave velocity of geopolymer concrete increases significantly in water saturated state. The static mechanical properties of geopolymer concrete decrease in water saturated state. The effect of water saturation on the static mechanical properties of geopolymer concrete is similar to that of ordinary silicate concrete, both of which show a negative deterioration effect [19]. It is mainly caused by the decrease of surface energy at the solid-liquid surface inside geopolymer concrete and the stress concentration in the interfacial transition zone. Firstly, the surface energy of material needs to be overcome continuously for the initiation and expansion of cracks, and the surface energy at the solid-liquid surface of material decreases in water saturated state [20]. Therefore, under the same external load, the initiation and expansion of cracks in geopolymer concrete with water saturated state are more likely to occur. The excess strain energy will cause the formation of more cracks, and these cracks continuously expand and interconnect, ultimately leading to a reduction in the strength of the geopolymer concrete. Secondly, there are a lot of interfacial transition zones between matrix and aggregate in geopolymer concrete, and there are many micro-cracks and pores in the interfacial transition zone. In water saturated state, on the one hand, these micro-cracks and pores will absorb water and expand, on the other hand, the expansion coefficient of various types of gel and aggregate after water absorption is not the same [21,22]. Therefore, water saturated state, further stress concentration will occur in the interfacial transition zone, which will weaken the strength of geopolymer concrete to a certain extent.

Table 3. Static mechanical properties of geopolymer concrete.

Specimen No.	Compressive strength /MPa		Splitting tensile strength /MPa		Flexural strength /MPa	
	Test value	Average value	Test value	Average value	Test value	Average value
S-D	54.1		4.2		7.2	
	53.6	54.4	4.4	4.4	6.9	7.2
	55.4		4.6		7.4	
S-W	47.1		3.5		6.4	
	48.2	48.0	3.7	3.7	6.2	6.2
	48.6		3.9		6.1	

**Fig. 6.** Static mechanical properties of geopolymer concrete

The static compressive strength of concrete material is an important parameter in structural design and calculation, and its value is directly related to the serviceability and safety of the structure [23]. Currently, the majority of design codes, especially those for hydraulic structures, have not yet accounted for the effect of water saturation on the static compressive strength of concrete materials. According to the above test results, the static compressive strength of geopolymer concrete is obviously deteriorated in water saturated water. Therefore, in order to ensure the safety and reliability of structure, the adverse effects caused by water saturation should be considered in the design and calculation of the structure in the long-term wet environment and hydraulic structure. In practice engineering, in order to avoid damage to existing building structures, ultrasonic -strength measurement method is usually used to evaluate the static compressive strength of concrete materials indirectly. Generally, the larger the ultrasonic wave velocity, the larger the static compressive strength of concrete [24]. However, based on the test results, although the ultrasonic wave velocity of geopolymer concrete in water saturated state increases, its static compressive strength significantly decreases. This means that these two indicators of geopolymer concrete change in opposite directions after water saturation. Therefore, when applying the ultrasonic -strength measurement

method, it is essential to consider the water saturation level of concrete material to avoid overestimating its actual static compressive strength.

3.2. Dynamic compressive strength and dynamic increase factor

The dynamic compression test results of geopolymer concrete are shown in Figure 7 and Table 5. Dynamic compressive strength (f_{cd}) and dynamic growth factor (DIF) characterize the dynamic compressive strength characteristics of geopolymer concrete. The f_{cd} is the peak stress reached by geopolymer concrete in the process of dynamic compression, that is, the peak stress in the dynamic stress-strain curve, and DIF is the ratio of f_{cd} to static compressive strength [25,26].

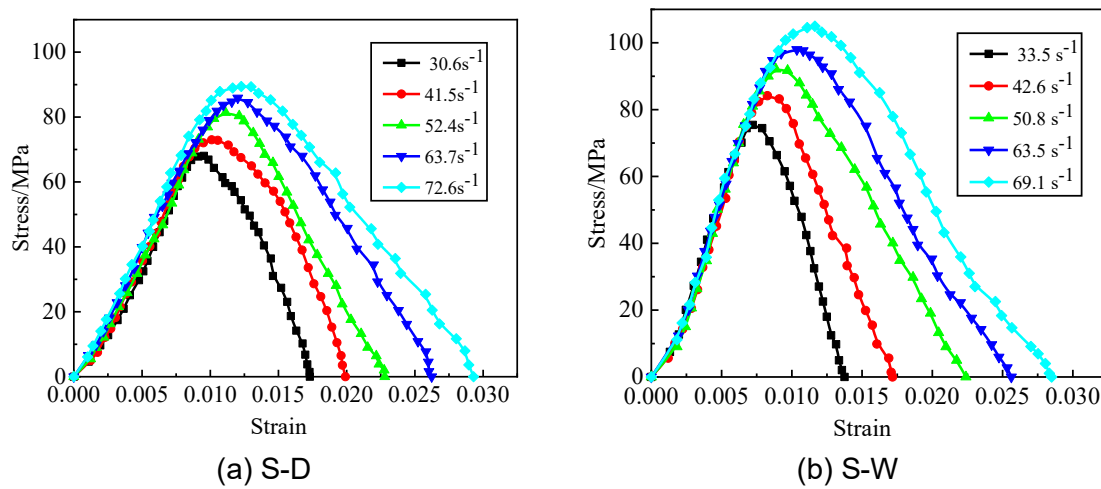


Fig. 7. Dynamic stress-strain curve of geopolymer concrete.

Table 4. Dynamic compression test results of geopolymer concrete.

Specimen No.	Strain rate (ϵ')/s ⁻¹	Dynamic compressive strength (f_{cd})/MPa	Dynamic increase factor (DIF)	Dynamic peak strain (ϵ_p)/10 ⁻³	Dynamic elastic modulus (E_d)/GPa	Impact toughness (IT)/KJ·m ⁻³	Pre-peak toughness (IT_p)/KJ·m ⁻³	Fractal dimension (D_f)
S-D	30.6	68.07	1.25	9.52	10.01	657.78	318.37	1.712
	41.5	72.74	1.34	10.49	10.21	870.62	430.47	1.817
	52.4	81.55	1.50	11.35	10.18	1240.65	524.57	1.987
	63.7	85.92	1.58	12.14	9.27	1338.75	579.30	2.089
	72.6	89.62	1.65	12.94	11.36	1530.54	625.65	2.213
S-W	33.5	75.07	1.56	7.25	15.01	712.67	224.96	1.635
	42.6	84.08	1.75	8.42	16.17	860.12	297.75	1.733
	50.8	92.62	1.93	9.23	15.18	1151.30	358.85	1.806
	63.5	98.42	2.05	10.85	15.69	1372.08	459.6	1.929

The f_{cd} of geopolymer concrete is shown in Figure 8. From this figure, the f_{cd} of S-D and S-W both exhibit obvious strain rate effects. The f_{cd} of S-D and S-W increases with the increase of strain rate ($\dot{\epsilon}$). At the same strain rate, the f_{cd} of S-W is larger than that of S-D. It can be seen that the f_{cd} of geopolymer concrete increases in water saturated state, and water saturation can improve the dynamic compressive strength characteristics of geopolymer concrete. In order to quantitatively characterize the effect of water saturation on the f_{cd} , linear fitting of the f_{cd} of geopolymer concrete and the $\dot{\epsilon}$ is carried out, and the change rate dynamic compressive strength (R_f) is calculated, as shown in Equation (1) :

$$R_f = (f_{cd(S-W)} - f_{cd(S-D)}) / f_{cd(S-D)} \quad (1)$$

where, the $f_{cd(S-W)}$ and $f_{cd(S-D)}$ are the f_{cd} of S-W and S-D respectively. The R_f of geopolymer concrete is shown in Figure 9. From this figure, the R_f of geopolymer concrete is all larger than 0, and has strain rate effect. With the increase of strain rate, the R_f of geopolymer concrete increases continuously, and the improvement effect of water saturation on the f_{cd} increases continuously. In the strain rate range of $30 \sim 75 \text{ s}^{-1}$, the R_f of geopolymer concrete is $8.61\% \sim 19.01\%$. The effect of pore water inside geopolymer concrete on its strength is related to the loading rate. Under quasi-static load (low strain rate), water saturation "weakens" the strength of geopolymer concrete, while under dynamic compression load (high strain rate), water saturation "enhances" the strength of geopolymer concrete. Geopolymer concrete is destroyed in a very short time under high strain rate, and the crack propagation rate is much larger than that under quasi-static load [27]. Therefore, the pore water inside geopolymer concrete does not have enough time to reach the crack tip and can only form a half-moon-shaped plane on the crack surface. Affected by the surface tension of liquid, these half-moon-shaped planes will exert an inward tensile constraint stress on the crack, thus hindering or delaying the further expansion of cracks [28,29]. Therefore, the f_{cd} of geopolymer concrete in water saturated state is larger than that in dry state. But even so, in practical engineering, it is not appropriate to take into account the enhancement effect of water saturation on the f_{cd} when designing structures that are subjected to the coupling effects of dynamic load and wet environment. This is because these structures (such as wharf, dam, pier, etc.) are occasionally subjected to dynamic loads during their service, but are subjected to static loads most of the service life. According to the test results, the static compressive strength of geopolymer concrete decreases obviously in water saturated state. Therefore, for such structures, it is safer and more reliable to use the static compressive strength in water saturated state as the design index.

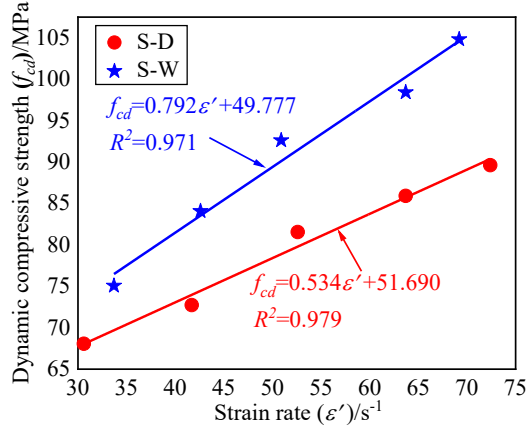


Fig. 8. Dynamic compressive strength of geopolymer concrete.

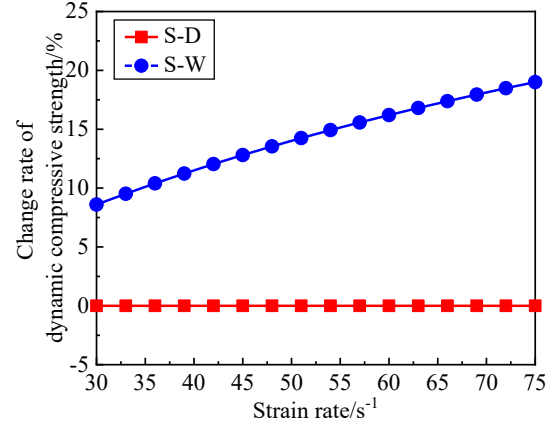


Fig. 9. Change rate of dynamic compressive strength of geopolymer concrete.

The *DIF* reflects the strengthening effect of strain rate on the strength of concrete. The *DIF* of geopolymer concrete is shown in Figure 10. From this figure, the *DIF* of S-D and S-W is consistent with f_{cd} , and both increase with the increase of strain rate. The relationship between *DIF* and strain rate can be expressed as a linear function, as shown in Equation (2). At the same strain rate, the *DIF* of S-W is larger than that of S-D. This is mainly because the static compressive strength of geopolymer concrete decreases and the f_{cd} increases in water saturated state. In addition, the increase rate of *DIF* of S-W with strain rate is also larger than that of S-D, which can be seen from the slope of the fitted line in Equation (2). It follows that the rate sensitivity of geopolymer concrete strength is improved by the presence of pore water after water saturation. As an important index to characterize the difference in strength of concrete under static and dynamic loads, the *DIF* has been gradually adopted by engineering designers and incorporated into relevant specifications. For example, Formula (3) is the *DIF* model of concrete adopted by Comité Euro-International du Béton (CEB) [30]. The *DIF* value of geopolymer concrete calculated according to Equation (3) is shown in Figure 6. It can be seen that CEB model can well predict the *DIF* of S-D, and the model curve is in good agreement with the test results. However, the CEB model significantly underestimates the *DIF* of S-W, and the model curve differs greatly from the test results, which indicates that the CEB model is not suitable for geopolymer concrete in water saturated state. This is mainly because the CEB model only considers the effect of strain rate, and does not consider the concrete material in some special service environment (such as water saturation, high temperature, corrosion environment, etc.) [31,32]. Therefore, for geopolymer concrete in water saturated state, the *DIF* fitting formula in Equation (2) is superior to the CEB model.

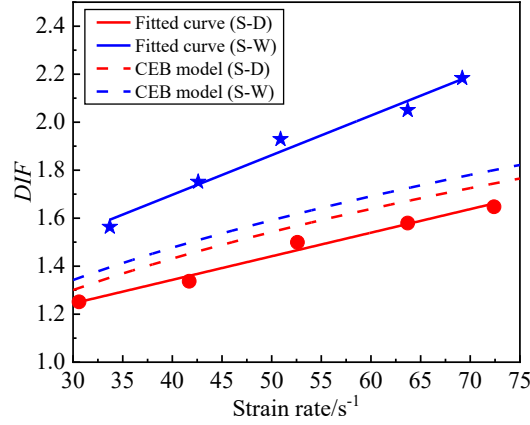


Fig. 10. Dynamic increase factors of geopolymer concrete.

$$\begin{aligned} \text{S-D: } DIF &= 0.0098\varepsilon' + 0.950, \quad R^2 = 0.979 \\ \text{S-W: } DIF &= 0.0165\varepsilon' + 1.037, \quad R^2 = 0.971 \end{aligned} \quad (2)$$

$$\begin{aligned} DIF &= \gamma(\varepsilon'/\varepsilon'_0)^{1/3} \\ \lg \gamma &= 6.16\delta - 2, \quad \delta = 1/(5 + 9f_{cs}/10), \quad \varepsilon'_0 = 3 \times 10^{-5} \text{ s}^{-1}, \quad \varepsilon' > 30 \text{ s}^{-1} \end{aligned} \quad (3)$$

3.3. Dynamic peak strain and dynamic elastic modulus

The dynamic peak strain (ε_p) characterizes the dynamic compressive deformation characteristics of geopolymer concrete. The ε_p is the strain corresponding to the peak stress of geopolymer concrete during the dynamic compression process. The ε_p of geopolymer concrete is shown in Figure 11. From this figure, the strain rate strengthening effect of the ε_p of geopolymer concrete is significant. The ε_p increases linearly with the increase of strain rate. The ε_p of S-D is larger than that of S-W at the same strain rate. In order to quantitatively analyze the effect of water saturation on the ε_p of geopolymer concrete, the change rate of dynamic peak strain (R_ε) is defined, and its solution process is consistent with R_f . The R_ε of geopolymer concrete is shown in Figure 12. From this figure, the R_ε of S-W is less than 0 in the strain rate range of 30 ~ 75 s⁻¹. The R_ε of S-W increases with the increase of strain rate. When the strain rate is small, the ε_p of S-W decreases significantly, resulting in a large difference between the R_ε of S-W and S-D. When the strain rate is large, the reduction of R_ε of S-W is small. The minimum of R_ε of S-W is -28.88%, and the ε_p of S-W decreases by 28.88% compared with S-D at this time. From the above analysis, the dynamic compression deformation characteristics of geopolymer concrete decreases after water saturation. The free water in the pores and cracks limits the deformation of geopolymer concrete, thus reducing the ε_p of geopolymer concrete [33]. Geopolymer concrete is a heterogeneous material, which contains various types and sizes of pores and cracks. On one hand, compared to air, water in the pores of geopolymer concrete is more difficult to compress. Under impact compression load, the volume of water in the pores of geopolymer concrete is difficult to change, and the water can not be expelled in a short time [34]. Therefore, the water in the pores of geopolymer concrete after water saturation restricts the deformation and damage

of these pores. On the other hand, according to microscopic hydrodynamics, for very small cracks, the viscosity of free water increases significantly. This viscous effect exerts a reverse force on crack propagation, thereby hindering the extension of cracks [35]. With the strain rate increases, the rate of deformation and failure of geopolymer concrete accelerates, and the ability of free water in the pores and cracks to restrict deformation weakens relatively [36]. Consequently, the decreasing range of ε_p of geopolymer concrete after water immersion decreases with the increase of strain rate.

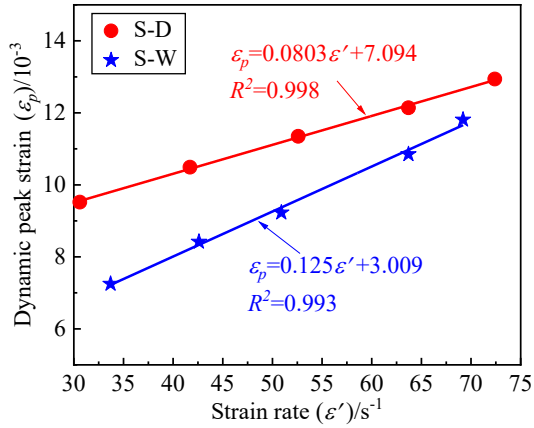


Fig. 11. Dynamic peak strain of geopolymer concrete.

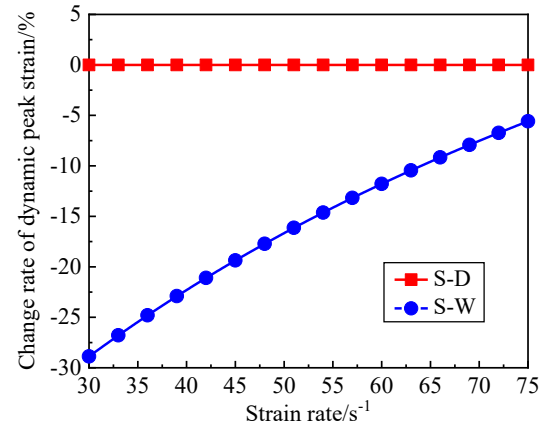


Fig. 12. Change rate of dynamic peak strain of geopolymer concrete.

The dynamic elastic modulus (E_d), which is the slope of the linear elastic stage in the ascending section of the dynamic stress-strain curve, characterizes the difficulty of deformation of geopolymer concrete under dynamic compressive load. The E_d of geopolymer concrete is shown in Figure 13. From this figure, the E_d of S-D and S-W is not sensitive to strain rate, and the E_d of geopolymer concrete has no obvious change trend with the increase of strain rate. On the whole, water saturation improves the stiffness of geopolymer concrete, and the E_d of S-W is larger than that of S-D. The average E_d of S-D and S-W is 10.21 GPa and 15.54 GPa respectively, and the E_d of S-W increases by 52.20% compared with that of S-D. At present, the variation trend of the E_d of concrete with strain rate is not uniform. Wang et al. believed that the E_d of concrete increased with the increase of strain rate [37], while Su et al. found that the E_d of concrete decreased with the increase of strain rate [38]. In addition, Lok et al. believed that the E_d of concrete was independent of strain rate [39]. This is mainly related to the inconsistency of test equipment and means. However, the effect of water saturation on the E_d of concrete is consistent [40,41]. After water saturation, the water in the pores delay the deformation of geopolymer concrete and increases its deformation difficulty, so the E_d of geopolymer concrete increases. In water saturated state, the deformation degree of geopolymer concrete decreases, the stiffness increases. And water saturation improves the "brittle-hardness" of geopolymer concrete. Therefore, for structures constructed with geopolymer concrete, the failure in water saturated state will become more sudden, and the failure precursor will be less noticeable than that in dry state. This feature is of great significance for deformation monitoring and failure warning of

structures in practical engineering.

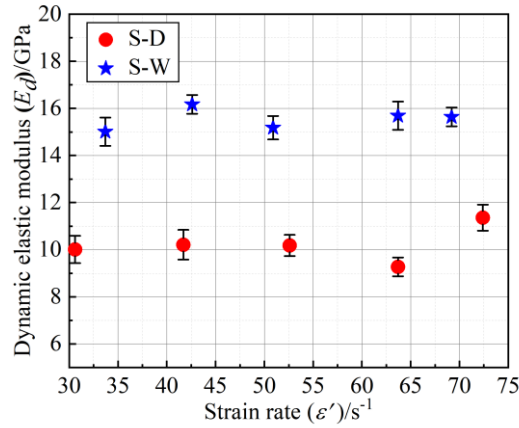


Fig. 13. Dynamic elastic modulus of geopolymer concrete.

3.4. Impact toughness and pre-peak toughness

In dynamic compression test, there are generally two indexes used to characterize the impact energy consumption characteristics of concrete [42]. One is impact toughness (IT), which is the area under the dynamic stress-strain curve. The other is dissipative energy, that is, the difference between the energy carried by the incident wave and the energy carried by the reflected and the transmitted waves. The IT is a comprehensive reflection of the strength characteristics and deformation characteristics of materials, which can effectively characterize the energy consumption characteristics of the material from the initial loading stage to complete instability and failure [43]. The difference between the incident energy and the reflected and transmitted energy is essentially the energy dissipated by the entire test system, which includes not only the energy dissipated by the specimen but also the kinetic energy generated by the splash fragments of the specimen and other forms of energy produced during the test [44]. The latter two parts of energy are difficult to calculate accurately by experimental means, and can not be ignored when the loading rate is high. Therefore, the IT can characterize the impact energy consumption characteristics of geopolymer concrete. The IT of geopolymer concrete is shown in Figure 14. From this figure, the IT of both S-D and S-W increases with the increase of strain rate, showing an obvious strain rate effect. When the strain rate is the same, the IT of S-D and S-W is not much different. Considering the dispersion caused by the heterogeneous characteristics of geopolymer concrete itself, it can be considered that water saturation has no obvious effect on the impact energy consumption characteristics of geopolymer concrete. Since the IT is a comprehensive reflection of the strength and deformation characteristics of geopolymer concrete in the whole failure process, although the f_{cd} of S-W is larger, its deformation degree is lower, so the impact energy consumption characteristics of S-W have no obvious change. According to the above analysis, although the f_{cd} of geopolymer concrete increases after water saturation, its IT does not change significantly. Therefore, from the point of view of energy, it can not be considered that geopolymer concrete after water saturation can withstand more external loads. Special attention

should be paid to hydraulic structures involving energy absorption and protection functions to avoid one-sidedness simply from the point of view of strength, resulting in overestimation of structural properties.

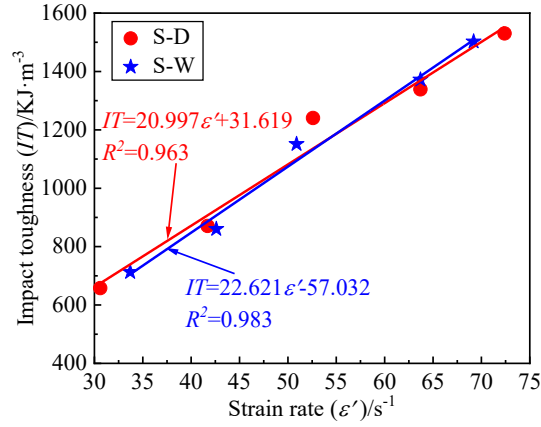


Fig. 14. Impact toughness of geopolymer concrete.

From the test results in Figure 14, the energy consumption characteristics of geopolymer concrete in the whole impact failure process are not affected by pore water. However, the effect of pore water is not exactly the same before and after the specimen reaches the critical state (such as peak stress). Excess pore water pressure can be generated in the pore before the critical state, and the pore water pressure can disappear after the specimen is destroyed. Therefore, it can be inferred that the energy consumption characteristics of geopolymer concrete in different stages of the impact failure process are different. For this purpose, the pre-peak toughness (IT_p), that is, the area contained in the rising section of the dynamic stress-strain curve, is defined to further analyze the energy consumption characteristics of geopolymer concrete at different stages of the impact failure process. The IT_p of geopolymer concrete is shown in Figure 15. From this figure, the IT_p of geopolymer concrete increases linearly with the increase of strain rate. When the strain rate is the same, the IT_p of S-D is larger than that of S-W, and water saturation results in the lower energy consumption of geopolymer concrete before it reaches the critical state. The overall rigidity of geopolymer concrete increases after water saturation, and the excess pore water pressure can slow down the instability of pores to a certain extent. Part of the external load energy is used to overcome the cohesive force and the excess pore water pressure of geopolymer concrete [45]. Therefore, the IT_p of geopolymer concrete after water saturation is relatively small. In order to quantitatively characterize the effect of water saturation on the IT_p of geopolymer concrete, the change rate of pre-peak toughness (R_{IT}) is defined, and its solution process is consistent with R_f and R_ϵ . The R_{IT} of geopolymer concrete is shown in Figure 16. From this figure, the variation trend of R_{IT} with strain rate is consistent with that of R_ϵ . In the strain rate range of 30 ~ 75 s⁻¹, the R_{IT} of S-W is less than 0, which is -43.26% ~ -14.07%. With the increase of strain rate, the energy of pore water to delay deformation is relatively weakened, so the R_{IT} of S-W increases [46].

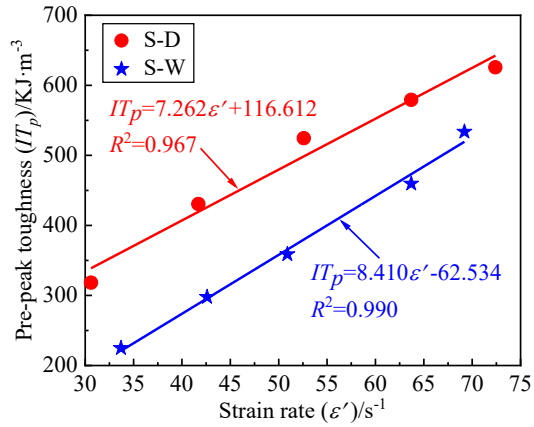


Fig. 15. Pre-peak toughness of geopolymer concrete.

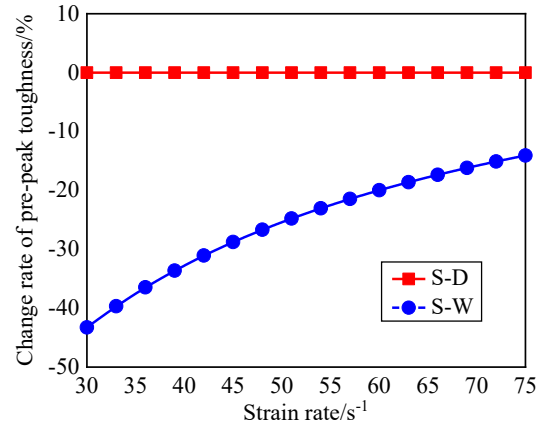
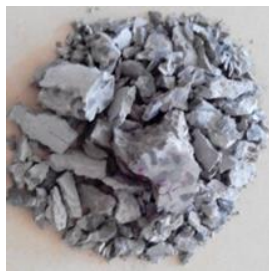


Fig. 16. Change rate of pre-peak toughness of geopolymer concrete.

3.5. Fracture morphology and fractal characteristics

The fracture morphology of geopolymer concrete is shown in Figure 17. From this figure, the fracture morphology of S-D and S-W has strain rate sensitivity. With the increase of strain rate, the fracture degree of S-D and S-W increases, the size of fragments decreases, and the quantity of fragments increases. When the strain rate is similar, the fracture degree of S-D is more serious than that of S-W. In order to further quantify the difference of fracture degree between S-D and S-W, the collected specimen fragments are screened by standard screens with diameters of 40 mm, 20 mm, 10 mm, 5 mm and 2.5 mm, respectively, and the mass of retained fragments on the screens is weighed. Then, according to Equation (4), the $\ln[M(r)/M_T]-\ln r$ curve is drawn, and the fragment fractal dimension (D_f) is solved [47].



30.6 s⁻¹



52.4 s⁻¹



72.6 s⁻¹

(a) S-D



33.5 s⁻¹



50.8 s⁻¹



69.1 s⁻¹

(b) S-W

Fig. 17. Fracture morphology of geopolymer concrete.

$$\ln[M(r)/M_T] \sim (3-D_f) \ln r \quad (4)$$

where, M_T is the total mass of fragments, and $M(r)$ is the mass of fragments with a particle size less than r . The D_f of geopolymer concrete is shown in Figure 18. From this figure, with the increase of strain rate, the D_f of S-D and S-W increases continuously, showing a strong strain rate sensitivity. It can be seen that the fracture degree of specimen is closely related to the D_f , and the former can be quantitatively characterized by the latter, that is, the higher the fracture degree, the larger the D_f value. When the strain rate is the same, the D_f of S-D is larger than that of S-W. According to the meaning of D_f , it shows that S-D has a more serious fracture degree and the fragmentation scale distribution is more complex [48]. This conclusion is consistent with the result in Figure 14, which further verifies the feasibility and correctness of using the D_f to describe the fracture degree of geopolymer concrete.

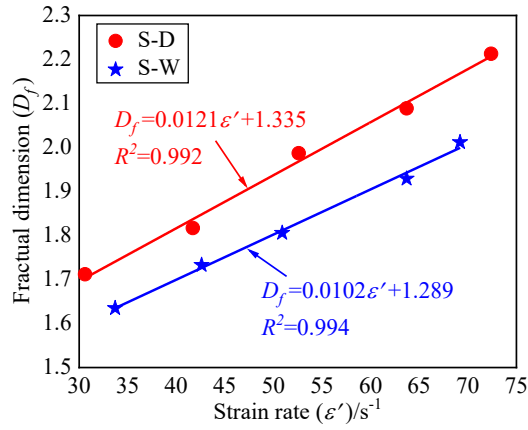


Fig. 18. Fragment fractal dimension of geopolymer concrete.

The relationship between fragment fractal dimension (D_f) and dynamic compressive strength (f_{cd}) and impact toughness (IT) of geopolymer concrete is shown in Figure 19 and Figure 20 respectively. The D_f of geopolymer concrete has good positive correlation with f_{cd} and IT . With the increase of D_f , the f_{cd} and IT of geopolymer concrete increase linearly. When the D_f is the same, the f_{cd} of S-W is larger than that of S-D. Geopolymer concrete after water saturation can withstand larger external load under the same fracture degree. It should be noted that in terms of S-D or S-W alone, the larger the f_{cd} , the larger the D_f . In combination with Figure 6 and Figure 16, the f_{cd} of S-W is larger, but its D_f is smaller when the strain rate is the same. In fact, there is no contradiction between the two, the former is mainly related to the strain rate effect, the latter is caused by the effect of pore water. When the D_f is the same, the IT of S-W is larger than that of S-D. It can be seen that S-W consumes more energy when it reaches the same Fracture degree. In other words, geopolymer concrete is more resistant to damage after water saturation.

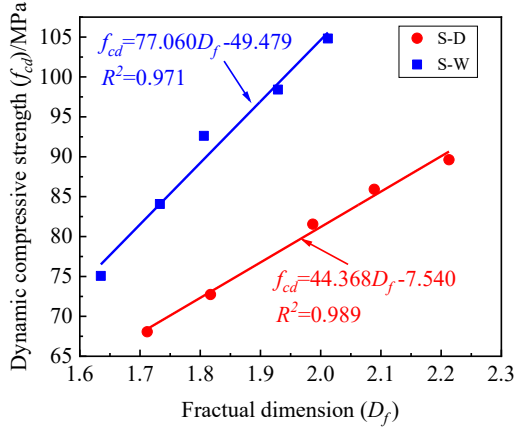


Fig. 19. Relation between fragment fractal dimension and dynamic compressive strength of geopolymer concrete.

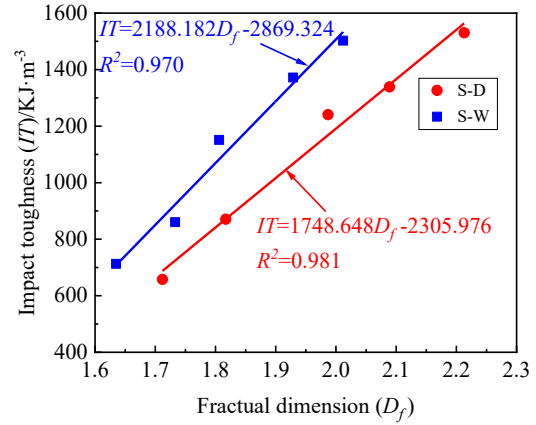


Fig. 20. Relation between fragment fractal dimension and impact toughness of geopolymer concrete.

4. Conclusion

The quality test, ultrasonic wave velocity test, static mechanical test and dynamic compression test are carried out on geopolymer concrete in dry and water saturated conditions. The physical properties and static mechanical properties of geopolymer concrete before and after water saturation are compared, and the effects of water saturation and impact load on the mechanical properties of geopolymer concrete are analyzed. The main conclusions are as follows:

(1) Geopolymer reaches the water saturated state after water immersion for 180 d. Water saturation increases the ultrasonic wave velocity of geopolymer concrete, but has obvious negative effect on its static mechanical properties. After water saturation, the compressive strength, splitting tensile strength and flexural strength of geopolymer concrete decrease.

(2) Geopolymer concrete shows strong strain rate sensitivity under impact load, and the dynamic compressive strength, *DIF*, dynamic peak strain, impact toughness, pre-peak toughness and fracture fractal dimension of geopolymer concrete increase with the increase of strain rate. The dynamic elastic modulus of geopolymer concrete is not sensitive to strain rate.

(3) Water saturation increases the strength and stiffness of geopolymer concrete under impact load, while reducing its deformation capacity, with no significant effect on its energy consumption characteristics. The dynamic compressive strength and dynamic elastic modulus of geopolymer concrete increase after water saturation, the dynamic peak strain and pre-peak toughness decrease, and the impact toughness exhibits no significant alteration.

(4) The *DIF* of geopolymer concrete increases significantly after water saturation. The Comité Euro-International du Béton (CEB) model can well predict the *DIF* of geopolymer concrete in dry state, but significantly underestimate the *DIF* value of geopolymer concrete in water saturated state. Based on the test results, a *DIF* fitting formula for geopolymer concrete in water saturated state is proposed.

(5) The fragments of geopolymer concrete under impact load have fractal characteristics. After water saturation, the fracture degree and fragment fractal dimension of geopolymer concrete decrease. The fragment fractal dimension of geopolymer concrete is positively correlated with dynamic compressive strength and impact toughness. When the fractal dimension is the same, the dynamic compressive strength and impact toughness of geopolymer concrete after water saturation increase.

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Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

Zhihang Wang: Formal analysis, Writing – original draft, Writing – review & editing. **Dexian Zhao:** Funding acquisition, Investigation, Methodology, Writing – review & editing. **Chaojia Liu:** Data curation, Formal analysis, Writing – original draft. **Chao Zhang:** Methodology, Funding acquisition, Resources. **Mengyang Li:** Methodology, Funding acquisition, Resources. **Erlei Bai:** Funding acquisition, Investigation, Methodology, Writing – review & editing. All the authors have approved the final manuscript.

Use of AI statement

None.

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