

Article

Impacts of Water Saturation on the Mechanical Behavior of Basalt/Glass Fiber-Reinforced Recycled Aggregate Concrete Under Varying Stresses: Insights from Macro and Micro Perspectives

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Abstract

Recycled aggregate concrete (RAC) offers an effective approach to reducing the environmental burden associated with construction and demolition waste. In this study, a fiber-reinforced RAC was developed by replacing part of the cement with fly ash and ground granulated blast-furnace slag, while glass fibers or basalt fibers were incorporated as reinforcing materials. A systematic experimental program was conducted to evaluate the mechanical behavior of the proposed concrete under different saturation conditions. The results show that the best toughness performance was achieved in the natural moisture state. In comparison, compressive and flexural strengths reached their maximum values under dry conditions, whereas splitting tensile strength peaked in the natural state. Based on the experimental data, prediction equations were established for the splitting tensile and flexural strengths by considering both saturation degree and fiber content. A stress–strain model under uniaxial compression was also developed. In addition, scanning electron microscopy (SEM) was employed to examine the fiber–matrix interface and hydration products, thereby clarifying the microstructural characteristics of the concrete at different saturation levels.

Keywords: recycled aggregate concrete; water saturation; basalt fiber and glass fiber; toughness; SEM



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1. Introduction

Driven by accelerating industrialization and urbanization, the construction industry has undergone rapid expansion, accompanied by a growing amount of construction waste [1]. According to an official report released by China's Ministry of Housing and Urban-Rural Development, the total amount of construction waste nationwide exceeded 3 billion tons in 2020, and it is projected to reach 4 billion tons by 2025 [2]. If not promptly treated and utilized, this waste not only leads to the depletion and waste of natural resources but also poses negative impacts on society and the environment [3,4]. Accordingly, the effective recycling and reuse of concrete waste is essential for promoting the sustainable development of the construction industry [5].

Over the past decade, extensive research has been conducted on utilizing demolished waste concrete as recycled aggregates (RAs) for the production of recycled aggregate concrete (RAC). A general consensus drawn from these studies is that concrete incorporating RAs exhibits inferior performance compared to conventional natural aggregate concrete (NAC). Specifically, as the RA replacement ratio increases, the resulting concrete demonstrates deteriorated workability [6], reduced density [7], diminished elastic modulus [8], compromised mechanical strength [9], as well as exacerbated drying shrinkage [10] and creep deformation [11]. These performance degradations are fundamentally attributed to the presence of porous residual mortar attached to the surface of the RAs [12,13].

To mitigate the negative influence of adhered mortar, various physical and chemical treatments have been explored to enhance the quality of recycled aggregates [14]. These treatment methods are generally divided into two categories: removing the adhered mortar and improving the properties of the remaining mortar. Bru et al. employed microwave heating to weaken the initial interfacial transition zone (ITZ) between natural aggregates and attached mortar. Subsequently, mechanical grinding was employed to effectively remove the adhered mortar, resulting in high-quality recycled concrete aggregates [15]. Tam et al. used three acids of the same concentration—hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and phosphoric acid (H_3PO_5)—to soak the RCA for 24 h to remove the adhered mortar, and found that hydrochloric acid was the most effective among them [16]. Kou et al. subjected recycled concrete aggregates to carbonation treatment in a 100% CO_2 environment at a pressure 0.1 bar higher than atmospheric pressure. This treatment improved the mechanical performance and chloride penetration resistance of the aggregates, while also mitigating drying shrinkage [17].

It is well established that fiber incorporation can substantially improve the performance of concrete [18–21]. Accordingly, numerous experimental studies have explored the use of fibers to enhance the properties of recycled aggregate concrete (RAC). J.A. Carneiro et al. reported that, for RAC with a 25% recycled aggregate replacement level, the incorporation of 0.75% hooked-end steel fibers increased the compressive strength by 13% [22]. K.R. Akça et al. reported that incorporating 1% polypropylene fibers into RAC with a 55% recycled aggregate replacement ratio increased the splitting tensile and flexural strengths by 31% and 4%, respectively [23].

Furthermore, owing to the high water absorption capacity of recycled aggregates, the influence of water on the mechanical properties of recycled aggregate concrete (RAC) is considerably more profound and complex. On the one hand, variations in the degree of water saturation may trigger the secondary hydration of unreacted cement particles within the matrix, thereby affecting the interfacial adhesion between the fibers and the cementitious matrix. On the other hand, as the saturation degree increases, the accumulation of internal pore water pressure significantly affects microcrack propagation and interfacial sliding. Most existing studies concerning the effect of water on RAC have primarily focused on the preparation and curing stages. For instance, Etxeberria et al. [8] pre-soaked the aggregates prior to mixing to improve the interfacial transition zone (ITZ) between the recycled aggregates and the matrix; meanwhile, Poon et al. [24] introduced additional water during the mixing process so that the performance of recycled aggregates could closely approach that of natural aggregates. Several studies have indicated a negative correlation between the water absorption of recycled aggregates and the compressive strength of the resulting concrete [25,26], although the observed results exhibit considerable scatter. However, some studies have also reported an anomalous increase in the strength of RAC [27,28], which may be attributed to deviations in the effective water-to-binder ratio and the fact that the parent concrete of the recycled aggregates was of high strength. In practical engineering applications, concrete structures are exposed to environments with

highly variable humidity, which can likewise exert a substantial impact on the overall performance of the concrete.

In this study, a novel eco-friendly recycled aggregate concrete (RAC) material is proposed, in which ordinary cement is partially replaced (approximately 20%) by fly ash and ultrafine slag. In terms of fiber reinforcement, two distinct types of fibers were considered and experimentally compared: basalt fibers, which are widely utilized in concrete reinforcement, and glass fibers, which offer a lower market cost but have received comparatively less attention in existing literature. This paper investigates and analyzes the experimental results regarding the fundamental static mechanical properties—including compressive strength, splitting tensile strength, flexural strength, and associated toughness—of the fiber-reinforced RAC (FRRAC) under various degrees of water saturation. Based on these experimental findings, coupled with empirical formulas and relevant mechanical principles, coupling equations were formulated to describe the relationships of splitting tensile and three-point bending strengths with the saturation degree and fiber dosage. Furthermore, a constitutive stress–strain model was developed to characterize the uniaxial compressive stress–strain behavior of the RAC. Finally, scanning electron microscopy (SEM) was employed to conduct a parametric analysis of the microstructural features of the fiber interfacial bonding and the cementitious matrix.

2. Experimental Setup

2.1. Raw Materials

Five groups of recycled aggregate concrete (RAC) specimens were prepared using an identical mix proportion. The primary variables were the water saturation state, fiber type, and fiber volume fraction. Specifically, the saturation conditions were categorized into an oven-dried state, a natural moisture state, and a fully water-saturated state. Basalt fibers and glass fibers were utilized, with volume fractions of 0%, 1%, and 1.5%. This experimental program aims to investigate the variation patterns of the static mechanical properties of fiber-reinforced recycled aggregate concrete under different saturation conditions.

The selected fiber dosages encompass the optimal contents for both types of fibers, while the variations in water saturation adequately simulate the typical service environments that RAC might encounter in practical engineering.

The basalt and glass fibers used in the tests were supplied by Shandong Senhong Engineering Materials Co., Ltd., Jinan, China. The physical parameters and geometric characteristics of the fibers are detailed in Table 1.

The recycled coarse aggregates were produced by spiral grinding of waste concrete blocks collected from a demolished residential construction site in Chongqing, China. The oven-dried density and water absorption of the recycled aggregate were measured to be 2.41 g/cm³ and 4.07%, respectively. According to the Chinese national standard GB/T 25177-2010 [29], the recycled aggregate used in this study is categorized as Grade II recycled aggregate. Selected materials used in the experiment are shown in Figure 1.



Figure 1. Photo of part materials.

Table 1. Physical properties and geometric size of basalt and glass fiber.

Fiber Type	Equivalent Diameter (mm)	Length (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (Kg/m ³)
Basalt	10	12	1131	45	2.64
Glass	12	12	1824	75	2.68

The constituent materials and mix proportions of the recycled aggregate concrete (RAC) are listed in Table 2. In this study, four cementitious materials were incorporated into the mixtures:

Table 2. Mix proportion of RAC (kg/m³).

Sample	Cement	River Sand	Natural Aggregate	Recycled Aggregate	Water	HRWR	Fiber Type	Volume Fraction	Silica Fume	Fly Ash	BF Slag
P	243.6	706	441	441	194	8.83	/	/	48.7	28.2	42.4
G1.0	243.6	706	441	441	194	8.83	Basalt	1.0%	48.7	28.2	42.4
G1.5	243.6	706	441	441	194	8.83	Basalt	1.5%	48.7	28.2	42.4
B1.0	243.6	706	441	441	194	8.83	Glass	1.0%	48.7	28.2	42.4
B1.5	243.6	706	441	441	194	8.83	Glass	1.5%	48.7	28.2	42.4

Type 52.5 ordinary Portland cement (OPC), conforming to Chinese national standards, was used in this study. Its particle size, density, and specific surface area were 20–30 µm, 3.17 g/cm³, and 0.385 m²/g, respectively. Silica fume, Class I fly ash, and ground granulated blast furnace slag (GGBFS) were used as supplementary cementitious materials. The silica fume contained more than 92% SiO₂, with a particle size of 0.1–0.3 µm and a 7-day activity index of 116%. The fly ash complied with Chinese standards and had a density of 2.6 g/cm³ and an 8% sieve residue. The GGBFS had a density of 3.1 g/cm³, a specific surface area of 0.429 m²/g, and a 28-day activity index of 98.5%. Their chemical compositions and loss on ignition (LOI) are presented in Table 3. River sand with a particle size below 0.6 mm and a fineness modulus of 2.4 was used as the fine aggregate. A polycarboxylate-based high-range water-reducing admixture (HRWR) from Zhongyan Technology Co., Ltd., China, was added to all mixtures to ensure workability and improve strength development. The HRWR had a water-reduction rate of at least 27%. The water-to-binder and HRWR-to-binder ratios were 0.55 and 0.025, respectively.

Table 3. Chemical content (%) and LOI of silica fume, fly ash and ultra-fine BF slag.

Composition	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	LOI
Silica fume	92.20	0.51	0.32	0.85	0.97	/	3.00
Fly ash	60.90	4.90	24.47	6.70	0.68	1.50	2.00
Ultra-fine BF slag	34.50	34.00	17.70	1.03	6.01	1.64	0.84

As shown in Table 2, a composite cementitious material system utilizing silica fume (SF), fly ash (FA), and ground granulated blast-furnace slag as partial replacements for cement was adopted in this study. Both practice and research have demonstrated that the incorporation of an appropriate amount of GGBS can improve the compressive strength and elastic modulus of concrete [30–32]. Concurrently, the active components in SF and FA can react with the calcium hydroxide generated during cement hydration to undergo a secondary hydration reaction. This process produces additional gel products that fill the internal pores, thereby densifying the concrete microstructure and enhancing its later-age strength. The combined incorporation of these three materials not only reduces the high

consumption of cement but also enables the large-scale recycling of industrial solid wastes, endowing the RAC with significant environmental and economic benefits.

2.2. Specimen Preparation

To ensure satisfactory workability and uniform distribution of aggregates and fibers, the RAC was mixed following the procedure presented in Figure 2. The fresh concrete was then placed into ABS plastic molds, including $100 \times 100 \times 100$ mm cubes for uniaxial compression and splitting tensile tests and $40 \times 40 \times 160$ mm prisms for three-point bending tests. Subsequently, the specimens were compacted by vibration for 30 s.

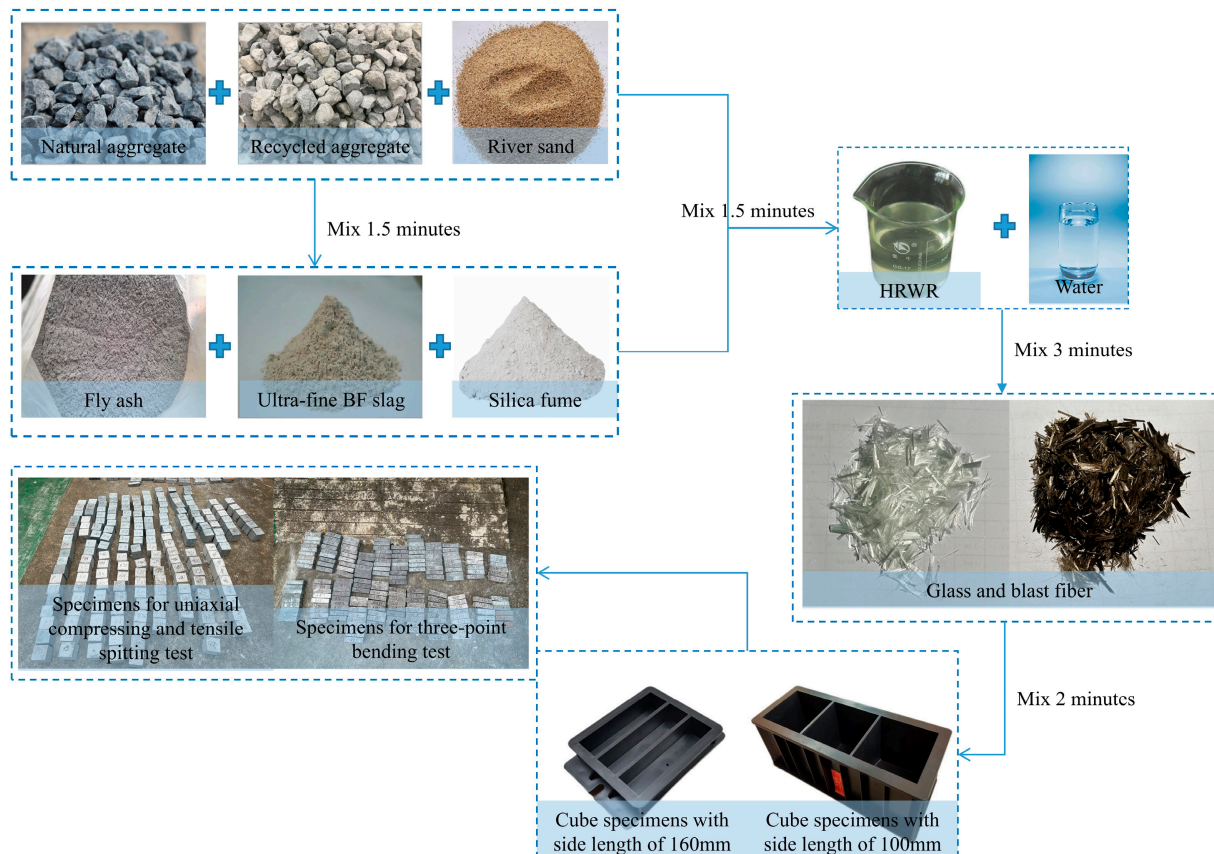


Figure 2. Mixing procedures of RAC with fibers.

Since vibration mainly promotes horizontal movement of the fresh mixture, and RAC has relatively low flowability compared with conventional concrete, the fibers were considered to be randomly distributed, with little risk of settling in the molds [33]. The RAC specimens were initially kept in the molds for 24 h under a temperature of 20 ± 5 °C and a relative humidity above 90%. Subsequently, the specimens were demolded and subjected to ambient curing for 28 days.

In total, 135 specimens were prepared for the experimental program. These specimens were classified into three groups, A, B, and C, according to their moisture-conditioning states. For each group, five RAC mixtures with different fiber types and volume fractions were considered, with three replicate specimens prepared for each mechanical test. Figure 3 illustrates the sample preparation under different moisture conditions. The samples in Group A were dried in an oven at 125 °C for 24 h (Figure 3a). Conversely, the samples in Group B were immersed in water until testing (Figure 3b). Before testing, the immersed specimens were taken out and their surface water was carefully removed using a damp cloth. The Group C specimens were maintained at room temperature before testing.

The formula for calculating the saturation degree of recycled aggregate concrete is as follows:

$$S_r = \frac{m_s - m_d}{m_w - m_d} \times 100\% \quad (1)$$

where m_s is the mass of the specimen in the current state, m_w is the mass of the specimen in the water-saturated state, and m_d is the mass of the specimen in the completely oven-dried state.



Figure 3. Sample processing: (a) Drying treatment; (b) Saturation treatment.

2.3. Testing Methods

Following the requirements specified in the Chinese standard GB/T 50018-2019 [34], the specimens were subjected to uniaxial compression using a 2000 KN computer-controlled electro-hydraulic servo testing system, as shown in Figure 4a. The axial deformation of the specimens was measured by a linear variable differential transformer (LVDT) mounted between the loading plates, from which the stress–strain curves were obtained. Vaseline was coated on both loading surfaces to reduce end restraint caused by friction. A spherical bearing block was used above the specimen to promote uniform stress distribution during loading.

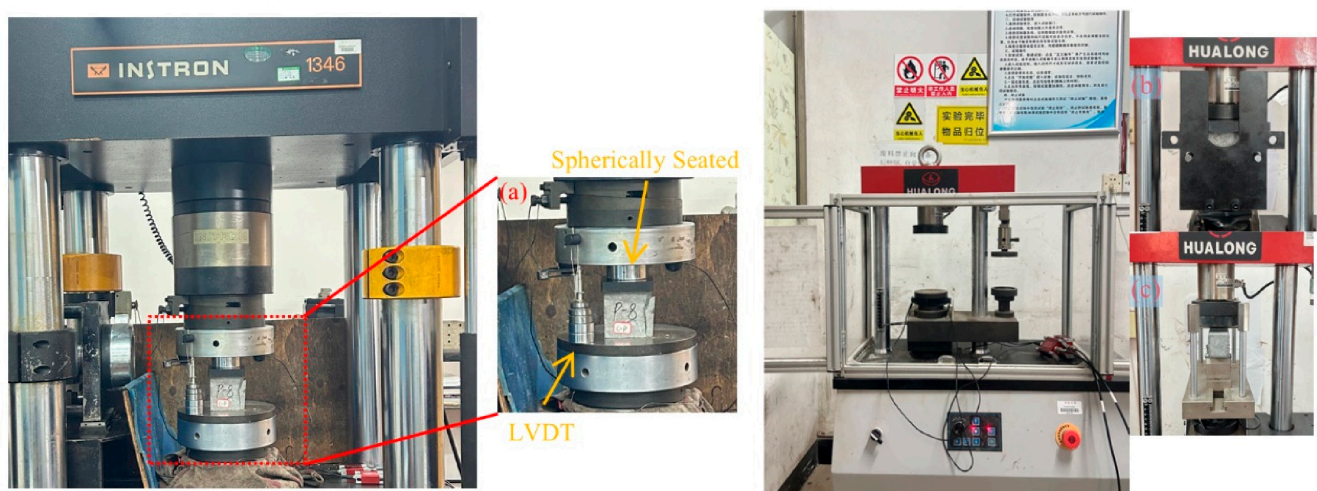


Figure 4. Experimental setup for mechanical tests: (a) uniaxial compression; (b) splitting tension; (c) three-point bending.

A static splitting tensile test was installed on 45 cube specimens using an Instron 1342 electro-hydraulic servo testing machine (Instron, Norwood, MA, USA) with a maximum

capacity of 250 kN (as shown in Figure 4b). Three specimens were tested for each type, and the average value was taken as the final test result.

According to the “Hydraulic Concrete Test Code,” the splitting tensile strength (σ_t) of the cube specimens can be expressed by the following formula:

$$\sigma_t = \frac{2P}{\pi A} \quad (2)$$

In the formula, σ_t —Splitting tensile strength of concrete (MPa); P —Ultimate load (N); A —Area of the splitting surface of the specimen (mm²).

To obtain the axial tensile strength from the measured splitting tensile strength, a conversion coefficient of 0.9 was used. Since 100 mm × 100 mm × 100 mm cubes are non-standard specimens, a size correction factor of 0.85 was also applied to the measured splitting tensile strength.

As shown in Figure 4c, three-point bending tests were performed on 27 prism specimens with dimensions of 40 × 40 × 160 mm³ using the Instron 1342 electro-hydraulic servo testing machine equipped with the appropriate bending fixtures. The test procedure followed GB/T 17671-1999.

A displacement-controlled loading mode was applied with a loading rate of 0.01 mm/min. The midspan deflection of the specimen was monitored by an LVDT during the test. The bending strength (f_b) is calculated according to the following Formula (3):

$$f_b = \frac{3FL}{2bh^2} \quad (3)$$

In the formula, L —Span (mm); F —Peak load (N); h —Height of the specimen (mm); b —Width of the specimen (mm).

3. Experimental Results

3.1. Results of Uniaxial Compression

3.1.1. Compressing Failure Mode

Dry state: The matrix stiffness of the concrete specimens is at its highest level, and the failure is typically instantaneous and explosive. Due to the lack of internal moisture lubrication, the frictional resistance at the crack surfaces is high, leading to a rapid release of fracture energy. The brittleness is most pronounced, accompanied by loud bursting sounds and extensive dust emission. Compared to plain concrete specimens (Group P), clear “tearing” or “snapping” sounds caused by fiber pull-out or rupture can be heard during the failure of FRRAC. Although covered with dense cracks, the FRRAC specimens can maintain their overall structural integrity.

Natural state: Crack propagation is relatively stable. The fiber network functions effectively to delay the formation of major cracks. The specimens exhibit typical compressive cracking characteristics, with a moderate amount of spalling.

Water-saturated state: The failure process is relatively muffled, completely lacking the explosive nature observed in the dry state. The crack surfaces frequently slide along interfaces fully softened by water, and the specimens often crush and collapse into loose fragments under compression. In contrast, FRRAC maintains a certain structural shape due to the bridging effect of the internal fibers, and complete collapse rarely occurs.

Furthermore, Figure 5 illustrates the upper cross-sections of the plain recycled aggregate concrete (P), glass fiber-reinforced recycled aggregate concrete (GFRAC), and basalt fiber-reinforced recycled aggregate concrete (BFRAC) specimens upon compressive failure under different saturation states.

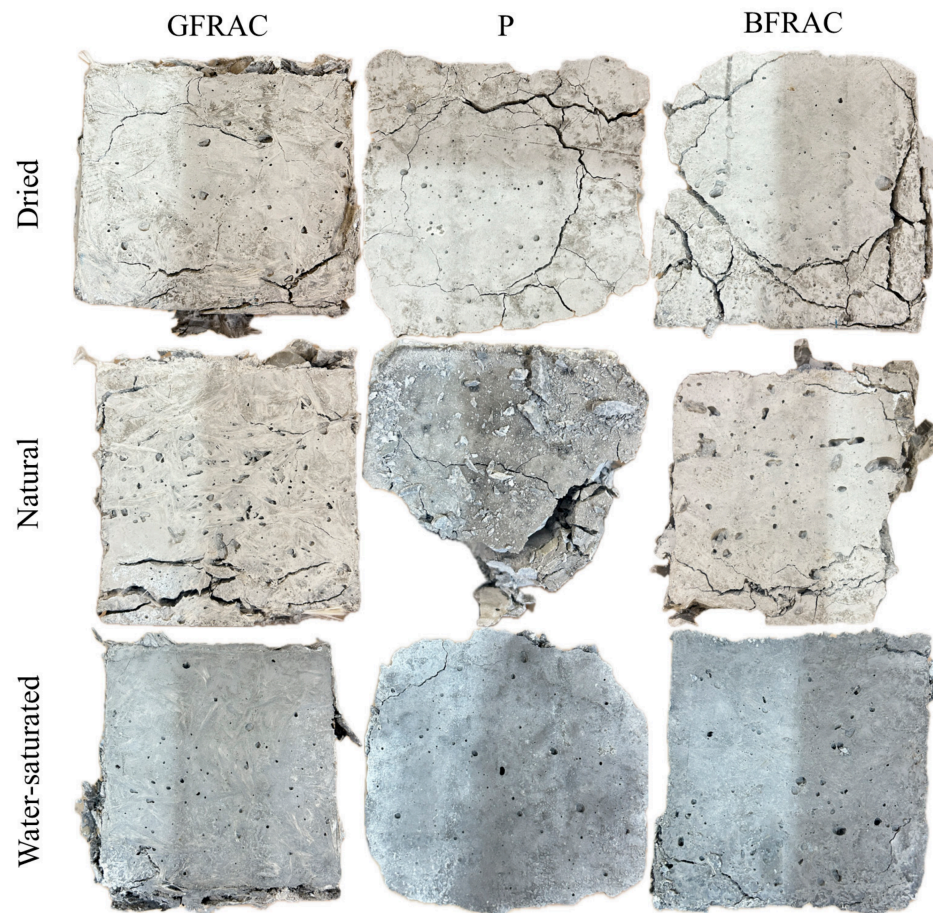


Figure 5. Compressive failure modes of plain RAC and FRRAC under different saturation states.

3.1.2. Performance Analysis of Compressing

Table 4 and Figure 6 present the mechanical parameters and load–displacement responses of the specimens under uniaxial compression.

Table 4. Experimental parameters of specimens compressing.

Specimen	Fiber Type	V_f	S_r (%)	f_c (Mpa)	cov	δ_c (mm)	I_0	I_1
DP	/	/	0	71.21	0.039	1.56	2.03	1.47
NP	/	/	60	55.19	0.025	1.04	2.31	/
WP	/	/	100	67.03	0.034	1.25	2.07	1.67
DB1.0	Basalt	1.0	0	49.90	0.033	1.05	1.86	1.63
NB1.0	Basalt	1.0	59	46.70	0.027	1.15	2.22	1.69
WB1.0	Basalt	1.0	100	41.41	0.030	1.10	1.97	1.68
DB1.5	Basalt	1.5	0	50.48	0.058	1.03	2.01	1.72
NB1.5	Basalt	1.5	62	48.21	0.046	1.26	2.08	1.65
WB1.5	Basalt	1.5	100	44.74	0.029	0.94	1.99	1.70
DG1.0	Glass	1.0	0	57.65	0.036	1.14	2.02	1.74
NG1.0	Glass	1.0	61	55.93	0.046	1.43	2.50	1.73
WG1.0	Glass	1.0	100	49.71	0.034	1.13	1.95	1.64
DG1.5	Glass	1.5	0	51.67	0.038	1.12	1.87	1.64
NG1.5	Glass	1.5	59	47.68	0.046	1.17	2.06	1.71
WG1.5	Glass	1.5	100	48.36	0.061	1.10	1.94	1.66

Note: In the specimen labels, the first letter identifies the moisture condition: D for dry, N for natural, and W for water-saturated. The second letter represents the fiber type, namely B for basalt fiber and G for glass fiber, while the number indicates the fiber volume fraction. In the table, V_f is the fiber volume fraction (%), S_r is the saturation degree (%), f_c is the compressive strength (MPa), δ_c is the peak displacement (mm), and I_0 and I_1 are toughness indices.

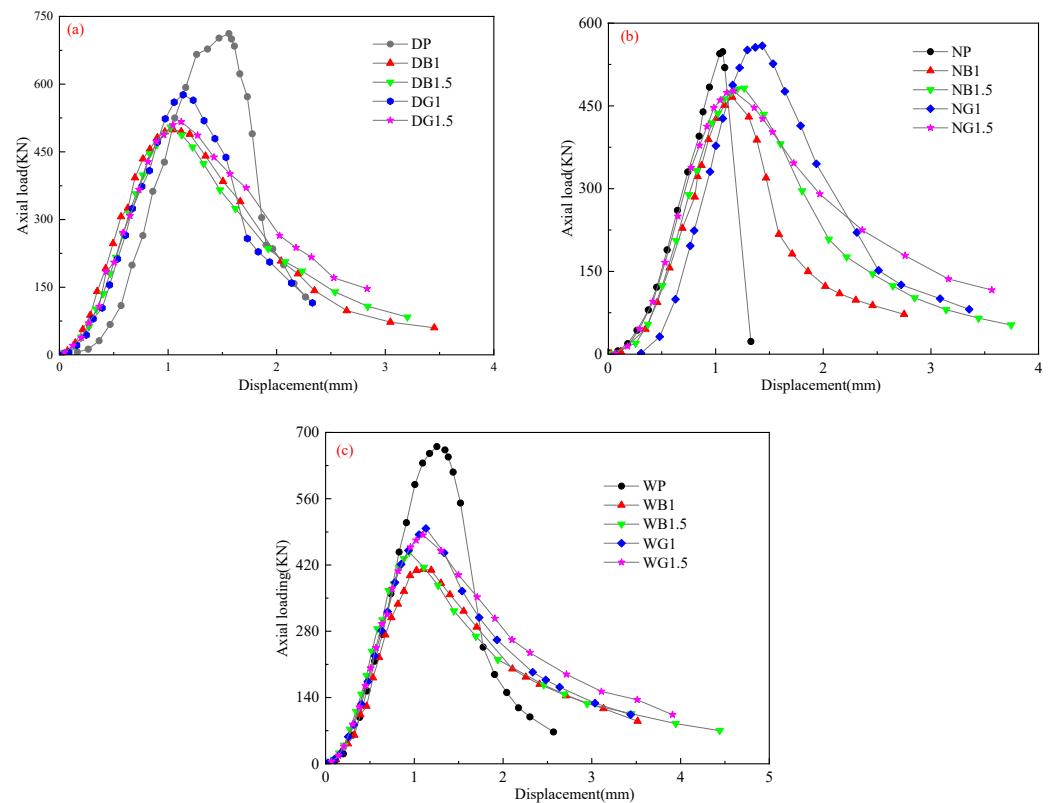


Figure 6. The axial load–displacement curve: (a) dried (b) natural (c) water-saturated.

According to Table 4, the compressive strength of FRRAC exhibits a decreasing trend with increasing moisture content for both basalt-fiber- and glass-fiber-reinforced specimens. The statistical results indicate that, compared to the dried state, the sample group with the largest decrease in compressive strength under saturated conditions was B1.0, with a reduction of 17.01%. The sample group with the smallest decrease was G1.5, with a reduction of 6.41%. For non-fiber-reinforced RAC, the compressive strength did not decrease continuously with increasing moisture content; instead, it first declined and then recovered. Moreover, for recycled aggregate concrete without fibers, the load–displacement curve was smoother under saturated conditions, with a significant increase in plasticity after the peak (as shown in Figure 6).

The underlying mechanisms can be attributed to the following factors: Under dry conditions, the moisture content in the interfacial transition zone between the recycled aggregates and the cement paste is reduced. The shrinkage of the cement paste during the hardening process enhances the mechanical interlocking between the aggregates and the cement matrix. This further improves the interfacial bonding performance, thereby contributing to the elevated strength of the concrete. Conversely, following water saturation, the unhydrated cement particles within the old residual mortar attached to the recycled aggregates have the opportunity to undergo secondary hydration by reacting with moisture from the new cement paste. This reaction yields supplementary hydration products, such as ettringite, calcium hydroxide (CH), and calcium silicate hydrate (C-S-H) gels. These products effectively fill the internal pores and microcracks, densifying the concrete microstructure and consequently improving its strength.

Furthermore, considering that there are only three replicate specimens for each mixture, the inherent natural variability of the materials can easily confound the interpretation of percentage-based differences. To address this, a two-way analysis of variance (ANOVA) was employed to re-evaluate the dataset, with the detailed results presented in Table 5.

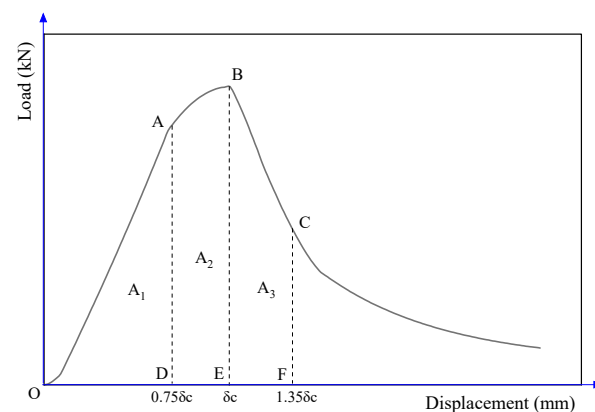
Table 5. Two-way ANOVA results for compressive strength.

Source	df	F Value	p Value	Partial η^2	95% CI Lower	95% CI Upper
Fiber Configuration (FC)	3	187.399	0.004	0.961	48.840	49.928
Saturation State (SS)	2	195.921	0.004	0.945	48.912	49.855
FC $\times$ SS interaction	6	13.279	0.001	0.776	48.442	50.325

Note: df = degrees of freedom; F-value = statistical value of the F-test; p-value = level of statistical significance ($p < 0.05$ indicates statistical significance); Partial η^2 = effect size for ANOVA; CI = confidence interval.

Compressive ductility and toughness characterize the deformation capacity and post-cracking energy absorption of concrete. These properties are generally quantified by the area under the uniaxial compressive load–displacement curve. Because recycled aggregates contain porous old mortar and weak interfacial transition zones, plain RAC tends to fail in a brittle manner. Fiber reinforcement, however, can improve the failure mode and enhance the post-peak load-bearing capacity of the material.

To more accurately capture this fiber reinforcing mechanism, this study proposes an advanced and modified evaluation method for compressive toughness, drawing upon the ASTM-C1080 and JSCE-SF4 testing standards [35–37]. This method establishes the characteristic displacement corresponding to the peak load (denoted as δ_c) as the benchmark, selecting three critical displacement nodes— $0.75\delta_c$, δ_c , and $1.35\delta_c$ —as references. Based on these nodes, the integrated area under the load–displacement curve is partitioned into three characteristic regions with distinct physical significance (as illustrated in Figure 7):

**Figure 7.** Advanced evaluation method of compressive toughness.

A_1 : The area enclosed by the curve segment OA and the abscissa within the interval from the initial loading stage to $0.75\delta_c$ (i.e., polygon OAE). This region primarily reflects the linear elastic work performed by the material prior to microcrack initiation.

A_2 : The integrated area corresponding to the curve segment AB within the interval from $0.75\delta_c$ to the peak displacement δ_c (i.e., polygon ABEF).

A_3 : The integrated area corresponding to the curve segment BC within the softening regime from the peak displacement δ_c to $1.35\delta_c$ (i.e., polygon BCFG). This region directly represents the frictional pull-out energy dissipation generated by the fibers bridging macroscopic cracks.

To quantitatively evaluate the toughness evolution characteristics of the fiber-reinforced recycled aggregate concrete, this study introduces two dimensionless toughness indices, I_0 and I_1 , which are calculated using the following equations:

$$I_0 = \frac{A_1 + A_2}{A_1} \quad (4)$$

$$I_1 = \frac{A_1 + A_2 + A_3}{A_1 + A_2} \quad (5)$$

In the aforementioned equations, the toughness index I_0 is utilized to evaluate the elastoplastic deformation and energy absorption capacity of the FRAC. Conversely, the toughness index I_1 is specifically designed to quantify the post-peak deformation and energy dissipation performance of the material. Namely, it characterizes the ability of the fibers to maintain structural integrity and sustain loads after matrix failure, without triggering severe and sudden brittle deformation. This directly reflects the enhancing effect of the fiber network on the ultimate ductility of the recycled aggregate concrete.

As shown in Figure 8, the I_0 values for the four batches of FRRAC all reach their maximum in the natural state. According to the definition of compressive toughness (I_0), it is observed that in the dry and saturated states, the area in the inelastic region before the peak strength of RAC reduces relatively.

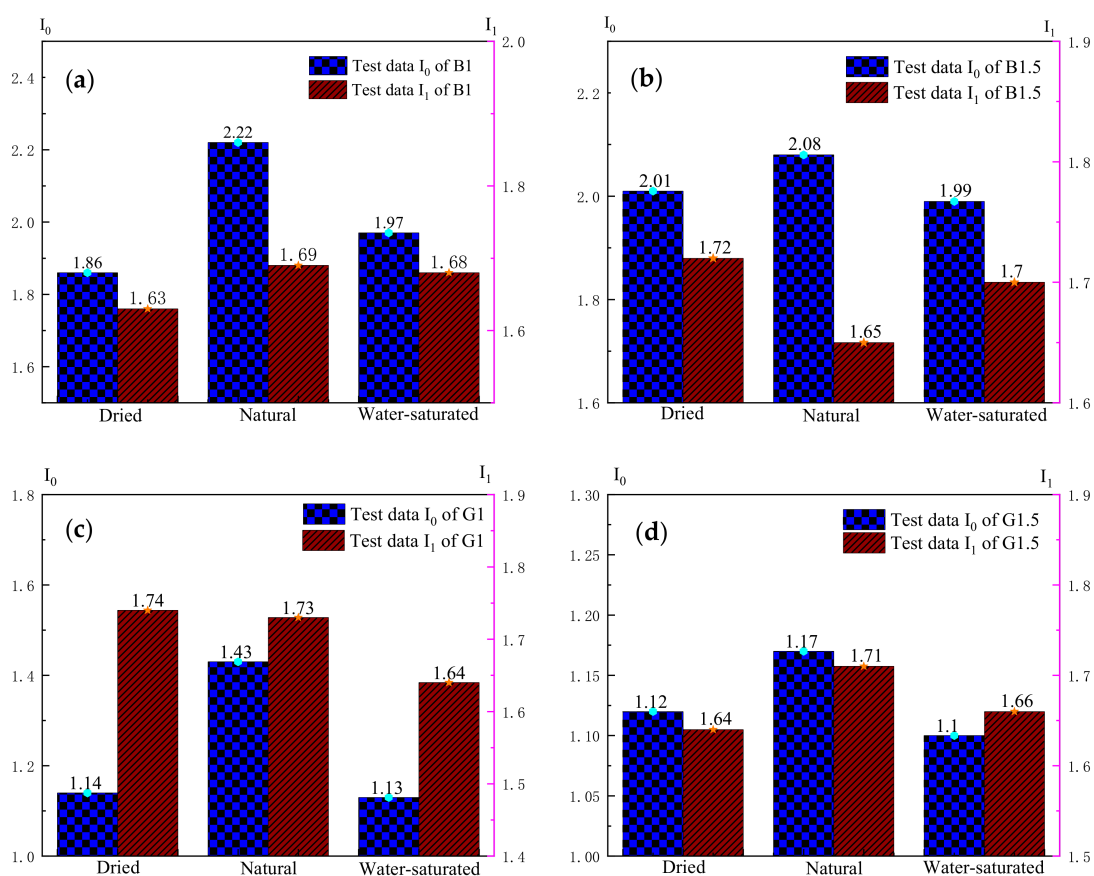


Figure 8. Toughness indexes of RAC with different fibers: (a) B1 (b) B1.5 (c) G1 (d) G1.5.

The potential reasons are as follows: During the drying process, the moisture content within the ITZ decreases, and the cement mortar undergoes shrinkage. This phenomenon leads to an increase in the elastic modulus of the concrete (a significant manifestation is that the peak displacement of RAC at failure in the dry state is substantially lower than that in the natural state). Under compression, the material becomes more prone to elastic deformation while inelastic deformation diminishes, which consequently results in a relative reduction in the area of the pre-peak inelastic region. Conversely, in the water-saturated state, the secondary hydration reaction within the RAC generates additional hydration products that fill the internal pores. This process enhances the strength and stiffness of the RAC to a certain extent, slightly improving its elastic performance under compression and reducing its inelastic deformation.

Additionally, it is noticeable that the I_1 values for all four batches show very little variation with saturation. The maximum difference between different states is only 4.07%. According to the definition of I_1 , this value reflects the concrete's energy absorption and resistance to damage after failure. Combining Figure 6 and Table 4 (where in the natural state, the unreinforced RAC has not even reached 1.35 times δc at complete failure), the stability of I_1 can be attributed to the inclusion of fibers. After peak strength, fibers bridge developing cracks and restrict their further propagation. The associated pull-out and rupture processes require additional energy dissipation, thereby improving the toughness and residual load-bearing capacity of the concrete.

3.2. Results of Splitting Tensile Test

3.2.1. Tensile Failure Mode

Dry state: Matrix shrinkage in Group P leads to the closure of internal inherent microcracks, generating high frictional resistance. Consequently, the splitting fracture is extremely rapid and violent, with aggregates being directly split observable at certain parts of the cross-section. For FRRAC, directly ruptured fibers are visible at the fracture surface, and the failure is accompanied by dense snapping sounds of fiber breaking.

Natural state: The failure process is relatively stable.

Water-saturated state: Free water fills the cracks and provides a lubricating effect, while the internal hydrostatic pressure accelerates crack opening. The specimens split silently under a lower tensile load, lacking any explosive force during the failure process. The fracture trajectory predominantly develops by detouring along the softened interfaces (such as the peeling of old mortar), resulting in a relatively rugged fracture profile.

Additionally, Figure 9 presents the macroscopic splitting fracture modes of the plain RAC (Group P) and FRRAC specimens at varying degrees of water saturation.

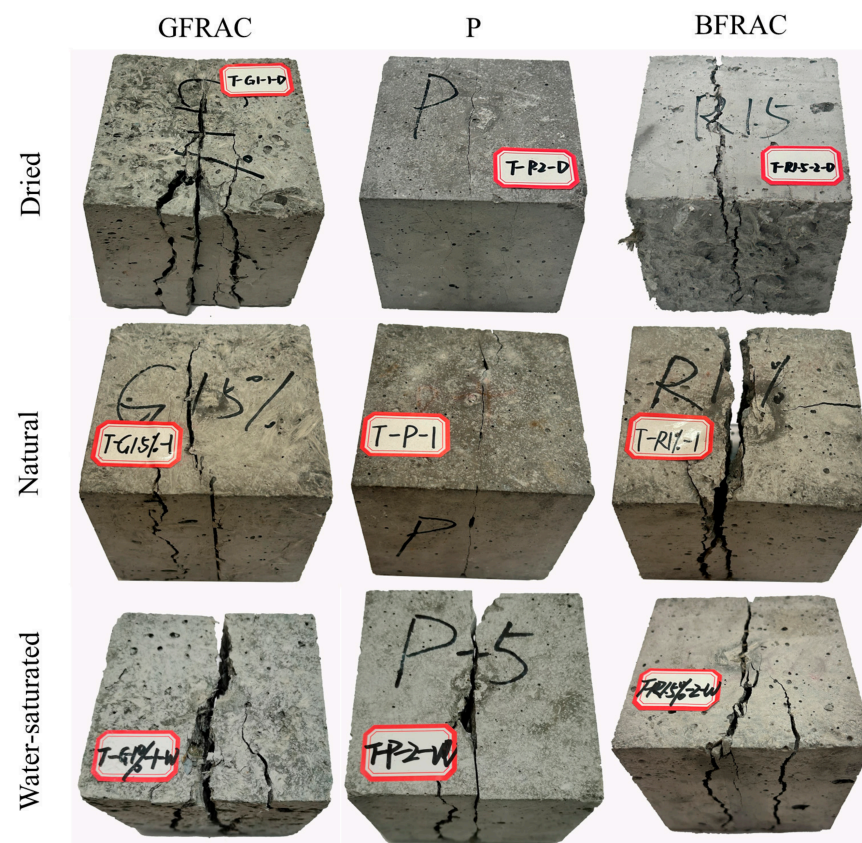


Figure 9. Splitting failure modes of plain RAC and FRRAC under different saturation states.

3.2.2. Tensile Performance Analysis

Table 6 and Figure 10 present the mechanical properties and stress–strain responses of the specimens measured from the cube splitting tensile tests.

Table 6. Experimental parameters of splitting test.

Specimen	Fiber Type	V_f (%)	f_t (MPa)	cov	ε_t (mm)	G_t (J)	f_t/f_c
DP	/	/	5.51	0.027	0.0369	107.23	0.077
DB1.0	Basalt	1.0	4.80	0.035	0.0402	107.23	0.096
DB1.5	Basalt	1.5	4.72	0.024	0.0338	107.76	0.094
DG1.0	Glass	1.0	5.64	0.023	0.0383	128.81	0.098
DG1.5	Glass	1.5	5.76	0.037	0.0567	168.52	0.111
NP	/	/	5.59	0.030	0.0356	111.53	0.101
NB1.0	Basalt	1.0	5.27	0.048	0.0349	118.80	0.113
NB1.5	Basalt	1.5	5.04	0.042	0.0340	120.65	0.105
NG1.0	Glass	1.0	5.89	0.039	0.0365	130.29	0.105
NG1.5	Glass	1.5	5.82	0.016	0.0345	126.78	0.126
WP	/	/	5.26	0.048	0.0380	115.47	0.078
WB1.0	Basalt	1.0	4.39	0.066	0.0370	99.47	0.106
WB1.5	Basalt	1.5	4.90	0.054	0.0439	107.72	0.110
WG1.0	Glass	1.0	5.27	0.016	0.0366	120.78	0.106
WG1.5	Glass	1.5	4.90	0.056	0.0369	107.72	0.101

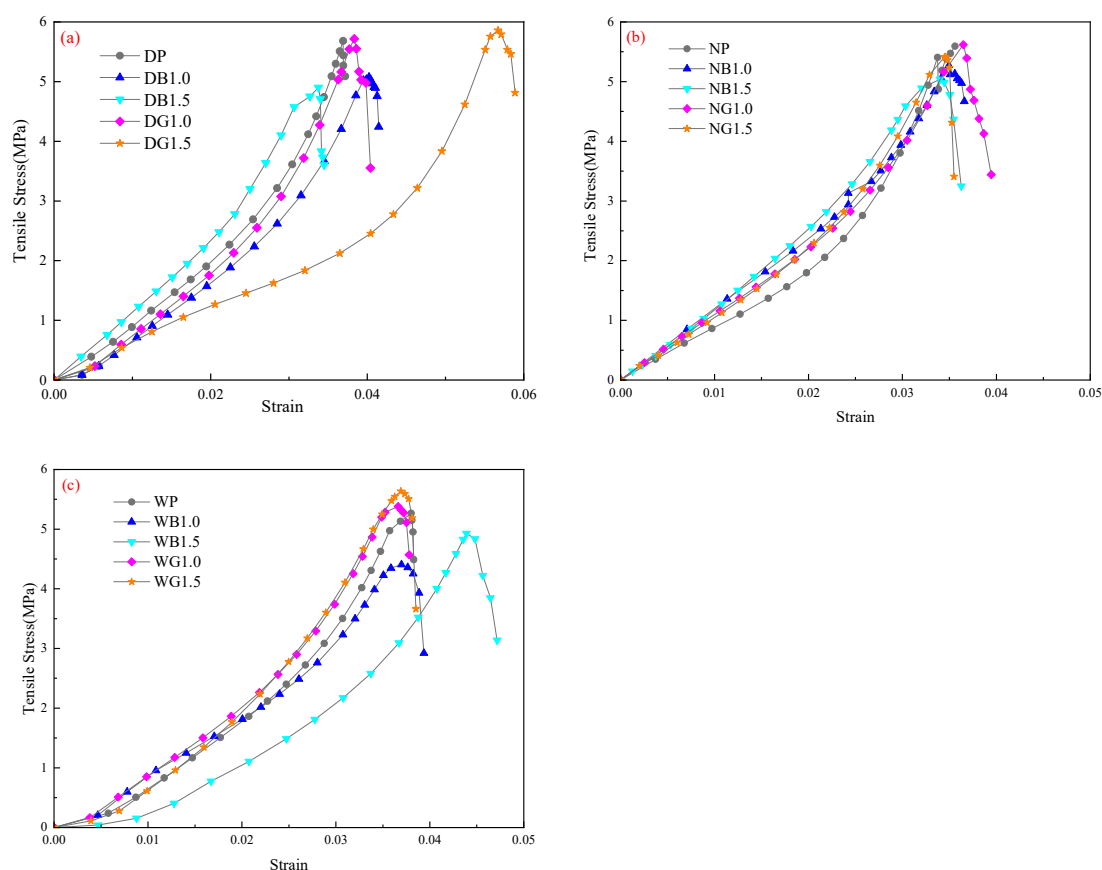


Figure 10. The tensile Stress–strain curve: (a) dried (b) natural (c) water-saturated.

Similarly, a two-way analysis of variance (ANOVA) was conducted on the splitting tensile strength of FRRAC with respect to fiber content and degree of water saturation. The detailed results are presented in Table 7.

Table 7. Two-way ANOVA results for splitting tensile strength.

Source	df	F Value	p Value	Partial η^2	95% CI Lower	95% CI Upper
Fiber Configuration (FC)	3	6.395	0.008	0.615	4.852	5.550
Saturation State (SS)	2	5.366	0.022	0.472	4.899	5.503
FC $\times$ SS interaction	6	0.737	0.630	0.630	4.596	5.806

As can be seen from Tables 6 and 7, distinct from the trend of compressive strength with respect to saturation, the splitting tensile strength of both plain RAC and the two types of FRRAC exhibits an initial increase followed by a decrease with increasing water saturation. That is, the splitting tensile performance is optimal in the natural state. Compared to the natural state, the peak stress of BFRRAC with fiber volume fractions of 1% and 1.5% decreased by 8.9% and 6.3% in the dry state, and by 18.3% and 7.3% in the water-saturated state, respectively. For GFRRAC, the corresponding reductions were 4.2% and 1.0% in the dry state, and 10.5% and 15.8% in the water-saturated state. In contrast, for plain RAC without fibers, the splitting tensile strength only decreased by 1.4% and 5.9% in the dry and water-saturated states, respectively, compared to the natural state. These data undoubtedly indicate that the splitting tensile strength of recycled aggregate concrete is highly sensitive to the presence of fibers, especially under water-saturated conditions. Furthermore, the significance of the interaction between fiber content and water saturation is noticeably lower for splitting tensile strength than for compressive strength.

In general, the splitting tensile strength of fiber-reinforced concrete ($f_{ts,f}$) can be regarded as the superposition of the splitting tensile strength of plain concrete (f_{ts}) and the contribution from fiber reinforcement ($\Delta f_{ts,f}$) [38,39]. The saturation level indirectly influences both components by affecting the density of the concrete matrix and the bond performance between fibers and the matrix. The general expression of the equation is shown in Equation (6):

$$f_{ts,f} = f_{ts}(S_r) + \Delta f_{ts,f}(S_r) \quad (6)$$

where $f_{ts}(S)$: a function representing the influence of moisture content on the splitting strength of plain concrete; $\Delta f_{ts,f}(S)$: a function representing the influence of moisture content on the fiber reinforcement effect.

Typically, the splitting tensile strength of plain concrete exhibits a “first increase, then decrease” trend with varying moisture content (i.e., an optimal moisture level exists). Therefore, the relationship was fitted using a quadratic polynomial, and the corresponding expression is presented in Equation (7):

$$f_{ts}(S_r) = aS_r^2 + bS_r + c \quad (7)$$

where a is less than 0, and b and c are coefficients determined by the concrete mix proportions (e.g., type of cement, water-to-cement ratio, etc.).

The incorporation of fibers can inhibit crack formation in concrete, but the reinforcement effect is influenced by moisture content. For instance, when the moisture content is too high, the bond strength between the fibers and the matrix may decrease. In this study, a linear reinforcement model was adopted for fitting, as expressed in Equation (8):

$$\Delta f_{ts,f} = \alpha V_f(1 - \beta S_r) \quad (8)$$

where α denotes the fiber type coefficient; V_f (%) is the fiber volume fraction; β is the coefficient representing the influence of saturation level.

By combining the effects of plain concrete and fiber reinforcement, a composite equation is derived:

$$f_{ts,f}(S_r) = aS_r^2 + (b - \alpha V_f \beta) S_r + (c + \alpha V_f) \quad (9)$$

Based on the data in Table 6, fitting was performed separately for the two types of fiber-reinforced recycled aggregate concrete: For basalt fiber, the fitting coefficients were: $a = -1.933$, $b = -0.509$, $c = 5.292$, $\alpha = -0.425$, $\beta = 2.463$; the coefficient of determination was $R^2 = 0.913$. For glass fiber, the fitting coefficients were: $a = -2.183$, $b = 2.759$, $c = 5.332$, $\alpha = -0.295$, $\beta = 3.232$; the coefficient of determination was $R^2 = 0.995$.

As presented in Figure 11, color mapping was used to compare the predicted and experimental splitting tensile strengths. The similar color distribution under the same fiber content and saturation degree confirms the good agreement between the model predictions and test results.

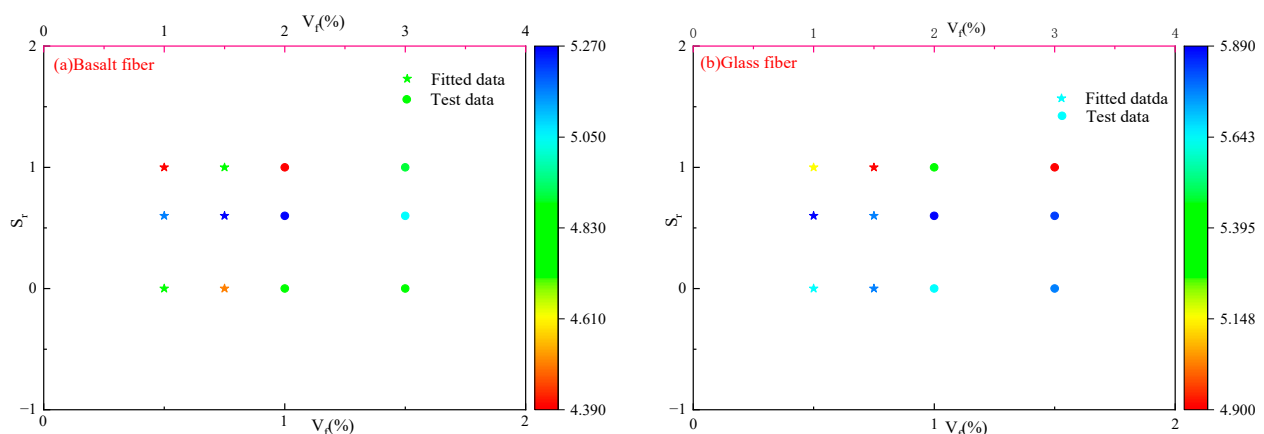


Figure 11. Chart of fitted values and Experimental values of tensile strength.

From Figure 10, the stress–strain responses of the specimens in the natural state are generally comparable, whereas DG1.5 in the dry state and WB1.5 in the saturated state exhibit stronger pre-peak plasticity than the other groups.

For RAC, splitting energy characterizes the fracture energy absorption capacity of a specimen during the splitting tensile test. It serves as a key indicator for evaluating the toughness and crack resistance of RAC. To facilitate analysis, the splitting energy test results for the five prepared groups of specimens are presented as a line chart in Figure 12. The data distribution indicates that glass fibers consistently outperform basalt fibers across the three saturation states. According to the physical properties of the two fibers presented in Table 2, the elastic modulus of glass fiber is considerably higher than that of basalt fiber. This higher stiffness enables GFRRAC to better resist crack opening during the splitting process, thereby requiring greater energy consumption before failure.

3.3. Results of Three-Point Bending Test

3.3.1. Bending Failure Mode

Dry state: Matrix shrinkage leads to the strongest internal mechanical interlocking, resulting in the most abrupt failure process. It can even be observed on the fracture surface that the relatively weak recycled aggregates are directly ruptured. **Natural state:** The failure process remains relatively sudden, although the load-bearing duration is longer than that in the dry state. **Water-saturated state:** Abundant free water fills the pores of the residual mortar in the recycled aggregates. Under flexural tension, the water pressure accelerates crack tip propagation. The fracture sound is muffled, and the fracture surface is rugged, with cracks predominantly detouring and peeling along the new-old interfaces severely softened by moisture (shown in Figure 13).

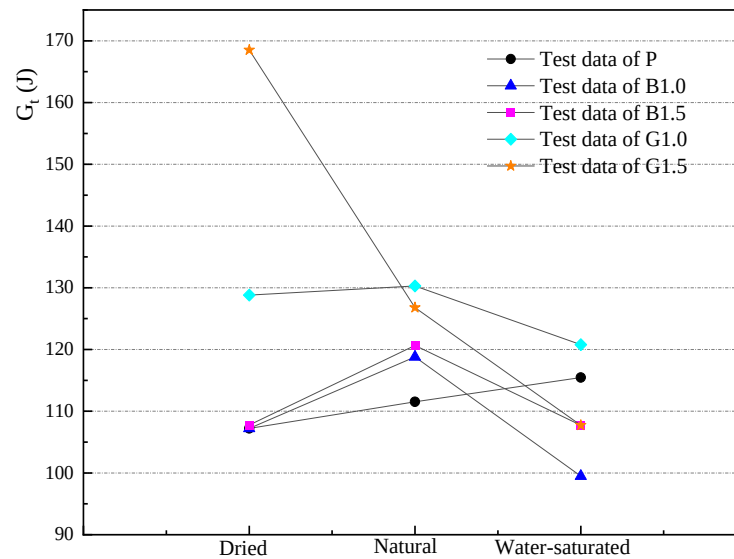


Figure 12. Effect of fiber type and saturation condition on fracture energy.

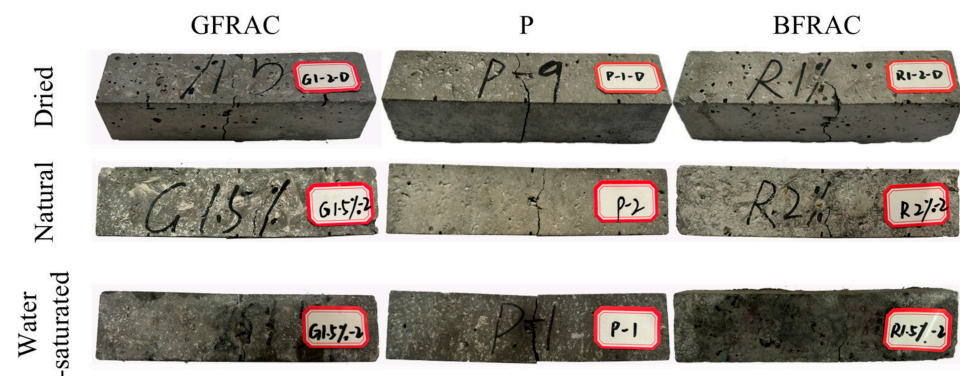


Figure 13. Three-point bending failure modes of plain RAC and FRRAC under different saturation states.

3.3.2. Bending Performance Analysis

Table 8 and Figure 14 present the mechanical parameters and load–displacement responses of the specimens measured from the three-point bending tests.

Table 8. Experimental parameters of three-point bending test.

Specimen	Fiber Type	V_f	f_f (MPa)	cov	δ_c (mm)	G_f (J)	f_f/f_c
DP	/	/	9.98	0.020	0.564	0.502	0.14
DB1.0	Basalt	1.0	9.84	0.025	0.388	0.578	0.20
DB1.5	Basalt	1.5	9.26	0.030	0.363	0.484	0.18
DG1.0	Glass	1.0	11.32	0.027	0.345	0.697	0.20
DG1.5	Glass	1.5	9.78	0.038	0.314	0.540	0.19
NP	/	/	9.26	0.021	0.482	0.639	0.17
NB1.0	Basalt	1.0	10.36	0.026	0.412	0.773	0.22
NB1.5	Basalt	1.5	8.63	0.034	0.432	0.534	0.18
NG1.0	Glass	1.0	9.31	0.045	0.427	0.887	0.16
NG1.5	Glass	1.5	9.12	0.048	0.476	0.685	0.19
WP	/	/	9.75	0.016	0.446	0.624	0.15
WB1.0	Basalt	1.0	7.79	0.046	0.396	0.519	0.19
WB1.5	Basalt	1.5	7.36	0.048	0.439	0.488	0.16
WG1.0	Glass	1.0	8.59	0.094	0.452	0.522	0.17
WG1.5	Glass	1.5	7.93	0.046	0.372	0.651	0.16

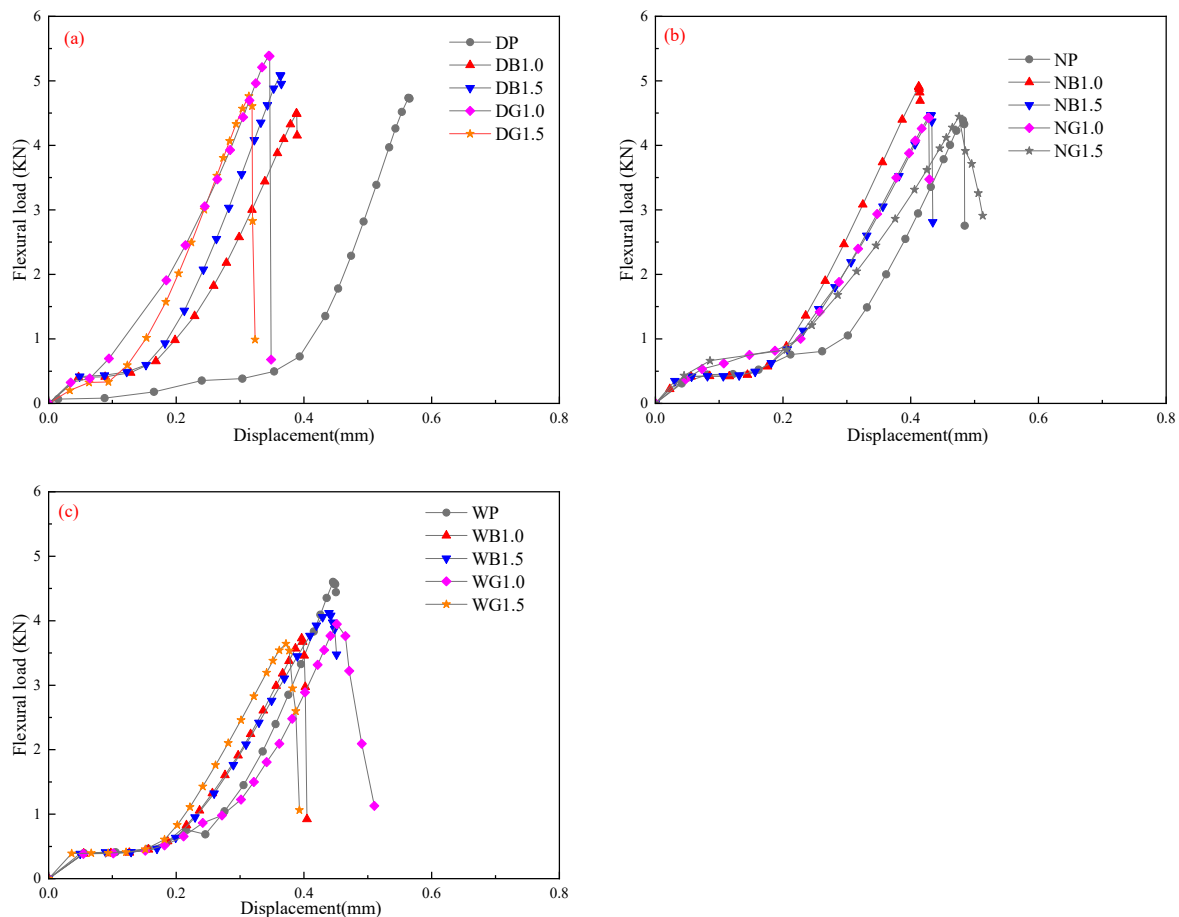


Figure 14. The flexural Loading-Displacement curve: (a) dried (b) natural (c) water-saturated.

Similarly, a statistical inference analysis (two-way ANOVA) was conducted on the flexural strength of FRRAC with respect to fiber content and the degree of water saturation, with the results presented in Table 9.

Table 9. Two-way ANOVA results for flexural strength.

Source	df	F Value	p Value	Partial η^2	95% CI Lower	95% CI Upper
Fiber Configuration (FC)	3	3.443	0.034	0.320	8.474	9.739
Saturation State (SS)	2	16.839	3.66×10^{-5}	0.605	8.559	9.654
FC $\times$ SS interaction	6	1.099	0.394	0.231	8.013	10.200

As shown in Table 8, with the exception of Group B1, the variation trend of the flexural strength with the degree of saturation for the remaining groups aligns with that of the uniaxial compressive strength. Specifically, the strength of the fiber-reinforced groups decreases continuously with increasing saturation, whereas the strength of the plain (unreinforced) group initially decreases and subsequently increases. The distinct difference, however, lies in the magnitude of variation. The plain recycled aggregate concrete exhibits minor fluctuations in flexural strength with varying saturation, showing differences of only 7.8% and 5.3%. In contrast, the fiber-reinforced RAC demonstrates a substantially larger variation amplitude; especially under water-saturated conditions, the minimum variation reaches 14.7%. The potential reasons are as follows: During the flexural failure of concrete, both a compression zone and a tension zone exist. The failure is predominantly governed by the tension zone because the tensile strength of concrete is generally far lower than its compressive strength. As established in the preceding analysis, the splitting

tensile strength of FRRAC is highly susceptible to the combined effects of fibers and water, experiencing a significant reduction particularly in the water-saturated state. Additionally, Table 9 indicates that the degree of saturation has a highly significant impact on the flexural strength.

From the perspective of material damage mechanics, the influence of saturation on the degradation of matrix strength and interfacial fiber slippage can be incorporated into the flexural strength model of fiber-reinforced concrete [40–42]. The flexural strength of concrete can be described by coupling the matrix strength degradation term with the fiber reinforcement term. The corresponding equation is expressed as:

$$f_f = f_{f0}(1 - S^n)(1 + kV_f) \quad (10)$$

where f_f is the flexural strength of fiber-reinforced concrete, corresponding to the peak stress measured in the three-point bending test (MPa); f_{f0} denotes the flexural strength of plain concrete in a dry state ($S = 0$), also in MPa; n is defined as the damage index induced by saturation, which is closely related to the pore characteristics of the concrete matrix and reflects the weakening effect of water saturation on matrix strength. A larger n value indicates a more pronounced weakening effect in the equation; k is the effective fiber reinforcement coefficient, which is influenced by the saturation level.

The coefficient k can be further expressed as:

$$k = k_0(1 - \mu S_r) \quad (11)$$

where k_0 is the reinforcement coefficient under dry conditions; μ is the interfacial weakening coefficient, representing the deterioration of the fiber–matrix bond caused by moisture. This formulation implies that as the saturation level S_r increases, the value of k decreases, indicating a reduction in the fiber’s reinforcing effectiveness under flexural loading.

Combining Equations (10) and (11) yields a general fitting equation for predicting the flexural strength of recycled aggregate concrete at different saturation degrees. The proposed equation was subsequently used to fit the experimental data of both basalt- and glass-fiber-reinforced recycled aggregate concrete:

$$f_f = f_{f0} \left(1 + aS_r + bS_r^2 \right) \left[1 + k_0(1 - \mu S_r)V_f \right] \quad (12)$$

The resulting fitting coefficients for each type are as follows: BFRRAC: $a = 0.029$, $b = -0.322$, $k_0 = -0.039$, $\mu = 2.393$; GFRAC: $a = 0.062$, $b = -0.172$, $k_0 = -0.020$, $\mu = 4.783$. The fitted curves and experimental test data are presented in Figure 15.

Flexural toughness reflects the energy absorption and failure resistance of a material during bending, which can be quantified using the area enclosed by the load–displacement curve [43]. In this study, the area under the load–deflection curve up to $1.2\delta_f$ was adopted to quantify flexural toughness, where δ_f is the deflection at peak load. The calculation formula is expressed as follows:

$$\begin{cases} G_f = \int_0^{1.2\delta} \left(P_f + \frac{mg}{1000} \right) d\eta_1 \delta \\ P_f = f_f \frac{bh^2}{L} = f_{f0}(1 - S^n) \left[1 + k_0(1 - \mu S)V_f \right] \frac{bh^2}{L} \end{cases} \quad (13)$$

As shown in Figure 16, bending toughness exhibits a nonmonotonic variation with saturation, increasing first and then decreasing, which is consistent with the trend observed for splitting energy. The greatest variation occurs in the G1.0 group, where the bending toughness in dry and saturated conditions is only 78.6% and 55.9% of its value in the natural state. The smallest variation occurs in the B1.5 group, where the bending toughness

in dry and saturated states is 90.6% and 91.4% of the natural state value. The reasons for this may be as follows: an appropriate increase in saturation helps refine the interfacial transition zone and relieve internal stress concentration in concrete. In contrast, excessive saturation may lead to the formation of excessive water films around the recycled aggregates during hardening, which reduces the bonding strength between the aggregates and the surrounding cementitious matrix.

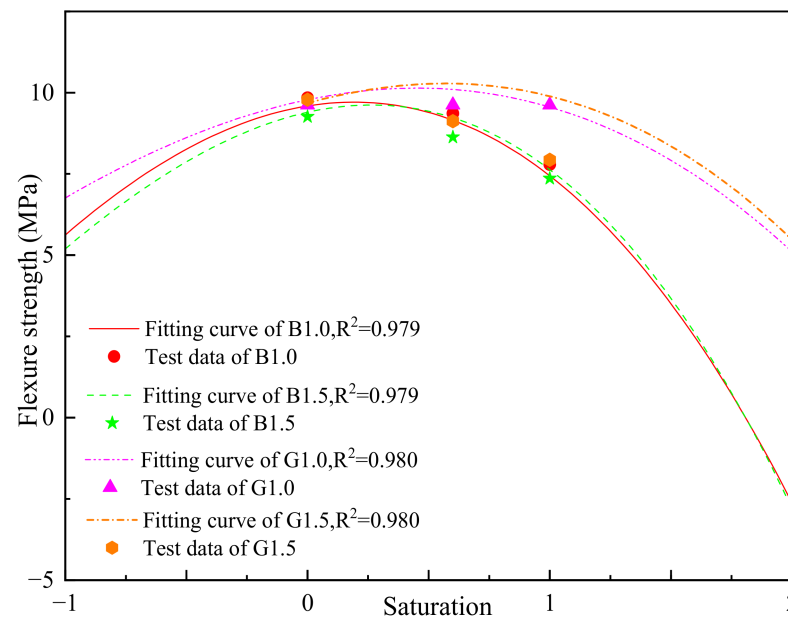


Figure 15. Graph of bending strength fitting curve.

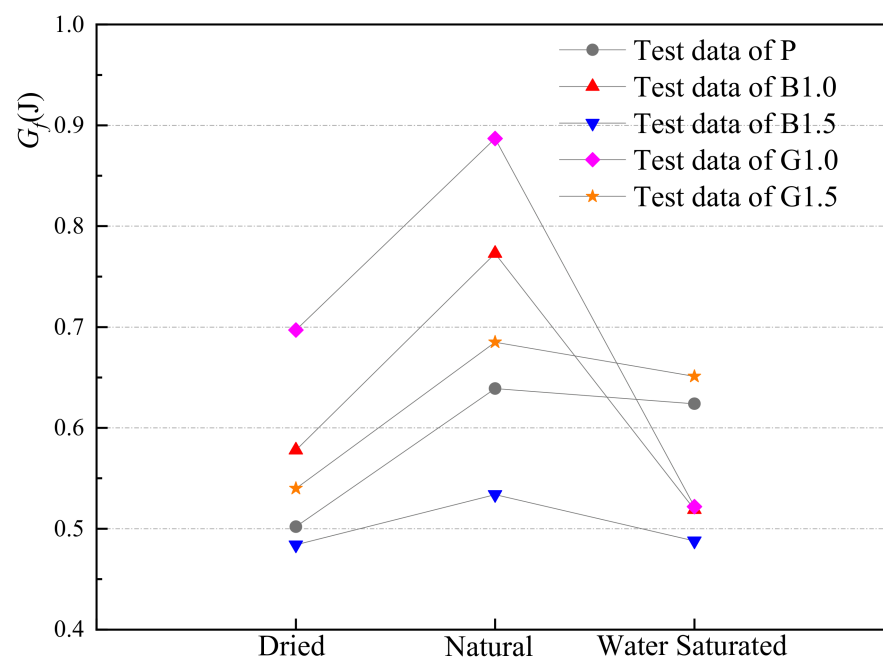


Figure 16. Effects of fiber type and saturated water content on the fracture energy.

Additionally, from the observation of the line chart and table, it is evident that, under all three saturation conditions, the bending toughness and bending strength of the 1.0% fiber group samples are better than those of the 1.5% group. In terms of bending performance, the incorporation of 1.0% glass fiber and basalt fiber shows better results than the 1.5% incorporation.

3.4. Constitutive Model Under Axial Compression

Compressive strength is the most basic and commonly used mechanical property indicator of concrete [44]. In various building structures, concrete components mainly bear compressive loads. For example, the foundation, columns, and other vertical load-bearing components primarily support the building's weight and other vertical loads [45]. For recycled aggregate concrete, thorough research on compressive strength must be conducted before advancing to the study of other strength properties and establishing a complete material performance system.

In this experiment, to facilitate analysis, the stress–strain curves of concrete with different saturation levels and fiber contents were normalized (as shown in Figure 17). Figure 17 presents the normalized stress–strain curves, with $\varepsilon/\varepsilon_c$ and σ/σ_c used as the x- and y-axes, respectively, where σ_c and ε_c are the peak stress and peak strain. The curves of RAC and FRRAC are generally similar in shape to those of ordinary concrete.

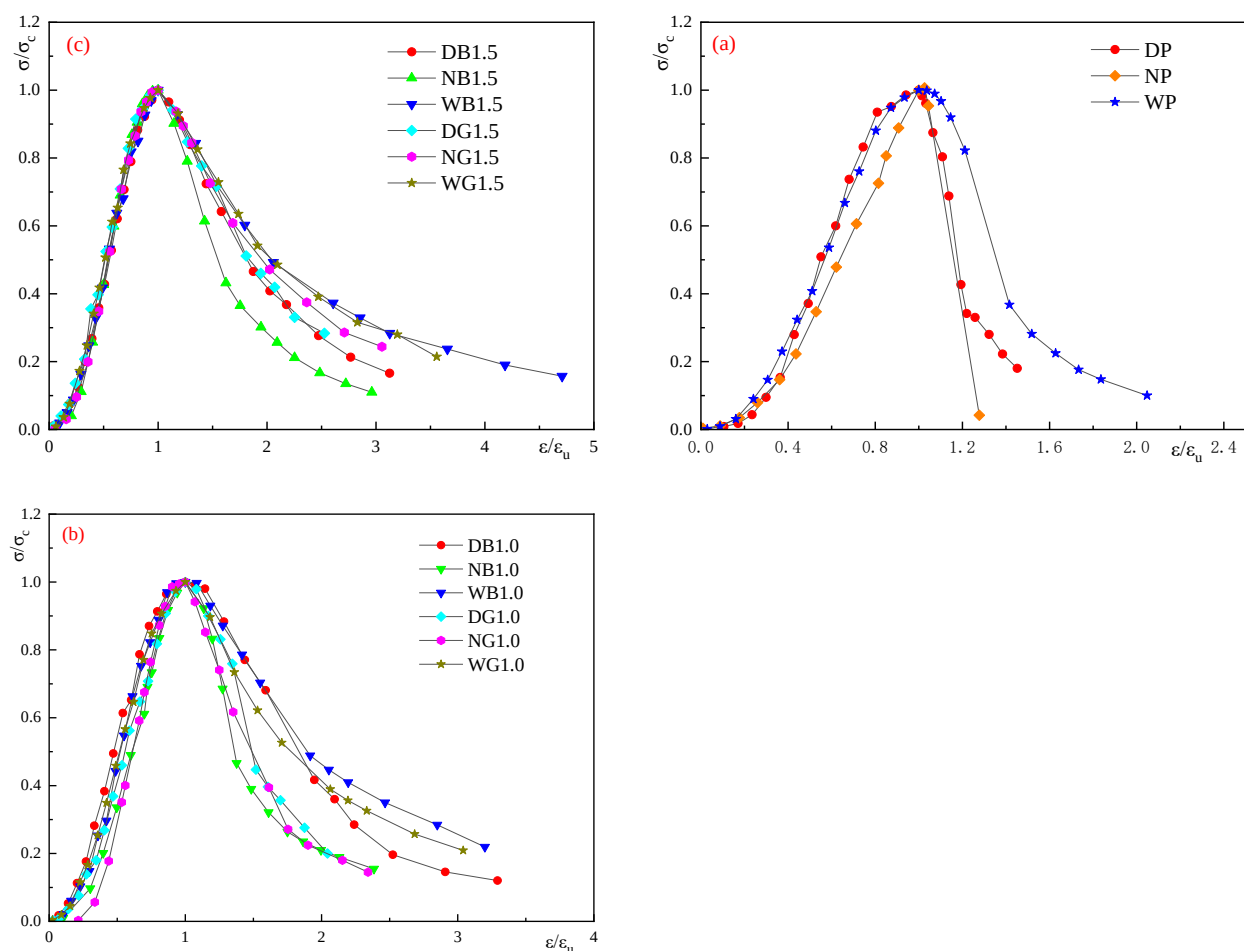


Figure 17. Normalized Stress–Strain curves with different fiber dosage: (a) 0% (b) 1.0% (c) 1.5%.

Based on previous studies on recycled aggregate concrete and fiber-reinforced concrete, the following equation was adopted for preliminary fitting [46]:

$$y = \begin{cases} ax + (3 - 2a)x^2 + (a - 2)x^3 & (0 \leq x < 1) \\ \frac{x}{b(x-1)^2 + x} & (x \geq 1) \end{cases} \quad (14)$$

Here, parameter a describes the modulus-to-peak secant modulus ratio, while parameter b characterizes the plasticity of FRRAC; a lower b value corresponds to a gentler post-peak softening response.

To facilitate the measurement of the impact of fibers, the fiber characteristic value λ_f is introduced, and its definition is as follows:

$$\lambda_f = V_f l_f / d_f \quad (15)$$

In the equation, V_f is the fiber volume fraction, and l_f and d_f correspond to the fiber length and diameter, respectively.

The fitted values of parameters a and b for each group are summarized in Table 10. The results indicate that the experimental points align well with the fitted curves. As the moisture saturation increases, the parameter a in the rising phase typically decreases first and then increases. This is mainly because moisture introduced during the transition from dry to natural conditions fills some pores and microcracks, while simultaneously weakening chemical bonding and mechanical interlocking in the ITZ [47,48]. When concrete is under stress, it becomes easier for slippage and micro-damage to occur at the interface, leading to a reduction in the elastic modulus. The increase in porosity and micro-cracks results in a decrease in the initial elastic modulus of the concrete. With further saturation, water progressively occupies the pores within the recycled aggregates and cement paste. This pore-filling effect decreases the proportion of empty voids and enhances the compactness of the concrete matrix. As a result, the deformation resistance of the concrete is improved, leading to reduced strain at a given stress and an increase in elastic modulus.

Table 10. Fitting results of parameters a and b .

Specimen	λ_f	S_r (%)	Parameter a	Correlation Coefficient R^2	Parameter b	Correlation Coefficient R^2
DP	0	0	−0.73	0.9955	35.21	0.9843
NP	0	0.6	−1.18	0.9416	89.20	0.9606
WP	0	1.0	−0.59	0.9968	11.51	0.9756
DB1.0	12	0	−0.17	0.9966	3.05	0.9814
NB1.0	12	0.6	−1.18	0.9814	8.53	0.9878
WB1.0	12	1.0	−0.29	0.9974	2.24	0.9988
DG1.0	10	0	−0.59	0.9905	5.80	0.9760
NG1.0	10	0.6	−1.47	0.9933	7.36	0.9966
WG1.0	10	1.0	−0.19	0.9995	2.99	0.9934
DB1.5	18	0	−0.48	0.9952	2.86	0.9978
NB1.5	18	0.6	−0.55	0.9981	5.26	0.9985
WB1.5	18	1.0	−0.40	0.9953	1.82	0.9973
DG1.5	15	0	−0.08	0.9978	2.59	0.9941
NG1.5	15	0.6	−0.50	0.9991	2.28	0.9983
WG1.5	15	1.0	−0.15	0.9993	1.87	0.9979

By contrast, parameter b shows a nonmonotonic trend in the descending stage, increasing initially and then decreasing. This behavior may be attributed to the fact that, under low saturation, water first occupies interconnected pores and microcracks, which enhances the interfacial transition zone between recycled aggregates and the surrounding cement paste. At higher saturation, the numerous internal pores in the recycled aggregate are filled with water, and during the compression of the concrete, the pore water pressure gradually increases [49,50]. This pore water pressure deteriorates the aggregate–paste bonding and consequently reduces the strength of the interfacial transition zone.

Based on the experimental results, regression analysis was carried out to correlate parameters a and b with the fiber characteristic value λ_f and the saturation degree S_r . The fitted relationships are expressed as follows:

$$\begin{cases} a = (0.014\lambda_f^2 - 0.935\lambda_f + 12.810)S_r^2 + (0.011\lambda_f^2 + 0.228\lambda_f - 7.815)S_r + (-0.031\lambda_f^2 + 0.866\lambda_f - 6.191) \\ b = (-0.236\lambda_f^2 + 7.720\lambda_f - 72.179)S_r^2 + (0.149\lambda_f^2 - 5.103\lambda_f + 52.065)S_r + (0.177\lambda_f^2 - 3.595\lambda_f + 29.856) \end{cases} \quad (16)$$

The equation constitutes the constitutive equation for the axial compression performance of FRRAC. When $S_r = 0$, this equation degenerates into the constitutive equation of FRRAC in dry state. When $\lambda_f = 0$, it applies to recycled aggregate concrete without fibers. By substituting the parameter values obtained from Equation (16) into Equation (14), a comparison was made between the normalized stress–strain experimental curve for FRRAC and the curve from the calculation model, as presented in Figure 18. Thus, Equation (14), expressed in a piecewise form, is capable of capturing the full stress–strain behavior of FRRAC subjected to uniaxial compression.

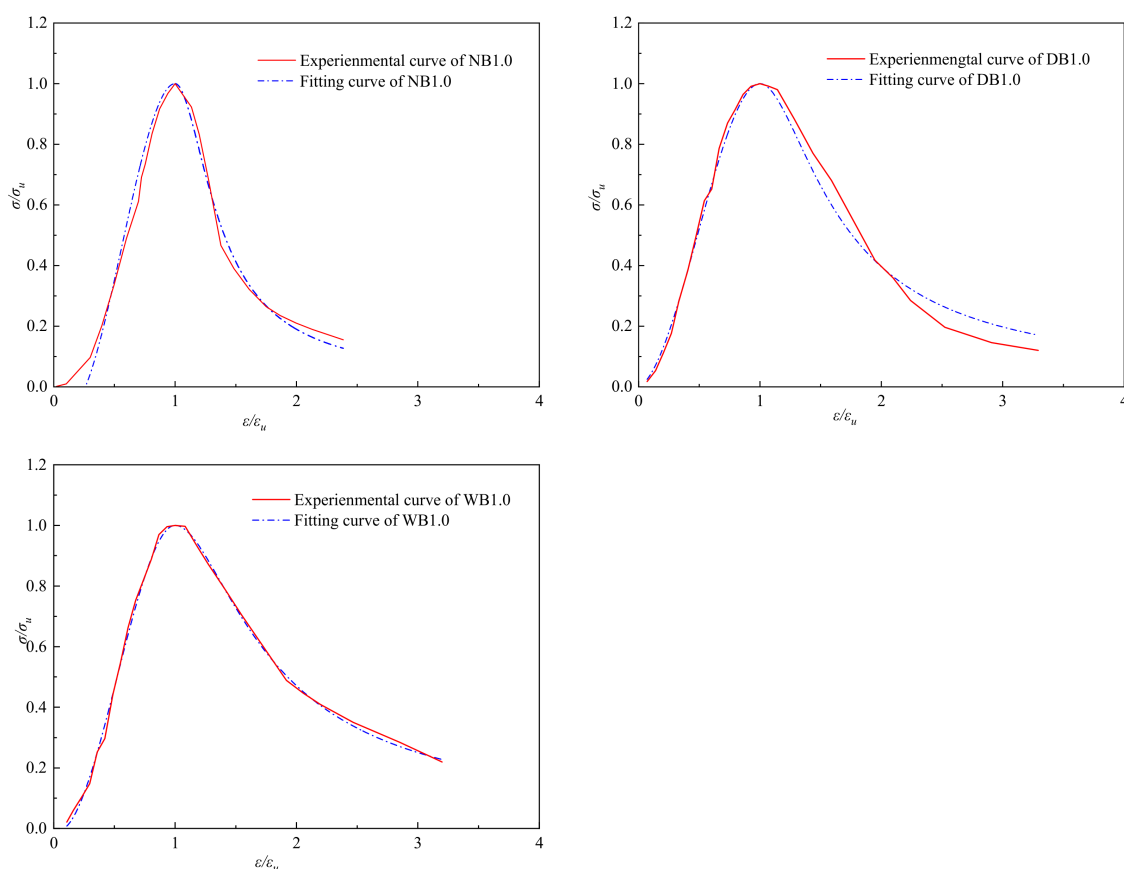


Figure 18. Comparison between experimental and fitted curves.

4. Discussion

4.1. Formula Validation

Based on Equation (16), by inputting various fiber characteristic values and degrees of saturation, the corresponding parameters a and b can be calculated. These calculated values, along with their respective simulated values, are plotted in Figure 19; the simulated values are plotted on the x -axis, while the calculated values are plotted on the y -axis.

As illustrated in Figure 20, the points representing parameters a and b are relatively evenly distributed on both sides of the identity line. However, it is evident that the dispersion of the points around the regression line for parameter b is significantly lower than that for parameter a , and the slope of the line corresponding to b is closer to 1.

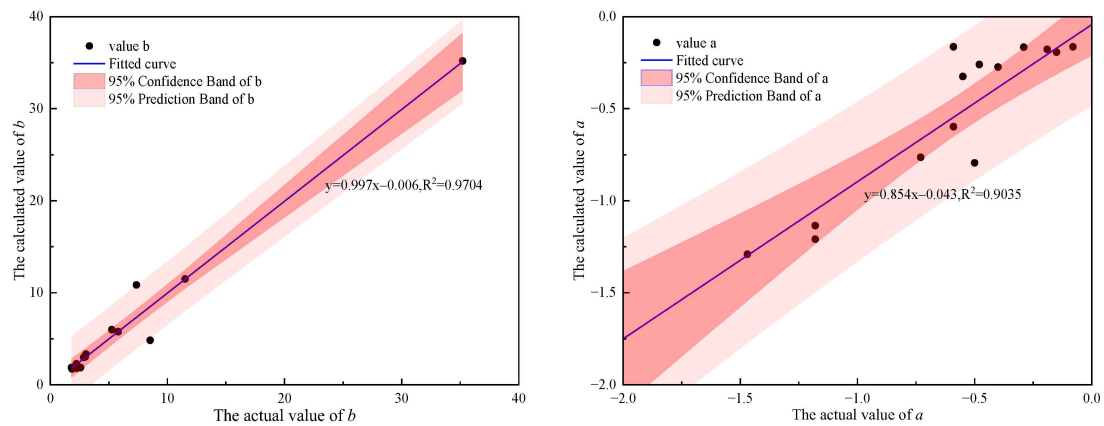


Figure 19. Experimental/Calculation diagram of values a and b .

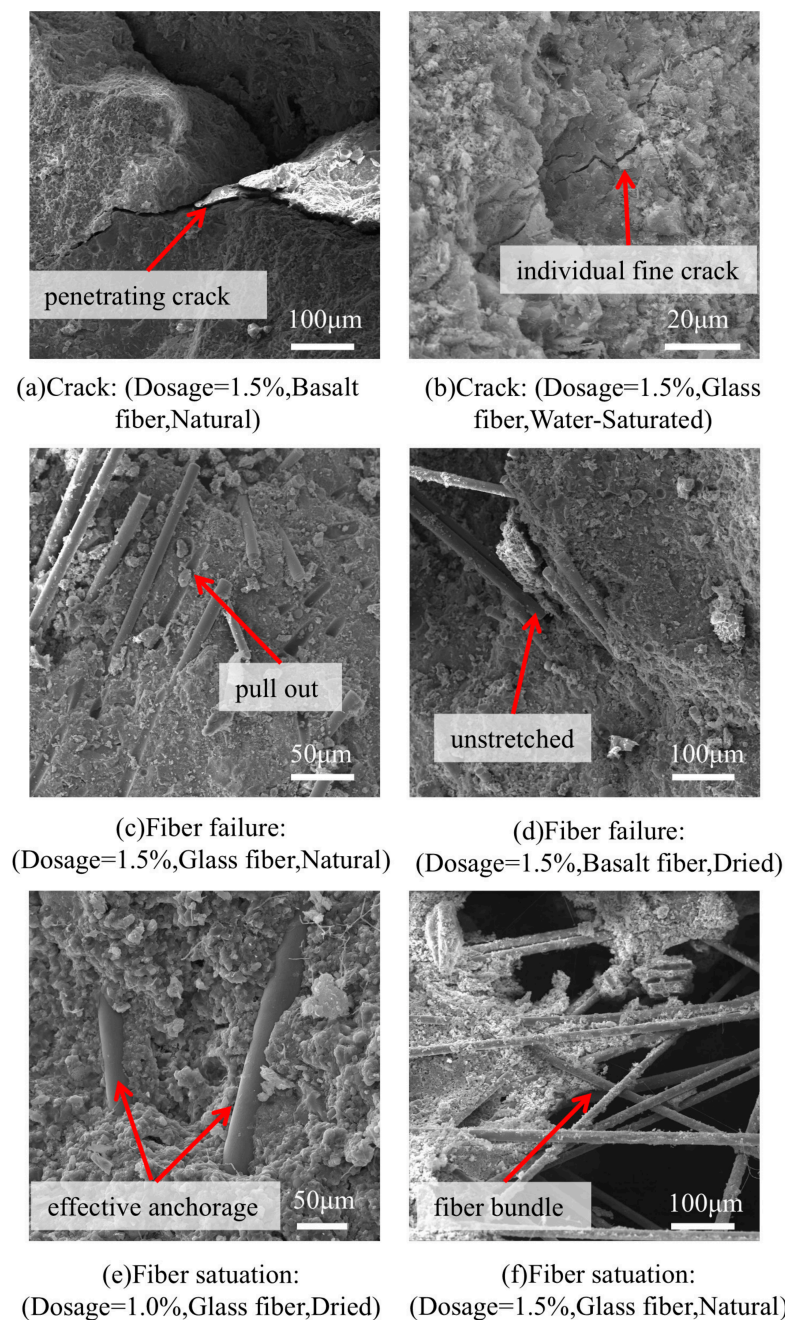


Figure 20. Microgram of specimens.

Meanwhile, considering that the experimental design comprises only 3 levels of water saturation and 5 fiber conditions, and that the fitting of Equation (16) involves multiple parameters, there is a substantial risk of overfitting. Therefore, this study performed Leave-One-Out Cross-Validation (LOOCV) to refine the model and verify its reliability and generalization capability. Given the total sample size of 15, one sample was iteratively isolated as the validation set while the remaining 14 samples were used for training and modeling. This cycle was repeated 15 times, ensuring that each sample was individually predicted exactly once. Let the original true value be y_i and the predicted value obtained through successive LOOCV extrapolation be $\hat{y}_i$, where $i = 1, 2, \dots, 15$. Finally, the core indicators, namely the Root Mean Square Error (RMSE) and the cross-validated coefficient of determination (R^2_{LOOCV}), were derived. The specific calculation formulas are as follows:

$$\begin{aligned} RMSE &= \sqrt{\frac{1}{n} \sum_{i=1}^{15} (y_i - \hat{y}_i)^2} \\ R^2_{LOOCV} &= 1 - \frac{\sum_{i=1}^{15} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{15} (y_i - \bar{y})^2} \end{aligned} \quad (17)$$

where $\bar{y}$ is the mean of the dependent variable. The detailed results are presented in Table 11.

Table 11. LOOCV parameters for values a and b .

Parameter	Regression Model	Sample Size	RMSE	R^2_{LOOCV}
a	Multiple linear regression	15	0.195	0.765
b	Multiple nonlinear regression	15	5.871	0.938

Table 11 reveals that the cross-validated R^2_{LOOCV} values for both a and b exceed 0.7. This threshold confirms that the overfitting risk is constrained to an acceptable margin and the model retains strong predictive generalizability. Moreover, the demonstrably higher R^2_{LOOCV} for parameter b corroborates the reduced scatter observed in Figure 19. Mechanistically, this implies that Equation (8) yields a highly accurate fit for the post-peak descending branch of the stress–strain curves of FRRAC, albeit with relatively larger discrepancies during the pre-peak ascending branch. Lastly, it should be acknowledged that due to the limited experimental sample size, the analysis regarding other fiber types and a wider range of saturation conditions remains insufficient. Consequently, the applicability scope of the proposed model is limited, which warrants further investigation in future research.

4.2. Microstructural Analysis

The microstructural characteristics of recycled aggregate concrete reinforced with basalt and glass fibers are shown in Figure 20, as observed using scanning electron microscopy (SEM).

As shown in Figure 20a,b, the failure of the concrete progresses from a single fine crack and eventually forms a penetrating crack. Figure 20c,d indicate that in fiber-reinforced concrete, during early failure, some fibers become ineffective due to pull-out or breakage, while others, due to their position or other factors, do not undergo tensile deformation. As shown in Figure 20e, fibers of appropriate length are effective in anchoring, bonding, and bearing tensile forces [51,52]. However, as shown in Figure 20f, when the fiber content is high, fibers tend to become entangled and form fiber bundles, reducing the effective bonding between the fibers and the surrounding cementitious materials, potentially creating weak points that decrease the strength and toughness of the concrete.

Figure 21 illustrates the process by which cement particles dissolve on their surfaces upon encountering water, undergoing hydration reactions. During the setting and

hardening process, some crystals are generated, which are the primary source of the concrete's strength.

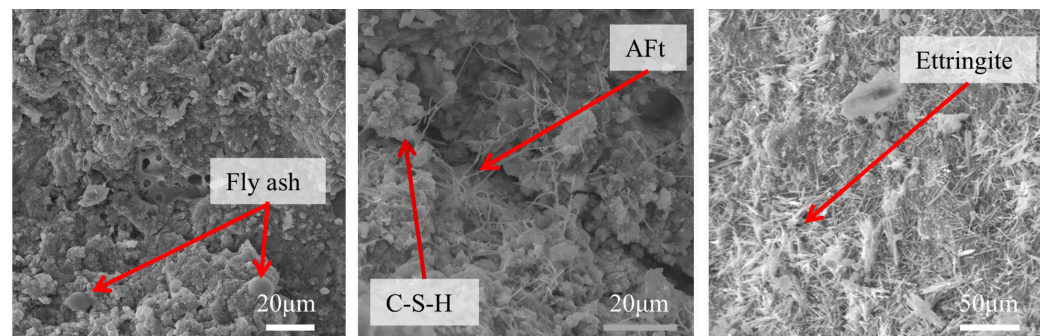


Figure 21. Microscopic images of hydration products.

In a dry environment, cement hydration products gradually lose moisture, leading to structural alterations in the crystals of products such as calcium hydroxide and calcium silicate hydrate gels, which may become denser and finer. However, due to moisture deficiency, microcracks may emerge within the hydration products situated in the ITZ (as illustrated in Figure 22a). These microcracks inevitably degrade the toughness and impermeability of the ITZ.

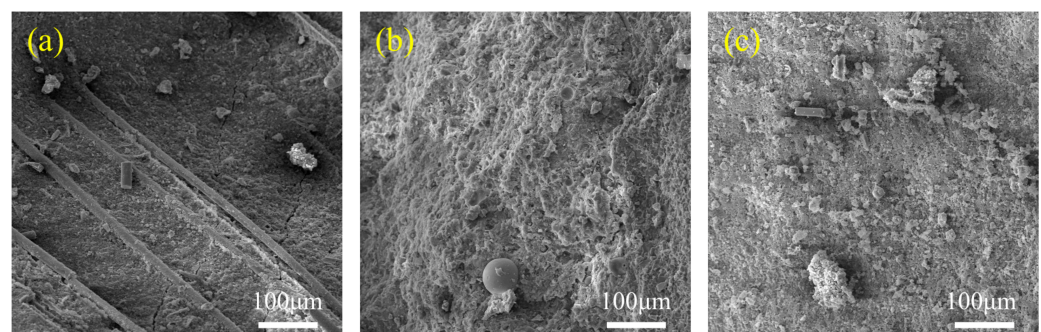


Figure 22. Microscopic images of cement matrix: (a) Dried (b) Natural (c) Water-Saturated.

Conversely, in the water-saturated state, although the total generation of hydration products may increase due to the abundance of moisture, the dilution effect of water can cause these products to be more dispersed throughout the concrete matrix. Furthermore, under saturated conditions, highly soluble hydration products like CH are prone to dissolve and migrate, resulting in a heterogeneous distribution of internal chemical compositions (as depicted in Figure 22c). Concurrently, the internal pores are completely filled with water, reaching a saturated state. Driven by this moisture filling, the pore walls are subjected to hydrostatic pressure, which can induce a certain degree of expansion. Capillary pores, in particular, appear more fully engorged in the saturated state, leading to a marginal increase in pore size. Taking Group B1.5 as an example, quantitative image analysis was conducted on the scanning electron microscopy images of the fractured FRRAC specimens under various saturation states using ImageJ software (version 1.54p). Based on the calculated area fractions, the porosities in the dry, natural, and water-saturated states were determined to be 9.8%, 11.7%, and 12.3%, respectively.

5. Conclusions

The main purpose of this study is to clarify the effects of varying saturation degrees on the static strength and toughness properties of FRRAC. For this purpose, glass fiber

and basalt fiber were incorporated at varying volume fractions for comparative analysis. Based on the experimental results, several strength prediction equations and a stress–strain model were developed, which may serve as a reference for future research on recycled aggregate concrete. Finally, SEM observations were conducted on representative specimens to reveal the microstructural evolution of the cement matrix, fibers, and other constituents under varying saturation states. On the basis of these findings, the main conclusions are summarized as follows:

(1) The compressive and flexural strengths of fiber-reinforced recycled aggregate concrete decrease continuously with increasing water saturation. Compared to the water-saturated state, the maximum improvements in these strengths under the dry state are 20.50% and 31.78%, respectively. In contrast, the splitting tensile strength exhibits an initial increase followed by a decrease as saturation increases, reaching its peak in the natural state, which is 9.79% and 20.05% higher than those in the dry and water-saturated states, respectively.

(2) The compressive toughness, as well as the splitting and flexural fracture energies of FRRAC, generally follow an “increase-then-decrease” trend with increasing water saturation, achieving their maximum values in the natural state.

(3) The proposed prediction equations for splitting tensile and flexural strengths effectively incorporate the effects of water saturation and fiber incorporation, yielding statistical coefficients of determination (R^2) greater than 0.9, which indicates a high degree of predictive accuracy. Additionally, the stress–strain model developed from uniaxial compression tests was validated using the leave-one-out cross-validation (LOOCV) method. The cross-validated R^2_{Loocv} values for parameters a and b are 0.765 and 0.938, respectively, suggesting that parameter b (characterizing the post-peak descending branch) provides a more robust fit than parameter a (characterizing the pre-peak ascending branch).

(4) Under identical fiber dosage and saturation conditions, the glass fiber-reinforced RAC outperforms the basalt fiber-reinforced RAC in terms of compressive, splitting tensile, and flexural strengths, with maximum improvements of 19.76%, 22.03%, and 15.04%, respectively. However, this performance advantage diminishes as the degree of water saturation increases.

(5) With the same fiber type, there is no monotonic relationship between concrete strength and fiber content across different saturation levels. Overall, concrete specimens with a fiber volume fraction of 1.0% exhibit higher strength and toughness than those with 1.5%. Therefore, it is suggested that the optimal dosage for both fiber types is approximately 1%.

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