



Article

Fractal Acoustic Emission Characteristics and Energy Evolution of High-Water-Resistance Concrete Backfill: Roles of Water-to-Cement Ratio and Fiber Volume Fraction

Shuaigang Liu ¹ , Zizheng Zhang ^{1,*} , Jianxiong Yang ^{2,3,*} , Kun Fang ⁴, Zilu Liu ¹ and Xiaohe Wang ¹

¹ School of Resource & Environment and Safety Engineering, Hunan University of Science and Technology, Xiangtan 411201, China; liushuaigang@hnust.edu.cn (S.L.); liuzl@cumt.edu.cn (Z.L.); wangxh_1994@hnust.edu.cn (X.W.)

² School of Mechanics & Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China

³ State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering, Sichuan University, Chengdu 610065, China

⁴ School of Mines, China University of Mining and Technology, Xuzhou 221116, China; fangkun0918@cumt.edu.cn

* Correspondence: 1010096@hnust.edu.cn (Z.Z.); jyang169@uottawa.ca (J.Y.)

Abstract

Fiber-reinforced high-water-resistance concrete backfill (FHWCB) is a rapid-setting cementitious backfill system used for underground support and backfilling, but its stability is strongly affected by mixture water content and fiber dispersion. This study investigated the fresh-state behavior, mechanical performance, acoustic emission (AE) fractal characteristics, b-value response, and energy evolution of FHWCB. Mixtures with water-to-cement ratios (w/c) of 1.0–1.8 and fiber volume fractions (V_f) of 0–0.5% were prepared and tested using fresh property measurements, unconfined compression, thermogravimetry, AE monitoring, correlation dimension analysis, b-value analysis, and strain energy partitioning. Increasing w/c improved flowability and delayed setting, but weakened the hydration skeleton and reduced early-age compressive strength by approximately 56–61%. Fiber reinforcement showed a non-monotonic effect: $V_f = 0.3\%$ increased compressive strength by approximately 16–26%, whereas excessive fiber addition reduced strength because of fiber clustering and weak local zones. AE amplitude sequences exhibited measurable fractal characteristics. A higher correlation dimension indicated distributed microdamage, while decreasing correlation dimension and b-value reflected the transition toward localized macrocrack growth. Energy analysis showed that the peak elastic strain energy density decreased from approximately 0.60 to 0.39 MJ/m³ as w/c increased. The proposed AE fractal–b-value–energy framework provides a quantitative basis for tracking damage progression and optimizing FHWCB for underground engineering.



Academic Editors: Xiaohan Yang, Lihai Tan and Gaofeng Liu

Received: 9 July 2026

Revised: 6 August 2026

Accepted: 13 August 2026

Published: 14 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: acoustic emission; correlation dimension; b-value; fractal damage evolution; energy dissipation; fiber-reinforced high-water-resistant concrete backfill; water-to-cement ratio

1. Introduction

Backfill mining has become an essential technology for controlling strata movement, reducing surface subsidence, disposing of mine-derived solid wastes, and improving resource recovery in underground mining [1]. In gob-side entry retaining and goaf filling,

the backfill body is not merely a waste disposal medium but a load-bearing structural component that must satisfy conflicting requirements: it should remain sufficiently pumpable during placement, harden rapidly after casting, and maintain adequate strength and damage tolerance under mining-induced disturbance [2,3]. These requirements become more demanding as mining activities move toward greater depths, where high in situ stress, repeated excavation disturbance, and complex hydro-mechanical environments accelerate the degradation of cementitious backfill materials [4].

High-water-resistance concrete backfills (HWCBS), usually produced from a two-component sulfoaluminate-based cementitious system, offer a practical solution for underground filling because it combines high water demand, rapid setting, and early strength development [5,6]. After the two components are mixed, the rapid formation of ettringite and gel-like hydration products builds an interlocking skeleton that governs the early mechanical response of the material. Nevertheless, the performance of its response is strongly governed by the selected water-to-cement ratio (w/c). A higher water-to-cement ratio improves initial flowability while prolonging workable time, but it also increases the amount of free water, delays structural build-up, enlarges the pore space, and weakens the hardened matrix [7]. Conversely, reducing the water-to-cement ratio favors a more compact hydration skeleton and higher early strength but narrows the placement window. Therefore, mixture optimization cannot be based on strength or workability alone; it requires a coupled evaluation of fresh-state evolution, hydration-related physicochemical behavior, and fracture resistance [8,9].

Fiber reinforcement provides an effective means of improving the brittleness and post-peak integrity of cementitious backfills [10,11]. Polypropylene fibers can bridge microcracks, redistribute local tensile stress, delay crack coalescence, and maintain residual load-bearing capacity after matrix cracking [12]. However, the reinforcing effect does not necessarily increase monotonically with fiber volume fraction (V_f). An insufficient fiber volume fraction provides limited crack-bridging capacity, whereas excessive fibers may reduce flowability, promote fiber clustering, introduce weak interfacial zones, and generate additional defects in the matrix. The mechanical benefit of fibers is therefore controlled by a balance among dispersion quality, fiber–matrix bonding, hydration product development, and crack-bridging efficiency [13,14]. This balance is particularly important for HWCBS, in which the high water content and rapid hydration process make the fresh-state structure and hardened fracture behavior strongly coupled [5,15].

The failure of FHWCB is a progressive multi-scale process involving pore closure, microcrack initiation, interfacial separation around fibers, fiber extraction, crack coalescence, and post-peak frictional shear slip [16,17]. Acoustic emission (AE) monitoring is well suited to capturing these internal damage events in real time, because transient elastic waves are released when irreversible microstructural changes occur during loading [18,19]. Conventional basic AE indices, including ring-down count, signal amplitude, and released AE energy, can describe the intensity of damage activity, but they are often insufficient to quantify the nonlinear transition from distributed microcracking to localized fracture. Fractal theory provides a useful framework for this purpose. Since Mandelbrot's formulation of fractal geometry and the subsequent development of the Grassberger–Procaccia algorithm, the correlation dimension has become widely applied to quantify dynamic complexity of nonlinear time series [20]. In AE analysis, a relatively high correlation dimension generally indicates spatially or temporally distributed damage activity, whereas a sharp decrease suggests fracture activity is becoming controlled by fewer large-magnitude events [21]. In addition, the AE b -value, originally adapted from the seismological frequency–magnitude scaling law, can reflect the changing proportion between minor and major fracture events [22]. The combined evolution of correlation

dimension and b-value therefore has strong potential for identifying instability precursors in brittle or quasi-brittle geomaterials.

Previous studies have applied AE fractal parameters and b-value analysis to rocks, concrete, and cemented tailing backfills [23–25], and recent work has examined the mechanical and damage behavior of fiber-reinforced backfill materials under selected conditions [26–28]. However, most available studies have considered fresh properties, mechanical strength, microstructure, AE damage indicators, or energy evolution separately. A systematic framework linking water-to-cement ratio, fiber volume fraction, AE fractal characteristics, b-value response, and strain energy evolution remains limited, especially for FHWCB. The same HWC/B/FHWCB material system was previously investigated in Ref. [5], mainly from the perspective of material characteristics and basic performance. The present study extends that work by focusing on the coupled AE fractal–b-value–energy response during compression failure. Specifically, this study clarifies how water-to-cement ratio and fiber volume fraction jointly regulate damage complexity, fracture localization, elastic energy storage, and dissipated energy evolution.

To address this limitation, the present study investigates the fresh-state behavior, mechanical response, AE fractal characteristics, b-value evolution, and strain energy dissipation of FHWCB from mixing to compression failure. The objectives are to: (1) clarify how water-to-cement ratio and fiber volume fraction jointly regulate fresh-state evolution and strength development; (2) characterize the transition from distributed microdamage to localized failure using AE correlation dimension and b-value; (3) establish the relationship between fractal damage indicators, elastic energy storage, and irreversible energy dissipation; and (4) develop an energy-based damage constitutive model for describing the compression failure process of FHWCB.

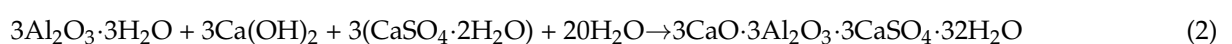
2. Materials and Experimental Program

2.1. Materials

2.1.1. High-Water-Resistance Concrete Materials

The high-water-resistance concrete materials employed in this work were provided by China University of Mining and Technology after in-house development. The binder system was supplied as two powder components, Component A and Component B. During specimen preparation, Components A and B were mixed at a mass ratio of 1:1. According to the supplier's formulation, the main and auxiliary materials used to prepare the component powders were proportioned at a mass ratio of 5:1. The particle size distributions of the two components were determined using an S3500 laser particle size analyzer (Microtrac Inc., Montgomeryville, PA, USA); the corresponding crystalline phases were identified with a D8 ADVANCE X-ray diffraction system, as shown in Figure 1. Component A had a particle size range of 0.9–218 µm, with most particles distributed between 1 and 100 µm. Component B had a particle size range of 1–146 µm, with most particles distributed between 2 and 66 µm.

After the two powder components come into contact with the mixing water, the sulfoaluminate phases react rapidly with CaO and CaSO₄ in the presence of setting control agents. The main hydration reactions generate ettringite and Al-bearing gel products, forming an interlocking needle-like and reticular microstructure. This hydration skeleton gradually develops into the load-bearing framework of the hardened backfill, as expressed in Equations (1) and (2).



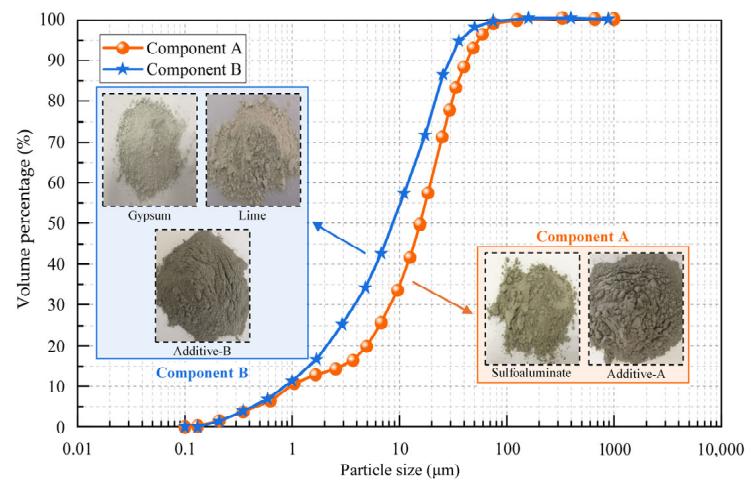


Figure 1. Particle size distributions of Components A and B of the high-water-resistance concrete materials.

2.1.2. Mixing Water and Polypropylene Fiber

Tap water was used as the mixing liquid to reduce variability in pore solution chemistry. Monofilament polypropylene fibers were added as the reinforcing phase. The fibers had a tensile strength of 600 MPa, an elastic modulus of 3.5 GPa, a diameter of 18 μm , a length of 6 mm, an elongation at break of 15%, and a specific gravity of 0.91.

2.1.3. Selection of Fiber Volume Fraction

Polypropylene fibers were introduced to improve the crack resistance and post-cracking integrity of FHWCB. From a mechanical perspective, fibers can bridge microcracks, redistribute local tensile stress, delay crack coalescence, and enhance energy dissipation after matrix cracking. However, the reinforcing effect of randomly distributed short fibers is not governed only by fiber strength or stiffness. It is also strongly affected by fiber length, aspect ratio, orientation, dispersion quality, fiber–matrix interfacial bonding, and the rheological behavior of the fresh slurry. Therefore, fiber addition is expected to show a non-monotonic influence: insufficient fiber content provides limited crack-bridging capacity, whereas excessive fiber content may impair dispersion, reduce workability, and introduce weak local zones.

The fiber volume fraction range used in this study was determined by combining the above mechanical consideration with previous studies and practical workability requirements for underground backfill placement. Existing studies on polypropylene-fiber-reinforced cementitious composites and cemented paste backfill have shown that low-to-moderate fiber dosages can improve crack resistance, post-peak integrity, and deformation capacity, while excessive fiber addition may reduce workability, promote fiber agglomeration, disturb matrix uniformity, and weaken the fiber–matrix interface. These considerations are particularly important for FHWCB because the material must maintain sufficient flowability during placement while developing adequate resistance to cracking after hardening.

Accordingly, polypropylene fiber volume fractions of 0, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% were adopted. The mixture without fibers was used as the reference group. The low-dosage groups were used to evaluate the initial crack-bridging contribution of fibers, the moderate dosage groups were used to identify the effective reinforcing range, and the relatively high-dosage groups were used to examine the possible adverse effects associated with excessive fiber addition. This design enables the non-monotonic influence of fiber content on the fresh-state behavior, mechanical performance, AE characteristics, and energy evolution of FHWCB to be systematically evaluated.

2.2. Specimen Preparation and Curing

The mix-design parameters and experimental schedule are summarized in Table 1. The selected water-to-cement ratios and fiber volume fractions were chosen to represent practical mixture proportions used in HWCB applications. Cylinders measuring 50 mm in diameter and 100 mm in height were cast for the unconfined compression tests. For each mixture and curing age, at least three independent replicate specimens were prepared. When the deviation among parallel specimens was abnormal, additional specimens were tested to ensure the reliability of the results.

Table 1. Mixture variables and experimental program.

Test/Measurement	w/c	V _f (%)	Age or Monitoring Duration
UCS tests	1.0, 1.2, 1.5, 1.8	0, 0.1, 0.2, 0.3, 0.4, 0.5	0.5, 1, 3, 7, 14, 28 days
Viscosity tests	1.0, 1.2, 1.5, 1.8	0.3	Up to 40 min
Setting time tests	1.0, 1.2, 1.5, 1.8	0.3	-
Zeta potential	1.0, 1.2, 1.5, 1.8	0.3	0 min
pH	1.0, 1.2, 1.5, 1.8	0.3	0, 5, 10, 15, 20 min
TG/DTG	1.0, 1.5, 1.8	0.3	28 days
EC	1.0, 1.5, 1.8	0, 0.3, 0.5	up to 2 days
Matrix suction and VWC	1.0, 1.5, 1.8	0.3	up to 28 days

All specimens followed the same four-stage mixing and curing protocol. Initially, the predetermined dosage of polypropylene fiber was dry-mixed with the powder components under low-speed mixing for 3 min to improve fiber distribution and mitigate fiber agglomeration. Second, the required amount of mixing water was introduced separately into Components A and B, and each slurry was mixed for 5 min. Third, the A and B slurries were combined and mixed for an additional 2 min before being cast into molds. Finally, the specimens were cured at 20 °C and a relative humidity of at least 95% until the designated test age. Fiber dispersion was controlled by the dry-mixing procedure and mixing duration. After demolding, exposed specimen sections were visually examined to check the uniformity of fiber distribution and to identify possible fiber agglomeration.

2.3. Experimental Testing and Monitoring Procedures

2.3.1. Unconfined Compression and AE Monitoring

UCS was determined on a servo-controlled electronic testing machine. Before testing, both loading faces of each specimen were ground with sandpaper to ensure parallel and planar loading faces. The specimens were loaded under monotonic displacement loading at 0.5 mm/min, and the stress–strain response was acquired automatically throughout the test. AE activity was monitored simultaneously using a PCI-II system for AE signal acquisition. AE signals were acquired using resonant AE sensors with a resonant frequency of 150 kHz. The detection threshold, sampling rate, and preamplifier gain were set to 35 dB, 2 MS/s, and 40 dB, respectively. The same acquisition parameters were used for all specimens to ensure comparability among different mixtures. These acquisition settings determined the detectable amplitude range and provided the basis for interpreting the AE amplitude bands discussed in Section 3.2.2.

In addition, the RA value was calculated as the ratio of rise time to peak amplitude of an AE waveform, $RA = RT/A_p$, where RT is the time interval from the first threshold crossing to the peak amplitude and A_p is the corresponding peak amplitude. In this study, RA was used as a supplementary AE descriptor to compare the fracture mode tendency with the amplitude-based correlation dimension. Two AE sensors were attached to opposite sides of each specimen to capture the damage-related signals generated during compression.

Petroleum jelly was used as the acoustic couplant, and the sensors were fixed with tape to maintain stable contact with the specimen surface during compression. Before loading, pencil lead breaks were used to check the coupling quality and signal acquisition stability of the AE system.

2.3.2. Thermogravimetric Analysis

Thermogravimetric analysis was carried out with a Q5000 IR instrument (TA Instruments, New Castle, DE, USA) to characterize the evolution of hydration products. The powdered specimens were heated over a temperature interval of room temperature to 1000 °C using a ramp of 10 °C/min in a continuous N_2 atmosphere. The thermogravimetric mass loss curve and the corresponding derivative thermogravimetric curve were recorded simultaneously.

2.3.3. Hydrate Reaction Monitoring Program

To capture early-age hydration development of FHWCB, electrical conductivity (EC), volumetric water content (VWC), and matrix suction were continuously monitored. Specimens with selected w/c values of 1.0, 1.5, and 1.8 were used for this monitoring program, as summarized in Table 1. EC was used to characterize the ion concentration and mobility in the pore solution, which vary continuously during dissolution, precipitation, and hydration product formation [29]. Changes in VWC were tracked to estimate hydration-related water uptake, while matrix suction was measured to evaluate the degree of self-desiccation. These parameters provide complementary information for interpreting the time-dependent changes in flowability, hydration rate, and mechanical development of FHWCB. EC and VWC were recorded using a 5TE soil moisture probe, whereas matrix suction was measured with an MPS-6 water potential probe. The sensors were embedded at the center of the plastic cylindrical molds during casting, and all data were automatically collected using an EM50 data logger (METER Group, Inc., Pullman, WA, USA). Sensor accuracies followed the manufacturer's specifications [30].

2.3.4. Viscosity and Setting Time Testing

The rheological property of the freshly mixed slurry was assessed with an NDJ-5S viscometer (Shanghai Changji Geological Instrument Co., Ltd., Shanghai, China) fitted with spindle No. 1, providing direct viscosity measurements under a constant shear rate [31]. The measurement was started immediately after mixing to capture the early evolution of slurry viscosity. During testing, the spindle was carefully immersed in the slurry to avoid air-bubble entrapment. Three repeated measurements were conducted for each mixture to ensure reproducibility. The setting behavior was evaluated using a Humboldt Vicat apparatus (Humboldt Mfg. Co., Elgin, IL, USA) [32]. The initial setting time was determined according to ASTM C807-21 [33]. Because no standard method is available for defining the final setting time of FHWCB, an adapted procedure was adopted. A 5 mm plunger served as the indenter; the final set was defined as the point at which plunger penetration resistance was sufficient to prevent the outer ring of the plunger from leaving a visible indentation on the specimen surface after 30 s of contact. At least three replicates were examined for each mixture, and the reported values are the arithmetic means of the replicate tests.

2.3.5. Zeta Potential and pH Measurements

Zeta potential measurements were used to characterize electrostatic interactions among particles in the FHWCB suspension. This parameter reflects the repulsive interaction between similarly charged particles within the electrical double layer and is sensitive to suspension stability, pH, and the ionic environment of the system [34]. The zeta

potential of different FHWCB mixtures was measured using a Malvern Zetasizer Nano ZS90 analyzer (Malvern Panalytical Ltd., Worcestershire, UK) based on the electrophoretic mobility of particles in diluted suspensions. The suspension concentration was 0.1 g/L, and distilled water was used for dilution. In parallel, slurry pH was measured using an Oakton pH 6+ meter (Oakton Instruments, Vernon Hills, IL, USA) to track the evolution of the alkaline pore solution environment during early hydration. All zeta potential and pH tests were repeated three times to confirm measurement repeatability.

2.4. Statistical Analysis

Replicate-based experimental results are reported as mean $\pm$ standard deviation. Normality and homogeneity of variance were examined using the Shapiro–Wilk test and Levene’s test, respectively. When these assumptions were satisfied, one-way or two-way analysis of variance was performed followed by Tukey’s post hoc test. When these assumptions were not satisfied, the Kruskal–Wallis test followed by Dunn’s multiple comparison test was used. A significance level of $p < 0.05$ was adopted.

For AE-derived parameters, replicate AE records were processed using the same correlation dimension and b-value calculation procedures. The resulting curves were normalized by the peak stress time, interpolated onto a common normalized time grid, and used to calculate the mean curves and standard deviation bands. Statistical comparisons of AE-derived time series responses were performed using scalar descriptors extracted from each AE record, including characteristic pre-peak, near-peak, and post-peak values of correlation dimension and b-value.

3. Results and Discussion

3.1. UCS Response of FHWCB to Water-to-Cement Ratio and Fiber Volume Fraction

Table 2 lists the complete UCS dataset expressed as mean $\pm$ standard deviation, and Figure 2 presents the associated strength trends. The relatively small standard deviations indicate acceptable repeatability among replicate specimens. Statistical analysis confirmed that the UCS differences among different w/c and Vf groups were significant at most curing ages ($p < 0.05$). Figure 2a compares the UCS of mixtures containing Vf = 0.3% across four w/c levels, using the mixture with w/c = 1.0 as the reference. For all curing ages, UCS declines progressively with increasing water-to-cement ratio. When w/c increases from 1.0 to 1.8, the corresponding strength losses at 0.5, 1, 3, 7, 14, and 28 days are about 61%, 57%, 56%, 51%, 51%, and 48%, respectively. These results show that the weakening effect of excessive water content is significant at early ages and remains evident after 28 days of curing.

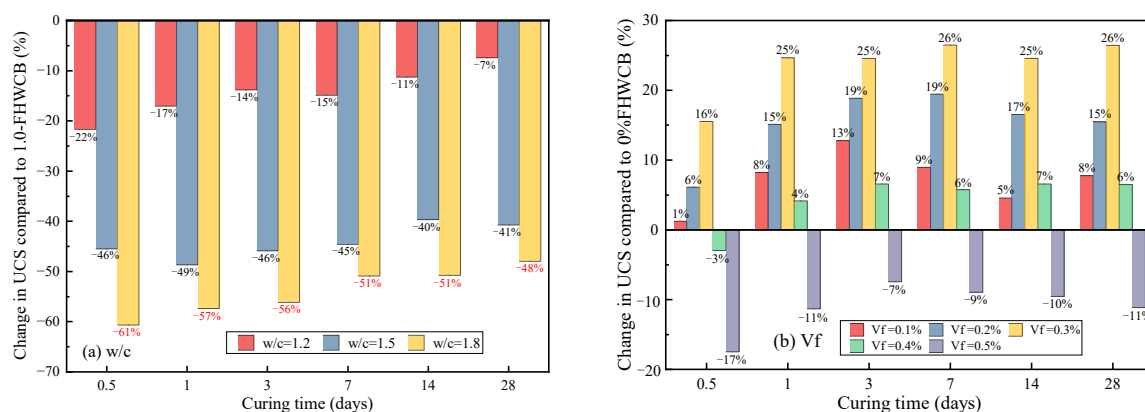


Figure 2. UCS response of FHWCB to different mixture parameters.

Table 2. UCS values of FHWCB mixtures after different curing times (MPa, mean $\pm$ SD).

w/c	Vf (%)	Curing Time (Days)					
		0.5	1	3	7	14	28
1.0	0	10.0 $\pm$ 0.14	13.88 $\pm$ 0.54	15.62 $\pm$ 0.59	17.35 $\pm$ 0.65	18.05 $\pm$ 1.09	19.96 $\pm$ 0.81
	0.1	10.61 $\pm$ 0.31	16.62 $\pm$ 0.58	18.26 $\pm$ 0.18	18.84 $\pm$ 0.44	19.41 $\pm$ 0.38	20.68 $\pm$ 0.30
	0.2	11.16 $\pm$ 0.05	18.05 $\pm$ 0.37	19.62 $\pm$ 0.85	20.27 $\pm$ 0.99	20.53 $\pm$ 1.22	21.62 $\pm$ 0.46
	0.3	12.14 $\pm$ 0.36	19.62 $\pm$ 0.43	20.99 $\pm$ 0.10	21.69 $\pm$ 0.83	22.55 $\pm$ 0.41	23.92 $\pm$ 0.33
	0.4	10.19 $\pm$ 0.21	16.52 $\pm$ 0.31	18.42 $\pm$ 0.84	18.35 $\pm$ 0.55	18.99 $\pm$ 0.75	19.87 $\pm$ 0.73
	0.5	8.97 $\pm$ 0.19	13.08 $\pm$ 0.45	16.00 $\pm$ 0.42	16.74 $\pm$ 0.50	16.82 $\pm$ 0.20	17.60 $\pm$ 0.61
1.2	0	8.48 $\pm$ 0.38	13.44 $\pm$ 0.45	14.32 $\pm$ 0.25	14.61 $\pm$ 0.40	16.07 $\pm$ 0.42	17.54 $\pm$ 0.52
	0.1	8.12 $\pm$ 0.12	14.04 $\pm$ 0.25	15.29 $\pm$ 0.29	15.90 $\pm$ 0.52	17.64 $\pm$ 0.50	19.25 $\pm$ 0.81
	0.2	8.82 $\pm$ 0.24	15.34 $\pm$ 0.17	16.85 $\pm$ 0.50	16.93 $\pm$ 0.25	18.77 $\pm$ 0.51	20.48 $\pm$ 0.53
	0.3	9.50 $\pm$ 0.31	16.27 $\pm$ 0.40	18.09 $\pm$ 0.39	18.46 $\pm$ 0.32	20.00 $\pm$ 0.21	22.15 $\pm$ 0.53
	0.4	7.98 $\pm$ 0.14	13.63 $\pm$ 0.15	14.97 $\pm$ 0.37	15.44 $\pm$ 0.91	17.16 $\pm$ 0.82	18.53 $\pm$ 0.81
	0.5	7.00 $\pm$ 0.22	12.46 $\pm$ 0.12	13.24 $\pm$ 0.30	13.60 $\pm$ 0.40	14.72 $\pm$ 0.28	16.23 $\pm$ 0.32
1.5	0	5.72 $\pm$ 0.20	8.07 $\pm$ 0.12	9.12 $\pm$ 0.37	9.50 $\pm$ 0.16	10.92 $\pm$ 0.15	11.21 $\pm$ 0.29
	0.1	5.79 $\pm$ 0.04	8.74 $\pm$ 0.07	10.28 $\pm$ 0.37	10.35 $\pm$ 0.34	11.42 $\pm$ 0.15	12.08 $\pm$ 0.28
	0.2	6.07 $\pm$ 0.22	9.29 $\pm$ 0.27	10.84 $\pm$ 0.17	11.35 $\pm$ 0.08	12.73 $\pm$ 0.52	12.94 $\pm$ 0.10
	0.3	6.61 $\pm$ 0.08	10.06 $\pm$ 0.35	11.36 $\pm$ 0.51	12.01 $\pm$ 0.28	13.61 $\pm$ 0.23	14.17 $\pm$ 0.28
	0.4	5.55 $\pm$ 0.08	8.41 $\pm$ 0.30	9.72 $\pm$ 0.12	10.05 $\pm$ 0.08	11.64 $\pm$ 0.24	11.93 $\pm$ 0.37
	0.5	4.72 $\pm$ 0.15	7.16 $\pm$ 0.16	8.44 $\pm$ 0.13	8.65 $\pm$ 0.24	9.88 $\pm$ 0.14	9.96 $\pm$ 0.08
1.8	0	4.20 $\pm$ 0.04	6.70 $\pm$ 0.12	7.39 $\pm$ 0.04	8.40 $\pm$ 0.25	8.90 $\pm$ 0.19	10.08 $\pm$ 0.9
	0.1	4.14 $\pm$ 0.05	7.20 $\pm$ 0.22	7.95 $\pm$ 0.19	9.22 $\pm$ 0.49	9.68 $\pm$ 0.20	11.07 $\pm$ 0.10
	0.2	4.48 $\pm$ 0.06	7.90 $\pm$ 0.12	8.80 $\pm$ 0.03	9.72 $\pm$ 0.14	10.21 $\pm$ 0.46	11.66 $\pm$ 0.30
	0.3	4.78 $\pm$ 0.09	8.37 $\pm$ 0.11	9.20 $\pm$ 0.11	10.65 $\pm$ 0.28	11.10 $\pm$ 0.34	12.44 $\pm$ 0.44
	0.4	4.02 $\pm$ 0.06	6.99 $\pm$ 0.12	7.72 $\pm$ 0.33	8.86 $\pm$ 0.13	9.51 $\pm$ 0.26	10.65 $\pm$ 0.27
	0.5	2.44 $\pm$ 0.04	5.83 $\pm$ 0.10	6.64 $\pm$ 0.29	7.73 $\pm$ 0.05	8.16 $\pm$ 0.31	9.02 $\pm$ 0.25

The reduction in UCS with increasing w/c is mainly attributed to the weakening of the hydrate framework responsible for load transfer. Figure 3 shows that the lower-w/c mixtures exhibit more pronounced mass loss responses associated with hydration products such as ettringite (AFt), aluminum gels (AH₃), together with calcium silicate hydrate (C–S–H) phases. These thermogravimetric features indicate that a lower water-to-cement ratio favors the formation of a denser solid skeleton. In contrast, a higher water-to-cement ratio leaves more unbound water in the fresh matrix. After hydration and curing, this excess water is transformed into capillary voids and weakens the contact between hydration products [26], thereby reducing the effective load-bearing area of the hardened FHWCB.

The matrix suction and volumetric water content results further support this interpretation. As shown in Figure 4, mixtures with lower w/c develop more negative matrix suction, reflecting stronger water consumption and self-desiccation during hydration. The stabilized matrix suction values are approximately -335 , -297 , and -212 kPa for w/c = 1.0, 1.5, and 1.8, respectively.

Meanwhile, the data in Figure 5 indicate that the corresponding volumetric water contents are approximately 0.470, 0.484, and 0.503 m³/m³. These results indicate that a lower w/c leads to a denser matrix and a more compact fiber–matrix interfacial zone, which improves the cracking resistance and inhibits crack propagation. Accordingly, the strength enhancement under lower w/c conditions is governed by synergistic contributions from increased hydration product density, reduced capillary porosity, and improved interfacial bonding.

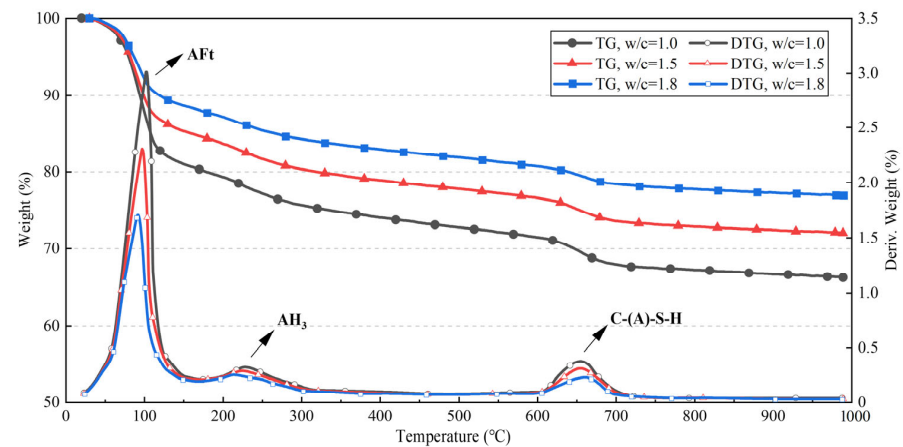


Figure 3. TG/DTG curves of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$.

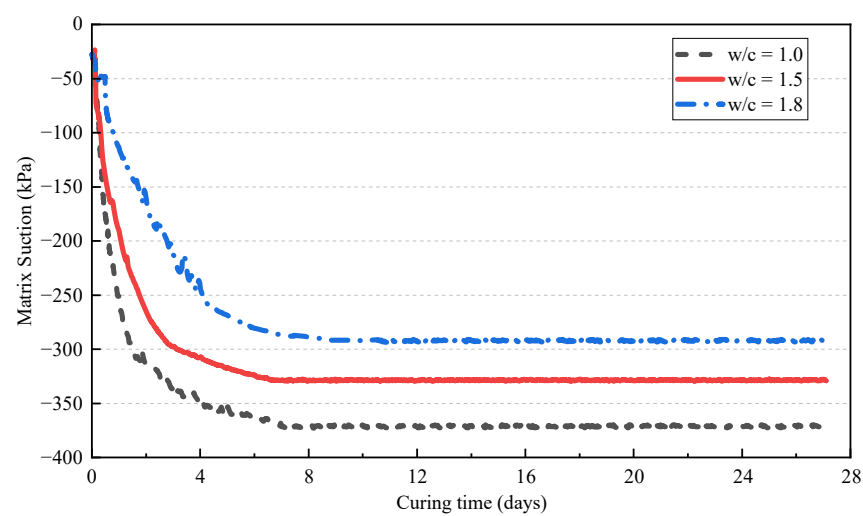


Figure 4. Temporal variation in matrix suction for FHWCB prepared with different w/c values at $V_f = 0.3\%$.

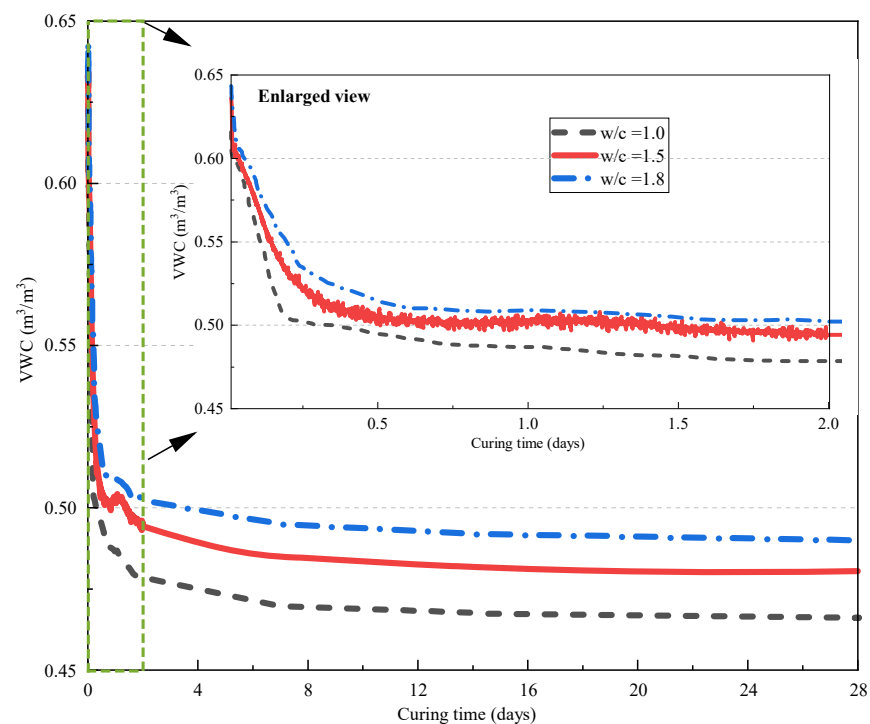


Figure 5. Temporal variation in VWC for FHWCB prepared with different w/c values at $V_f = 0.3\%$.

Figure 2b compares the UCS response to fiber volume fraction at $w/c = 1.5$, using the fiber-free mixture as the reference. The influence of fiber volume fraction is clearly non-monotonic. As V_f increases from 0 to 0.3%, the UCS increases progressively. At $V_f = 0.3\%$, UCS at the corresponding curing ages increases by about 16%, 25%, 25%, 26%, 25%, and 26%, respectively. When V_f was increased to 0.4%, the strengthening effect decreases, although limited improvement is still observed at several curing ages. When $V_f = 0.5\%$, the UCS becomes lower than that of the fiber-free mixture, with reductions of approximately 17%, 11%, 7%, 9%, 10%, and 11% at the corresponding curing ages.

This non-monotonic behavior reflects the competition between fiber reinforcement and fiber-induced defects. At an appropriate dosage, polypropylene fibers are relatively well-dispersed in the matrix and can bridge developing microcracks, transfer tensile stress across crack surfaces, and restrain crack opening. These effects improve specimen integrity and enhance its effective carrying capacity. However, excessive fibers reduce mixture uniformity and increase the probability of fiber clustering. Fiber-rich regions and entrapped voids act as weak zones, leading to local stress concentration and a weakened fiber–matrix interface [35]. As a result, the beneficial crack-bridging effect is partly or completely offset by defect-induced damage. Therefore, within the investigated range, $V_f = 0.3\%$ provides the most effective reinforcement for FHWCB.

3.2. AE Fractal Characteristics of FHWCB Governed by Water-to-Cement Ratio and Fiber Volume Fraction

3.2.1. Correlation Dimension Evaluation of AE Sequences

The characteristic parameters associated with AE mainly include ringing count, energy, amplitude, rise time, duration, and frequency, as shown in Figure 6. Among these parameters, the ring-down count records how often an AE waveform crosses the detection threshold and is commonly used to describe the activity level of internal damage. AE amplitude represents the relative intensity of the AE source and is sensitive to crack coalescence, fiber interface separation, fiber extraction, and local frictional sliding [8,17,24]. During the compression failure of FHWCB, AE signals are generated through multiple damage mechanisms, including pore closure, the onset of microcracking, crack extension, interfacial separation, fiber bridging, fiber extraction, and post-peak crack surface friction. Owing to the nonlinear and scale-dependent nature of these damage mechanisms, the resulting AE parameter sequences contain information on multi-scale fracture evolution and can therefore be treated as nonlinear time series signals with fractal attributes.

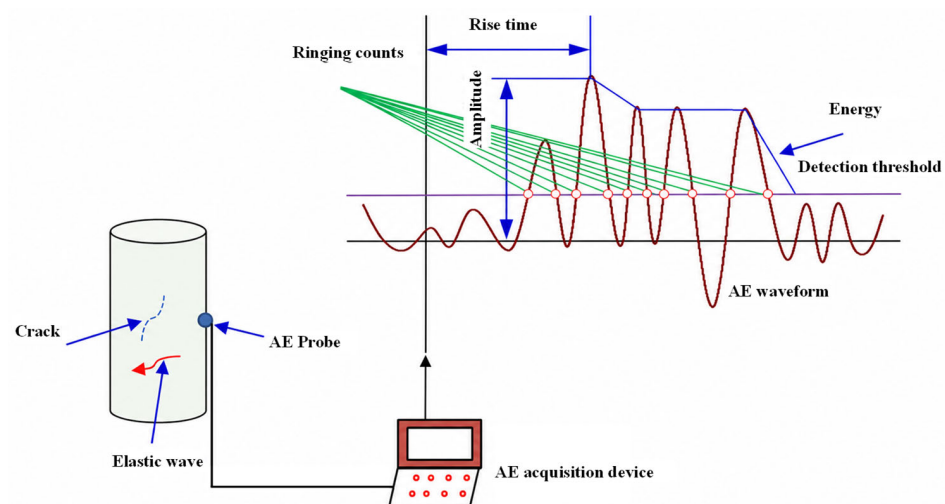


Figure 6. Description of AE characteristic parameters.

Fractal theory has been widely used to characterize irregular fracture processes, pore structures, crack networks, and AE sequences in rock and cementitious materials [17,23]. In particular, the correlation dimension obtained using the Grassberger–Procaccia (G–P) procedure can quantify phase space complexity within a reconstructed phase space trajectory [20]. For AE analysis, a higher correlation dimension generally indicates that AE events originate from more distributed and complex damage sources, whereas a lower correlation dimension suggests that the AE activity becomes increasingly controlled by localized fracture sources [23]. Accordingly, correlation dimension D was used here to characterize AE complexity evolution during FHWCB failure.

For an AE parameter sequence:

$$X = \{x_1, x_2, x_3, \dots, x_n\} \quad (3)$$

Using a unit time delay, the first m -dimensional phase space vector is:

$$X_1 = \{x_1, x_2, x_3, \dots, x_m\} \quad (4)$$

Successive vectors were generated by shifting the starting point of the sequence, yielding the reconstructed phase space matrix:

$$X = \begin{cases} X_1 & : (x_1, x_2, \dots, x_m) \\ X_2 & : (x_2, x_3, \dots, x_{m+1}) \\ X_3 & : (x_3, x_4, \dots, x_{m+2}) \\ X_4 & : (x_4, x_5, \dots, x_{m+3}) \\ \vdots & \vdots \end{cases} \quad (5)$$

For N reconstructed vectors, the correlation integral was calculated as:

$$C(r) = \frac{1}{N^2} \sum_{i,j=1}^N H(r - |X_i - X_j|) \quad (6)$$

where $H(x)$ is the Heaviside step function:

$$H(x) = \begin{cases} 1 & (x > 0) \\ 0 & (x \leq 0) \end{cases} \quad (7)$$

The distance threshold r was determined from the mean pairwise distance using the scale coefficient k :

$$r = k \cdot \frac{1}{N^2} \cdot \sum_{i=1}^N \sum_{j=1}^N |X_i - X_j| \quad (8)$$

where $i, j = 1, 2, \dots, N$. When a scaling interval exists, $C(r)$ follows a power law relationship with r .

The correlation dimension D is therefore obtained from:

$$D = \lim_{r \rightarrow 0} \frac{\ln C(r)}{\ln r} \quad (9)$$

The correlation dimension D was evaluated from the gradient of the fitted linear portion in the $\ln C(r)$ versus $\ln r$ plot. In this study, the embedding dimension was set to $m = 4$, and the scale coefficient k was selected from 0.2 to 1.4 with an interval of 0.2. The same calculation parameters were used for all mixtures to ensure that the variation in D mainly reflected the influence of mixture design and damage evolution rather than differences in

the calculation procedure. The rationality of the selected embedding dimension and scaling interval is further examined in Section 3.2.2.

3.2.2. Fractal Verification of AE Amplitude Sequence

Under the acquisition settings described in Section 2.3.1, most AE events are concentrated in the range of approximately 35–60 dB throughout the loading process, as shown in Figure 7. These low-amplitude events are associated with small-scale damage activities, such as pore closure, scattered microcrack initiation, stable microcrack propagation, and local friction. Medium-amplitude events in the range of approximately 60–80 dB appear intermittently and become more evident in the later part of loading. A small number of events exceed 80 dB, indicating the occurrence of local high-intensity damage sources, such as crack coalescence, abrupt crack propagation, or fiber–matrix interfacial failure.

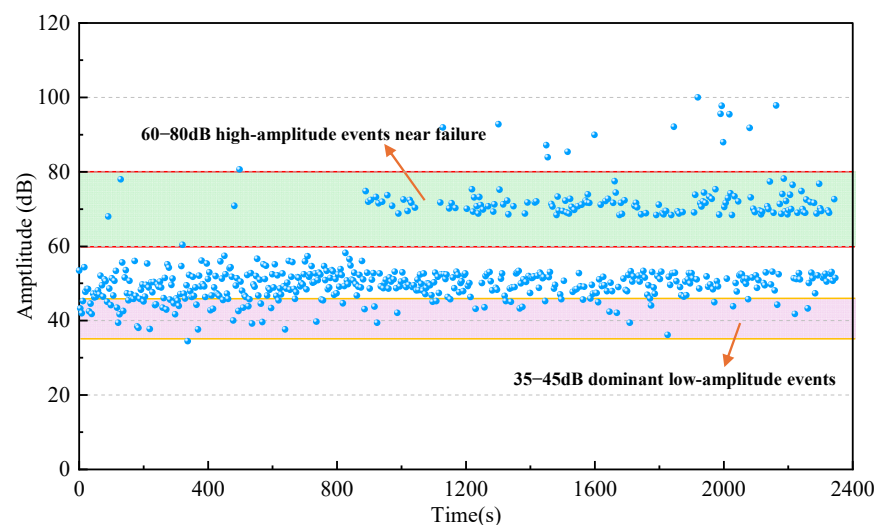


Figure 7. Representative AE amplitude sequence of 7-day cured FHWCB at $V_f = 0.3\%$ and $w/c = 1.5$.

It should be emphasized that the AE amplitude evolution in Figure 7 does not show a simple monotonic increase with loading time. Instead, the amplitude record is characterized by persistent low-amplitude activity accompanied by intermittent medium- and high-amplitude bursts. This feature is typical of quasi-brittle cementitious composites, in which microcracking, local stress redistribution, fiber-related interactions, and crack surface friction occur alternately during loading. Therefore, AE amplitude should be interpreted as a fluctuating damage response signal rather than as a single-direction indicator of fracture severity.

Figure 8a shows the $\ln C(r) - \ln r$ fitting result for the representative AE amplitude sequence of 7-day cured at $V_f = 0.3\%$ and $w/c = 1.5$. The fitted slope gives a correlation dimension of $D = 2.7939$, and the corresponding fitting coefficient is $R^2 = 0.8736$. Although AE signals generated during fracture are transient and non-stationary, an identifiable linear scaling region can still be observed within the selected k range, indicating that the AE amplitude sequence of FHWCB has measurable fractal characteristics.

The embedding dimension saturation analysis is shown in Figure 8b. The calculated correlation dimension increases at low embedding dimensions and then gradually approaches a stable plateau when m reaches 4. Further increasing m causes only limited variation in D , indicating that $m = 4$ is sufficient to reconstruct the AE phase space while avoiding unnecessary dimensional redundancy.

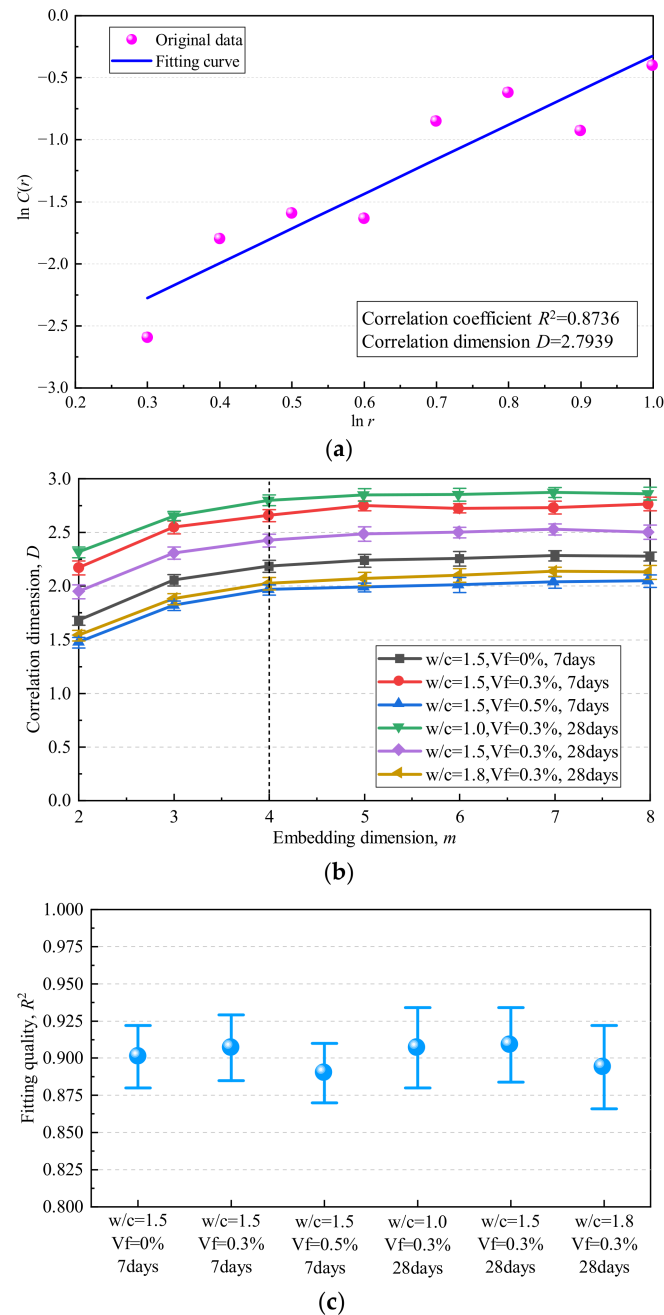


Figure 8. Validation of AE correlation dimension analysis. (a) Representative $\ln C(r)$ – $\ln r$ fitting result for the AE amplitude sequence of 7-day cured at $V_f = 0.3\%$ and $w/c = 1.5$. (b) Embedding dimension convergence from $m = 2$ to 8. (c) Summary of G–P fitting quality across all analyzed AE sequences.

The fitting quality of the selected scaling interval was further evaluated for all analyzed AE sequences. As summarized in Figure 8c, the R^2 values were generally higher than 0.85, with an overall mean value of $R^2 = 0.9010 \pm 0.0220$. These results indicate that the selected scaling interval $k = 0.2$ – 1.4 provides acceptable and stable fitting quality for the correlation dimension calculation under different mixture conditions.

3.2.3. AE Correlation Dimension Under Varied Water-to-Cement Ratio and Fiber Volume Fraction

Figures 9 and 10 compare the evolution of AE amplitude correlation dimension under varied V_f values and water-to-cement ratios. The loading time was normalized by the peak stress time, and $t/t_p = 1$ corresponds to the peak stress point. The curves are plotted as mean responses of replicate specimens, and error bars indicate standard deviations. Overall,

the correlation dimension decreases after the peak stress for all mixtures, indicating that the AE process gradually loses complexity as damage becomes more localized. However, the magnitude and evolution pattern of D are strongly affected by both mixture variables.

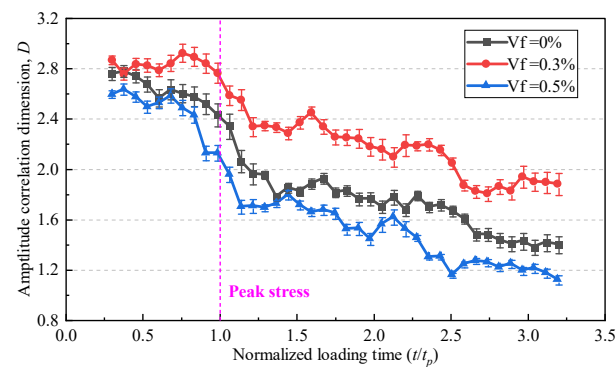


Figure 9. Evolution of the AE amplitude correlation dimension of 7-day cured FHWCB with different V_f values at $w/c = 1.5$.

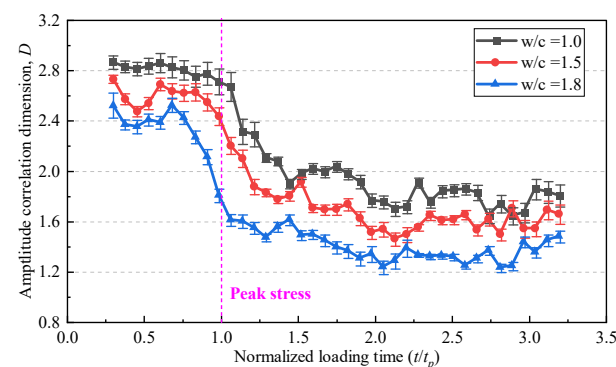


Figure 10. Evolution of the AE amplitude correlation dimension of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$.

Figure 9 shows the V_f influence at $w/c = 1.5$. Before peak stress, the mixture with $V_f = 0.3\%$ maintains the highest correlation dimension among the three representative mixtures. The fiber-free mixture shows an intermediate level, while the mixture with $V_f = 0.5\%$ generally exhibits the lowest D . This response implies that a suitable fiber volume fraction increases AE source complexity by promoting distributed microcracking. Well-dispersed polypropylene fibers can bridge developing cracks, transfer tensile stress across crack surfaces, and delay rapid crack coalescence. As a result, AE events are generated by a broader population of damage sources, leading to a higher correlation dimension. After peak stress, the correlation dimension of all mixtures decreases, but the $V_f = 0.3\%$ mixture remains at a relatively higher level over most of the post-peak range. This suggests that fiber-mediated crack bridging continues to influence post-peak damage process. Instead of rapidly developing into a single dominant fracture path, the specimen with an appropriate fiber volume fraction maintains more distributed damage activity. In contrast, the $V_f = 0.5\%$ mixture shows a lower correlation dimension, especially after peak stress. This indicates that excessive fiber addition does not further improve the fracture resistance of FHWCB. Excessive fibers may reduce slurry uniformity, increase fiber–matrix interaction, and promote local fiber clustering. These fiber-rich regions can introduce weak interfacial zones and entrapped defects, which become preferential sites for crack initiation and propagation. Consequently, AE activity becomes less complex and more localized, resulting in a lower correlation dimension. Therefore, Figure 9 confirms the non-monotonic effect of fiber volume fraction from a fractal perspective: the optimal fiber volume fraction is not the

highest dosage, but the dosage that provides sufficient crack bridging while maintaining good dispersion and matrix integrity [12,36]. The statistical descriptors extracted from the replicate AE records also show that the $V_f = 0.3\%$ mixture has a higher pre-peak mean D and a higher near-peak D than the $V_f = 0.5\%$ mixture, confirming that moderate fiber additions maintain more distributed AE activity.

Figure 10 examines the w/c effect at $V_f = 0.3\%$. The mixture with $w/c = 1.0$ maintains the highest correlation dimension over most of the loading process, followed by $w/c = 1.5$, whereas the mixture with $w/c = 1.8$ generally shows the lowest D . This trend indicates that reducing the water-to-cement ratio produces a more spatially distributed and complex damage process. Lower water content promotes the formation of a denser cementitious skeleton and improves the contact between hydration products and fibers. Under compression, microcracks are more likely to initiate and propagate through multiple tortuous paths, generating a more complex AE source population. Increasing the water-to-cement ratio reduces the correlation dimension because excess water enlarges particle spacing in the fresh matrix, weakens the hardened skeleton, and leaves capillary voids after hydration. These pores and weak interfacial regions lower crack growth resistance. Damage therefore localizes more readily, and AE activity becomes governed by fewer dominant fracture paths. This explains why the mixture with $w/c = 1.8$ shows a lower D during the normalized loading process. The replicate-based descriptors show the same trend, with lower- w/c mixtures maintaining higher correlation dimension levels during the stable damage stage and near the peak stress region.

Taken together, Figures 9 and 10 demonstrate that AE source complexity is controlled by the two mixture variables. Proper fiber incorporation increases damage source diversity by activating crack bridging and pull-out mechanisms, whereas excessive fiber volume fraction promotes defect-induced localization. A lower water-to-cement ratio enhances matrix compactness and maintains a more distributed fracture process, whereas a higher ratio weakens the hydration skeleton and accelerates the loss of AE complexity. Therefore, AE correlation dimension provides a quantitative fractal indicator for evaluating the combined effects of mixture design on damage localization in FHWCB [37].

3.2.4. Coupled Evolution of Correlation Dimension and AE b-Value

The AE b-value was calculated from the amplitude distribution using a Gutenberg–Richter-type frequency–magnitude relationship [38,39]. Because AE amplitude A is recorded in dB, the AE magnitude proxy M was defined as $M = A/20$. The cumulative number of AE hits with magnitude equal to or greater than M was then expressed as:

$$\log_{10} N(\geq M) = a - bM \quad (10)$$

where $N(\geq M)$ is the cumulative number of AE hits, a is a fitting constant, and b is the AE b-value. In this study, b was obtained from the slope of the linear regression between $\log_{10} N(\geq M)$ and M using the least-squares method. A moving-window strategy was adopted to track the temporal evolution of b-value during loading. Each b-value was calculated using 100 consecutive AE hits, and the window was shifted by 20 hits for the next calculation. The same window size and step size were used for all specimens to ensure comparability among different mixtures. The calculated b-value sequences were then normalized by peak stress time and statistically processed following the procedure described in Section 2.4.

Figure 11 presents the systematic evolution of AE b-value and its coupling with fractal indicators during FHWCB failure. Figures 11a and 11b show the b-value responses under different V_f and w/c conditions, respectively, using the same variable control design as the correlation dimension analysis in Figures 9 and 10. In Figure 11a,b, the curves

represent mean responses of replicate specimens, and error bars indicate standard deviations. Figure 11c further compares the coupled evolution of amplitude-based correlation dimension, RA-based correlation dimension, and AE b-value for a representative specimen.

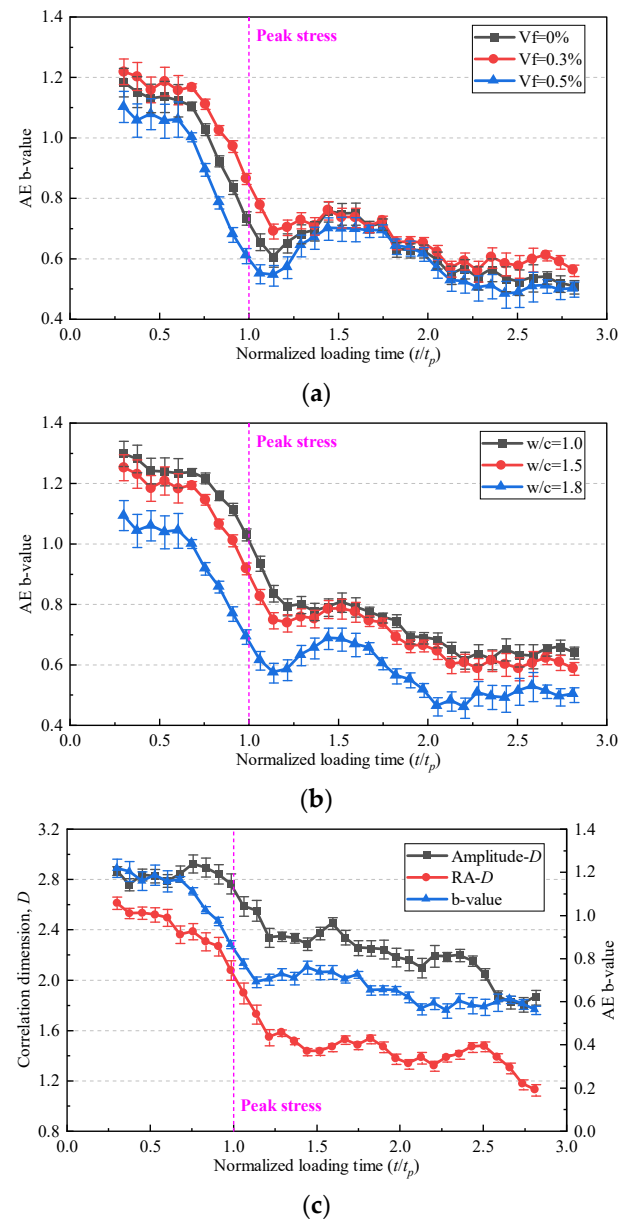


Figure 11. AE b-value evolution and its coupling with fractal indicators during FHWCB failure. (a) b-value evolution of 7-day cured FHWCB with different V_f values at $w/c = 1.5$. (b) b-value evolution of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$. (c) Coupled evolution of Amplitude- D , RA- D , and b-value for 7-day cured FHWCB at $V_f = 0.3\%$ and $w/c = 1.5$.

As shown in Figure 11a, the b-value evolution is strongly affected by fiber volume fraction. Before peak stress, the $V_f = 0.3\%$ mixture generally maintains a relatively higher b-value and shows a more gradual decrease, indicating that the AE population is dominated by small amplitude and distributed damage events. In contrast, the $V_f = 0.5\%$ mixture exhibits a lower b-value and a sharper decrease near the peak stress region, suggesting that excessive fiber addition promotes the transition toward larger fracture events and more localized damage. This trend is consistent with the correlation dimension results in Figure 9 and supports the interpretation that moderate fiber addition delays fracture localization, whereas excessive fiber content introduces weak local zones.

Figure 11b shows the effect of water-to-cement ratio at $V_f = 0.3\%$. The lower- w/c mixtures maintain relatively higher b -values during the stable damage stage, indicating that AE activity is mainly composed of small-scale distributed events. As w/c increases, the b -value decreases more rapidly and reaches a lower level near-peak stress, suggesting that high water content weakens the hydration skeleton and accelerates the transition from distributed microcracking to localized macrocrack propagation. This behavior agrees with the correlation dimension evolution in Figure 10.

Figure 11c shows that amplitude-based D , RA-based D , and b -value decrease concurrently as loading approaches peak stress. The decrease in D indicates a reduction in AE source complexity, whereas the decrease in b -value reflects an increasing proportion of large-amplitude fracture events. Their concurrent decline demonstrates that the damage process evolves from distributed microdamage to localized crack growth. After peak stress, the three indicators fluctuate at relatively low levels, which can be attributed to repeated local stress redistribution, fiber debonding, fiber pull-out, crack surface friction, and intermittent crack propagation.

Therefore, the combined use of correlation dimension and b -value provides complementary damage information. Correlation dimension reflects AE source complexity, whereas b -value captures the event-size distribution. A simultaneous decrease in these parameters indicates that the AE process becomes less complex and increasingly controlled by larger fracture events. Thus, the coupled reduction in D and b -value can serve as an indicator of fracture localization and emerging instability in FHWCB.

3.2.5. Coupled Stress–AE–Fractal Response Under Different Mixture Conditions

Figures 12–15 further present the synchronized stress response with AE ringing count, cumulative ringing count, AE amplitude, and correlation dimension under different mixture conditions. Figures 12 and 13 address V_f effects for 7-day specimens at $w/c = 1.5$, whereas Figures 14 and 15 show the influence of water-to-cement ratio for 28-day specimens at $V_f = 0.3\%$.

As shown in Figure 12, AE activity is relatively weak during the initial loading period and becomes more active as loading proceeds. The cumulative ringing count increases gradually at first and then rises more rapidly around and after the peak stress, indicating accelerated internal damage accumulation. For all fiber volume fractions, AE amplitudes are dominated by low-to-medium values, with only intermittent high-amplitude bursts. This result is consistent with Figure 7 and indicates that FHWCB failure is governed by persistent small-scale damage activity accompanied by occasional high-intensity fracture events. Fiber volume fraction clearly changes the stress-AE response. The fiber-free specimen shows rapid AE activity development once the stress reaches a relatively high level, indicating limited resistance to crack propagation in the unreinforced matrix. With fiber addition, the AE response becomes more distributed in time because fibers bridge developing cracks and delay abrupt crack opening. Among the tested mixtures, the $V_f = 0.3\%$ specimen shows a relatively high stress level and a stable post-peak response, suggesting that this fiber volume fraction provides a favorable balance between matrix strength and crack-bridging efficiency. When V_f increases to 0.4% and 0.5%, AE ringing activity remains intense, and high-amplitude events appear intermittently during loading. This does not necessarily indicate better reinforcement. Excessive fiber volume fraction may increase local heterogeneity, reduce slurry uniformity, and generate weak fiber-rich regions. These defects can promote localized cracking and cause unstable AE bursts. Thus, the AE response further supports the conclusion that the reinforcement effect of fiber volume fraction is non-monotonic.

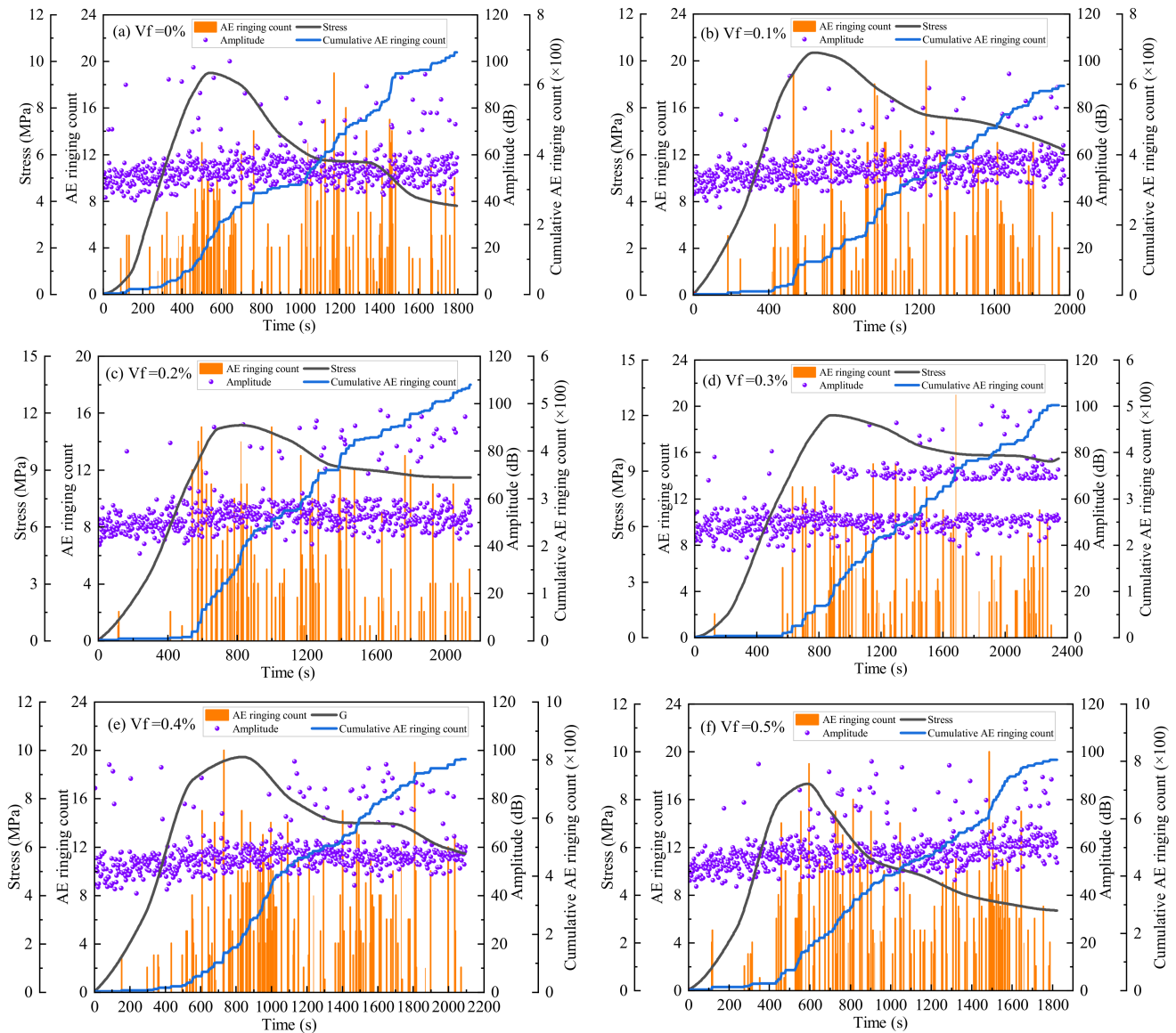


Figure 12. Stress response and AE parameters of 7-day cured FHWCB with different V_f values at $w/c = 1.5$.

Figure 13 shows the corresponding stress correlation dimension relationships under different V_f values. For all mixtures, the amplitude-based correlation dimension is generally higher than the ringing-count-based correlation dimension, indicating that AE amplitude contains richer information about fracture source intensity and damage complexity. Both amplitude-based D and ringing-count-based D tend to decrease with loading, especially after the stress reaches the peak region. This decreasing trend indicates that AE activity gradually evolves from a complex and distributed process toward a more localized fracture process. The $V_f = 0.3\%$ mixture maintains a relatively high and stable amplitude-based correlation dimension over a longer loading interval, whereas the $V_f = 0.5\%$ mixture exhibits a more pronounced reduction in D . This confirms that appropriate fiber addition delays the loss of AE complexity, while excessive fibers accelerate damage localization.

Figure 14 shows that the peak stress of FHWCB decreases as the water-to-cement ratio increases. For instance, the $w/c = 1.0$ specimen exhibits the highest peak stress, while the specimen with $w/c = 1.8$ exhibits the lowest peak stress. This mechanical trend reflects the weakening effect of excessive water on the hardened matrix. The AE response also changes significantly with water-to-cement ratio. For lower water-to-cement ratios,

AE activity remains relatively controlled before peak stress, and the cumulative ringing count grows more gradually, indicating that the denser matrix can sustain higher stress and postpone rapid damage accumulation. In contrast, the $w/c = 1.8$ specimen shows more continuous ringing activity and a faster increase in cumulative ringing count during loading, suggesting that the porous matrix promotes earlier microcrack initiation and more sustained damage development.

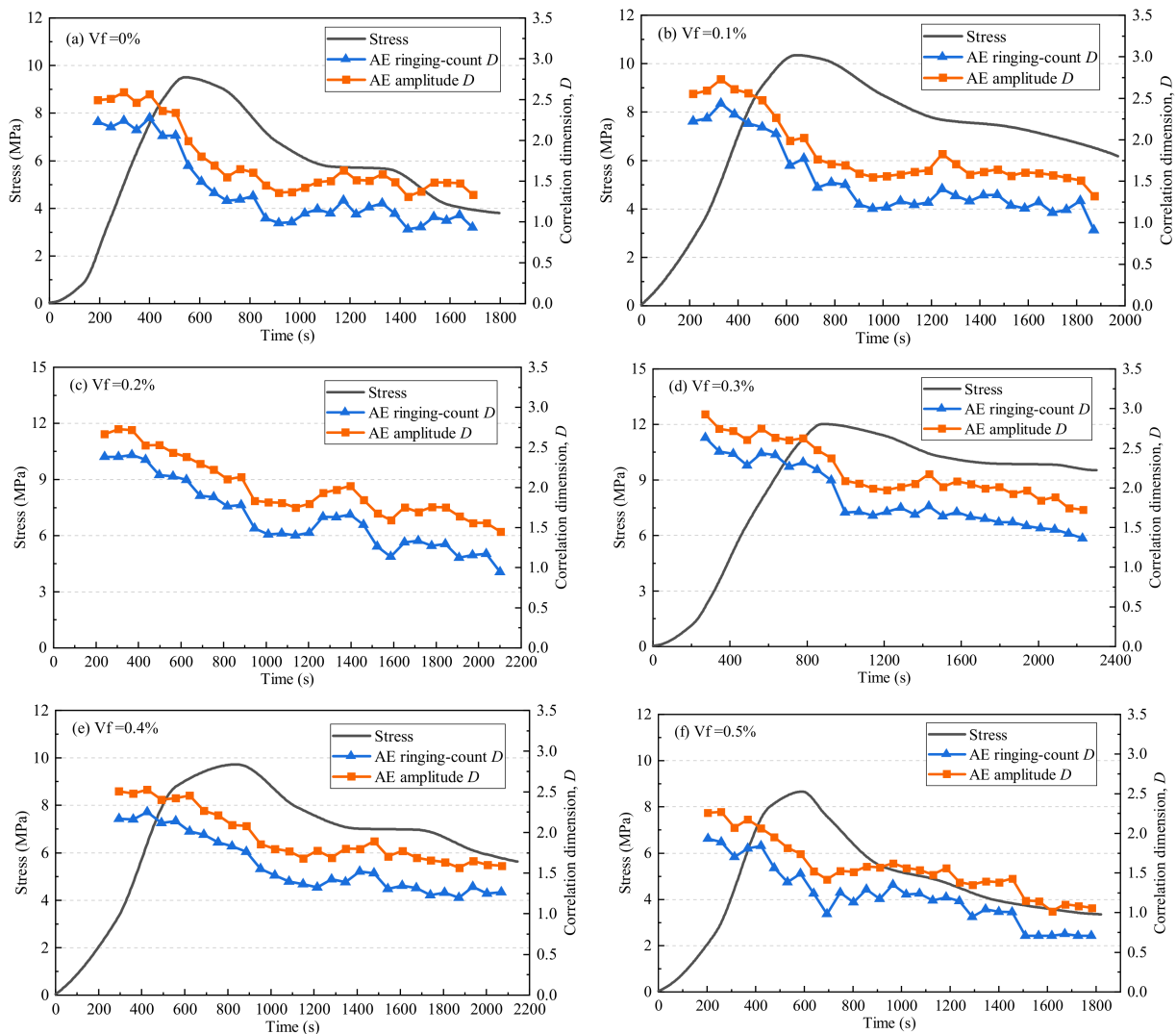


Figure 13. Stress and AE correlation dimension evolution of 7-day cured FHWCB with different V_f values at $w/c = 1.5$.

The AE amplitude distributions in Figure 14 show that low-to-medium amplitude events dominate the loading process for all water-to-cement ratios, while higher-amplitude events occur intermittently. With increasing water-to-cement ratio, AE activity becomes more continuous, indicating that the internal structure is more susceptible to progressive damage. This is mainly because higher water content produces a more porous hydration skeleton and weakens the fiber–matrix interface, allowing cracks to propagate more easily through pores and weak interfacial regions [40].

Figure 15 further confirms this interpretation from the perspective of correlation dimension. Both amplitude-based D and ringing-count-based D decrease with loading, and their overall levels decline as the water-to-cement ratio increases. The $w/c = 1.0$ and 1.2 specimens maintain relatively high correlation dimensions, whereas the $w/c = 1.5$ and

especially $w/c = 1.8$ specimens show lower values. This indicates that a lower water-to-cement ratio favors a more complex and distributed damage process, while excessive water promotes fracture localization.

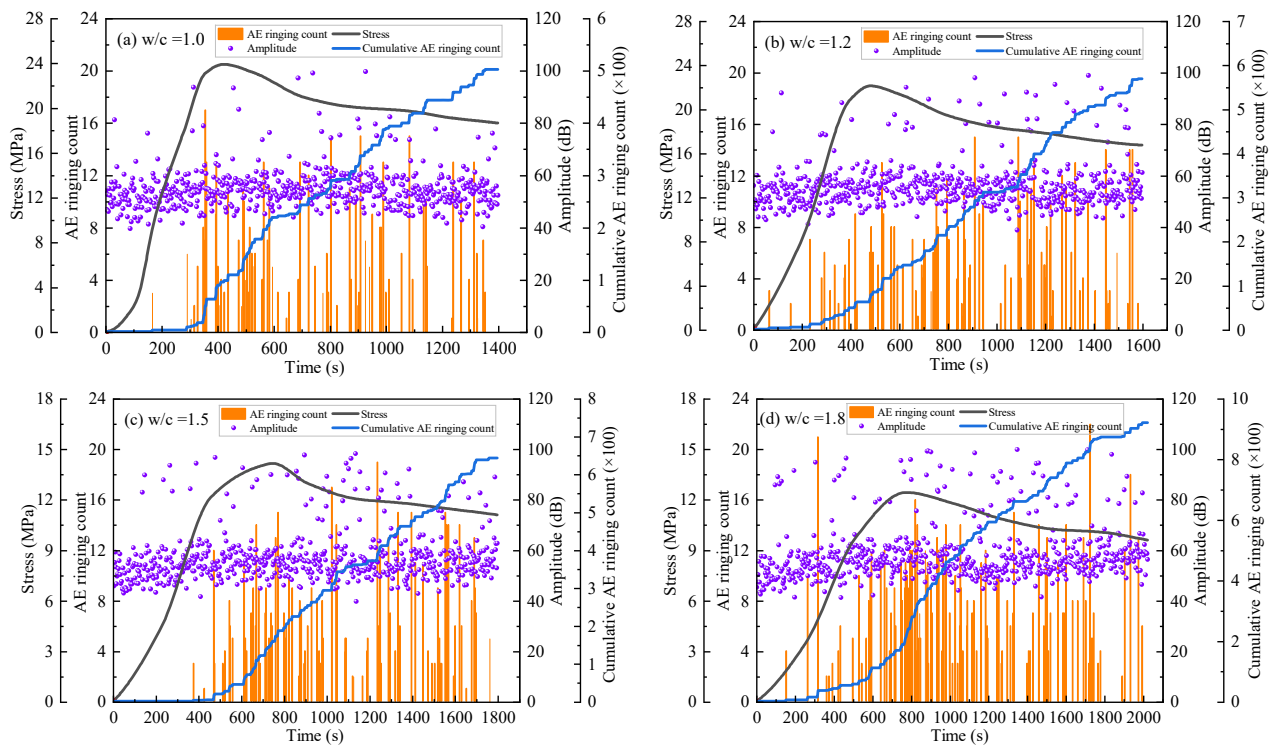


Figure 14. Stress and AE parameter evolution of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$.

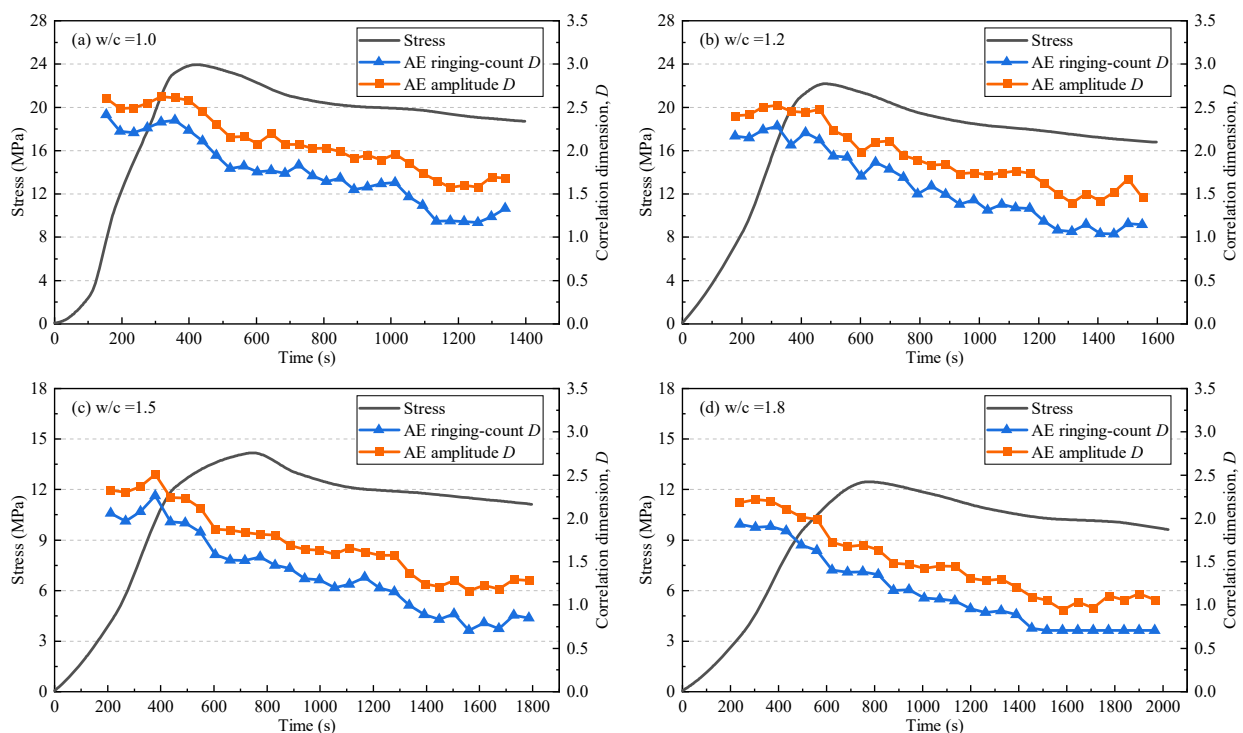


Figure 15. Stress and AE correlation dimension evolution of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$.

Overall, Figures 12–15 demonstrate that mixture design controls not only the macroscopic mechanical response but also the internal organization of AE damage sources. A suitable fiber volume fraction and a lower water-to-cement ratio help maintain distributed microcracking and delay the loss of AE complexity. Excessive fiber volume fraction or excessive water content increases structural heterogeneity and weakens the matrix, leading to more localized AE activity and a faster decline in correlation dimension. Therefore, AE fractal parameters can effectively reveal the internal damage evolution of FHWCB and provide a quantitative basis for identifying instability precursors.

3.2.6. Mechanistic Implications of AE Fractal Evolution

Figure 16 schematically illustrates the mechanism underlying AE fractal evolution and fracture localization in FHWCB. The change in AE correlation dimension reflects competition among matrix compactness, fiber-bridging efficiency, and defect-controlled localization. In mixtures with a dense hydration skeleton and well-dispersed fibers, microcracks tend to follow multiple tortuous routes rather than rapidly merging into a dominant fracture surface. Fibers then bridge developing cracks, transfer tensile stress across crack faces, and dissipate fracture energy through interfacial separation and pull-out. These mechanisms diversify AE sources and sustain a relatively high correlation dimension, indicating distributed damage.

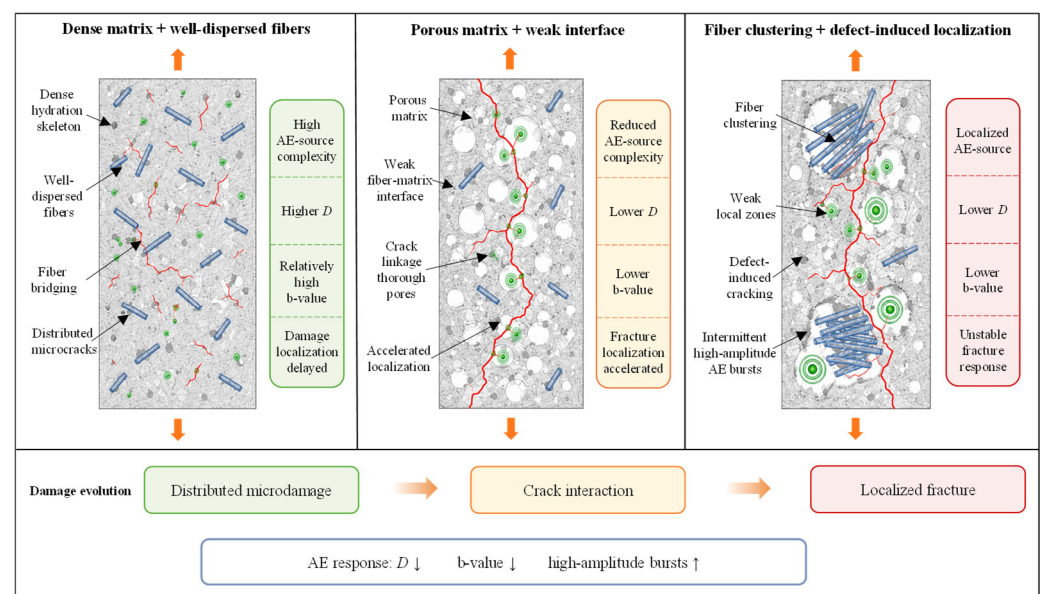


Figure 16. Mechanism of AE fractal evolution and fracture localization in FHWCB. The vertical orange arrows indicate the correspondence between microstructural condition and damage mode, the horizontal arrows indicate the progressive transition from distributed microdamage to crack interaction and localized fracture, and the black arrows indicate representative crack or defect features. The symbols $\downarrow$ and $\uparrow$ denote decreasing and increasing trends of AE indicators, respectively.

An appropriate fiber volume fraction can improve the damage tolerance of FHWCB by delaying crack localization. For the mixtures investigated in this study, $V_f = 0.3\%$ provided the most favorable fractal response. At this dosage, the fiber-bridging effect was sufficient to restrain rapid crack coalescence without causing severe fiber clustering. Therefore, AE events remained more dispersed during loading, and the correlation dimension was maintained at a relatively high level. By contrast, excessive fiber addition generated fiber clusters and weak local interfaces, reducing matrix uniformity. Such defect-rich regions became preferred sites for crack initiation and growth, driving AE activity toward

localization. Consequently, the correlation dimension decreased and intermittent high-amplitude AE bursts became more apparent.

The water-to-cement ratio mainly controls the compactness of the hydration skeleton and the quality of the fiber–matrix interface. A high water-to-cement ratio increases pore volume and weakens bonding between hydration products and fibers. Cracks can then link more easily through pores and weak interfaces, promoting earlier fracture localization. This explains why mixtures with higher w/c exhibited lower correlation dimensions and more continuous AE activity. Conversely, a lower water-to-cement ratio produced a denser matrix, improved fiber–matrix interaction, and forced cracks to propagate through more complex paths, thereby maintaining a higher AE source complexity.

Thus, the AE correlation dimension is more than a signal processing output; it describes the internal organization of damage sources and the degree of fracture localization in FHWCB. The joint evolution of correlation dimension and b -value further shows that instability involves two concurrent changes: AE source complexity decreases and large-amplitude fracture events become more prevalent. Accordingly, the combined occurrence of decreasing D , decreasing b -value, and intermittent high-amplitude AE bursts marks the transition from distributed microdamage to localized fracture. This interpretation provides a fractal perspective on FHWCB failure and indicates that AE fractal indicators can support instability warning and mixture optimization for underground support.

3.3. Energy Evolution and Energy-Based Damage Characterization of FHWCB

3.3.1. Method for Calculating Strain Energy

The compression failure of FHWCB can be described as an energy conversion process involving input, storage, dissipation, and release [41,42]. During uniaxial loading, the external work supplied by the testing machine is partly stored as recoverable elastic strain energy, whereas the remainder is dissipated through irreversible damage processes, including pore collapse, microcrack initiation, crack extension, fiber interface separation, fiber extraction, and crack surface friction. Figure 17 schematically presents the energy partitioning under uniaxial compression. Here, σ_1 indicates the first principal stress under uniaxial compression, ε_1 is defined as the elastic strain at a given stress level, while U_e and U_d represent the elastic strain energy density and dissipated energy density of the specimen, respectively.

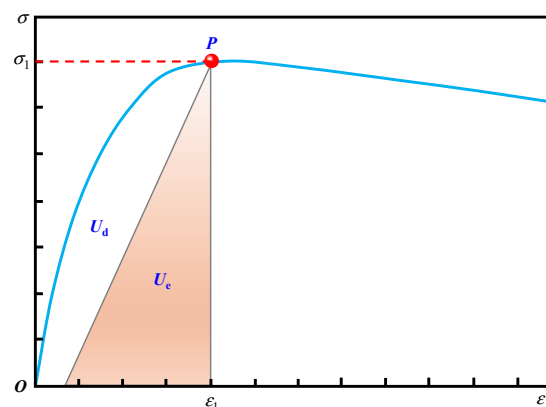


Figure 17. Energy partitioning of a specimen subjected to uniaxial compression.

Within the framework of energy evolution, U denotes the total energy introduced into the specimen by external loading. Neglecting heat exchange and other minor losses, the first-law energy balance can be expressed as [43,44]:

$$U = U_e + U_d \quad (11)$$

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 \quad (12)$$

$$U_e = \frac{1}{2} \sigma_1 \varepsilon_1^e + \frac{1}{2} \sigma_2 \varepsilon_2^e + \frac{1}{2} \sigma_3 \varepsilon_3^e \quad (13)$$

where σ_2 and σ_3 represent the second and third principal stresses, with ε_2 and ε_3 correspond to the respective strains.

According to Hooke's law [45]:

$$U_e = \frac{1}{2E} \left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) \right] \quad (14)$$

where E is the elastic modulus, with μ denoting the Poisson's ratio.

For uniaxial compression, where $\sigma_2 = \sigma_3 = 0$, the expression for the strain energy per unit volume simplifies to the following:

$$U_e = \frac{\sigma_1^2}{2E} \quad (15)$$

3.3.2. Energy Evolution of FHWCB with Different Fiber Volume Fractions

Figure 18 shows the energy evolution of 7-day cured FHWCB specimens with different V_f values at $w/c = 1.5$. For all mixtures, the total input energy density U increases continuously with strain, indicating the continuous work performed by the external loading system. The dissipated energy density U_d is low at the early loading stage and rises rapidly once damage accumulation intensifies. The elastic strain energy density U_e initially increases with stress, reaches a maximum near the peak stress region, and then decreases or stabilizes as irreversible damage becomes dominant.

The fiber-free specimen shows relatively limited capacity for energy storage and post-peak energy dissipation. After the matrix reaches its damage threshold, microcracks propagate and coalesce quickly because no effective fiber bridging is present. As a result, the post-peak stress drop is more pronounced, and stored elastic energy is rapidly converted into dissipated energy. Fiber addition alters both the stress response and the energy partitioning behavior. When V_f increases to 0.1–0.3%, peak stress, total input energy, and dissipated energy all increase to varying extents. The $V_f = 0.3\%$ mixture, in particular, shows the highest stress level and the most favorable energy response among the tested fiber volume fractions, indicating that a suitable fiber volume fraction improves the ability of FHWCB to absorb and dissipate energy around peak stress. Fibers bridge cracks, transfer stress across crack faces, and consume extra energy through interfacial separation, pull-out, and frictional sliding, thereby delaying abrupt crack coalescence and improving post-peak integrity.

However, increasing the fiber volume fraction to 0.4% and especially to 0.5%, weakens the energy-related benefit. The $V_f = 0.5\%$ specimen shows a lower peak stress and a reduced energy-bearing capacity compared with the $V_f = 0.3\%$ mixture. This result is consistent with the UCS results in Figure 2b. Excessive fiber volume fraction can cause fiber clustering, reduce slurry uniformity, and introduce weak local zones. These defects promote premature crack initiation and localized failure, reducing the efficiency of elastic energy storage and limiting the beneficial energy dissipation role of fibers.

Therefore, the influence of fiber volume fraction on energy response is also non-monotonic. Properly dispersed fibers enhance the energy absorption and damage tolerance capacity of FHWCB, whereas excessive fibers introduce structural defects that reduce both mechanical strength and energy-bearing capacity. Within the investigated range, $V_f = 0.3\%$ provides the best balance between fiber bridging, energy dissipation, and matrix integrity.

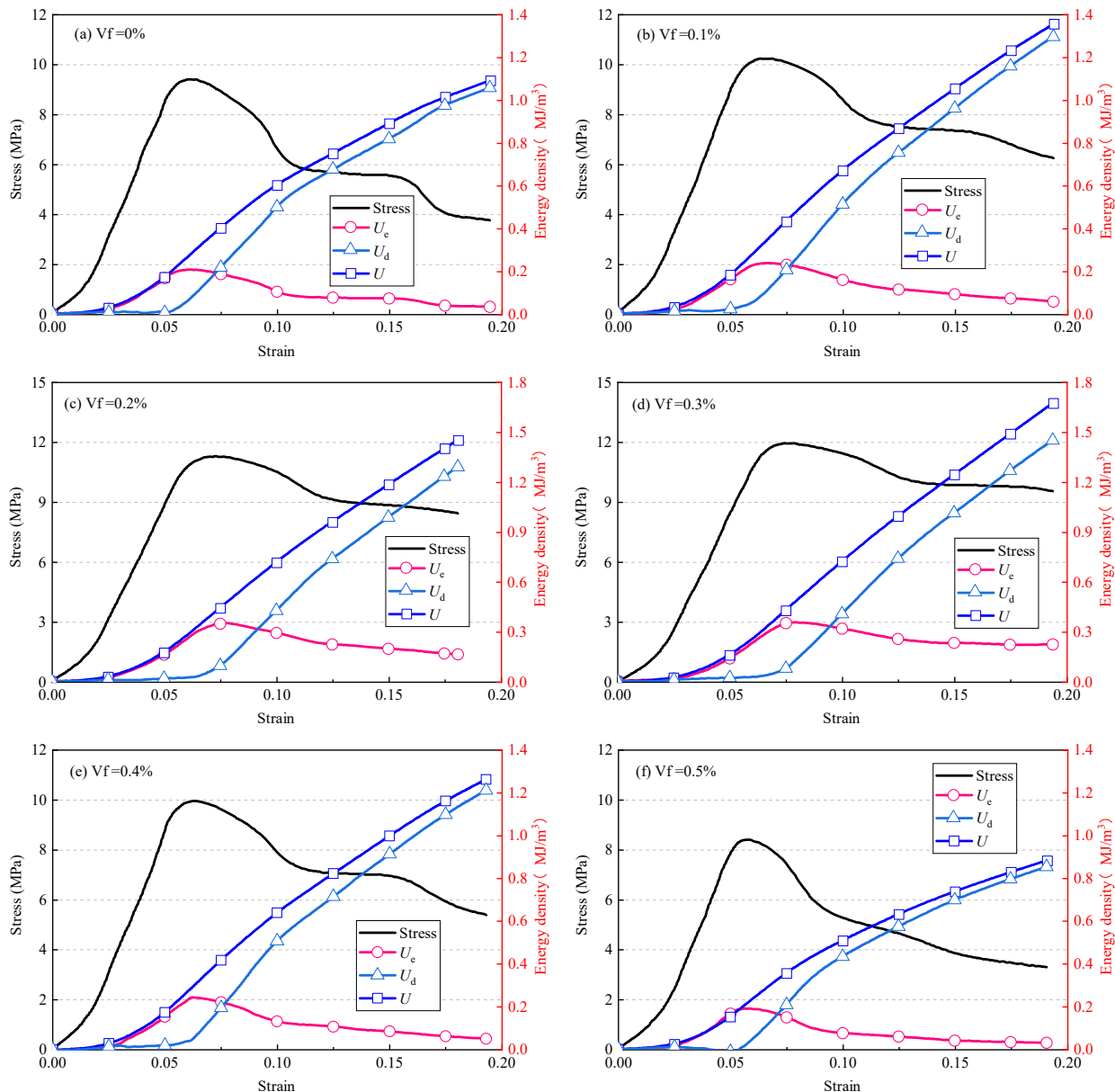


Figure 18. Energy evolution of 7-day cured FHWCB with different V_f values at $w/c = 1.5$.

3.3.3. Effect of Water-to-Cement Ratio on Energy Evolution

Figure 19 presents the energy evolution of 28-day cured FHWCB specimens with different w/c values at $V_f = 0.3\%$. Increasing the water-to-cement ratio lowers peak stress and progressively reduces the specimen's energy-bearing capacity. This trend agrees with the UCS results and confirms that water content strongly affects both strength development and energy evolution. The peak elastic strain energy density decreases with increasing w/c . The peak U_e values are approximately 0.60, 0.55, 0.40, and 0.39 MJ/m^3 for $w/c = 1.0, 1.2, 1.5$, and 1.8 , respectively. The reduction in U_e indicates that high- w/c mixtures have a weaker capacity to store recoverable elastic energy before failure. This is mainly because excess water increases capillary porosity and weakens the hydration skeleton, thereby reducing stiffness, strength, and fiber–matrix bonding quality.

The evolution of U and U_d also reflects the weakening effect of increasing w/c . For lower water-to-cement ratios, the denser matrix allows the specimen to sustain higher stress and accumulate more external work before failure. As a result, both the total input energy and dissipated energy reach higher levels. In contrast, high- w/c mixtures fail at

lower stress levels and require less energy to develop macroscopic damage. Although these mixtures may show more continuous damage activity during loading, their overall energy absorption capacity is lower because the porous matrix provides less resistance to crack propagation.

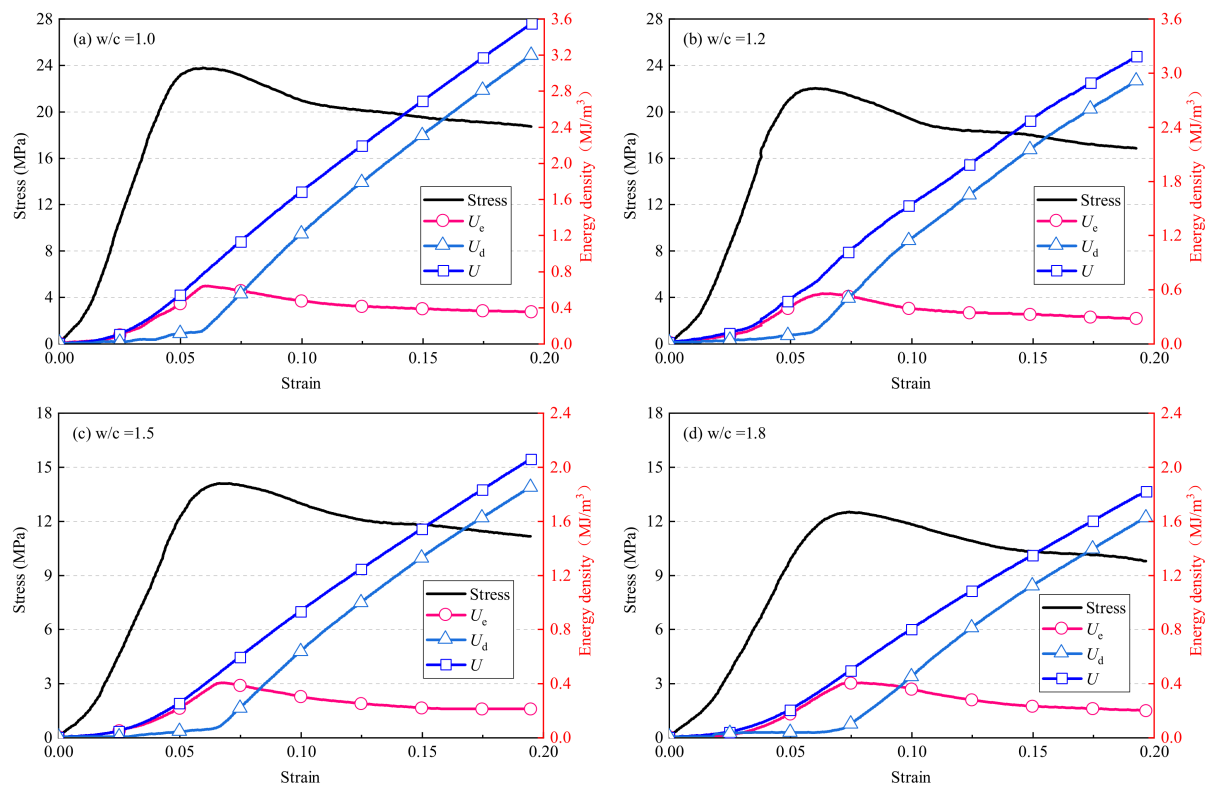


Figure 19. Energy evolution of 28-day cured FHWCB with different w/c values at $V_f = 0.3\%$.

The energy results show that reducing the water-to-cement ratio improves both UCS and the ability of FHWCB to store elastic energy and dissipate fracture energy. Although a higher water-to-cement ratio enhances fresh-state flowability, it produces a more porous and weaker hardened structure, causing earlier damage localization and lower energy-bearing capacity. Accordingly, water-to-cement ratio selection should balance placement requirements with post-hardening damage resistance.

3.3.4. Energy-Based Damage Constitutive Model

Using the energy partitioning method described in Section 3.3.1, the dissipated energy density U_d was used to characterize irreversible damage accumulation in FHWCB. Compared with stress or strain alone, U_d directly reflects the energy consumed by pore collapse, microcrack propagation, fiber–matrix debonding, fiber pull-out, and crack surface friction [46]. Therefore, it provides a physically meaningful basis for defining the damage variable.

The dissipative strain energy ratio P_d represents the proportion of dissipated strain energy density in the total input strain energy density at a given loading state. The damage variable d was then determined by normalizing P_d according to Equation (16).

$$d = 1 - \exp(-P_d/P_a) \quad (16)$$

where P_a is the mixture-specific reference dissipative strain energy ratio. For each mixture condition, P_a was calculated as the average value of P_d at the peak stress point from replicate specimens.

The constitutive relationship for the specimens is established as follows:

$$\sigma_c = E_0 \varepsilon_1 (1 - d) = E_0 \varepsilon_1 \exp(-P_d/P_a) \quad (17)$$

where σ_c is the theoretical stress.

Figure 20 compares experimental stress–strain curves with model predictions for representative FHWCB mixtures with different V_f values. The predicted curves match the experimental rising branches well and capture the peak stress and post-peak degradation reasonably. This agreement indicates that the proposed energy-based damage model describes the main compression failure behavior of FHWCB. Appropriate fiber incorporation increases energy absorption and postpones damage localization, resulting in a slower degradation process. In contrast, excessive fiber or water content accelerates damage accumulation by introducing weak zones, increasing porosity, or degrading fiber–matrix bonding quality. The model therefore provides a quantitative link among mixture design, irreversible energy dissipation, and macroscopic stress–strain behavior in FHWCB.

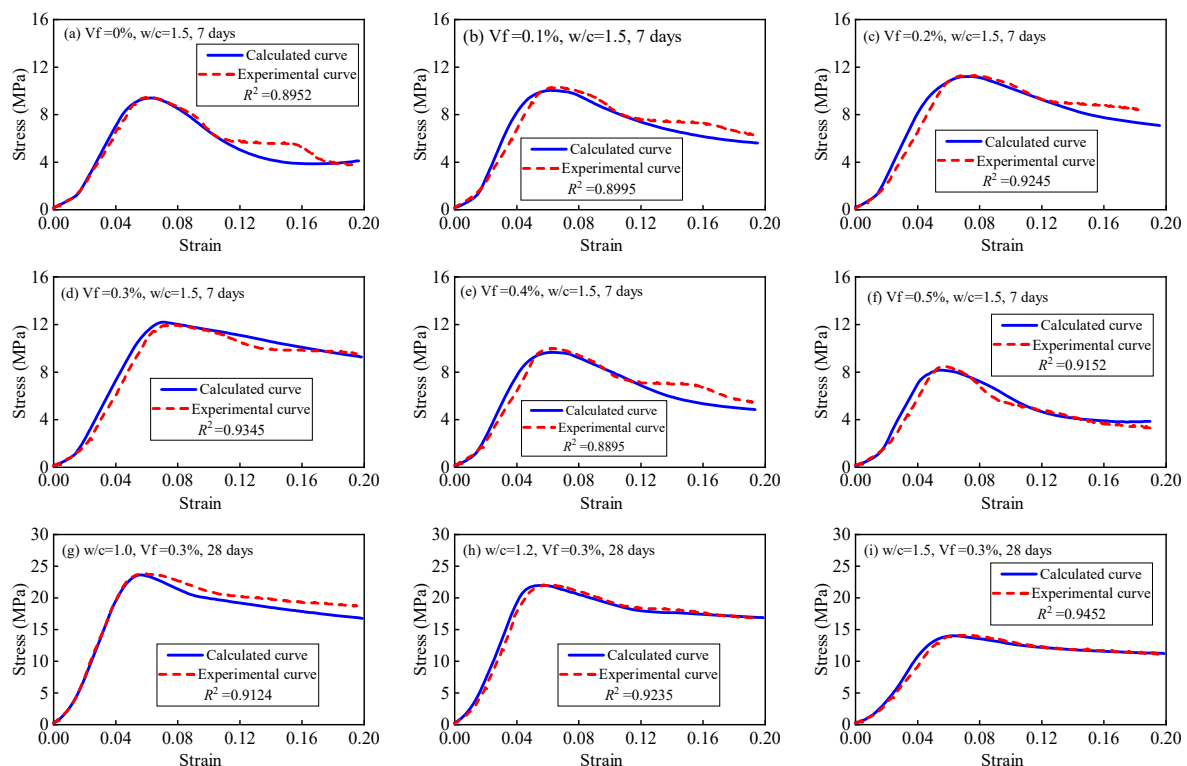


Figure 20. Representative experimental and modeled stress–strain curves of FHWCB with varied V_f and w/c values.

3.4. Effect of Water-to-Cement Ratio and Fiber Volume Fraction on Fresh Properties of FHWCB

3.4.1. Apparent Viscosity and Hydration-Related Physicochemical Evolution

The rheological response of FHWCB slurry at different w/c values and fiber volume fractions is shown in Figure 21. Apparent viscosity increased steadily with time, and a distinct inflection point appeared near the initial setting time (shown in Section 3.4.2). This behavior is consistent with the non-Newtonian flow characteristics of rapid-setting cementitious systems [47–49]. Viscosity development can be divided into two stages: a slow-growth stage before the inflection points and an accelerated stage that ultimately leads to an almost complete loss of flowability. This transition is controlled primarily by rapid hydration after the two components are mixed. As free water is consumed during hydration product formation, especially ettringite precipitation, particle bonding develops

and interparticle friction during shear increases, thereby raising viscosity. At the same time, continued growth of hydration phases increases the solid fraction of the suspension. According to the Krieger–Dougherty model [50], suspension viscosity is strongly governed by solid concentration. The increasing solid fraction thus enhances particle interactions and further contributes to the sharp viscosity rise.

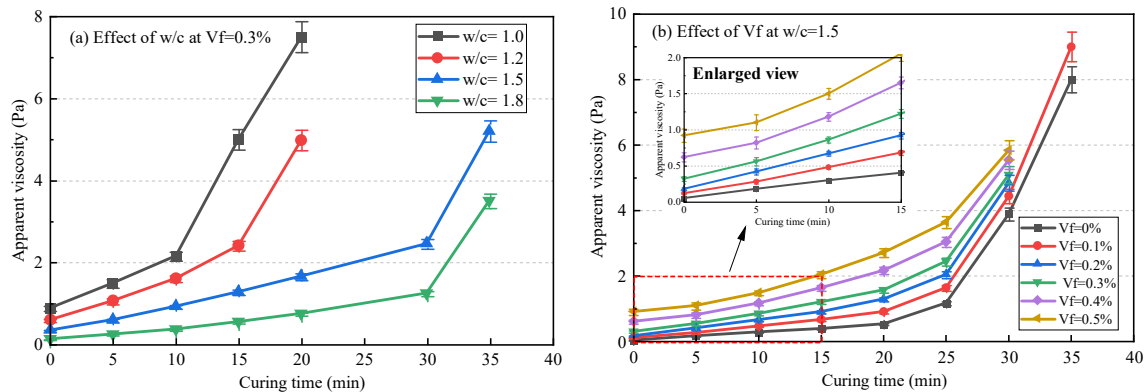


Figure 21. Apparent viscosity evolution of fresh FHWCB with different mixture parameters.

Although all FHWCB slurries show a similar time-dependent viscosity pattern, the water-to-cement ratio strongly affects the timing of the viscosity inflection point. A higher water-to-cement ratio delays this transition, whereas increasing fiber volume fraction, brings it forward, consistent with the initial setting-time trend. Before the inflection point, lower-ratio slurries have higher viscosity and poorer flowability. After the transition, their viscosity increases more abruptly and often exceeds the measurable range of the instrument. This behavior is attributed to faster hydration kinetics at lower water-to-cement ratios, where higher solid concentration, larger solid–liquid contact area, enhanced particle dissolution, and higher pore solution ion concentration accelerate structural build-up.

Figure 22 shows the early-stage EC evolution of FHWCB. Although EC was continuously monitored for up to 2 days, only the initial approximately 60 min are presented because this period contains the dominant EC variation associated with rapid ion dissolution, precipitation, and early hydration product formation. After this stage, the EC response changed more gradually, mainly reflecting the progressive stabilization of pore solution chemistry. The EC fluctuations arise from dissolution and hydration of water-reactive components, which release Ca^{2+} , OH^- , SO_4^{2-} , and alkali ions. At lower water-to-cement ratios, the EC response is more pronounced, with a higher peak and a lower stabilized value, indicating stronger ion release and faster ion consumption during early hydration. Reduced water content increases the contact frequency between cement particles and water, thereby accelerating dissolution and hydrolysis and elevating the EC peak. Moreover, less mixing water allows a larger fraction of cement to hydrate rapidly. This process consumes ions more quickly and converts free water into capillary and bound water, reducing the volume of pore solution. Subsequent hydration product deposition further blocks pore channels, resulting in reduced slurry fluidity.

Cement hydration releases a high concentration of dissolved ions, compressing the electrical double layer. The double-layer thickness ($1/k_d$) depends on ionic concentration (c) and valence (z) as described by Equation (18) [51].

$$k_d = 0.329 \times 10^{10} (cz^2)^{1/2} \quad (18)$$

Consequently, the decrease in electrical potential weakens interparticle repulsion and promotes particle aggregation [52]. Zeta potential measurements support this mechanism

(Figure 23): the absolute zeta potential value is consistently lower for FHWCB at $w/c = 1.0$ than for mixtures with a ratio of 1.8. These results indicate that a higher water-to-cement ratio enhances interparticle repulsion and consequently lowers system viscosity. This interpretation is consistent with previous studies [6,15,34].

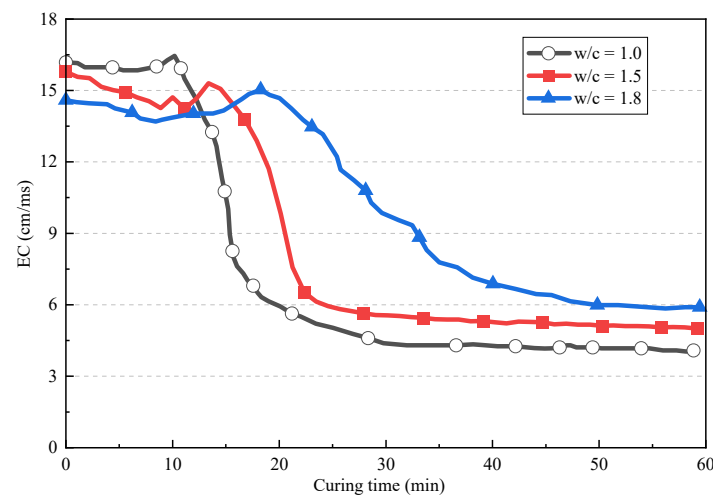


Figure 22. Effect of w/c on EC evolution of FHWCB at $V_f = 0.3\%$.

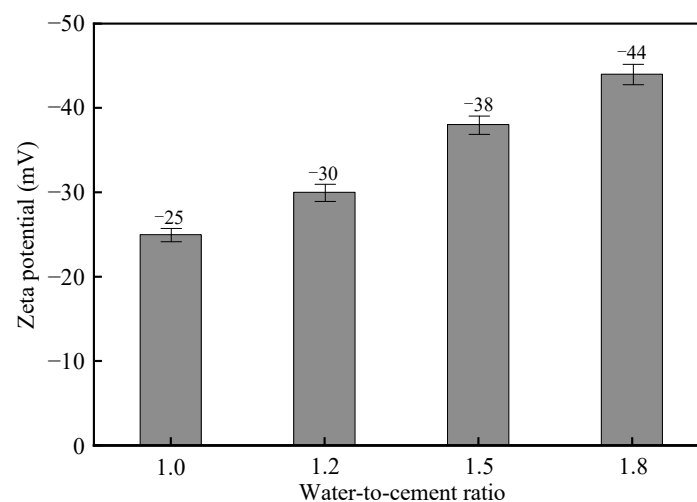


Figure 23. Zeta potential of FHWCB with different w/c values at $V_f = 0.3\%$.

The coupled variation of water-to-cement ratio, pH, and zeta potential provides additional evidence. The results show that changing the water-to-cement ratio modifies the zeta potential of FHWCB, while zeta potential also responds to changes in pH. Figure 24 illustrates the time-dependent pH response at different w/c values, supporting the observed zeta potential variations.

Fiber incorporation reduces the flowability of cementitious systems, consistent with earlier reports on fiber-reinforced cement-based materials [31,53–55], and the same behavior is observed for FHWCB. The fibers adversely affect workability, but the inflection point in the viscosity–time curve remains largely insensitive to fiber volume fraction. This can be attributed to the chemical inertness of polypropylene fibers during hydration of the cementitious components. Figure 25 presents the early-stage EC evolution of FHWCB slurries with different fiber volume fractions. Consistent with the EC analysis in Figure 22, only the initial approximately 60 min are shown here to compare the rapid ion release and early hydration responses among different fiber contents. The EC curves of slurries containing $V_f = 0\%$, 0.3% , and 0.5% nearly overlap, with similar peak intensities and peak

times during the initial increase and subsequent decrease. This result further indicates that polypropylene fibers do not substantially alter the ionic dissolution and precipitation processes during early hydration. However, higher fiber volume fractions markedly increase apparent viscosity through physical mechanisms. First, increasing fiber content enhances the probability of fiber clustering and frictional contacts among cementitious particles and fiber surfaces. Second, abundant fiber surfaces may provide additional physical attachment sites for early hydration products, promoting the formation of a fiber-hydrate network. This network creates a denser particle arrangement and intensifies interparticle friction, thereby explaining the observed increase in apparent viscosity.

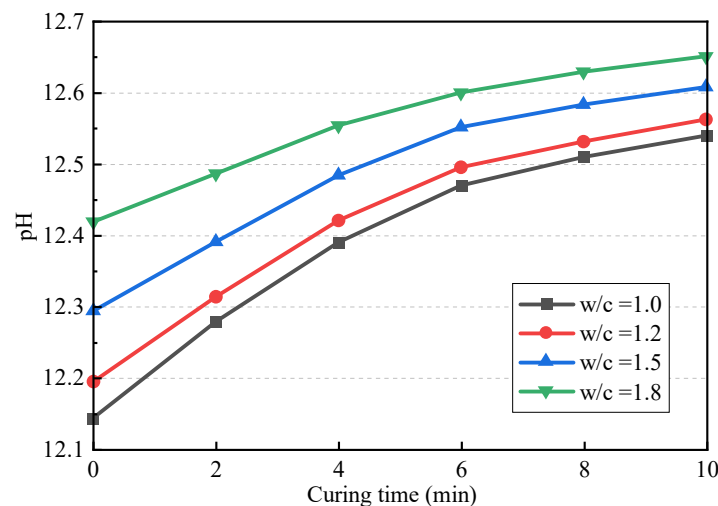


Figure 24. pH evolution of FHWCB with different w/c values at $V_f = 0.3\%$.

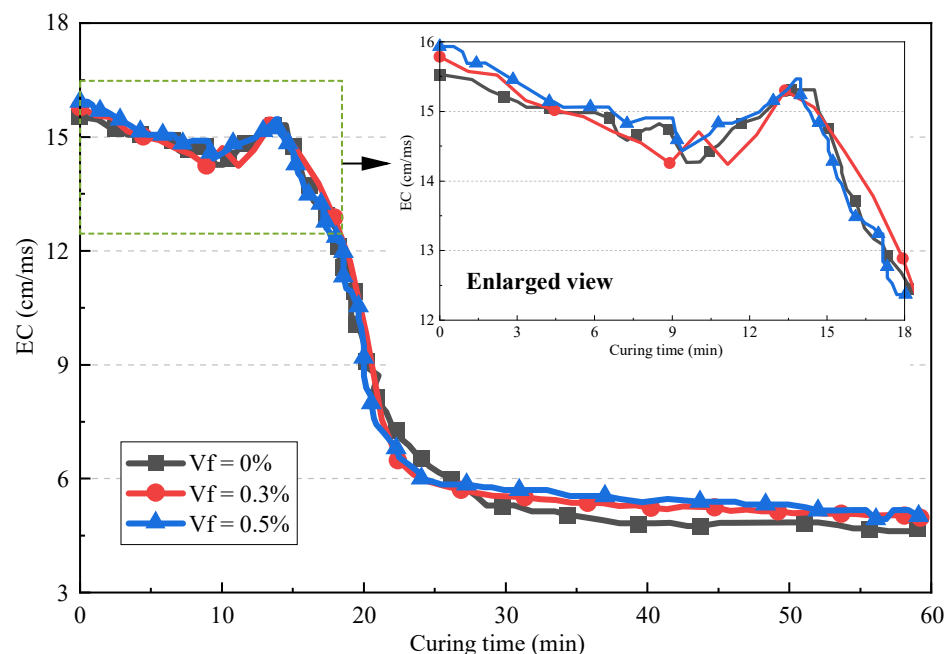


Figure 25. EC evolution of FHWCB with different V_f values for mixtures with $w/c = 1.5$.

3.4.2. Setting Behavior

Figure 26a presents the initial and final setting times of FHWCB mixtures at $V_f = 0.3\%$ under different w/c values, whereas Figure 26b gives the corresponding results at a fixed $w/c = 1.5$ with varying V_f values. Setting behavior shows a strong dependence on the water-to-cement ratio, with longer setting durations at higher ratios. For example, the mixture with $w/c = 1.0$ reached initial and final set at 15 min and 40 min, respectively.

Raising the ratio to 1.2, 1.5, and 1.8 prolonged the initial setting time by factors of about 1.267, 1.867, and 2.334, respectively. The final setting time similarly increased by factors of about 1.350, 1.575, and 1.800. This retardation is mainly related to the improved flowability of FHWCB mixtures (Figure 21), which can promote bleeding and particle segregation. Excess water delays ettringite formation and thus extends the setting process. This explanation is supported by hydration product development (Figure 3) and EC evolution (Figure 22) across the water-to-cement-ratio series, consistent with the setting behavior of sulfoaluminate cement reported by Zhang et al. [56].

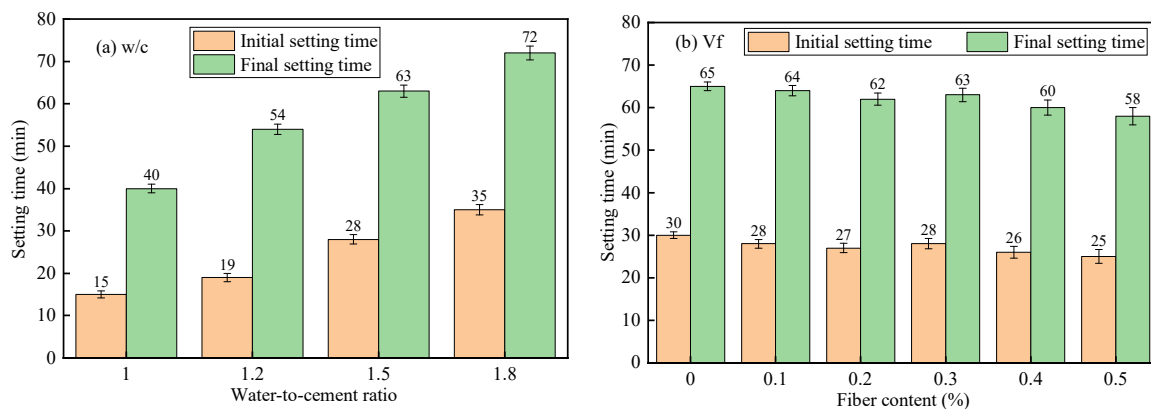


Figure 26. Setting times of FHWCB with different mixture parameters.

Fiber incorporation slightly shortens the setting time of FHWCB, but the acceleration is limited. In the reference mixture without fibers, initial and final setting occurred at 30 min and 65 min, respectively. As V_f increased to 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%, the corresponding initial setting times decreased to about 93.3%, 93.3%, 93.3%, 90.0%, and 93.3% of the reference value, while final setting times decreased to about 97.1%, 94.1%, 92.6%, 91.2%, and 94.1%, respectively. These results demonstrate that fiber volume fraction exerts only a marginal influence on the setting characteristics of FHWCB. This minimal effect can be explained by two counteracting mechanisms: (i) fibers displace a portion of the cementitious solids, effectively reducing the sulfoaluminate cement content per unit volume and moderately retarding the hydration process; (ii) the increased fiber surface area at higher dosages adsorbs more water, lowering the amount of free water available and promoting earlier setting. The overall negligible impact of fiber volume fraction on setting time is primarily attributable to the physicochemical stability of polypropylene fibers, which is corroborated by EC measurements (Figure 25) confirming their non-reactive nature in the cementitious environment, consistent with previous investigations [53,57,58].

In general, the rapid-setting behavior of FHWCB across different mix proportions is fundamentally governed by ye'elimite hydration [56,59]. This reaction promotes the swift and interlocking precipitation of ettringite, establishing a continuous AFt framework while consuming substantial mixing water. Although both water-to-cement ratio and fiber volume fraction regulate the dissolution kinetics of ye'elimite and gypsum, thereby modifying the setting process, the final setting of all FHWCB formulations remained within 75 min. This duration remains considerably shorter than that reported in the literature for conventional cement-based concrete [48,49]. It demonstrates that FHWCB retains its rapid hardening characteristics across a broad range of fiber volume fractions and water-to-cement ratios.

From an engineering perspective, the fresh property results define the placement-related constraints of FHWCB, whereas the UCS, AE, and energy evolution results reflect the post-hardening resistance to damage and fracture. Increasing w/c improves slurry flowability and extends the workable time, but excessive water weakens the hardened

matrix, accelerates damage localization, and reduces energy-bearing capacity. Increasing V_f can improve crack-bridging capacity and fracture resistance when fibers are sufficiently dispersed, but excessive fiber addition increases apparent viscosity, promotes fiber clustering, and may reduce pumping efficiency. Therefore, mixture design should balance fresh pumpability and setting requirements with post-hardening strength, AE-fractal damage stability, and energy dissipation capacity.

4. Conclusions

This study investigated how water-to-cement ratio and fiber volume fraction affect the fresh-state behavior, mechanical performance, AE fractal characteristics, b-value response, and energy evolution of FHWCB. The main conclusions are as summarized below:

- (1) Water-to-cement ratio had a pronounced influence on FHWCB strength development. When w/c increased from 1.0 to 1.8, UCS decreased consistently at all curing ages, mainly because excess water weakened the hydration skeleton, increased capillary porosity, and reduced fiber–matrix bonding quality. Conversely, lower w/c promoted matrix densification and improved load-bearing capacity.
- (2) Fiber reinforcement showed a clear non-monotonic effect. At $w/c = 1.5$, the optimal V_f was 0.3%, which increased UCS by approximately 16–26% at different curing ages. This improvement was attributed to effective fiber-bridging and crack-arresting effects. However, excessive fiber addition, especially $V_f = 0.5\%$, reduced strength because fiber clustering and weak local zones promoted defect-induced cracking.
- (3) AE amplitude sequences exhibited measurable fractal characteristics. The AE amplitude correlation dimension effectively described the complexity of damage evolution in FHWCB. A higher D indicated distributed microdamage, while a decrease in D reflected fracture localization. The $V_f = 0.3\%$ mixture maintained a relatively high correlation dimension, whereas high w/c and excessive fiber volume fraction accelerated the loss of AE source complexity.
- (4) The coupled evolution of correlation dimension and AE b-value provided useful precursor information for instability identification. The simultaneous decrease in D and b-value indicated that the AE process became less complex and that large-amplitude fracture events became increasingly dominant. This transition corresponded to the evolution from distributed microdamage to localized fracture.
- (5) Energy analysis showed that proper fiber incorporation enhanced the energy absorption and dissipation capacity of FHWCB, while excessive fiber volume fraction or excessive water content reduced its energy-bearing capacity. As w/c increased, the peak elastic strain energy density decreased from approximately 0.60 to 0.39 MJ/m³, confirming the weakening effect of excessive water. The proposed energy-based damage constitutive model is suitable for the static uniaxial compression damage process of FHWCB within the investigated mixture range, while its applicability under dynamic, cyclic, or field-scale conditions requires further validation.

Overall, the combination of $w/c = 1.5$ and $V_f = 0.3\%$ provided a favorable balance among workability, strength, fracture resistance, and energy dissipation within the investigated range. The proposed AE fractal–b-value–energy analysis offers a quantitative approach for evaluating damage evolution and identifying instability precursors in FHWCB. Nevertheless, the applicability of the present findings should be further examined considering possible scale effects associated with specimen size, fiber dispersion, and boundary conditions. Future research should incorporate larger-scale specimens, multi-sensor AE monitoring, and field-scale validation to improve the application of this analysis in underground backfill engineering.

Author Contributions: Conceptualization, S.L. and Z.Z.; methodology, S.L., Z.Z. and J.Y.; validation, S.L., Z.L. and X.W.; formal analysis, S.L. and K.F.; investigation, S.L., Z.L. and X.W.; resources, Z.Z., J.Y. and K.F.; data curation, S.L. and J.Y.; writing—original draft preparation, S.L., Z.L. and X.W.; writing—review and editing, Z.Z., J.Y. and K.F.; visualization, S.L. and X.W.; supervision, Z.Z. and J.Y.; project administration, Z.Z.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52504083).

Data Availability Statement: Data will be made available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HWCB	High-water-resistance concrete backfill
FHWCB	Fiber-reinforced high-water-resistance concrete backfill
UCS	Unconfined compressive strength
AE	Acoustic emission
RA	Rise time/amplitude ratio
G–P	Grassberger–Procaccia
TG	Thermogravimetric
DTG	Differential thermogravimetric
XRD	X-ray diffraction
EC	Electrical conductivity
VWC	Volumetric water content
C–S–H	Calcium silicate hydrate
AH ₃	Aluminum hydroxide gel
w/c	Water-to-cement ratio
V _f	Fiber volume fraction
<i>D</i>	Correlation dimension
<i>R</i> ²	Coefficient of determination
<i>U</i>	Total input strain energy density
<i>U_e</i>	Elastic strain energy density
<i>U_d</i>	Dissipated energy density
<i>P_d</i>	Dissipative strain energy ratio
<i>P_a</i>	Mean value of dissipative strain energy ratio
<i>d</i>	Damage variable
<i>E</i>	Elastic modulus
<i>μ</i>	Poisson's ratio

References

1. Kesimal, A.; Yilmaz, E.; Ercikdi, B.; Alp, I.; Deveci, H. Effect of properties of tailings and binder on the short-and long-term strength and stability of cemented paste backfill. *Mater. Lett.* **2005**, *59*, 3703–3709. [[CrossRef](#)]
2. Qi, C.; Fourie, A. Cemented paste backfill for mineral tailings management: Review and future perspectives. *Miner. Eng.* **2019**, *144*, 106025. [[CrossRef](#)]
3. Wu, A.; Wang, Y.; Ruan, Z.; Lu, H.; Wu, X. The composite structure of surrounding rock and cemented paste backfill in metal mines: A review and prospect. *Geomech. Geoengin.* **2026**, *21*, 271–307. [[CrossRef](#)]
4. Zou, Y.; Sharief, W.; Li, Z.; Fan, J.; Jiang, D.; Nelias, D. Numerical assessment of the influence of residual rock mass properties on destress blasting in deep mine. *Earth Energy Sci.* **2025**, *1*, 324–335. [[CrossRef](#)]
5. Liu, S.; Yang, J.; Cui, L.; Zhang, Z.; Fang, K. Microcrack evolution and mechanical performance of fiber-reinforced high water-resistant concrete backfill: A quantitative multi-scale study. *Constr. Build. Mater.* **2026**, *531*, 146674. [[CrossRef](#)]

6. Zuo, J.; Hong, Z.; Xiong, Z.; Wang, C.; Song, H. Influence of different W/C on the performances and hydration progress of dual liquid high water backfilling material. *Constr. Build. Mater.* **2018**, *190*, 910–917. [\[CrossRef\]](#)
7. Liu, H.; Xia, Y.; Bai, J.; Cao, Z.; Zhang, Z.; Zhao, H. Tri-axial compressive behavior of high-water material for deep underground spaces. *Deep. Undergr. Sci. Eng.* **2025**, *4*, 482–497. [\[CrossRef\]](#)
8. Sun, K.; Zhang, J.; He, M.; Li, M.; Wang, C.; Feng, W.; Li, F. Mechanical properties and damage evolution characteristics based on the acoustic emission of gangue and high-water-content materials based cemented paste backfill. *Constr. Build. Mater.* **2023**, *395*, 132324. [\[CrossRef\]](#)
9. Cavusoglu, I.; Yilmaz, E.; Yilmaz, A.O. Sodium silicate effect on setting properties, strength behavior and microstructure of cemented coal fly ash backfill. *Powder Technol.* **2021**, *384*, 17–28. [\[CrossRef\]](#)
10. Martínez, J.R.; Ríos, J.; Pérez-Soriano, E.M.; Cifuentes, H.; Leiva, C. Enhancing the matrix-fiber bond in ultra-high-performance fiber-reinforced concrete using a high performance plasticizer. Impact on the flowability, physical and mechanical properties. *Constr. Build. Mater.* **2025**, *470*, 140683. [\[CrossRef\]](#)
11. Libos, I.L.S.; Cui, L. Time- and temperature-dependence of compressive and tensile behaviors of polypropylene fiber-reinforced cemented paste backfill. *Front. Struct. Civ. Eng.* **2021**, *15*, 1025–1037. [\[CrossRef\]](#)
12. Li, L.; Sun, H.-X.; Zhang, Y.; Yu, B. Surface cracking and fractal characteristics of bending fractured polypropylene fiber-reinforced geopolymer mortar. *Fractal Fract.* **2021**, *5*, 142. [\[CrossRef\]](#)
13. Alsaif, A.; Abbas, Y.M. Mechanical and durability enhancements of lightweight fiber-reinforced cementitious composites via integration of recycled tire and industrial steel fibers. *J. Build. Eng.* **2025**, *111*, 113420. [\[CrossRef\]](#)
14. Xue, G.; Yilmaz, E.; Song, W.; Cao, S. Mechanical, flexural and microstructural properties of cement-tailings matrix composites: Effects of fiber type and dosage. *Compos. Part B Eng.* **2019**, *172*, 131–142. [\[CrossRef\]](#)
15. Liu, S.; Fall, M. The significance of mixing time in the development of the engineering properties of cemented fiber-reinforced tailings materials. *J. Build. Eng.* **2024**, *96*, 110648. [\[CrossRef\]](#)
16. Song, X.; Hao, Y. Mechanical response of stress damaged cemented tailings backfill based on pore structure and acoustic emission characteristics. *Constr. Build. Mater.* **2023**, *404*, 133278. [\[CrossRef\]](#)
17. Yang, J.; Zhao, K.; Yu, X.; Yan, Y.; He, Z.; Zhou, Y.; Lai, Y. Fracture evolution of fiber-reinforced backfill based on acoustic emission fractal dimension and b-value. *Cem. Concr. Compos.* **2022**, *134*, 104739. [\[CrossRef\]](#)
18. Sun, B.; Yan, Y.; Wang, S.; Qi, C.; Yang, H.; Zeng, S. Self-organized criticality and b-value characteristics of acoustic emission of rocks under different stress paths. *Rock Mech. Rock Eng.* **2025**, *58*, 851–866. [\[CrossRef\]](#)
19. Xing, L.; Wang, C.; Liang, M.; Zhang, B. Acoustic emission-based intelligent identification and dual early warning for coal fatigue failure under multistage cyclic loading. *Sci. Rep.* **2026**, *16*, 22949. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Albano, A.M.; Muench, J.; Schwartz, C.; Mees, A.I.; Rapp, P.E. Singular-value decomposition and the Grassberger-Procaccia algorithm. *Phys. Rev. A* **1988**, *38*, 3017. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Liu, D.; Zhang, W.; Jian, Y.; Tang, Y.; Cao, K. Damage precursors of sulfate erosion concrete based on acoustic emission multifractal characteristics and b-value. *Constr. Build. Mater.* **2024**, *419*, 135380. [\[CrossRef\]](#)
22. Zhang, M.; Zhang, J.; Fan, J.; Li, Z.; Chen, J.; Zou, Y.; Jiang, D.; Nelias, D. Model Interpretability and Intensity Prediction of Rockbursts Using a Method Innovation Based on the QGHSCSO-CatBoost Algorithm. *Rock Mech. Rock Eng.* **2026**, *59*, 2107–2136. [\[CrossRef\]](#)
23. Zhao, K.; Huang, Q.; Zhou, Y.; Yan, Y.; Yang, J.; Ma, C.; Nie, Q.; Chen, J.; Shi, Y. Fractal characteristics and acoustic emission b-value of cement superfine tailings backfill with initial defect consideration. *Nondestruct. Test. Eval.* **2024**, *39*, 384–407. [\[CrossRef\]](#)
24. Li, C.; Ma, Q.; Mao, T. Study on b-Value Characteristics of Acoustic Emission of Cemented Waste Rock Backfills during Short-Term Creep Process. *Metall. Min. Ind.* **2015**, *9*, 316.
25. Abdulkadir, S.B.; Chen, Q.; Yilmaz, E.; Wang, D. Comparative and meta-analysis evaluation of non-destructive testing methods for strength assessment of cemented paste backfill: Implications for sustainable pavement and concrete materials. *Materials* **2025**, *18*, 2888. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Liu, Z.; Fall, M. Cement-stabilized marine clay under thermal cycling: Strength, suction, and microstructure. *Int. J. Geo-Eng.* **2026**, *17*, 17. [\[CrossRef\]](#)
27. Yang, X.; Pan, C.; Zuo, Y.; Li, S.; Cao, J.; Pang, J.; Luo, Z.; Han, T.; Lv, D. Mechanical properties and failure mechanism of polypropylene fiber-reinforced phosphogypsum-based backfill material. *Structures* **2026**, *86*, 111393. [\[CrossRef\]](#)
28. Liu, S.; Zhang, Z.; Li, Z.; Fan, J.; Zou, Y.; Nelias, D. Fiber-Reinforced Roadside Backfill Body for Gob-Side Entry Retaining: Fracture Resistance, Damage Evolution, and Field Performance. *Rock Mech. Rock Eng.* **2026**. [\[CrossRef\]](#)
29. Zhou, W.-H.; Garg, A.; Garg, A. Study of the volumetric water content based on density, suction and initial water content. *Measurement* **2016**, *94*, 531–537. [\[CrossRef\]](#)
30. Decagon Devices Inc. 5TE Water Content, EC and Temperature Sensors: Operator's Manual, Version 4. Available online: <https://www.agrolan.com/UploadProductFiles/5TE%20manual.pdf> (accessed on 12 August 2026).

31. Li, L.G.; Xiao, B.-F.; Qian, Y. Glass fiber-reinforced mortar: Roles of average water film thickness and fiber length in fresh behaviours. *Constr. Build. Mater.* **2025**, *484*, 141857. [\[CrossRef\]](#)
32. Ipindola, O.; Shokouhian, M. Effect of polycarboxylate superplasticiser on the early-age behaviour of OPC-CSA mortar. *Proc. Inst. Civ. Eng.-Constr. Mater.* **2025**, *178*, 378–389. [\[CrossRef\]](#)
33. ASTM C807-21; Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle. ASTM International: West Conshohocken, PA, USA, 2021.
34. Sagade, A.; Fall, M. Study of fresh properties of cemented paste backfill material with ternary cement blends. *Constr. Build. Mater.* **2024**, *411*, 134287. [\[CrossRef\]](#)
35. Liu, S.; Fall, M.; Haruna, S. Understanding the Triaxial Behavior of Cemented Tailings Backfill Reinforced with Fibers. *Int. J. Geomech.* **2025**, *25*, 04025078. [\[CrossRef\]](#)
36. Colombo, I.S.; Main, I.; Forde, M. Assessing damage of reinforced concrete beam using “b-value” analysis of acoustic emission signals. *J. Mater. Civ. Eng.* **2003**, *15*, 280–286. [\[CrossRef\]](#)
37. Zhang, Y.; Zhou, C.; Liu, Y.; Wang, F.; Wang, X. Fractal-guided aggregate gradation design and fracture evolution characterization of fiber-reinforced coal gangue/slag-based geopolymer concrete. *Constr. Build. Mater.* **2026**, *534*, 146871. [\[CrossRef\]](#)
38. Holsamudrkar, N.; Banerjee, S. Acoustic Emission (AE) based health monitoring of RC beams strengthened with mechanically anchored hybrid Fiber Reinforced Cementitious Matrix (FRCM) system. *Case Stud. Constr. Mater.* **2024**, *21*, e03773. [\[CrossRef\]](#)
39. Gutenberg, B.; Richter, C.F. Frequency of earthquakes in California. *Bull. Seismol. Soc. Am.* **1944**, *34*, 185–188. [\[CrossRef\]](#)
40. Pang, B.; Zhang, R.; Yang, X.; Hou, X.; Tao, S.; Wang, Z. Interface engineered glass fibers improve performance and durability of stabilized silty clay. *iScience* **2026**, *29*, 116327. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Cao, S.; Che, C.; Zhang, Y.; Shan, C.; Liu, Y.; Zhao, C.; Du, S. Mechanical properties and damage evolution characteristics of waste tire steel fiber-modified cemented paste backfill. *Int. J. Min. Sci. Technol.* **2024**, *34*, 909–924. [\[CrossRef\]](#)
42. Liu, H.; Cao, W.; Cao, Z.; Sun, J.; Yu, B.; Zhao, H. Influence of stress path on the mechanical behavior of laterally confined coal. *Constr. Build. Mater.* **2025**, *466*, 140287. [\[CrossRef\]](#)
43. Yang, J.; Fall, M.; Guo, G. A three-dimensional hydro-mechanical model for simulation of dilatancy controlled gas flow in anisotropic claystone. *Rock Mech. Rock Eng.* **2020**, *53*, 4091–4116. [\[CrossRef\]](#)
44. Sun, X.; Zhang, Z.; Yu, W.; Liu, S.; Liu, Z.; Xu, S. Intelligent calibration of discrete element microscopic parameters using BP-RIP-Opt algorithm: Application to medium-hard rock simulations. *Powder Technol.* **2026**, *469*, 121769. [\[CrossRef\]](#)
45. Rychlewski, J. On Hooke’s law. *J. Appl. Math. Mech.* **1984**, *48*, 303–314. [\[CrossRef\]](#)
46. Xu, S.; Zhang, Z.; Yu, W.; Liu, S.; Yu, X.; Wu, Q.; Wu, H. Mechanical Properties and Damage Constitutive Model of Coal Subjected to Drying Temperatures and Anchored Conditions Under Impact Loading. *Nat. Resour. Res.* **2026**, *35*, 2731–2754. [\[CrossRef\]](#)
47. Meng, Y.; Gao, D.; Yang, L.; Fang, J. Properties of green ultra-high performance sulfoaluminate cement concrete incorporating recycled sand under sustained low temperature curing. *Cem. Concr. Compos.* **2025**, *164*, 106291. [\[CrossRef\]](#)
48. Zhao, J.; Ahmed, A.H.; Liebscher, M.; Karalis, G.; Al Saif, R.; Butler, M.; Mechtcherine, V. Temperature induced fast-setting of cement based mineral-impregnated carbon-fiber reinforcements for durable and lightweight construction with textile-reinforced concrete. *Cem. Concr. Compos.* **2024**, *154*, 105766. [\[CrossRef\]](#)
49. Günzel, F.; Moelich, G.; Kanyenze, S.; Kruger, P.; Combrinck, R. Investigating inherent cement setting mechanisms to improve the constructability performance of extrusion-based 3D concrete printing. *Innov. Infrastruct. Solut.* **2024**, *9*, 480. [\[CrossRef\]](#)
50. Gupta, Y.; Liu, Q.; Richards, J.J. Physical scaling for predicting shear viscosity and memory effects of lithium-ion battery cathode slurries. *Soft Matter* **2025**, *21*, 1489–1497. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Roshani, A.; Fall, M. Rheological properties of cemented paste backfill with nano-silica: Link to curing temperature. *Cem. Concr. Compos.* **2020**, *114*, 103785. [\[CrossRef\]](#)
52. Sofla, S.J.D.; James, L.A.; Zhang, Y. Insight into the stability of hydrophilic silica nanoparticles in seawater for Enhanced oil recovery implications. *Fuel* **2018**, *216*, 559–571. [\[CrossRef\]](#)
53. Si, W.; Cao, M.; Li, L. Establishment of fiber factor for rheological and mechanical performance of polyvinyl alcohol (PVA) fiber reinforced mortar. *Constr. Build. Mater.* **2020**, *265*, 120347. [\[CrossRef\]](#)
54. Cao, M.; Si, W.; Xie, C. Relationship of rheology, fiber dispersion, and strengths of polyvinyl alcohol fiber-reinforced cementitious composites. *ACI Mater. J.* **2020**, *117*, 191–204. [\[CrossRef\]](#)
55. Wang, W.; Shen, A.; Lyu, Z.; He, Z.; Nguyen, K.T.Q. Fresh and rheological characteristics of fiber reinforced concrete—A review. *Constr. Build. Mater.* **2021**, *296*, 123734. [\[CrossRef\]](#)
56. Zhang, J.; Guan, X.; Li, H.; Liu, X. Performance and hydration study of ultra-fine sulfoaluminate cement-based double liquid grouting material. *Constr. Build. Mater.* **2017**, *132*, 262–270. [\[CrossRef\]](#)
57. Cui, H.; Grace, J.R. Flow of pulp fibre suspension and slurries: A review. *Int. J. Multiph. Flow* **2007**, *33*, 921–934. [\[CrossRef\]](#)

58. Jiang, M.; Cao, S.; Yilmaz, E. Enhanced strength and fracture features of tailings-based concrete reinforced with fibers and X-shaped rocks. *J. Mater. Res. Technol.* **2025**, *36*, 62–71. [[CrossRef](#)]
59. Zhang, Y.; Wang, Y.; Li, T.; Xiong, Z.; Sun, Y. Effects of lithium carbonate on performances of sulpoaluminate cement-based dual liquid high water material and its mechanisms. *Constr. Build. Mater.* **2018**, *161*, 374–380. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.