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Compliant auxetic cementitious composites for piezoresistive sensing

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ABSTRACT

Auxetic cementitious cellular composites (ACCCs) exhibit high compressive deformation with recoverable behavior, demonstrating strong potential for self-sensing applications. In this study, compliant piezoresistive ACCCs were engineered to combine auxetic behavior with piezoresistive properties by reinforcing a cementitious matrix with polyvinyl alcohol (PVA) and carbon fibers. Uniaxial compression tests were conducted to evaluate their piezoresistive responses in damage sensing across distinct deformation stages, while Digital Image Correlation (DIC) and Acoustic Emission (AE) techniques were employed to investigate corresponding deformation and damage mechanisms. Cyclic loading tests further assessed the flexible sensing behavior of ACCCs within the recoverable deformation during the auxetic behavior range, with further insights obtained from microscopic analysis and X-ray computed tomography (CT). The piezoresistive sensing behavior of two typical ACCC specimens with different geometries was compared. The results demonstrate that the auxetic behavior promotes high compressive deformation, which can be delineated into four distinct mechanical stages. Each stage corresponds to specific damage mechanisms and exhibits characteristic piezoresistive responses, as reflected by stage-dependent variations in the fractional change in resistance (FCR). This staged behavior effectively extends the sensing range for damage detection. Under cyclic loading, the composites exhibit a reproducible piezoresistive response across an extended self-sensing range, attributable to their substantial recoverable deformation. This behavior highlights their superior strain and stress sensitivity, although residual plastic deformation progressively increases with greater loading amplitude. Given wide availability of cementitious materials, highly deformable ACCCs with piezoresistive strain/stress and damage sensing capabilities offer a cost-effective and sustainable solution for in-situ, real-time structural health monitoring.

1. Introduction

Conventional materials possess a positive Poisson's ratio, exhibiting lateral expansion under compression and lateral contraction under tension. In contrast, auxetic materials exhibit a negative Poisson's ratio, contracting laterally under compression and expanding laterally under tension [1–3]. Owing to this distinctive deformation behavior, auxetic cementitious composites have demonstrated favorable mechanical properties, including high fracture resistance and energy dissipation, due to their unique deformation characteristics. Xu et al. [4] utilized a fiber-reinforced cementitious composite as the foundational material and engineered a cellular structure with regularly spaced elliptical perforations, known as elliptical-shaped auxetic cementitious cellular composites (ACCCs). Undergoing uniaxial compression, the ACCCs exhibited an auxetic behavior characterized by a negative Poisson's

ratio. This distinct behavior observed was ascribed to the crack bridging mechanism occurring within the cementitious matrix. Once pre-compressed to a specific displacement, this elliptical-shaped ACCC demonstrated a level of recoverable deformation and a quasi-elastic response when exposed to dynamic cyclic loading [4–6]. Based on this, Xie et al. [5] have leveraged this innovative capability for energy harvesting by integrating PVDF (Polyvinylidene Fluoride) into ACCCs. Energy harvesting experiments have shown that the ACCC-PVDF system generates a sinusoidal output voltage with peaks reaching several volts during each cycle of cyclic loading. Xu et al. [7] developed a 3D auxetic cementitious-polymeric composite structure (3D-ACPC) comprising a 3D printed polymeric shell and cementitious mortar. This composite exhibits compressive strain-hardening behavior, ensuring high capacity for energy absorption. Chen et al. [8] fabricated 2D re-entrant, cross-chiral, and buckling-induced auxetic structures using engineered

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cementitious composites (ECC) and investigated their mechanical response through uniaxial compressive and flexural testing. Xie et al. [9] further developed peanut-shaped ACCCs to enhance energy dissipation capability, ductility, and toughness by mitigating stress concentration through the incorporation of peanut-shaped holes. Additionally, incorporating 3D-printed polymeric auxetic reinforcement structures into cementitious mortar produces composites with enhanced properties [10–14], such as notable compressive ductility, high recoverable deformability, and superior energy dissipation capability. However, current research on ACCCs is primarily focused on their mechanical behavior, with limited attention given to multifunctional properties such as self-sensing performances.

Recent studies have mainly explored the use of auxetic materials fabricated from metals and polymers for multifunctional applications such as self-sensing. Among them, auxetic structures serve as substrates onto which sensing materials (such as piezoelectric materials) are integrated [15–17]. The unique characteristics of auxetic materials—particularly their ability to undergo large deformations and exhibit elastomer-like behavior—are harnessed to enhance performance in self-sensing and potential energy harvesting applications. Many studies incorporated conductive materials (such as graphene oxide, carbon nanotube (CNT)) into polymer materials to fabricate piezoresistive auxetic sensor [18,19]. These approaches provide valuable references and insights that can be applied to the development of self-sensing capabilities in ACCCs.

Conductive fillers, such as carbon-based materials, have been added into cementitious composites to develop self-sensing cementitious composites (SSCC) [20,21]. Intrinsically self-sensing cementitious composites, exhibiting piezoresistive or pressure-sensitive properties, are structural materials formulated by incorporating conductive fillers—such as carbon fibers (CF) [22–28], carbon black [29–32], graphite [33,34], graphene [35–37], or carbon nanotubes (CNTs) [38–43]—into conventional concrete. This integrated design allows cementitious materials to generate their own monitoring data by detecting resistance variations in response to applied stress or strain. This eliminates the need for embedded, surface-mounted, or external sensors, making long-term and large-scale infrastructure monitoring more practical and cost-effective [44,45]. Despite these advantages, the inherent brittleness and limited deformability of SSCCs present significant challenges, restricting their practical applications in engineering scenarios that require high ductility. Fiber-reinforced cementitious materials—such as strain-hardening cementitious composites (SHCCs)—have been explored due to their superior tensile strain-hardening characteristics and excellent crack control capabilities [46–54], which present a promising route for enhancing the deformability of self-sensing cementitious materials. Several researchers have investigated strain-hardening cementitious composites incorporating conductive fillers, such as strain-hardening steel fiber-reinforced cementitious composites [55–57], ultra-high performance concrete (UHPC) embedded with CNTs [41,58], Engineered Cementitious Composite (ECC) containing carbon black [59]. These composites exhibit high ductility through multiple cracking, which extends the material's sensing range and enhances its damage-sensing capability [55]. This not only enables their application as self-sensing materials for strain measurement, but also facilitates the early detection of crack propagation and provides critical information on damage development in concrete structures [60], thereby supporting timely maintenance to prevent potential catastrophic failures. In response to the growing demand for deformable sensing materials in seismic infrastructure monitoring, Dang et al. [61] fabricated highly deformable self-sensing cementitious composites through monomer polymerization, enabling their application in full-scale shear wall monitoring under seismic loading. More recently, the incorporation of auxetic mechanisms has emerged as a promising strategy to further enhance the deformability of SSCCs. Barri et al. [62] integrated concrete mixture with graphite powder and auxetic polymer structures, resulting in a concrete material system that exhibits

unprecedented mechanical and electrical tunability due to snap-through buckling behavior. Xu et al. [63] incorporated carbon fiber into auxetic cementitious composites to enable electromechanical functionality. Similarly, Valverde-Burneo et al. [64] incorporated carbon fiber into flexible mortar to induce piezoresistive behavior in auxetic cementitious composites; however, the desired densification range was not achieved, which is attributed to the limited fiber bridging capacity at the joints of the auxetic composites.

In this study, highly deformable piezoresistive ACCCs were developed by reinforcing cementitious materials with both PVA fibers and carbon fibers (conductive fillers), aiming to achieve auxetic behavior and electrical conductivity. Uniaxial compression tests were carried out to characterize their sensing capabilities across different deformation stages. To gain insight into the associated deformation and damage mechanisms, DIC and acoustic emission techniques were utilized. Additionally, cyclic loading tests were performed to evaluate sensing performance within the recoverable deformation range, with further insights obtained from microscopic analysis and X-ray CT. Considering the abundance and cost-effectiveness of cement-based materials, highly deformable piezoresistive ACCCs offer a viable solution for in-situ and real-time sensing of crack propagation and damage evolution as a non-destructive testing (NDT) technique. Their recoverable deformation during their auxetic behavior range also enables their use as piezoresistive strain or stress sensors. This supports the advancement of smart civil infrastructure with integrated strain/stress, and damage sensing capabilities.

2. Experiments

2.1. Design of piezoresistive ACCCs for self-sensing

Self-sensing cementitious materials generally suffer from high brittleness and limited deformability, significantly constraining their applicability in engineering practice. In contrast, auxetic cementitious composites exhibit large compressive deformation enabled by their auxetic behavior, in which rotation of sections around hinge joints accommodates the applied compressive strains. This compliant mechanical response allows ACCCs to undergo distinct deformation stages driven by structural transformation and subsequent densification (i.e., internal reconfiguration of ACCCs), as shown in Fig. 1. Each of these stages corresponds to unique structural configurations associated with distinct stress levels. The underlying concept is that, when integrated with conductive materials, the highly deformable ACCCs can leverage their large deformation capacity to achieve an extended self-sensing range—surpassing the narrow detection limits typical of conventional brittle cement-based sensors.

Under monotonic compression, these distinct deformation stages are accompanied by characteristic crack initiation and propagation, which continuously modify the conductive network and result in an irreversible increase in electrical resistance. Consequently, the stage-dependent FCR response reflects the evolution of structural damage and enables multi-stage damage sensing. Notably, the sequential deformation stages exhibit different piezoresistive behaviors with distinct sensitivity magnitudes, thereby enabling multi-stage damage sensing performance across a broader range of compressive strain. This characteristic is particularly advantageous for applications requiring large sensor deformations, such as during seismic events, where conventional brittle cementitious sensors may be prone to failure.

In contrast, within the recoverable auxetic deformation range, ACCCs exhibit quasi-elastic behavior that makes them well suited for repeated strain or stress sensing. Under cyclic loading, the conductive network is reversibly changed while generating stable and repeatable piezoresistive signals in response to repeated strain or stress inputs, as illustrated in Fig. 1. Therefore, the monotonic and cyclic responses represent two distinct sensing regimes: the former is primarily associated with irreversible damage sensing, whereas the latter enables

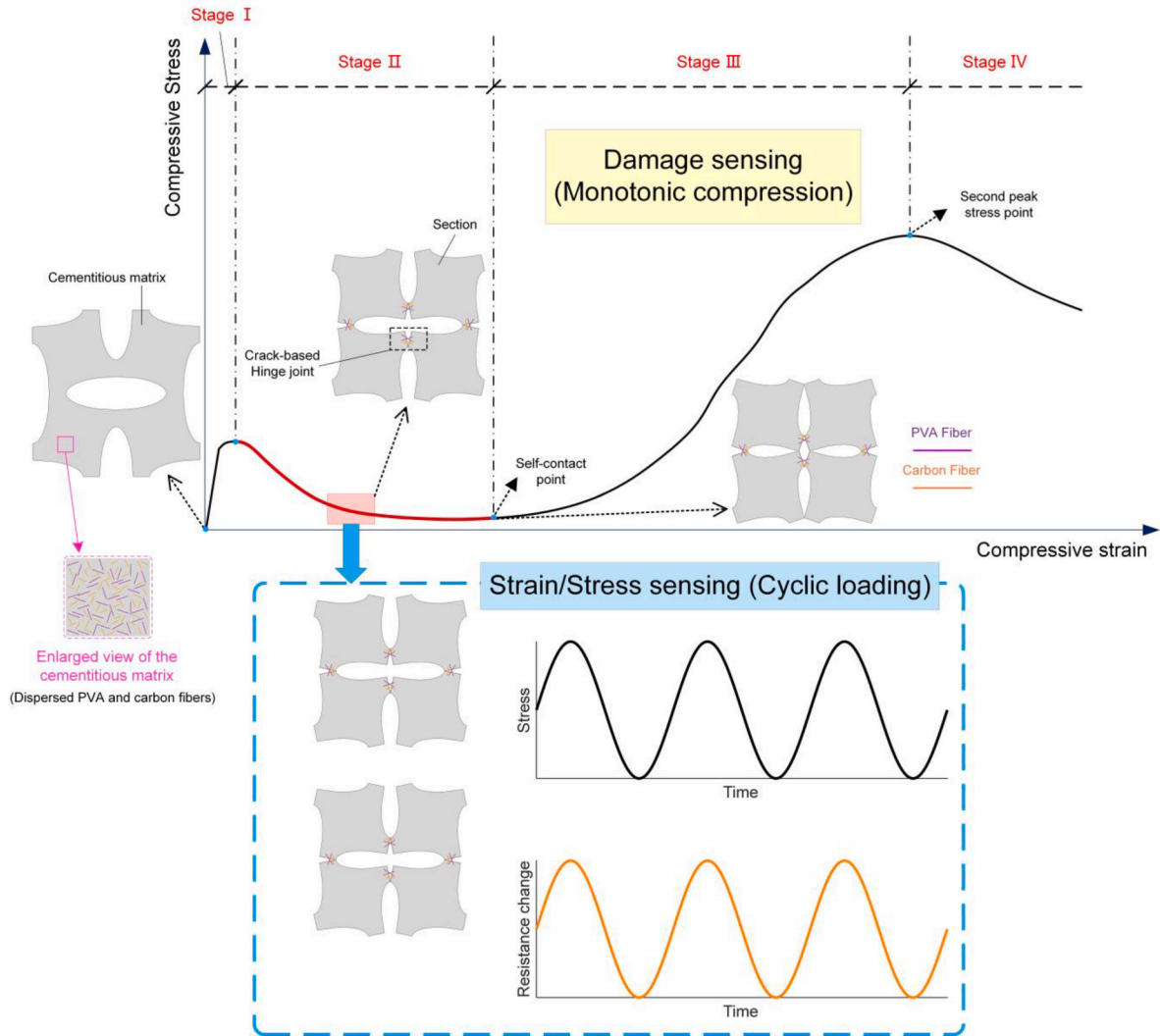


Fig. 1. Conceptual illustration of the two sensing regimes in piezoresistive ACCCs: irreversible damage sensing during monotonic compression and reversible strain/stress sensing during cyclic loading. An enlarged view of the cementitious matrix is provided on the left to illustrate the distribution of PVA fibers and carbon fibers within the matrix.

reversible strain/stress sensing.

However, the incorporation of conductive fillers may adversely affect the mechanical performance of ACCCs and can further attenuate their auxetic behavior due to reduced ductility. Consequently, achieving an optimal balance between electrical conductivity and mechanical integrity constitutes a critical design objective. Previous studies [6,65] have shown that mixtures with an extended softening range can promote the formation of hinge-like joints within the auxetic deformation range. Additionally, these mixtures should retain sufficient compressive strength to allow joint rotation upon contact with loading plates without causing structural failure. Building on earlier mixtures that employed PVA fibers to enhance the ductility of cementitious composites, carbon fibers were further selected as the conductive filler in this study. This selection is based on their inherent fiber-bridging ability within cementitious matrices, which provides a favorable balance between mechanical strength and electrical conductivity—unlike other conductive additives, such as carbon black, which lack fiber-reinforcing capabilities.

2.2. Specimen geometry and manufacturing

Besides the constituent materials, the compressive deformation of ACCCs was strongly affected by their geometric features. In previous

study [65,66], elliptical ACCCs with chiral sections (P25 and P50) exhibited a negative Poisson's ratio, demonstrating auxetic behavior under quasi-static compression. The designations P25 and P50 indicate the percentage increase in the major axis length relative to a specimen with a circular hole, corresponding to 25% and 50%, respectively. In contrast, specimens with circular holes showed no auxetic behavior under compression [65]. Hence, specimens P25 and P50 were selected for investigation of their piezoresistive behavior. The design parameters of P25 and P50 are summarized in Fig. 2 and Table 1, including l (specimen side length), a (half major-axis length of the elliptical hole), b (half minor-axis length of the elliptical hole), l_g (ligament length). The aspect ratio of the hole in ACCCs is defined as the ratio of the major axis to the minor axis. The hole in the P50 specimen has a higher aspect ratio than that in the P25 specimen, resulting in a smaller compressible space. Notably, P50 demonstrated a greater magnitude of negative Poisson's ratio than P25 prior to self-contact within their central elliptical holes during uniaxial compression [65]. d_{ab} is obtained by Eq. (1) and is inversely proportional to the compression force required for section rotation in the ACCC shape for auxetic behavior (see Appendix A).

$$d_{ab} = (a - b)/l \quad (1)$$

As shown in Fig. 2, the specimens were produced using an "indirect printing" technique combined with additive manufacturing-assisted

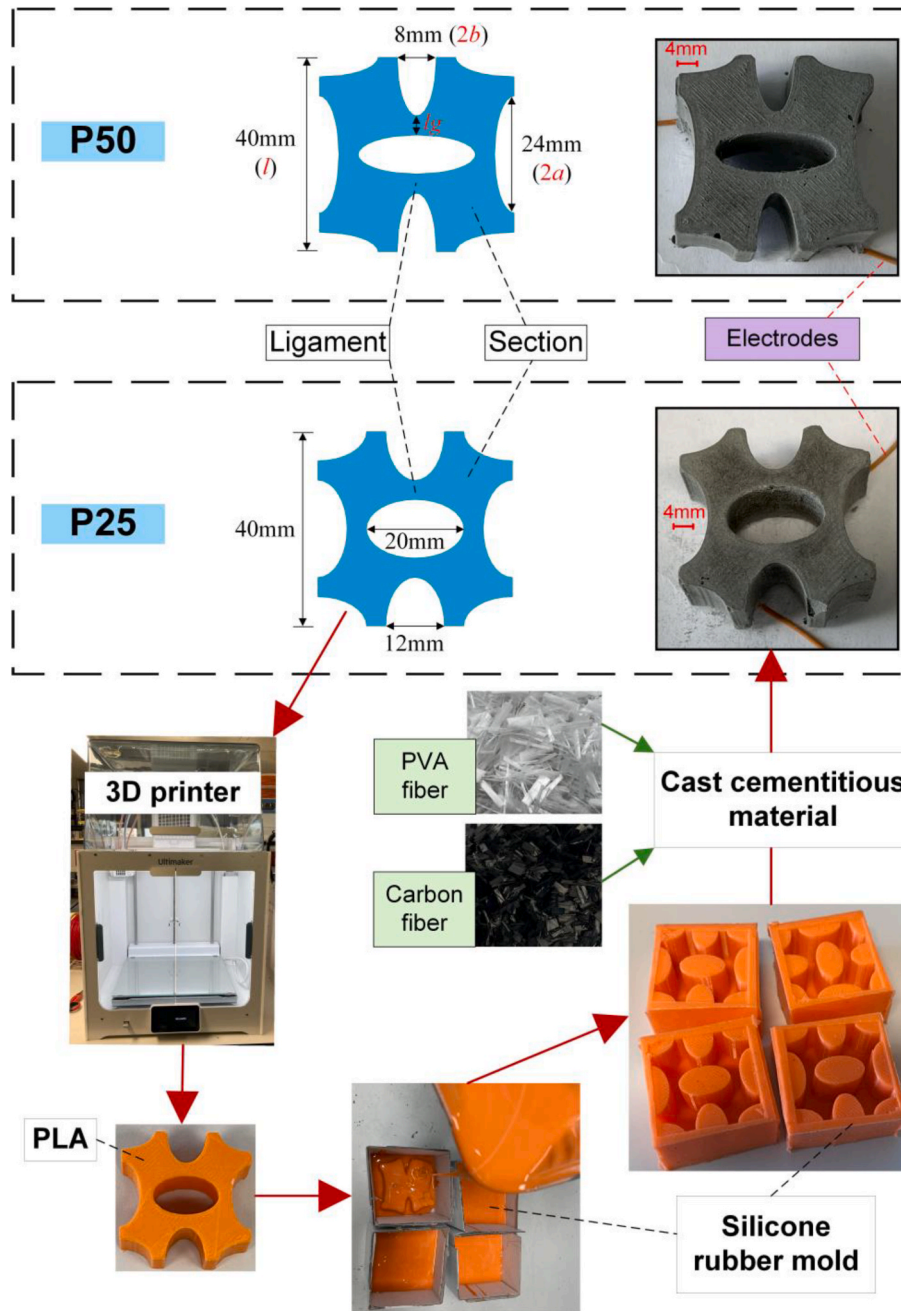


Fig. 2. Geometric parameters and manufacturing process of piezoresistive ACCC specimens.

Table 1
Geometric parameters of ACCC specimens.

Specimen	l (mm)	a (mm)	b (mm)	lg (mm)	d_{ab} (mm)	One Hole area (mm ²)	Specimen area (mm ²)	Specimen volume (mm ³)	Relative density
P25	40	10	6	4	0.1	188.5	846.0	16920.0	52.9%
P50	40	12	4	4	0.2	150.8	996.8	19936.0	62.3%

casting, as indicated in our previous study [6]. The geometric design parameters of the ACCCs were developed in Abaqus and exported as STL files. The STL files were used to fabricate polylactic acid (PLA) patterns using an Ultimaker S5 fused deposition modeling (FDM) 3D printer equipped with a 0.4 mm nozzle. The printed PLA patterns were subsequently used to produce silicone molds for casting the ACCC specimens. Owing to the printing accuracy of the FDM process and the use of a 0.4 mm nozzle, the dimensions of the printed PLA patterns may deviate

from the designed geometry by up to 0.4 mm. The mixture proportions of the ACCCs, detailed in Table 2, were tailored based on a previous study including CEM I 42.5 N, fly ash, sand (125 to 250 μm grain size), water, polycarboxylate superplasticizer, viscosity modifying agent (VMA), and Polyvinyl Alcohol (PVA) fiber and carbon fiber (CF). A fine-grained fiber reinforced mortar served as the constituent material, with RECS15 PVA fiber from Kuraray GmbH used as reinforcement at a 2.0% volume fraction and carbon fiber as a 1.0% volume fraction, as

Table 2

Mixing proportions of cementitious matrix (g/L).

Water-to-binder ratio	CEM I 42.5 N	Fly ash	Sand (125 μ m to 250 μ m)	Water	Superplasticizer (Glenium 51)	VMA	PVA fiber (by volume)	Carbon fiber (by volume)
0.50	446	527	446	489	2.0	0.5	2%	1%

shown in Table 3. Methylcellulose powder from Shanghai Ying Jia Industrial Development Co. Ltd. was employed as a VMA to enhance fiber distribution. MasterGlenium 51, a polycarboxylate-based superplasticizer by BASF (Germany), was utilized to achieve the desired workability. A water-to-binder ratio of 0.5 was chosen to ensure proper casting of the cement materials into the small mold, promoting good fluidity. The dry ingredients, which included CEM I 42.5, fly ash, sand, and VMA, were mixed using a Hobart machine for a duration of 4 min. Following this, water and superplasticizer were introduced into the dry mixture, and an additional mixing period of 2 min ensued. Subsequently, PVA fibers were then gradually introduced into the mortar and mixed for another 2 min. After that, carbon fibers were slowly added and mixed for an additional 2 min. To ensure uniform distribution of the fibers within the matrix, a high-speed rotation was applied for an additional 5 min. The fresh paste was then poured into silicone molds, filling each mold in two layers. Each layer underwent 20 s of vibration to ensure proper consolidation and uniform fiber distribution. Finally, two thin copper wires were embedded at the center of the specimen section along the diagonal, and plastic films with pre-reserved holes for accommodating the wires were applied to cover the molds, thereby preventing evaporation. All specimens were kept under laboratory ambient conditions for three days until sufficient mechanical strength was achieved for demolding. They were subsequently sealed in bags and cured for a total of 28 days to minimize moisture loss and maintain a comparable moisture state among the specimens.

With respect to the carbon fiber content, previous studies have generally reported that the electrical percolation threshold of carbon-fiber-reinforced cementitious composites is typically no greater than 1 vol%, although the reported values vary depending on the matrix composition, fiber characteristics, and fiber dispersion, with some studies reporting thresholds above 0.5 vol% [67–69]. Dong et al. [70] reported that the electrical resistivity of recycled carbon-fiber-reinforced cementitious composites decreased sharply as the carbon fiber content increased from 0 to 1 vol%, indicating that the conductive percolation threshold was close to 1 vol%. Beyond this content, the resistivity remained nearly constant, suggesting that a stable conductive network had been established. Therefore, 1 vol% carbon fiber was selected in the present study to ensure the formation of a stable and continuous conductive network. Furthermore, the cementitious mixture used in this study contains 2 vol% PVA fibers, which has previously been demonstrated to provide stable auxetic deformation and repeatable recoverable behavior of ACCCs [71]. The present study was therefore developed based on this validated mixture by incorporating an additional 1 vol% carbon fibers to introduce piezoresistive functionality while preserving the desired mechanical performance. Increasing the carbon fiber content would substantially increase the total fiber volume fraction, making fiber dispersion and mixing more difficult and potentially deteriorating the mechanical properties of the matrix, such as its strain-hardening behavior, as well as the stable auxetic deformation of the ACCCs.

Table 3

Material properties of fibers.

Fiber type	Diameter (μ m)	Length (mm)	Tensile strength (GPa)	Young's modulus (Gpa)	Density (g/cm ³)	Ultimate strain	Carbon content	volume resistivity (Ω -cm)
Carbon	8	6	3.7	235	1.75	-	>95%	1.5×10^{-3}
PVA	40	8	1.6	41	1.3	6.0%		

2.3. Experimental test

2.3.1. Mechanical property tests of material matrix

Uniaxial tensile tests were conducted on dog-bone specimens to characterize the tensile behavior of the cementitious matrix, following the procedure described in our previous study [9]. The dog-bone specimen dimensions follow the recommendations of the Japan Society of Civil Engineers [72]. These tests were performed on a TREBEL machine under displacement control, with a constant loading rate of 0.005 mm/s. Displacement within the gauge region was measured using linear variable differential transducers LVDTs. The compressive behavior of the cementitious matrix was determined through uniaxial compression tests, also following the setup from our previous study [9]. Tests were carried out on a UNITRONIC machine under deformation control at a displacement rate of 0.01 mm/s. Two LVDTs were mounted on opposite sides of each specimen to measure displacement. Cubic specimens with dimensions of 20 mm $\times$ 20 mm $\times$ 20 mm were prepared by cutting. A minimum of three replicates were tested for both uniaxial tension and compression.

2.3.2. Uniaxial compression test for piezoresistive ACCCs

As shown in Fig. 3a, uniaxial compression tests were conducted on piezoresistive ACCC specimens using a UNITRONIC machine under displacement control at a rate of 0.01 mm/s. To minimize friction between the specimens and the loading plates, plastic films were used, allowing for section rotation and facilitating the auxetic behavior (Fig. 3b). Additionally, the plastic films served as electrical insulation. Deformation across the entire specimen area was monitored using Digital Image Correlation (DIC) in Fig. 3a and b. Displacement measurements were recorded using Linear Variable Differential Transducers (LVDTs), as seen in Fig. 3b. For DIC analysis, the specimens were first painted white and then sprayed with a black speckle pattern. Images were captured every 10 s and processed with GOM Correlate software. The compressive stress-strain curve was derived by calculating stress as the compressive force divided by the initial cross-sectional area (40 mm $\times$ 20 mm) and strain as the applied displacement divided by the initial length (40 mm). To ensure the reliability of the results, at least three ACCC specimens were tested.

Conductive plates or meshes used as electrodes are typically embedded into the specimen. However, since the cross-sectional area of these embedded electrodes is often comparable to that of the specimen, it becomes difficult to ensure specimen integrity, making it prone to failure. In contrast, the use of fine copper wire electrodes minimizes the risk of compromising the mechanical properties of the specimen [73] while still providing stable electrical contacts. Therefore, two copper wires were diagonally embedded at the specimen center as electrodes (Fig. 3c) and connected to a digital multimeter (DMM) to measure the resistance of the piezoresistive ACCCs. The deformation and stress at the center of the section were negligible compared to those in the ligaments of the ACCC specimens. This helps minimize variations in contact resistance between the electrodes and cementitious materials when the

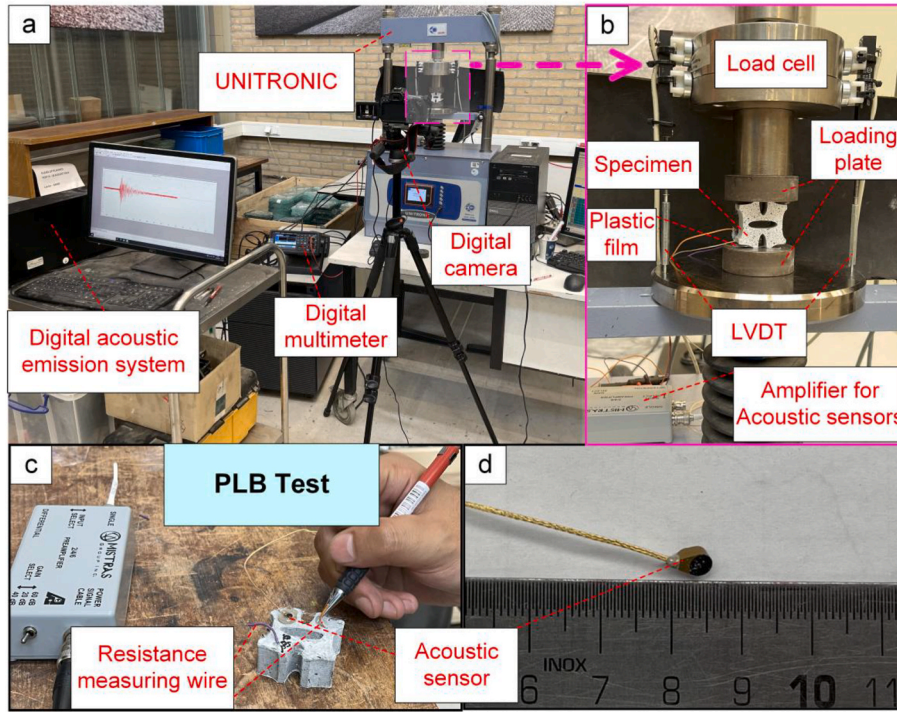


Fig. 3. Experimental setup for the uniaxial compression test of the piezoresistive ACCCs. (a) Overall testing system. (b) Detailed specimen configuration during compression. (c) PLB test for AE system verification. (d) Acoustic emission sensor used in the experiments.

specimens are stressed [21]. The relatively simple two-probe method is more suitable than the four-probe method for practical implementation in structures [40,58,70,74–79]. In the four-probe method, it is difficult to position two probes at a certain distance within the center of a section of ACCCs, and such placement may cause damage to the cross-sectional mechanical properties. This is because cracks in self-sensing cementitious materials tend to initiate around the embedded electrodes, as these electrodes introduce localized weaknesses into the structure [33,34]. Therefore, given the complex shape of ACCCs, the ease of arranging electrodes and wires during testing, and the need to minimize any damage to the specimen's mechanical integrity, the two-probe method was selected in this study [21]. The electrode positions and electrical connections remained unchanged throughout the experiments, thereby minimizing variations in contact resistance. All specimens underwent the same curing and conditioning procedures and were tested consecutively under laboratory ambient conditions. Therefore, all specimens were expected to have a comparable moisture state during testing, minimizing the influence of moisture variations on the comparative piezoresistive results. Due to the polarization effect, mechanical loading of the specimens was initiated once their electrical resistance had almost stabilized [30,31,33,34,40,78–83]. Although the polarization effect was controlled in the present study, its systematic quantification was not performed. A detailed investigation of polarization behavior and its influence on the piezoresistive response will be carried out in future work.

The fractional change of resistance (FCR) characterizes the self-sensing response of the specimen to deformation under stress conditions [84].

$$FCR = \frac{R - R_0}{R_0} = \Delta R / R_0 \quad (2)$$

where R refers to the resistance during compression. The electrical resistance before loading is chosen as the initial resistance R_0 . ΔR represents the change in resistance relative to R_0 .

Three specimens of each ACCC shape were tested under compression to measure their resistance changes. An additional specimen of each shape was employed to simultaneously monitor in situ electrical

resistance variations and acoustic emission for real-time damage detection in ACCCs. One miniature AE sensor (S9225 miniature sensor, 3.6 mm × 2.4 mm; operating frequency range: 300–1800 kHz) were attached to the center of the section of ACCCs, where stress and deformation are minimal, to capture acoustic emissions associated with material cracking during compression. As seen in Fig. 3c and d, the miniature AE sensor is much smaller than the dimensions of the ACCC specimens. The acoustic data were acquired using a Micro-II Express AE Chassis (Mistras Group, Inc.) [85–87] and subsequently processed in MATLAB. The AE signals were pre-amplified using a 40 dB threshold and then transmitted to the AE acquisition system. To ensure effective acoustic coupling between the sensors and the specimen surface, a silicone grease coupling agent was applied during installation, while also providing electrical insulation. The initial resistance of the specimens was measured both before and after bonding the AE sensors to confirm that their attachment did not influence the resistance measurement. Before testing, a Pencil Lead Break (PLB) test was performed on each specimen to calibrate the acquisition system and ensure sufficient signal amplitude, as shown in Fig. 3c. Following calibration, AE signals were continuously recorded during mechanical testing. As shown in Fig. 4a, the extracted key AE signal features include rise time (ms), counts (number of threshold crossings), duration (ms), amplitude (dB), energy (aJ). Previous research [88–92] has indicated that the characteristics of acoustic emission signals are correlated with specific damage mechanisms, which can be distinguished through AF (average frequency)–RA (rise time–amplitude ratio) analysis (Fig. 4b). AF is defined as the ratio of threshold crossing counts to signal duration, with high AF values reflecting sharp, high-frequency signals. RA represents the ratio of rise time to peak amplitude, therefore higher RA values suggest slower damage propagation. By analyzing AF and RA, damage types can be classified: high AF and low RA typically indicate tensile damage mode (such as tensile matrix cracks, fiber breakage), while low AF and high RA are associated with shear damage mode commonly linked to shear cracks, interfacial debonding or frictional sliding. As indicated in literature [89,92,93], the slope of the diagonal line (Fig. 4b) can be expressed as the ratio RA_{max}/AF_{max} , where RA_{max} and AF_{max} denote

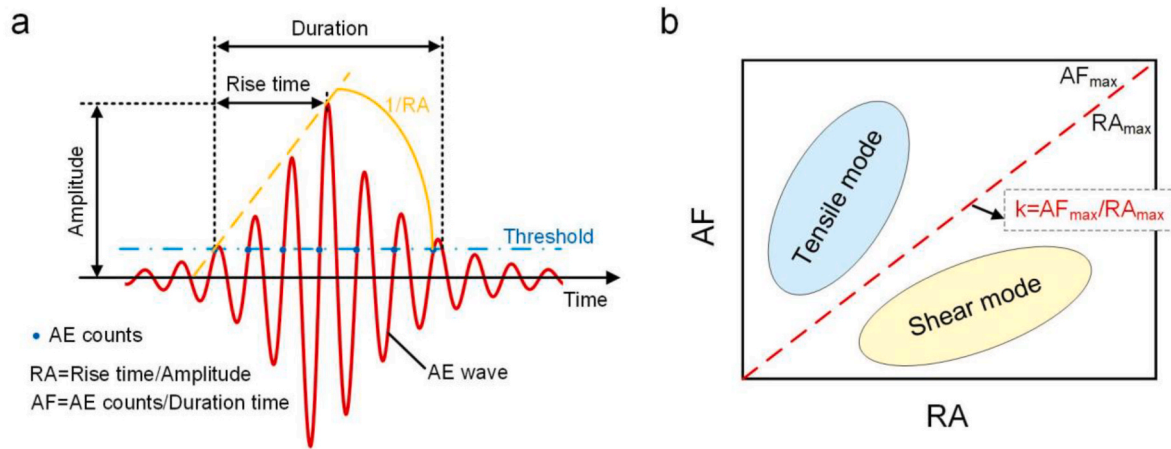


Fig. 4. AE waveform parameters (a) and damage mode classification (b).

the maximum values of RA and AF, respectively. This crack classification method has been reported to produce results that are less dependent on the sensor type [92,93].

2.3.3. Cyclic test for piezoresistive ACCCs

Fig. 5 shows the cyclic test setup and loading plan for piezoresistive ACCCs. The cyclic testing was conducted using an MTS fatigue machine with a 10 kN capacity. The resistance was measured with a DMM. Two wires were connected to the multimeter, and a plastic film reduced friction between the loading plate and the specimen, while also providing electrical insulation. To counteract slight horizontal movement from uneven deformation and asymmetrical cracks in the

cementitious materials during cyclic tests, tape was applied to the bottom loading plate. Considering the loading plan shown in Fig. 5c, the compression begins from zero and increases up to a displacement of U . Subsequently, cyclic loading is applied under displacement control using a sinusoidal waveform with a fixed amplitude A and a frequency of f . To ensure reliability, a minimum of three replicates were tested. The elliptical ACCC shape reported in literature [4,65] was subjected to pre-compression followed by cyclic loading within the auxetic behavior range. Its loading plan parameters, including both pre-compression and cyclic loading conditions, were adopted as a reference for the cyclic loading after pre-compression in the present study. The detailed loading plan parameters for the two piezoresistive ACCC geometries are summarized in Table 4. The minor axis of the central hole was used as a reference to normalize the loading parameters for each shape, as it determines the maximum allowable compression space.

Strain sensitivity (SAS) [80], commonly referred to as the gauge factor (GF) [33,80,94,95] during cyclic loading, is defined as:

$$GF = \frac{(\Delta R_{\max}/R_0)}{\varepsilon} = \Delta FCR_{\max} / \varepsilon \quad (3)$$

where ε refers to the compressive strain. $\Delta R_{\max}$ is the amplitude of resistance during cyclic loading. $\Delta FCR_{\max}$ is the amplitude of FCR during cyclic loading.

The stress sensitivity (SES) [33,80] against electrical resistance during cyclic loading was defined as:

$$SES = \frac{(\Delta R_{\max}/R_0)}{\sigma} = \Delta FCR_{\max} / \sigma \quad (4)$$

where σ represents the compressive stress.

During the monotonic compression tests, conducted under quasi-static loading at a very low loading rate of 0.01 mm/s, the electrical resistance was recorded at a sampling frequency of 3 Hz. During the cyclic compression tests, the sampling frequency was increased to 25 Hz to accurately capture the dynamic electrical response. The mechanical and electrical data acquisition systems were initiated and terminated simultaneously, allowing the mechanical and electrical responses to be accurately aligned based on their corresponding timestamps.

3. Experimental results and discussion

3.1. Material properties

Fig. 6 presents the tensile behavior of the cementitious matrix synergistically reinforced with PVA and carbon fibers. As reported in previous studies [6], a fiber-reinforced matrix exhibiting an extended

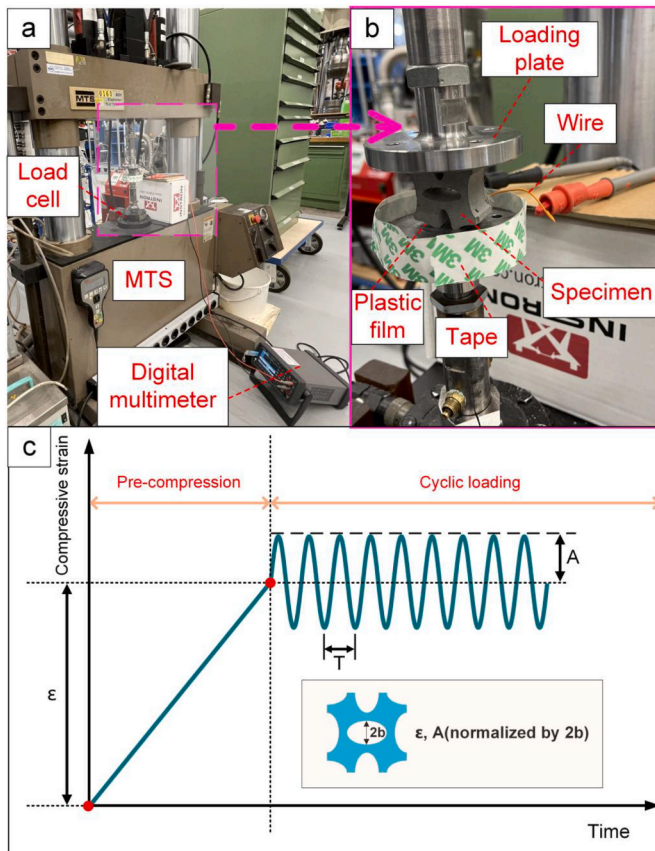


Fig. 5. Cyclic test for piezoresistive ACCCs.

Table 4
Parameters for the loading plan.

Specimen series	Pre-compression -U (mm)	Minor axis-2b (mm)	U/2b (%)	Amplitude-A (mm)	A/2b (%)	Amplitude-2A (mm)	2A/2b (%)
P25	4.00	12.00	33.33	0.57	4.76	1.14	9.52
P50	2.67	8.00	33.33	0.38	4.76	0.76	9.52

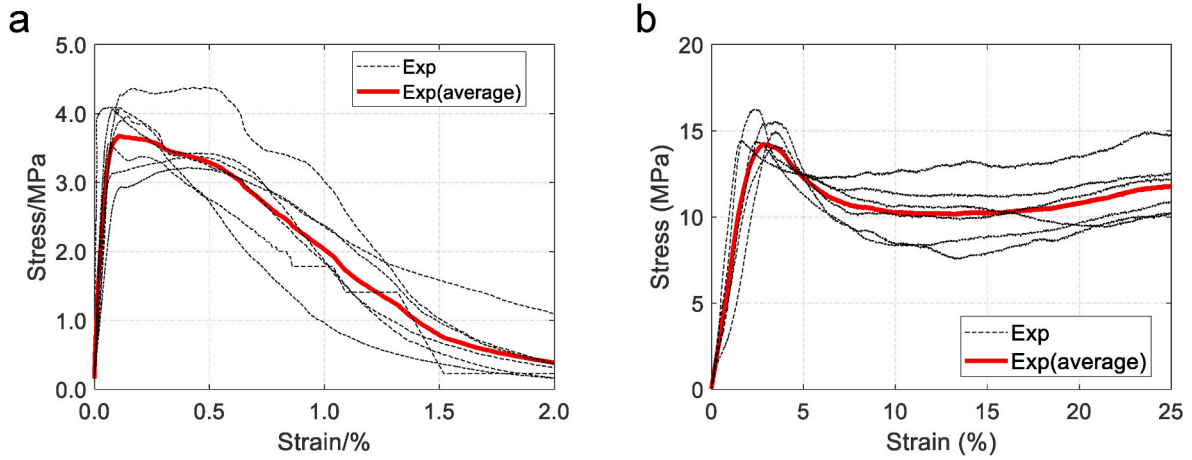


Fig. 6. Material properties: (a) under uniaxial tension and (b) under uniaxial compression.

softening response is beneficial for promoting fiber bridging across cracks in the hinge-like joints of ACCCs. As shown in Fig. 6a, following the initial elastic region, the material displays slight strain hardening,

which is subsequently followed by a prolonged softening phase. Nevertheless, while PVA fibers effectively enhance fiber bridging within the hinge-like joints, the bridging contribution of carbon fibers remains

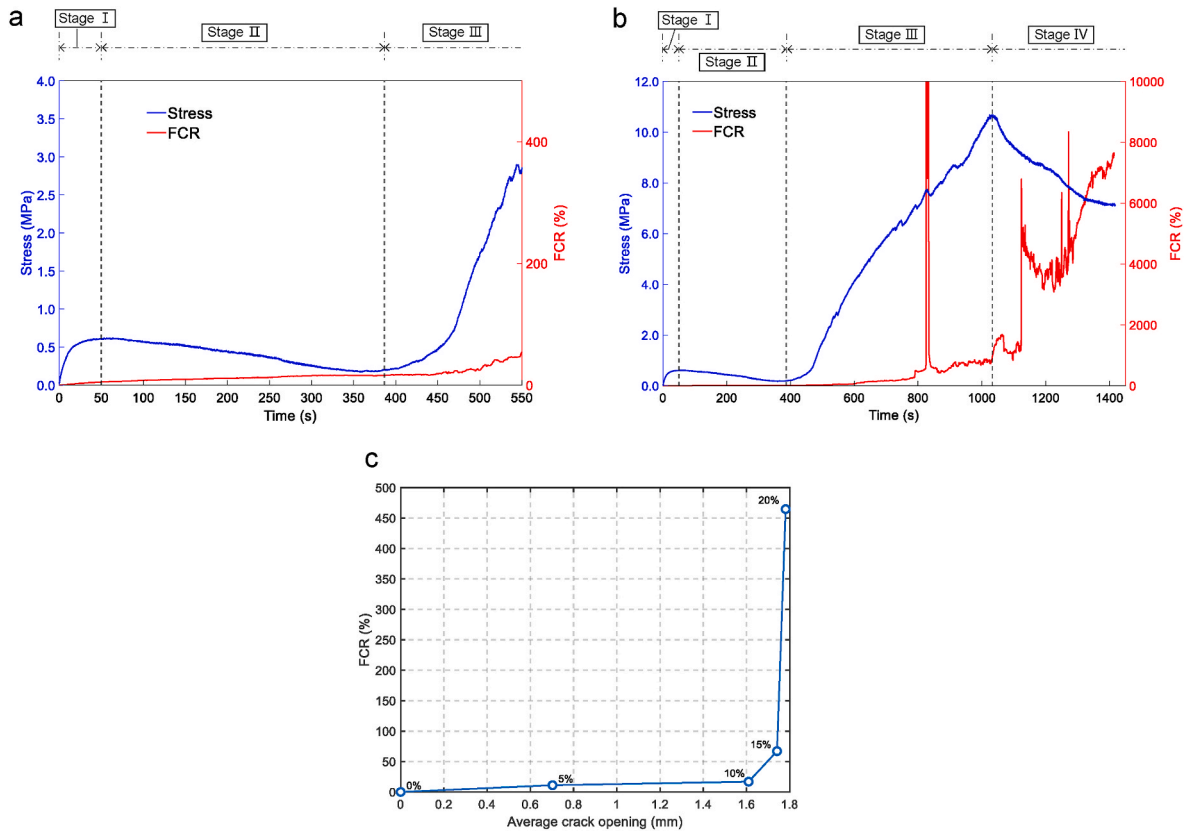


Fig. 7. Monotonic piezoresistive behavior of the P50 specimen. The overall process is divided into four time ranges to highlight different deformation stages and corresponding piezoresistive sensing behavior in greater detail. (a) Enlarged view of the early deformation stages. (b) Stress and FCR evolution during monotonic compression. (c) Relationship between the average crack opening at the joints and the FCR. The numbers shown on the curve denote the corresponding compressive strain levels.

limited, thereby reducing the strain-hardening range of the matrix compared to SHCC mixtures reinforced solely with PVA fibers as reported previously [6]. A previous study [64] also indicated that incorporating carbon fibers into flexible mortar did not achieve the desired densification range of ACCCs, owing to the limited fiber-bridging capability of carbon fibers. As shown in Fig. 6b, the compressive strength is approximately 14 MPa, which is comparable to that in previous studies [4,6,65]. This suggests that the mixture developed in this study has adequate compressive strength to accommodate joint rotation under loading plate contact, without incurring significant material damage at the contact interface where high compressive stresses and stress concentrations are expected.

3.2. Piezoresistive sensing of ACCCs under monotonic compression

Fig. 7 illustrates the evolution of compressive stress and FCR over time during the compression of P50. The entire process is divided into four time ranges to emphasize distinct deformation stages and their corresponding sensing responses. The corresponding deformation patterns of the specimens observed during compression are depicted in Fig. 8a, while the major strain distribution during the initial loading phase (captured via DIC) is presented in Fig. 8b. The complete evolution

of the FCR response during each deformation stage is also provided in the Supplementary Material (Fig. S1), where the stage-by-stage evolution can be examined in greater detail. The initial resistances of the P50 and P25 specimens shown in Figs. 7 and 9 are 0.568 k Ω and 0.961 k Ω , respectively.

As illustrated in Figs. 7 and 8, the full-range compressive stress–strain curves of P50 ACCCs exhibit a four-stage load-bearing mechanism driven by structural transformation and densification under compression. As shown in Fig. 7a and Fig. S1a, during Stage I, the compressive stress increases sharply in the initial loading phase, followed by a more gradual rise until reaching the first peak stress. Correspondingly, the FCR exhibits a nearly linear increase throughout this stage. This is because during the elastic stage and the subsequent strain-hardening stage—enabled by the fiber bridging effect—the bonding between the carbon fibers and the cementitious matrix does not degrade. The increase in resistance is primarily attributed to the compatible tensile deformation between the fibers and the cementitious matrix. In Stage II (Fig. 7a and Fig. S1b), once cracking initiates at the joint of the piezoresistive ACCCs, the stress begins to decline within the auxetic behavior range and continues until the self-contact point (i.e., self-contact within the central elliptical-shaped hole). This auxetic behavior is primarily driven by section rotation induced by fiber-

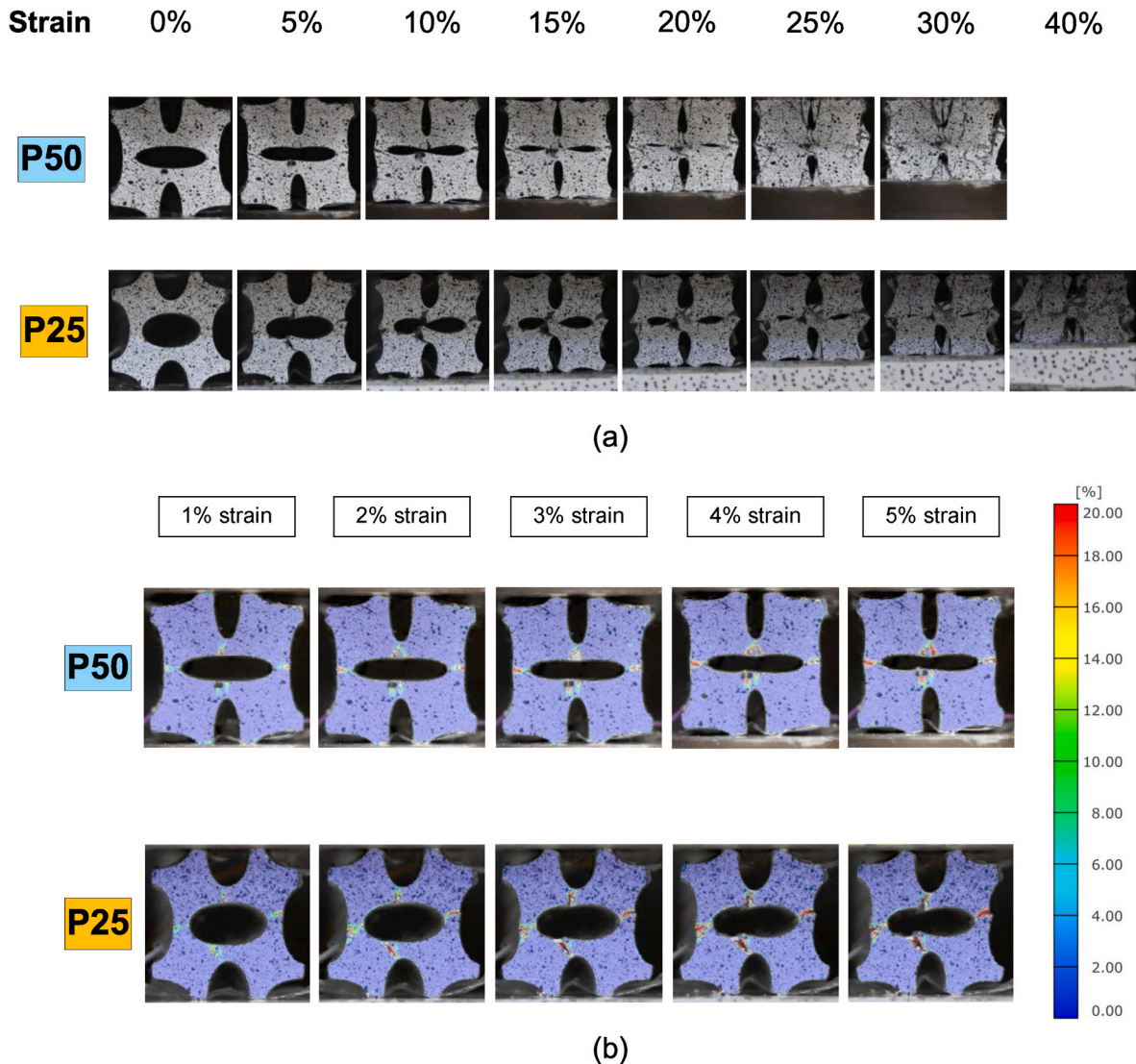


Fig. 8. Deformation pattern of piezoresistive ACCCs under uniaxial compression, (a) structural transformation, (b) major strain distribution captured by DIC analysis during the initial loading stage.

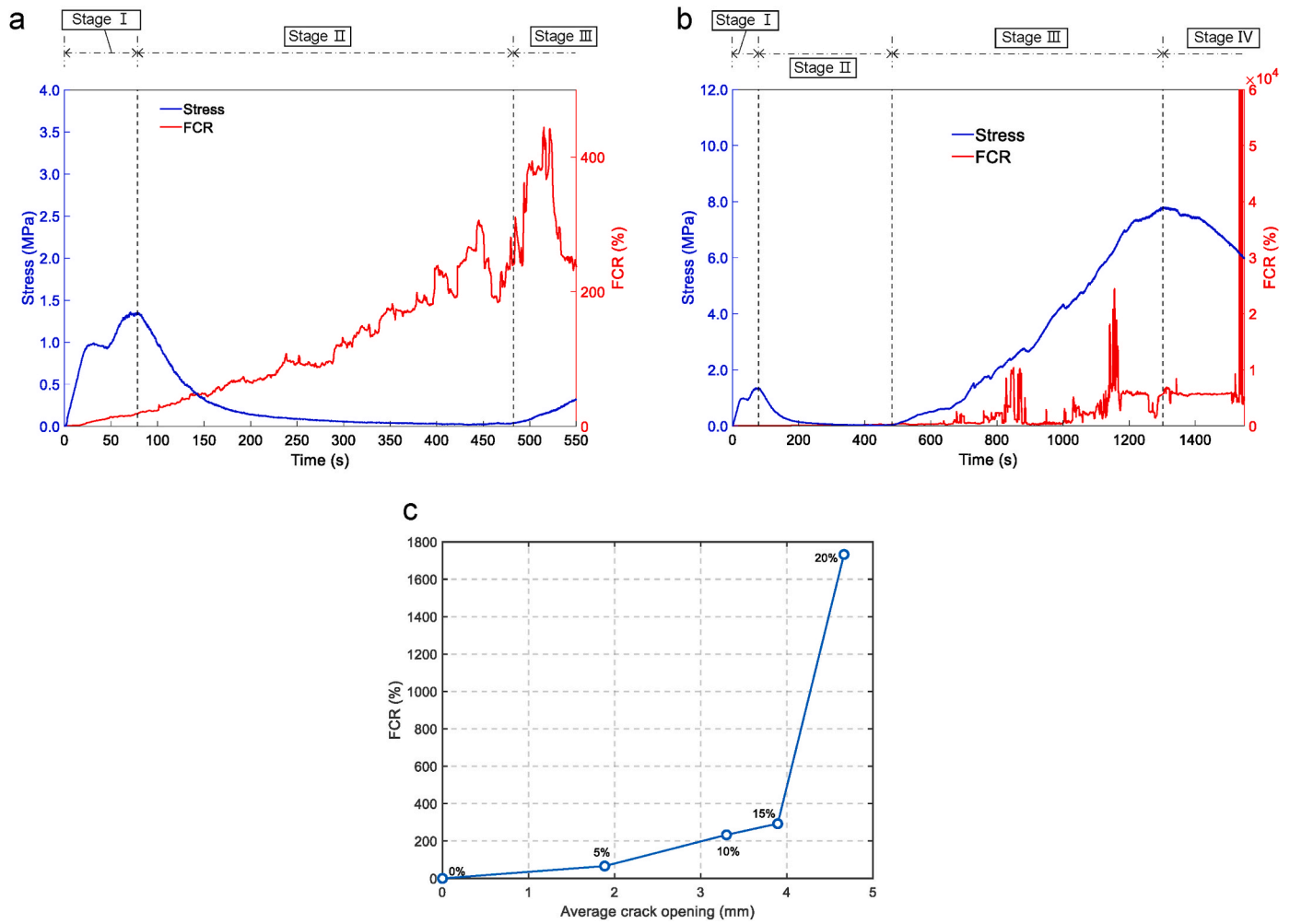


Fig. 9. Monotonic piezoresistive behavior of the P25 specimen. The overall process is divided into four time ranges to highlight different deformation stages and corresponding piezoresistive sensing behavior in greater detail. (a) Enlarged view of the early deformation stages. (b) Stress and FCR evolution during monotonic compression. (c) Relationship between the average crack opening at the joints and the FCR. The numbers shown on the curve denote the corresponding compressive strain levels.

bridging, thereby accommodating further compressive deformation with reduced load-bearing demand. During this stage, the FCR continues to increase linearly, albeit with a reduced slope, mainly due to the ongoing propagation of primary cracks within the joints, along with fiber debonding and pull-out. These damage mechanisms contribute to an increase in the contact resistance between the fibers and the surrounding cementitious matrix [22]. However, once the structure reaches the self-contact point, the FCR begins to rise more rapidly. In Fig. 7b and Fig. S1c, Stage III initiates when the internal hollow spaces are nearly fully compressed and closed, resulting in a significant shift in load transfer to the solid structural regions. This stage is characterized by a notable increase in crack formation. Nonetheless, the presence of fiber-bridging across these cracks enables the structure to retain its load-carrying capacity, leading to a continued rise in stress. Correspondingly, the FCR exhibits a marked increase during this stage, in contrast to Stages I and II, where the deformation is primarily governed by localized elastic-plastic behavior within the joints. Finally, in Stage IV, following the second peak stress, the onset of extensive cracking and structural damage within the sections causes the stress to significantly decrease (Fig. 7b and Fig. S1d). As the primary crack widens further and cuts off conductive pathways, the FCR shows a sudden increase in Stage IV. Meanwhile, the notable fluctuations in FCR during Stages III and IV are most likely attributed to the reconfiguration of conductive pathways between the electrodes, primarily due to the progressive closure of

internal hollow spaces. In addition, these fluctuations are also caused by stress redistribution associated with the initiation of new cracks, propagation of existing ones, and fiber debonding. The stress redistribution process involves the dynamic opening and closing of both pre-existing and newly formed cracks, as well as fiber debonding followed by re-contact with the surrounding cementitious matrix. These process continuously alter the conductive pathways between the electrodes. Specially, in Stages III and IV, following self-contact, the solid sections begin to bear the majority of the compressive load. Cracks may initiate at the center of these sections and subsequently close due to stress redistribution. This crack closure may lead to abrupt changes in the contact resistance at the location where the wires are embedded. Such changes could explain the sudden and pronounced fluctuation observed in the FCR at a specific moment during Stage III.

Fig. 9 shows the time-dependent evolution of compressive stress and FCR during the compression of P25. The complete evolution of the FCR response during each deformation stage is also provided in the Supplementary Material (Fig. S2), where the stage-by-stage evolution can be examined in greater detail. Similar to specimen P50, the variation of FCR correspondingly reflects the transition in load transfer and deformation behavior of piezoresistive ACCCs in different stages. Overall, specimen P25 exhibits a consistently higher FCR across all four stages when compared to P50. As depicted in Fig. 9a and Fig. S2a, during Stage I, the compressive stress rises sharply in the early loading phase.

Following the elastic region, initial cracking leads to a temporary stress drop, which is then followed by a slight stress increase due to minor strain-hardening effects induced by fiber-bridging. Afterward, the stress continues to increase gradually until it reaches the first peak. Meanwhile, the FCR shows an almost linear upward trend during this stage, albeit with some fluctuations. During Stage II (Fig. 9a and Fig. S2b), the onset of cracking at the joints of piezoresistive ACCCs leads to a progressive reduction in compressive stress throughout the auxetic deformation range, continuing until the self-contact point is reached. Compared to P50, the wider crack openings in P25 result in a lower stress during this stage. Concurrently, the FCR increases at a slightly faster rate, accompanied by more significant fluctuations. These pronounced variations in FCR are attributed to the larger cracks in P25, which intensify stress redistribution during the propagation of existing cracks, the initiation of new cracks, and fiber debonding. As illustrated in Fig. 9b and Fig. S2c, Stage III begins with the near-complete closure of the internal hole, marking a transition wherein the solid portions of the structure take on the primary load-bearing role. Although crack density increases during this phase, the presence of fiber bridging across the fracture surfaces contributes to maintaining structural integrity, thereby enabling a continued rise in compressive stress. As a result, the FCR increases significantly during this stage. In the final stage (Stage IV), the onset of a major crack following the second stress peak leads to a marked reduction in compressive stress, as illustrated in Fig. 9b and Fig. S2d. As this dominant crack continues to widen and cut off conduction branches, the FCR exhibits an abrupt increase in Stage IV. These pronounced variations in FCR in Stage III and IV also mainly from the intensive stress redistribution due to larger cracks. As illustrated in Fig. 3, the two wires were embedded diagonally through the section's center, resulting in conduction branches being primarily influenced by four joint cracks. Compared with the P50 specimens, the P25 specimens exhibited more uneven and asymmetric crack development at the four joints, leading to greater disruption of the conductive pathways and consequently larger fluctuations in the measured resistance.

Fig. 7c and 9c show the relationship between the average crack opening at the joints and the FCR of the P50 and P25 specimens during monotonic compression. At each compressive strain level, the average crack opening was calculated as the mean of the maximum crack openings measured at the four hinge joints. Crack openings were quantified directly from the recorded image sequence acquired for DIC using a calibrated image analysis method. The random black speckle pattern applied for DIC also enhanced crack visibility, facilitating crack identification and measurement. The specimen width (40 mm) served as the reference length for image calibration, allowing image measurements to be converted into actual crack widths. As shown in Figs. 7c and 9c, the FCR increases with the average crack opening at the joints for both P50 and P25 specimens. Before the onset of self-contact, the FCR increases relatively gradually with increasing crack opening. After the onset of self-contact, however, a small additional increase in crack opening results in a disproportionately large increase in FCR, indicating accelerated degradation of the conductive network caused by severe crack propagation. It should be noted that this crack-opening-based correlation is primarily applicable before the onset of self-contact. Beyond this stage, further compressive deformation is dominated by contact between adjacent sections, causing the joint cracks to progressively close under compression. Meanwhile, additional cracks initiate and propagate within the surrounding load-bearing solid sections and joints, making individual crack openings increasingly difficult to identify and quantify. Consequently, the electrical response is governed by the combined evolution of multiple cracks and conductive pathways, rendering the average opening of the four primary joint cracks no longer a suitable parameter for quantitatively describing the subsequent evolution of the FCR.

Compared with P50, P25 exhibits both larger average crack openings at the joints and higher FCR values at the same compressive strain level, reflecting its lower crack resistance and more extensive disruption of the

conductive network. Nevertheless, both geometries exhibit a similar overall relationship between crack opening and FCR. As the specimens approach the onset of self-contact, crack opening at the joints becomes progressively constrained and develops more slowly, whereas the FCR increases sharply. This indicates that the resistance change is no longer governed solely by crack opening at the joints, but is increasingly influenced by stress redistribution following self-contact. The resulting stress redistribution modifies the conductive network through different crack evolution mechanisms in both the load-bearing solid sections and joints.

Figs. 10 and 11 further present the test results of repeated piezoresistive ACCC specimens. Fig. 10a shows the full-range compressive stress–strain curves of both P50 and P25 piezoresistive ACCCs. A closer view of the stress–strain response up to 18% strain is provided in Fig. 10b. Fig. 10c shows the variation in Poisson's ratio of the specimens under compression, and Fig. 10d shows their peak compressive stresses. In Fig. 10a–b, the stress initially rises to a first peak, followed by a decrease attributed to the onset of primary cracking at the joints. The cracking initiates the formation of hinge-like joints that allow sectional rotation, marking the onset of auxetic behavior. This is shown in Fig. 10c, where the Poisson's ratio turns negative. As compression progresses and the central holes of the structures come into contact, the section rotation around the hinge-joint becomes constrained. Consequently, the compressive load is redistributed to the section regions of the ACCCs, resulting in a second rise in stress. This increase continues until a second peak stress is reached, corresponding to the onset of extensive cracking and structural damage within the sections. Concurrently, the negative Poisson's ratio gradually decreases in magnitude and eventually transitions toward positive values. Notably, the second peak stress is significantly higher than the first for both P25 and P50 specimens (Fig. 10d). This is because the first peak stress—associated with structural transformation—is primarily governed by the tensile damage of material at the joints.

Compared to P25, the central elliptical hole in P50 possesses a higher aspect ratio, which facilitates section rotation and contributes to a greater magnitude of negative Poisson's ratio. Due to its smaller minor axis, P50 reaches the self-contact point earlier, resulting in an earlier reduction in the negative Poisson's ratio. Nonetheless, P50 exhibits reduced cracking damage under compression, which enables it to sustain higher stress levels than P25 within the auxetic behavior range near the self-contact point. This enhanced auxetic effect suppresses lateral splitting, thereby promoting improved structural integrity and an extended auxetic range. As a result, P50 exhibits a higher second peak stress in the compressive stress–strain response. As discussed in Appendix A, an increase in b necessitates a higher compressive load to achieve the same moment required for plastic deformation of the joints and the associated sectional rotation, assuming identical tensile strength of the constituent materials. Simultaneously, the increased frictional resistance at the loading interfaces contributes to elevated tensile forces within the joints, as dictated by force equilibrium. This heightened tensile demand facilitates more pronounced cracking in the joint regions. Given that specimen P25 has a larger b than P50, it experiences higher tensile loads within the joints, resulting in a higher first peak stress compared to P50 (Fig. 10d). Consequently, P25 undergoes more severe joint cracking, as observed in Fig. 8. In particular, when the tensile force in the joints becomes substantial, the susceptibility to crack initiation and propagation increases due to material heterogeneity and pre-existing flaws. As a result, cracking is not confined to the central joint region but extends across other areas of the joints. This can lead to the formation of new hinge-like behavior in adjacent joints, potentially causing extensive joint cracking and a partial loss of the intended auxetic response. Following the onset of self-contact, the section primarily bears the increasing compressive stress to enable stress redistribution. This process relieves stress in certain parts of the section while concentrating it around pre-existing joint cracks, thereby intensifying local damage. Compared to P50, the larger crack openings in P25 amplify the stress

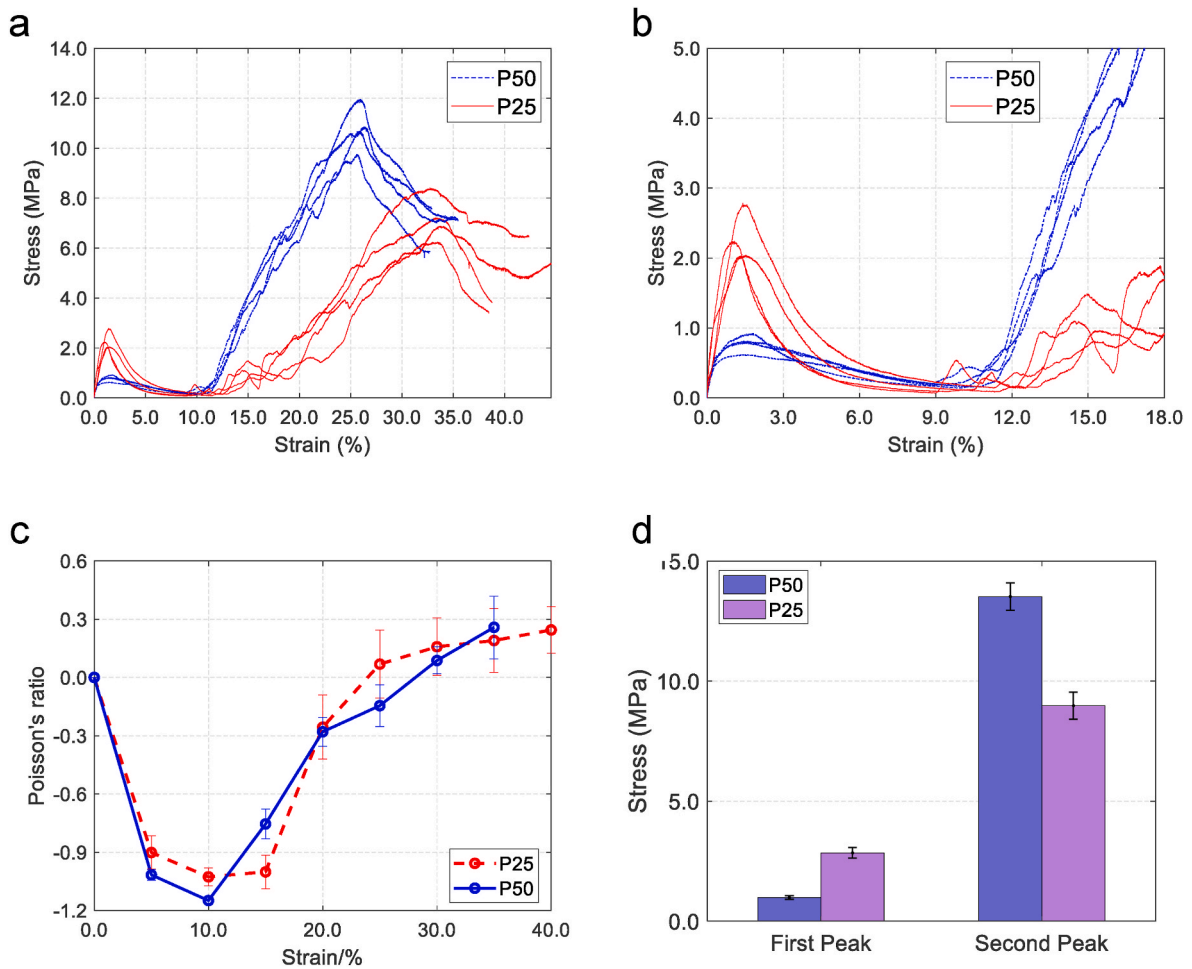


Fig. 10. Compression behavior of piezoresistive ACCCs, (a) compressive stress-strain curves, (b) magnified view of the initial loading stage including the high auxetic behavior range, (c) Poisson's ratio, (d) peak stress.

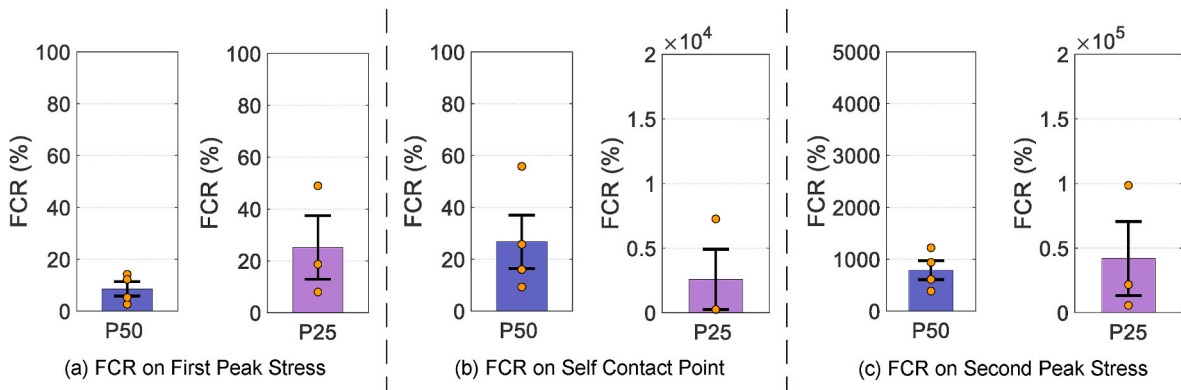


Fig. 11. FCR at critical transition points throughout different stages of compression.

concentration around the damaged regions. Additionally, severe stress concentrations emerge at other locations within the section, leading to extensive structural damage beyond the joints. This degradation in structural integrity results in a reduced second peak stress (Fig. 10d), indicating compromised load-bearing capacity after self-contact. Fig. 8 also shows that the deformation at the center of the section was negligible compared to that in the ligaments of the ACCC specimens. This minimizes variations in contact resistance between the electrodes and the cementitious materials when the specimens are under stress during piezoresistive measurements.

As shown in Fig. 11, the FCR of P50 at the self-contact point increases by only about three times compared to that at the first peak stress, with significant changes observed only at the second peak stress. In contrast, P25 shows severe cracking under compression, with a sharp increase in FCR starting from the self-contact point. By the second peak stress, the FCR surges by up to $4.2 \times 10^4\%$, accompanied by greater variability. Overall, both the FCR magnitude and scatter for P25 at the self-contact point and second peak stress are much higher than those of P50. This is because P50 shows greater tolerance against cracking under monotonic compression. The error bars in Fig. 11 are attributed to minor

dimensional inaccuracies from additive manufacturing and variability due to the heterogeneity of the cement-based material and manual casting.

3.3. Coupled piezoresistive and acoustic emission monitoring

Fig. 12 gives a comparison of the stress-strain results of P50 specimen with its accumulated AE event and AE event rate. The corresponding variation in FCR for the same specimen is presented in Fig. S3 (supplementary material), highlighting piezoresistive behavior consistent with that discussed for P50 above. Fig. S5 (supplementary material) displays the associated deformation patterns and major strain distribution obtained from DIC analysis. The deformation process can also be divided into four stages: Stage I (0–72 s), which spans from the initial loading to the first peak stress point; Stage II (72–403 s), extending from the first peak stress point to the onset of self-contact; Stage III (403–1032 s), covering the progression from self-contact to the second peak stress point; and Stage IV (1032–1315 s), from the second peak stress point to the final deformation stage. During Stage I, the AE event rate increases rapidly during the elastic deformation phase and reaches its peak value. During the transition into the plastic hardening phase, the AE event rate shows a slight initial decline, followed by a sharp decrease. Correspondingly, the accumulated AE events exhibit a near-linear increase during the elastic stage, with a notable reduction in slope upon entering the plastic region. By the time the specimen reaches the first peak stress, the AE event rate has significantly decreased. During Stage I, the FCR increases nearly linearly because the fiber-bridging capacity, without any bonding degradation, allows for compatible tensile deformation

between the fibers and the cement matrix. In Stage II, after the first peak, the applied stress begins to decline as the compressive deformation is primarily accommodated by sectional rotation around the hinge joints. During this stage, the AE event rate gradually decreases, reaching a very low level by the onset of self-contact. During this period, the accumulated AE events continue to increase but at a substantially reduced rate. Despite this, the FCR continues to increase, albeit with some fluctuations, attributed to the continued propagation of primary cracks within the joints, as well as fiber debonding and pull-out mechanisms. In Stage III, following the self-contact point, the AE event rate remains minimal until the stress increases to a certain level that initiates renewed crack propagation, as evidenced by a marked increase in AE activity. As the stress continues to rise in Stage III, a pronounced stress drop occurs due to the formation of a major crack. This event corresponds with a rapid decrease in AE event rate. In Stage IV, following the second peak stress, dominant cracks begin to fully develop, leading to a further decline in stress. At this stage, load-bearing capacity becomes localized around the primary cracks, facilitating their widening and accelerating overall structural failure. Due to stress redistribution and unloading of other minor cracks, the initiation of new fractures diminishes, resulting in the AE event rate approaching near-zero levels. Moreover, the major cracks during this stage may act as a barrier to the transmission of acoustic signals generated by subsequent microcrack events. This shielding effect further contributes to the decline in the AE event rate. However, during Stages III and IV, the FCR increases markedly due to the development of dominant cracks within the solid sections, accompanied by notable fluctuations resulting from the progressive closure of internal hollow spaces and ongoing stress redistribution associated with continuous

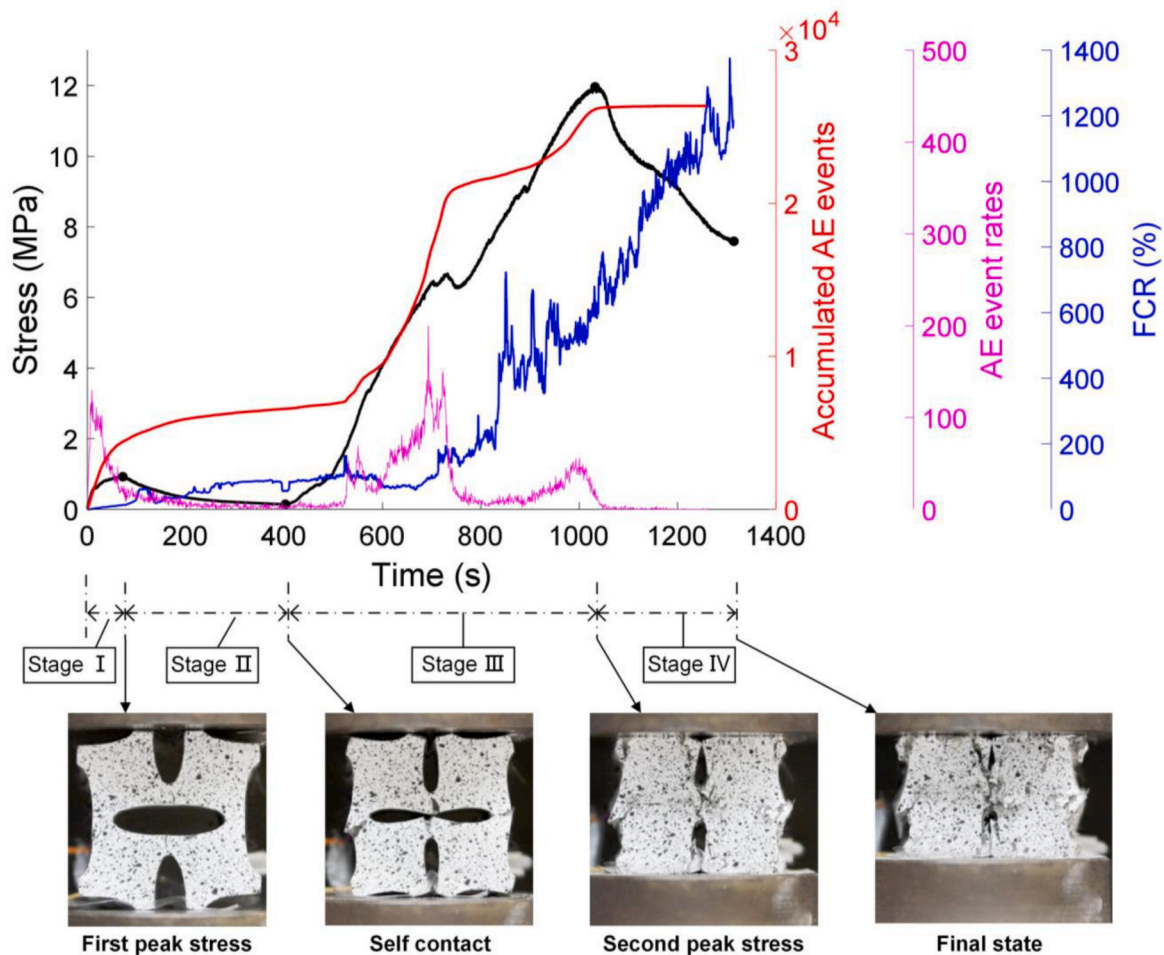


Fig. 12. Accumulated AE event and AE event rate in the time domain for P50 under compression.

cracking and fiber debonding. This suggests that, while AE activity diminishes as crack initiation events become less frequent, the FCR response continues to capture the progressive degradation of the conductive network associated with the widening of dominant cracks during the late stages of structural damage.

As shown in Fig. 13, the damage evolution of the P50 specimen throughout the four deformation stages was predominantly governed by tensile damage modes (95.7%), with a relatively minor contribution from shear-induced damage mode (4.3%). Herein, Fig. 13a shows the RA–AF distribution of AE signals during the four stages, with the dashed line indicating the tensile–shear mode boundary. Fig. 13b provides a zoomed-in view of the RA–AF distribution. Fig. 13c displays the number of events for each damage mode across the four stages. Fig. 13d shows the stage-wise proportions of the damage modes, where for each stage, the contribution of each mode is calculated as the number of AE events of that mode divided by the total number of AE events in that stage. In Stage I, the central hinge joint primarily accommodated deformation through matrix cracking and the initiation of fiber bridging, both characteristic of tensile damage. The sliding motion of the four peripheral joints in contact with the loading plates, necessary for enabling hinge formation in the middle of the structure, introduced frictional interactions that resulted in an increased proportion of low-energy shear modes (characterized by high RA and low AF values). As shown in Fig. 13b, in Stage II the majority of AE events were concentrated in the lower-left region of Fig. 13a, most likely associated with the continued propagation of the primary crack within the auxetic behavior range

(tensile mode) and with shear-mode progressive fiber debonding, including frictional fiber slip and fiber pullout [91]. Compared to Stage III, the overall AE activity in Stages I and II was relatively low, with fewer damage events and a smaller proportion of shear modes. The structure primarily underwent deformation via sectional rotation, rather than through extensive cracking during Stage III, which corresponded to a nearly linear increase in electrical resistance. Stage III—initiated after self-contact—was marked by a transition of crack propagation from the joints into the solid sections of the structure. This stage presents a significant rise in AE events dominated by tensile modes due to sudden fiber debonding initiation and crack opening, while the proportion of shear-mode events decreased correspondingly. This stage exhibited the highest AE activity, indicating substantial material damage, and was accompanied by a significant increase in electrical resistance. Finally, in Stage IV, the emergence and gradual propagation of dominant cracks became the primary damage mechanism. As no new cracks were formed, the AE activity declined rapidly, reaching the lowest level across all stages. Damage in this stage was almost exclusively associated with tensile-mode events related to the extension of dominant cracks, with negligible shear contributions. The structural response during Stage IV was characterized by continuous softening and a progressive loss of load-bearing capacity.

Fig. 14 compares the stress–strain response of the P25 specimen with its accumulated AE events and AE event rate. The corresponding variation in FCR for the same specimen is presented in Fig. S4 (supplementary material), highlighting piezoresistive behavior consistent with

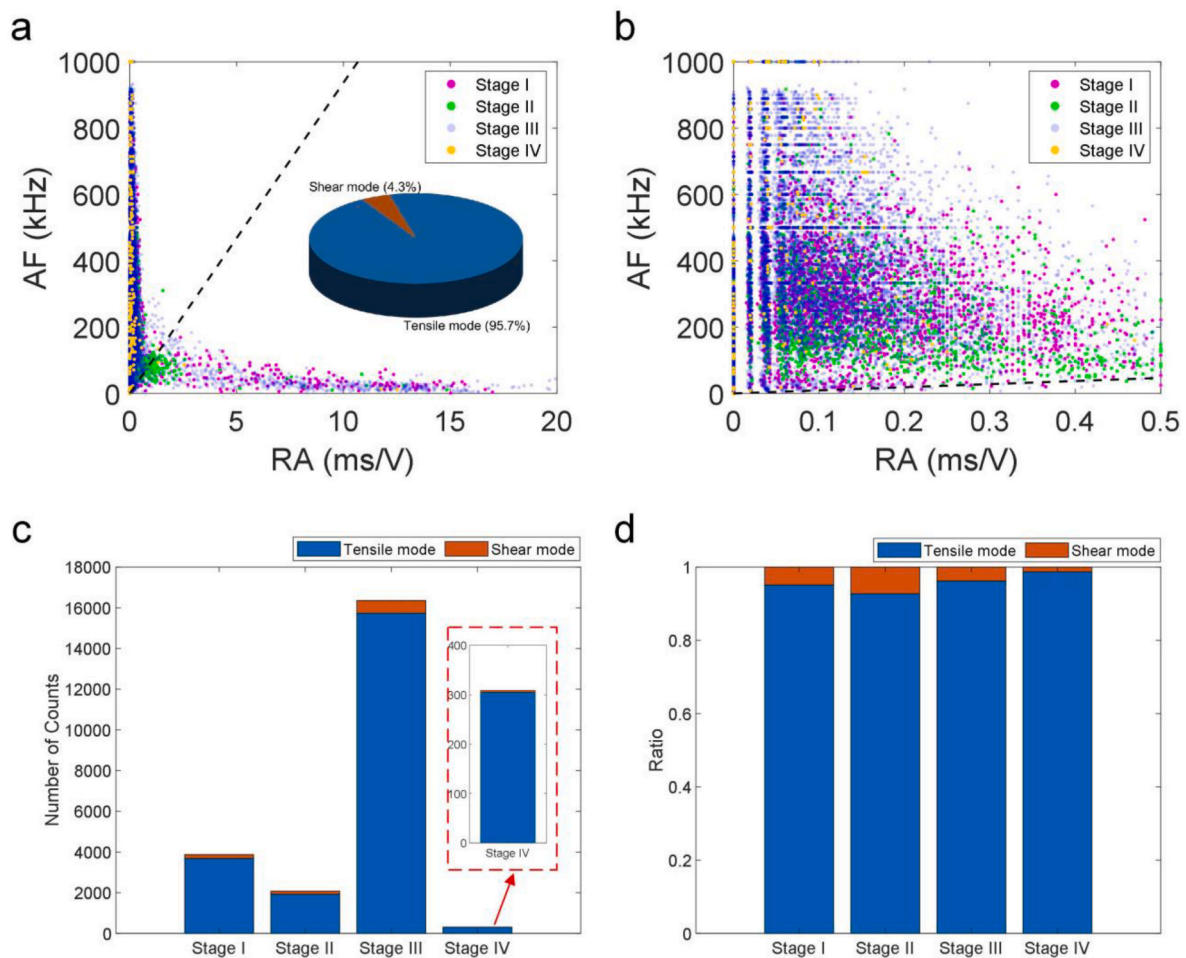


Fig. 13. AE-based damage mode classification and evolution in P50 specimen, (a) RA–AF distribution of AE signals during four stages, with dashed line indicating the tensile–shear mode boundary, (b) zoomed-in view for RA–AF distribution of AE signals, (c) number of events of damage modes during four stages, (d) stage-wise ratio of damage modes during four stages.

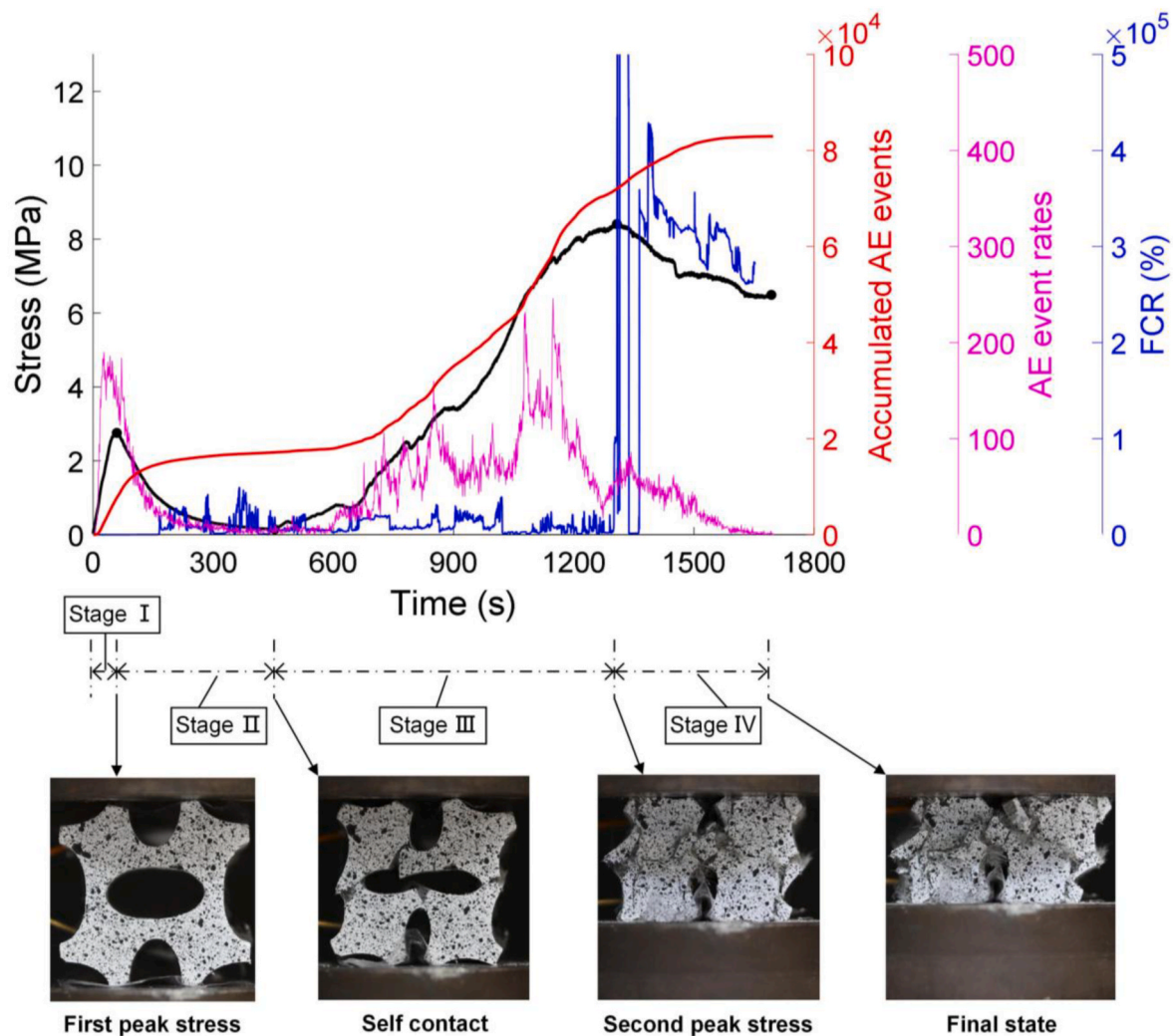


Fig. 14. Accumulated AE event and AE event rate in the time domain for P25 under compression.

that discussed for P25 above. Fig. S5 (supplementary material) displays the associated deformation patterns and major strain distribution obtained from DIC analysis. The deformation process is also divided into four stages: Stage I (0–59 s, initial loading to first peak stress), Stage II (59–453.2 s, first peak stress to onset of self-contact), Stage III (453.2–1307.4 s, onset of self-contact to second peak stress), and Stage IV (1307.4–1693.2 s, second peak stress to final deformation phase). The AE event rate of specimen P25 is higher than that of P50, resulting in a greater accumulation of AE events and a correspondingly higher FCR. Similar to P50, P25 exhibits a rapid increase in AE event rate during Stage I, peaking after the elastic deformation phase. As the specimen enters the plastic hardening phase, the AE event rate initially declines slightly before dropping sharply following the first peak stress. The accumulated AE events increase nearly linearly during the elastic stage, with a noticeable reduction in slope after reaching the first peak stress. During this stage, the FCR shows a relatively linear upward trend accompanied by significant fluctuations, likely due to crack propagation extending beyond the central joint region into adjacent joint areas. In Stage II, following the initial peak, the applied stress decreases after the first peak stress as compressive deformation is primarily accommodated by section rotation around the hinge joint. Nevertheless, cracking propagates beyond the central joint, giving rise to new hinge-like behavior in adjacent regions. This leads to extensive joint cracking and a partial reduction of the intended auxetic response, causing significant fluctuations in the FCR in this stage. During this stage, the AE

event rate continues to decrease until the onset of self-contact, where it reaches a very low level. In Stage III, following the onset of self-contact, the AE event rate remains low until the applied stress reaches a level sufficient to trigger renewed crack propagation, as indicated by a notable rise in AE activity. The continued increase in stress during this stage is facilitated by progressive cracking in solid section, which enables redistribution of the applied load up to the second peak stress. In Stage IV, beyond the second peak stress, dominant cracks begin to fully develop, resulting in a decline in stress. At this point, load-bearing capacity becomes concentrated around dominant cracks, promoting their widening and accelerating structural failure. As a result, the initiation of new cracks diminishes, resulting in the AE event rate approaching near-zero levels. Additionally, major cracks at this stage may obstruct the transmission of acoustic signals from subsequent cracking events, with this shielding effect further contributing to the reduced AE activity. Correspondingly, the FCR in Stage III demonstrates an increasing trend with pronounced fluctuations, primarily due to progressive severe cracking within the solid sections bearing the compressive load. Compared to P50, the intensified joint cracking further aggravates the progressive closure of internal voids and the ongoing stress redistribution caused by extensive cracking and fiber debonding, resulting in greater fluctuations. In Stage IV, the formation of dominant cracks leads to a sharp rise in FCR, reaching a significantly elevated level. This also suggests that the FCR response continues to reflect major crack formation at late stages of structural degradation even when AE activity

becomes limited.

As illustrated in Fig. 15, the damage evolution of the P25 specimen across the four deformation stages was primarily dominated by tensile damage mode, accounting for 93.0% of the total events, while shear-induced damage contributed only 7.0%. Overall, the damage mechanisms induced by compressive deformation across the four stages are generally similar to those in P50. However, in the P25 specimen, the four peripheral joints—being in direct contact with the loading plates—are subjected to higher compressive forces during Stage I. This increased load promotes enhanced frictional sliding at the interfaces, resulting in a greater occurrence of low-energy, shear-mode AE events (identified by high RA and low AF values) compared to P50. In Stage II, the number of AE events exceeds that observed in P50, primarily due to the propagation of multiple cracks beyond the central joint. This extensive cracking results in significant joint damage and a partial compromise of the designed auxetic response. The presence of multiple cracks also enhances frictional interactions between crack surfaces during section rotation, contributing to a higher proportion of shear-mode damage compared to P50, as illustrated in Fig. 15b. Correspondingly, as shown in Fig. 15a, AE events are primarily clustered in the lower-left region and partially extend into the low-energy, shear-dominated zone (high RA and low AF), suggesting the occurrence of frictional sliding along crack interfaces. The propagation of multiple cracks beyond the central joint also contributes to a higher proportion of shear-mode activity in Stages III and IV compared to P50.

It should be noted that the acoustic emission measurements were

conducted on one specimen for each geometry, which represents a limitation of the present study. The primary objective of the AE analysis was to provide mechanistic insight into the damage evolution associated with the piezoresistive response rather than to establish statistically representative AE characteristics. Consequently, the reported tensile/shear damage proportions should be interpreted as observations from the tested specimens rather than statistically validated values. Additional AE measurements on multiple specimens are required to evaluate the repeatability and variability of the AE characteristics and will be considered in future work.

3.4. Cyclic test for piezoresistive ACCCs

As illustrated in Fig. 16, both the FCR–strain and FCR–stress relationships exhibit sinusoidal behavior, demonstrating the excellent piezoresistive sensitivity of compliant ACCCs. Under displacement-controlled cyclic loading, the FCR decreases as compressive strain increases during the loading phase, and conversely, increases as the strain decreases during unloading. Once the cyclic response stabilizes, the compressive stress remains consistent across cycles, indicating negligible crack propagation and good repeatability. In particular, Fig. 16a illustrates that the compressive stress–strain response of the P50 specimen, subjected to an amplitude of A (see Table 4) at a frequency of 1 Hz, exhibits a quasi-linear behavior, reflecting good elastic recovery. The specimen exhibits high sensitivity at low stress, as its compliant and recoverable deformation induces changes in the conductive paths.

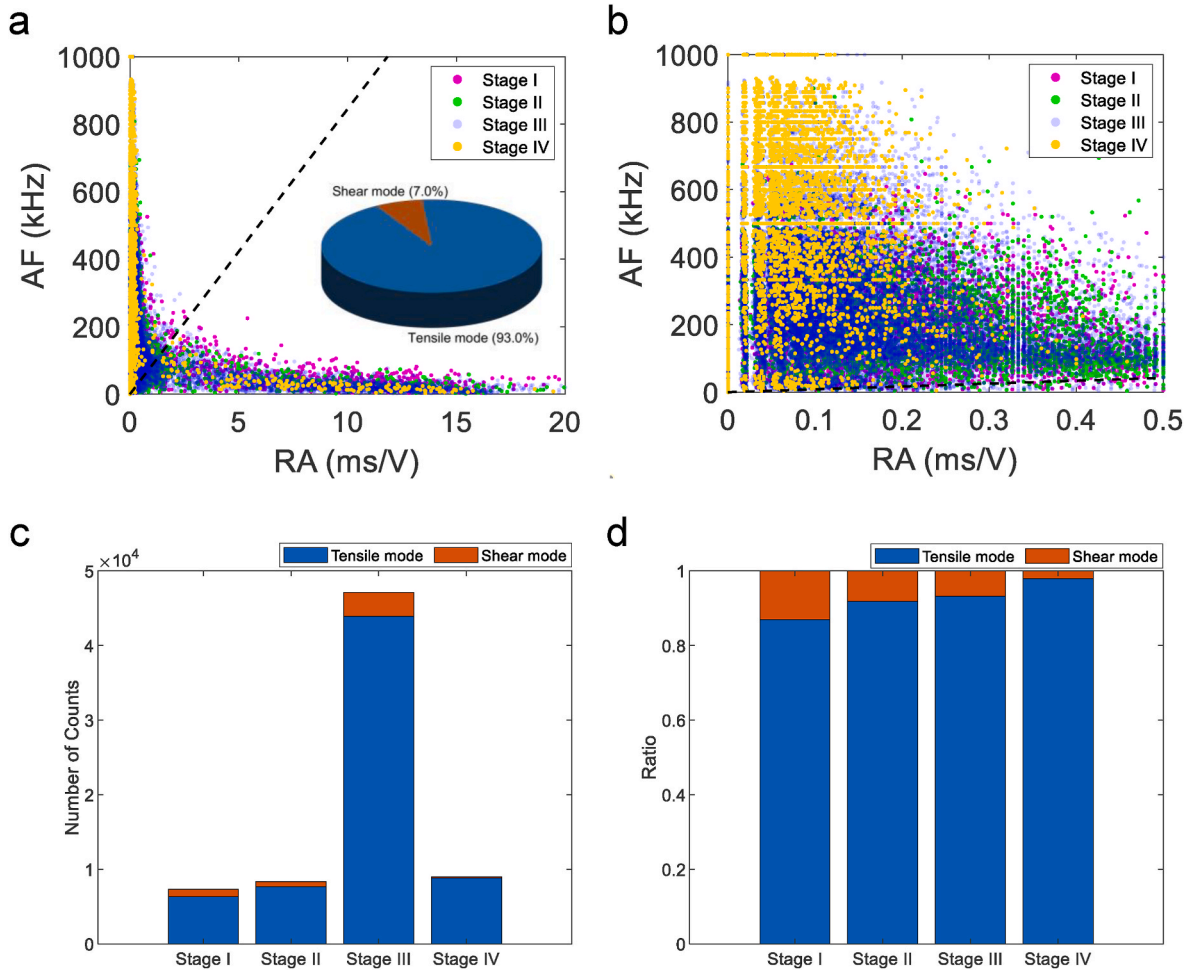


Fig. 15. AE-based damage mode classification and evolution in P25 specimen. (a) RA–AF distribution of AE signals during four stages, with dashed line indicating the tensile–shear mode boundary. (b) zoomed-in view for RA–AF distribution of AE signals. (c) number of events of damage modes during four stages. (d) stage-wise ratio of damage modes during four stages.

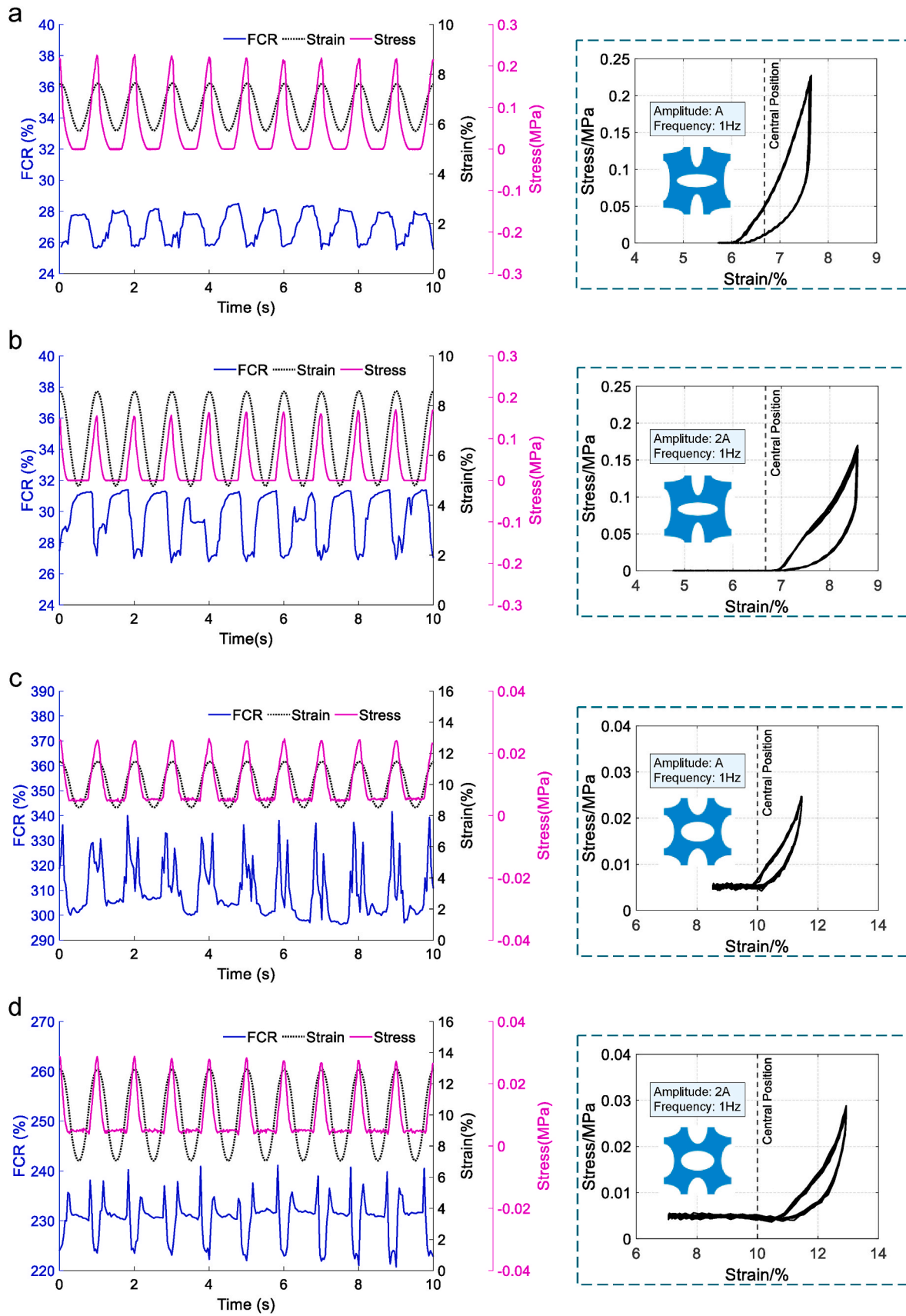


Fig. 16. FCR under cyclic test, (a) P50 (amplitude: A), (b) P50 (amplitude: 2A), (c) P25 (amplitude: A), (d) P25 (amplitude: 2A).

Although the ACCC specimens demonstrate a tendency to recover their original shape after unloading, residual plastic deformation is still observed. This effect becomes more evident at higher loading amplitudes (e.g., P50 under 2A (see Table 4) at 1 Hz in Fig. 16b), primarily due to the limited fiber-bridging capability within the joint region.

Conductive cementitious materials commonly contain microcracks, which typically have higher electrical resistance than the surrounding bulk. As these microcracks open and close under applied strain, they can significantly affect the electrical conductivity [34,96,97]. In Fig. 16, the relationship between electrical resistance and compressive strain is likely attributed to carbon fiber bridging within crack regions, encompassing both the tips of primary cracks and smaller microcracks distributed throughout the joints. As compressive strain increases, the crack region tends to open, allowing carbon fibers to bridge the gaps and form conductive pathways, thereby reducing contact resistance at the crack interfaces. Conversely, when the compressive strain decreases, the crack region progressively closes, disrupting the bridging effect and resulting in increased contact resistance at the crack interfaces.

As shown in Fig. 16c and d, the FCR observed in specimen P25 is higher than that of P50, indicating greater sensitivity to compressive strain. This enhanced response is mainly due to the presence of prominent primary crack tips along with numerous microcracks dispersed throughout the joint region in P25, which experience more significant opening and closing under cyclic loading. Additionally, as shown by the CT scan results in Appendix B and the microstructural analysis conducted with a digital optical microscope in Appendix C, P25 has a greater number of microcracks around the primary crack in the joints compared to P50, further contributing to its increased FCR response.

However, despite its higher sensitivity, P25 demonstrates less stable self-sensing performance compared to P50, as evidenced by greater fluctuations in its sinusoidal FCR curve. This instability is linked to extensive cracking at the joints, where damage is not confined to the central joint area but propagates across the entire joint region. Notably, the electrodes in P25 are positioned diagonally across two sections, and electrical conduction branches must traverse multiple cracks. The asynchronous opening and closing of these cracks during loading cycles disrupts the continuity of the conductive pathways, resulting in signal fluctuations. Furthermore, the mechanical response of P25 under cyclic loading is significantly reduced relative to P50, primarily due to the larger crack present at the joint. This manifests as increased plastic deformation in P25 during the unloading phase, reflecting its reduced structural integrity and diminished ability to recover elastically.

The electrical and mechanical performances of repeated specimens under a 1 Hz cyclic loading frequency and different loading amplitude are summarized in Fig. 17. As shown in Fig. 17a and b, the P25 specimens exhibit significantly higher Δ FCR values (defined as the peak-to-peak variation in FCR during cyclic loading) but lower stress compared to the P50 specimens. For both P25 and P50 specimens, increasing the loading amplitude results in higher Δ FCR and reduced stress. Fig. 17c and d further show that P25 demonstrates greater strain and stress sensitivity than P50. Specifically, in Fig. 17c, the strain sensitivity decreases with increasing loading amplitude for both P25 and P50. In contrast, Fig. 17d reveals that the stress sensitivity of P25 decreases with higher loading amplitude, whereas that of P50 increases. Due to the increased severity of cracking, the P25 specimens exhibit greater scatter in these measurements compared with the P50

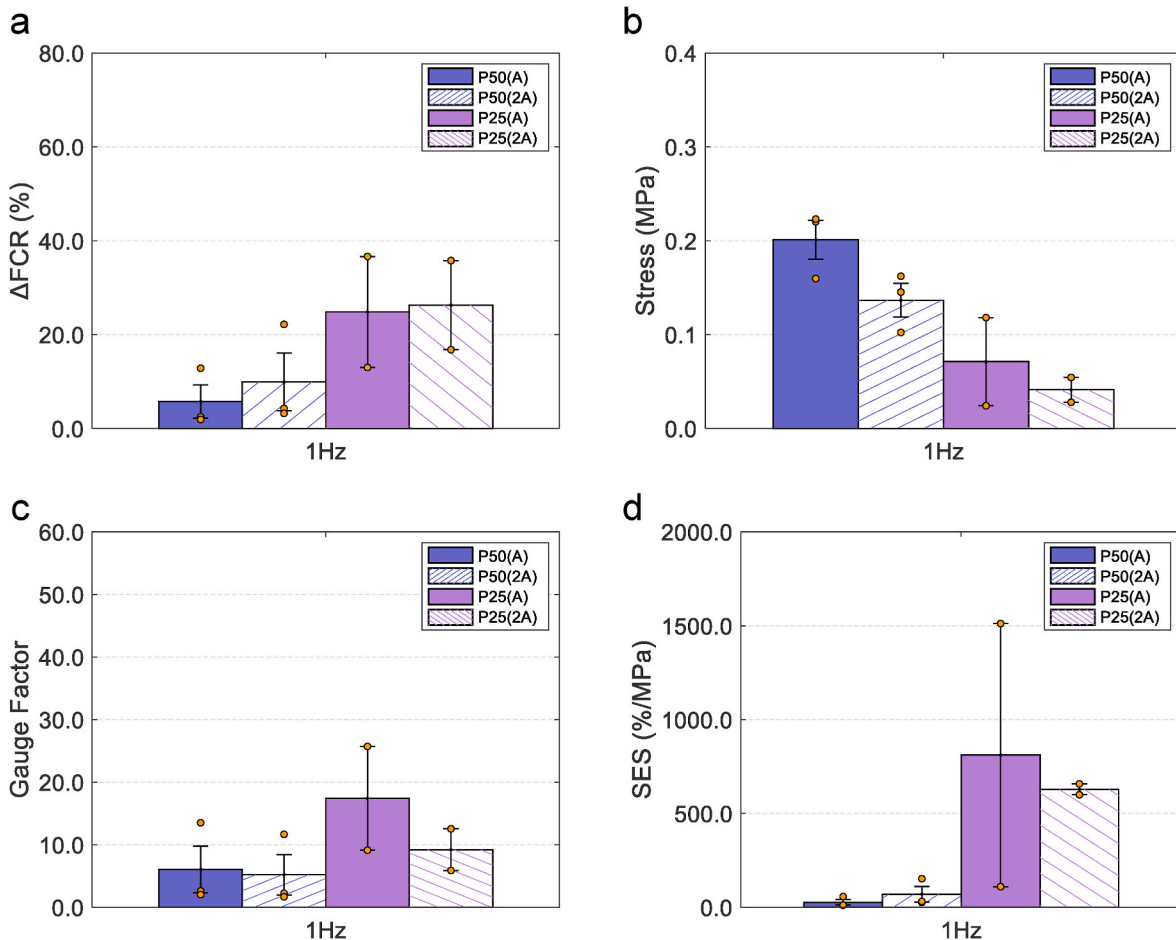


Fig. 17. Electrical and mechanical performance of repeated specimens under 1 Hz loading frequency: (a) Δ FCR, (b) stress, (c) gauge factor, and (d) SES. (Error bars represent standard deviation.)

specimens. In addition, since the third P25 specimen split during cyclic loading because of severe joint cracking after pre-compression, only the results from two repeated P25 specimens are presented in Fig. 17. These results collectively suggest that severe cracking in the hinge joints contributes positively to the electrical sensitivity of ACCCs, though with a trade-off in mechanical properties.

For the cyclic tests of the P25 specimens, one specimen experienced premature splitting failure during testing and therefore did not provide valid cyclic piezoresistive data. Consequently, the cyclic results for P25 were obtained from two successful specimens, resulting in relatively large scatter. The relatively large scatter observed for the P25(A) stress sensitivity in Fig. 17d is mainly attributed to the low stress level during cyclic loading. The cyclic tests were performed after pre-compression to Stage II (Fig. 1), corresponding to the auxetic deformation stage, where the compressive stress remains relatively low (Fig. 9). As shown in Fig. 17b, the two successful P25(A) specimens exhibited substantially different stress during cyclic loading. In contrast, the specimen subjected to the lower cyclic stress exhibited a larger FCR response (Fig. 17a), whereas the specimen subjected to the higher cyclic stress exhibited a smaller FCR response. Since SES is calculated by normalizing the FCR response with the corresponding stress, these opposite variations considerably amplify the calculated SES, resulting in the relatively large scatter. In addition, one P25 specimen experienced premature splitting during cyclic loading and could not be included in the analysis, further reflecting the relatively unstable deformation behavior of the P25 geometry. This behavior may be associated with the weaker fiber-bridging capacity at the larger hinge joints, which results in greater specimen-to-specimen variations in crack evolution and conductive network stability under cyclic loading. By comparison, the smaller hinge joints in the P50 geometry provide more effective fiber bridging and more stable auxetic deformation during Stage II (Fig. 7). Consequently, the cyclic stress, FCR, gauge factor, and SES of the three P50 specimens remain relatively consistent (Fig. 17), resulting in substantially smaller scatter than that observed for P25. The error bars shown in Fig. 17 can also be attributed to several factors: (1) slight dimensional inaccuracies resulting from additive manufacturing; (2) the effect of loading boundary conditions, as the ACCC undergoes minor horizontal movement during cyclic loading; and (3) variations caused by the heterogeneity of the cement-based material and manual casting.

A loading frequency of 1 Hz was selected based on our previous study [71] on recoverable ACCCs for energy harvesting, which demonstrated stable and repeatable mechanical behavior under cyclic loading. Higher loading frequencies were intentionally avoided because they could potentially damage the fiber-bridging capacity at the joints, thereby affecting the recoverable deformation and the repeatability of the piezoresistive response. The primary objective of the cyclic tests in the present study was to evaluate the repeatability and sensitivity of the piezoresistive response within the recoverable deformation range, rather than to investigate frequency-dependent behavior. Loading frequencies in practical civil infrastructure applications may vary depending on the specific application, and the influence of loading frequency on the mechanical and piezoresistive response will be investigated in future work.

Under monotonic loading, progressive crack initiation and propagation irreversibly disrupt the conductive network through fiber debonding, pull-out, and crack widening, resulting in a continuous increase in the FCR that reflects the accumulation of structural damage. In contrast, the cyclic tests were conducted within the recoverable auxetic deformation range, where crack opening and closure remain relatively small and largely reversible. In contrast, the cyclic tests were conducted within the recoverable auxetic deformation range, where crack opening and closure remain relatively small and largely reversible. The reversible change in electrical resistance is likely attributed to carbon-fiber bridging within crack regions, including both the tips of primary cracks and smaller microcracks distributed throughout the joints. During cyclic compression, increasing compressive strain promotes carbon-

fiber bridging across these crack regions, forming temporary conductive pathways and reducing the contact resistance at the crack interfaces [34, 55, 57]. Upon unloading, the crack regions progressively close, weakening these conductive pathways and increasing the contact resistance, thereby resulting in a reversible electrical response. Although direct *in-situ* observation of conductive pathway reconstruction during cyclic loading was beyond the scope of the present study, several experimental observations provide indirect support for the proposed mechanism. X-ray CT analysis (Appendix B) reveals numerous microcracks, pores, and voids around the joint region, providing potential locations for carbon fibers to bridge adjacent crack surfaces during cyclic loading. In addition, the microscopic observations (Appendix C) confirm the occurrence of fiber bridging, fiber debonding, and fiber pull-out at crack interfaces within the joints of the specimens after the pre-compression and subsequent cyclic loading, demonstrating active crack-bridging behavior of the carbon fibers. Together with the stable and repeatable FCR and mechanical responses observed during cyclic loading, these findings support the proposed reversible conductive pathway mechanism. Nevertheless, direct visualization of conductive pathway evolution during cyclic loading is still lacking. Future work will therefore employ *in-situ* characterization techniques, such as optical microscopy and X-ray CT under low-frequency cyclic loading, to directly investigate conductive pathway evolution and establish quantitative relationships among crack evolution, conductive network reconstruction, and piezoresistive response. This mechanistic understanding will further guide the optimization of fiber-cementitious matrix interactions and joint geometry to enhance the piezoresistive sensing performance of ACCCs. It should also be noted that the present study employed a hybrid fiber system comprising carbon fibers and PVA fibers. While carbon fibers directly contribute to electrical conduction, PVA fibers participate in the fiber-bridging mechanism by controlling crack opening and closure during cyclic loading. This, in turn, alters the stress state of the carbon fibers within the cementitious matrix, as well as the bridging state of carbon fibers across crack surfaces, thereby affecting the connectivity and electrical conductivity of the conductive pathways and, consequently, the piezoresistive response. Future work will investigate the coupled roles of carbon-fiber and PVA-fiber bridging in governing the evolution of the conductive network and the underlying piezoresistive sensing mechanism.

3.5. Discussion

As discussed in the Introduction, Xu et al. [63] incorporated carbon fibers into auxetic cementitious composites to impart electromechanical functionality. Similarly, Valverde-Burneo et al. [64] incorporated carbon fibers into flexible mortar to achieve piezoresistive behavior in auxetic cementitious composites. However, the desired densification stage was not achieved because of the limited fiber-bridging capacity at the joints. Compared with these previous studies, the present work provides several novel contributions. First, a newly developed cementitious mixture with quantitatively characterized tensile and compressive properties was adopted to achieve stable auxetic deformation and repeatable recoverable behavior of piezoresistive ACCCs under cyclic compression. Second, the functionality of ACCCs was extended from reversible strain sensing to progressive damage sensing under monotonic compression by correlating the piezoresistive response with different deformation stages. Third, coupled piezoresistive and AE monitoring was employed to investigate the damage evolution of ACCCs. In addition, X-ray CT and optical microscopy were used to characterize the crack distribution and fiber-bridging behavior of ACCC specimens after cyclic loading, providing direct microstructural evidence for the sensing mechanisms. Finally, the influence of different auxetic geometries (P25 and P50) on the piezoresistive sensing performance was systematically investigated.

For the monotonic compression tests, three specimens were tested for both the P25 and P50 geometries. For the cyclic tests, one P25

specimen experienced premature splitting failure during the pre-compression stage prior to cyclic loading because of the limited fiber-bridging capacity at the joints. Consequently, only two valid P25 specimens, together with three P50 specimens, were available for the cyclic piezoresistive analysis. For the monotonic compression tests, the P25 specimens exhibited a stage-dependent piezoresistive response and effective damage-sensing capability during the first two deformation stages. However, the limited fiber-bridging capacity at the joints resulted in severe cracking and conductive network disruption during the later stages. Consequently, the FCR increased rapidly, which was further amplified by the relatively low initial resistance, resulting in substantial specimen-to-specimen variability among the three tested specimens. In contrast, the P50 geometry exhibited a more stable auxetic deformation stage with higher compressive load-carrying capacity, enabling improved crack resistance at the hinge joints and more stable deformation. Consequently, both the monotonic damage-sensing response and the cyclic strain/stress-sensing response showed relatively small specimen-to-specimen variability, demonstrating more stable piezoresistive sensing performance. The measurement repeatability across specimens has been quantified by reporting the mean values and corresponding standard deviations in Figs. 11 and 17. These error bars provide a quantitative measure of the specimen-to-specimen variability.

The results in this study suggest that the piezoresistive performance of ACCCs is strongly influenced by the auxetic geometry through its effect on joint crack resistance and deformation stability, highlighting the importance of geometric design in achieving stable self-sensing performance. Compared with P50, the larger joint size of P25 generates higher tensile forces at the joints under compressive loading (see Appendix A), resulting in a greater tendency for crack formation. This tendency has also been reported in our previous study [71]. Consequently, P25 exhibits a larger FCR than P50 throughout all loading stages. In particular, severe crack propagation at the later stages almost completely interrupts the conductive network, leading to a rapid increase in FCR, reaching an average value of $4.2 \times 10^4\%$ with wide error bars (Fig. 11). Notably, one P25 specimen experienced premature splitting during compression, possibly owing to the heterogeneity of the cementitious material and the loading boundary conditions. This observation indicates that the current fiber-bridging capacity is insufficient to maintain the stable auxetic deformation of the P25 geometry. Although the incorporation of carbon fibers improves electrical conductivity, it also reduces the ductility of the cementitious composite. Therefore, the mixture design should be further optimized to enhance fiber-bridging capacity and ductility while maintaining sufficient conductivity, thereby enabling a wider range of ACCC geometries to achieve stable auxetic deformation for stable piezoresistive sensing. These results further demonstrate that both the mechanical behavior and the piezoresistive sensing performance of ACCCs, including the magnitude of the FCR response and the sensing range associated with the deformation capacity, can be potentially tailored through geometric design to satisfy the requirements of different structural health monitoring applications.

In this study, AE primarily detects crack initiation and distinguishes fracture modes through transient elastic waves, whereas the FCR response continuously reflects the evolution of the conductive network during deformation. Before complete crack penetration, the stage-dependent evolution of the FCR provides graded information corresponding to distinct deformation mechanisms, including the initial elastic-plastic deformation, ligament cracking accompanied by sectional rotation, and, following the onset of self-contact, stress redistribution together with multiple crack initiation and propagation in the load-bearing solid sections and joints. These progressive deformation mechanisms are accompanied by the continuous evolution of the conductive network, enabling multi-stage damage sensing. The large FCR observed in the late damage stage primarily reflects severe disruption of the conductive network and should not be interpreted as providing proportionally higher sensing resolution. In the final damage

stage, local failure becomes dominated by one or more major cracks, and the FCR response is governed primarily by the rapid increase in electrical resistance resulting from the loss of conductive pathways. Consequently, the FCR response becomes effectively binary and mainly serves as an indicator of severe structural damage rather than providing further quantitative information on damage evolution.

Most self-sensing cementitious materials in previous study are tested using cubic specimens, and their sensing performance is typically evaluated within a very narrow elastic strain range (on the order of a few hundred microstrains [29–31,76]). Because cement-based materials possess a high elastic modulus, even small deformations correspond to relatively high stresses (about 4–10 Mpa [27,29,31–33]), meaning that considerable stress is usually required to activate the sensing response. In contrast, the piezoresistive ACCCs developed in this study exhibit high sensitivity to very small forces during cyclic tests, capable of detecting stresses as low as nearly 0.2 Mpa (Fig. 17), while enabling recoverable strain sensing over a broader strain range. This superior sensing capability originates from the amplification effect of their auxetic behavior. As a result, these materials can function not only as cement-based sensors for structural strain/stress monitoring but also as multifunctional materials with auxiliary load-bearing capability when integrated with conventional structural elements or supporting systems.

4. Conclusions

This work conducted piezo-resistivity studies of compliant ACCCs via synergic effect of PVA and carbon fiber. Uniaxial compression tests assessed their piezoresistive responses for damage sensing across four distinct deformation stages, with DIC and AE used to analyze corresponding deformation and damage mechanisms. Within the recoverable auxetic deformation range, cyclic loading tests assessed the flexible sensing performance of piezoresistive ACCCs by correlating stress-strain behavior with FCR, with further insights obtained from microscopic analysis and X-ray CT. The main conclusions are as follows:

1. Under uniaxial compression, ACCCs demonstrate both conductive and auxetic behavior through a cementitious matrix synergistically reinforced with PVA and carbon fibers. The auxetic behavior facilitates large deformations, characterized by four distinct stages of mechanical response and associated damage mechanisms. Correspondingly, each stage exhibits distinct piezoresistive characteristics in terms of FCR, thereby expanding the damage sensing range for structural health monitoring applications. Notably, in the later stages of damage, the FCR response continues to reflect dominant crack development even when AE activity becomes limited.
2. After compressing the ACCCs into the auxetic deformation range, the recoverable deformation of compliant ACCCs under cyclic loading was utilized for self-sensing. This reversibility allows the composites to demonstrate a reproducible piezoresistive response across an extended self-sensing range, indicative of pronounced strain and stress sensitivity. However, residual plastic deformation of compliant ACCCs increased with the amplitude of cyclic loading.
3. Compared to P25, P50 features a larger aspect ratio of the central elliptical voids, resulting in a more pronounced negative Poisson's ratio effect. This enhanced auxetic behavior effectively suppresses crack propagation at the hinge joints, leading to more stable sensing performance. Although P25 exhibits severe crack development at the hinge joints, it demonstrates higher piezoresistive sensitivity.

Compliant auxetic cementitious composites demonstrate superior piezoresistive performance under both monotonic compression and cyclic loading, highlighting their suitability as self-sensing materials for stress/strain and damage monitoring in structural elements. The auxetic behavior of compliant ACCCs show high potential to amplify the piezoresistive sensitivity of cementitious materials. This advancement represents an important step toward the development of multifunctional

auxetic cementitious composites for next-generation smart infrastructure.

CRedit authorship contribution statement

Jinbao Xie: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yading Xu:** Conceptualization, Methodology, Writing – review & editing. **Yubao Zhou:** Formal analysis, Methodology, Writing – review & editing. **Zhaozheng Meng:** Software, Writing – review & editing. **Wen Zhou:** Investigation, Writing – review & editing. **Chen Liu:** Visualization, Writing – review & editing. **Mohammad Fotouhi:** Resources, Validation, Writing – review & editing. **Branko Šavija:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Mechanical analysis for the hinge joints in piezoresistive ACCCs

Fig. A1 presents the mechanical analysis of the hinge joints within piezoresistive ACCCs, focusing on the initial loading stage during which the structure remains within the elastic deformation stage. In line with Fig. 2, the geometric parameters of the ACCC are illustrated in Fig. A1a. As illustrated in Fig. A1b, with point *O* as the center, the equilibrium equations—encompassing both force and moment balance—are expressed using the following formulas Eqs. (A1)–(A3). In these equations, *F* represents force and *M* represents moment. The subscripts *x* and *y* correspond to the coordinate axis directions, while *J* denotes the joint. The parameter *lg* indicates the joint size in the *x*–*y* plane, and *t* represents the thickness of the ACCCs along the *z*-axis. Due to the symmetry of the structure, the mechanical analysis can be reduced to a quarter segment.

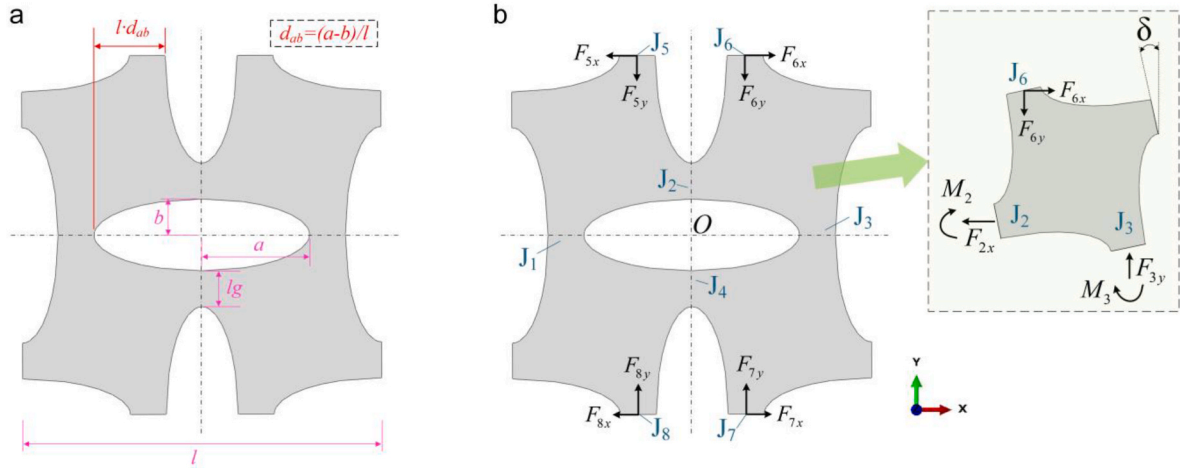


Fig. A1. Mechanical analysis for the hinge joints in piezoresistive ACCCs.

The moment equilibrium equations for this representative portion can be established as follows:

$$M_2 + M_3 + F_{2x} \cdot (a + lg / 2) = F_{3y} \cdot (a - b) \quad (A1)$$

The equilibrium of forces in the *y*-direction is expressed as: $F_{6y} = F_{3y}$ (A2)

The equilibrium of forces in the *x*-direction is expressed as:

$$F_{2x} = F_{6x} = \mu F_{6y} \quad (A3)$$

The section rotation of ACCCs is mainly caused by deformation at four key points: the top (*J*₂), bottom (*J*₄), left (*J*₁), and right (*J*₃). Deformation in the rest of the structure is minimal and can be approximated regarded as rigid body motion relative to the joints. Due to the structure's quarter rotational symmetry, when it rotates by a small angle δ , the angular deformations at *J*₂ and *J*₁ are identical, denoted as δ_1 and δ_2 , respectively.

$$\delta_1 = \delta_2 = \int \kappa ds \quad (A4)$$

Here, κ denotes the curvature at the joint, and ds represents the infinitesimal arc length of the deformation segment at the joint. Given that the elastic deformation segment s of the cementitious material is very small and that joints J_2 and J_1 share identical geometries, both s and κ can be considered constant at the joint.

$$\delta_1 = \delta_2 = \kappa s \quad (A5)$$

J_2 and J_1 share the same moment of inertia because they have identical geometries.

$$I = \frac{th^3}{12} \quad (A6)$$

From the bending moment–curvature relationship, the following inference can be made:

$$M_2 = M_3 = EI\kappa \quad (A7)$$

By integrating Eqs. (A1), (A2), and (A3), the following expression is derived:

$$M_2 + M_3 = F_{3y} \cdot [(a - b) - \mu(a + lg/2)] \quad (A8)$$

Eq. (A8) can be further simplified as

$$M_2 + M_3 \approx F_{3y} \cdot (a - b) \quad (A9)$$

Based on Eq. (1), Eq. (A9) can be further expressed as $M_2 + M_3 \approx F_{3y} \cdot l \cdot d_{ab}$ (A10)

According to Eq. (A10), the d_{ab} of P50 is approximately twice that of P25. Consequently, the yield stress of P25 is also roughly twice that of P50, which is in close agreement with their yield stress ratio shown in Fig. 10.

Appendix B. CT analysis of crack distribution around the joints of piezoresistive ACCCs

CT scans of fractured piezoresistive ACCC specimens subjected to cyclic loading reveal a primary crack (highlighted in pink), accompanied by secondary cracks and void regions (highlighted in cyan) distributed around the hinge-like cracking joint. Both front and back views are provided for detailed analysis. As shown in Figs. B1 and B2, the fracture surfaces in the main crack region exhibit noticeable roughness, which is likely associated with extensive fiber debonding initiation, fiber slippage, and fiber pull-out of PVA and carbon fibers during crack propagation, as well as the presence of larger pores and air voids. The main crack generally extends along the thickness direction, but with a slightly tortuous path, reflecting the combined influence of fiber–matrix interactions and the intrinsic heterogeneity of the cementitious composite. Compared to specimen P50, P25 exhibits a higher density of minor cracks and voids surrounding the primary crack. As discussed previously, the crack width at the P25 joint is larger than that at P50, which promotes greater involvement of nearby cementitious material, particularly fibers, in resisting the propagation of the main crack. This resistance mechanism contributes to the formation of additional microcracks and voids. While such mechanisms further enhance the FCR response of P25, they simultaneously result in a reduction of its mechanical performance.

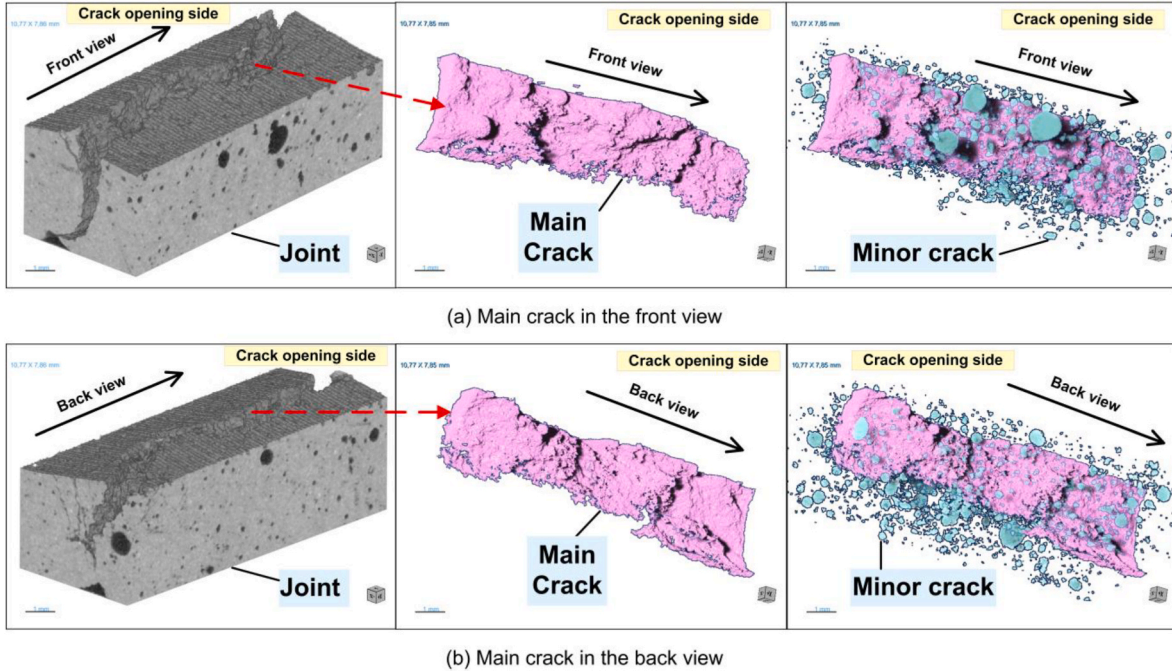


Fig. B1. Reconstructed CT scan images showing the main crack in the P50 joint after cyclic loading, (a) the front view, (b) the back view. The region highlighted in pink indicates the main crack, while the region in cyan denotes minor cracks and voids.

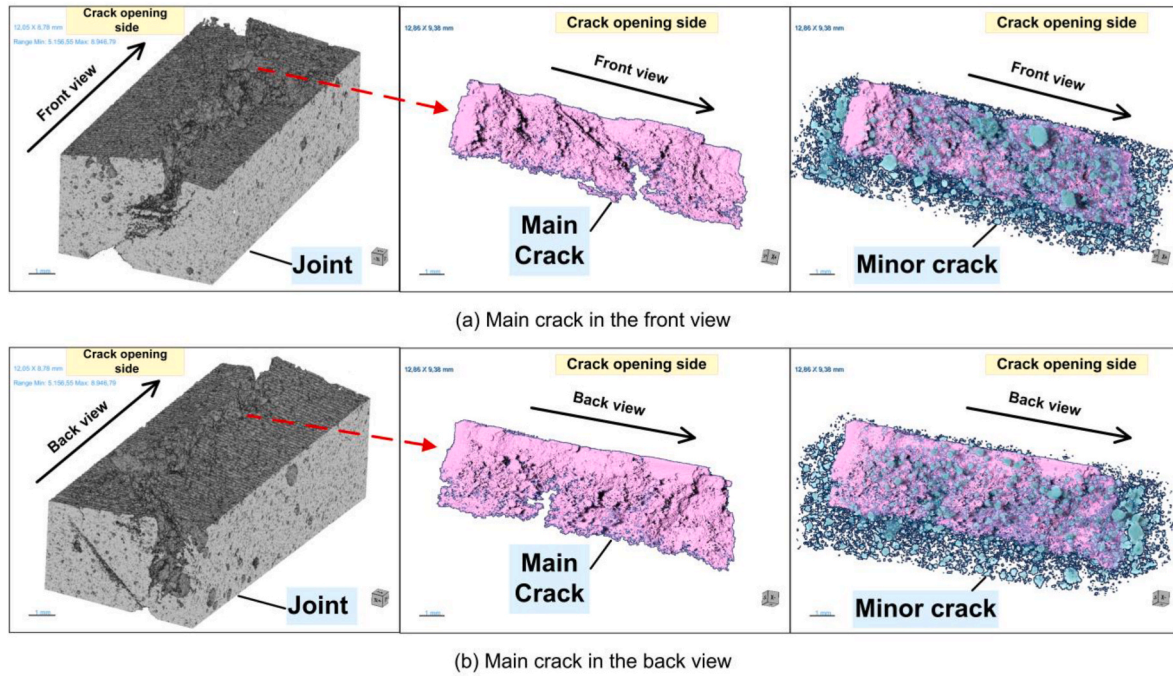
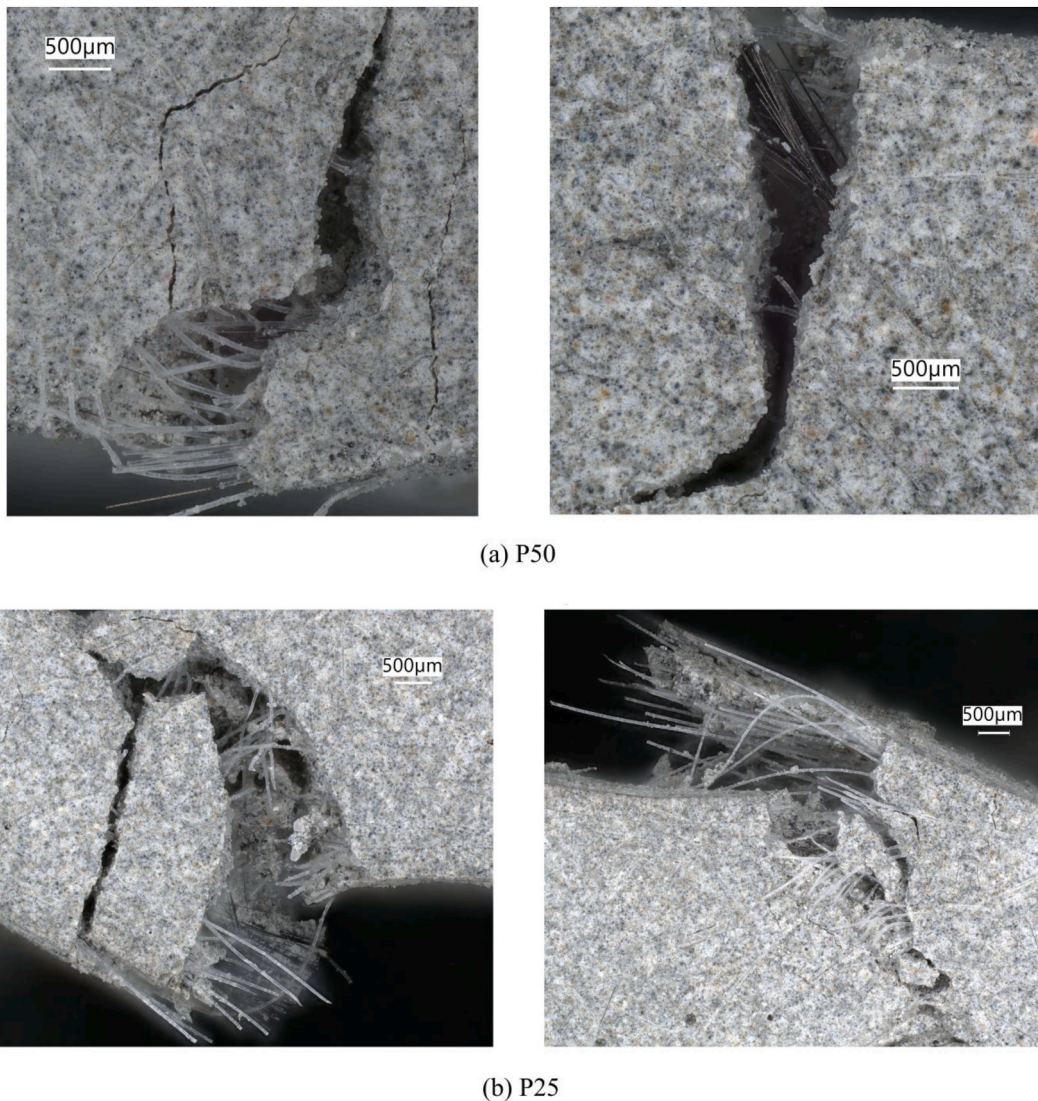


Fig. B2. Reconstructed CT scan images showing the main crack in the P25 joint after cyclic loading, (a) the front view, (b) the back view. The region highlighted in pink indicates the main crack, while the region in cyan denotes minor cracks and voids.

Appendix C. Microscopic analysis of fiber bridging behavior around the joints of ACCCs

A digital optical microscope was employed to investigate fiber bridging and pull-out behaviors at crack locations within the joint regions of piezoresistive ACCC specimens subjected to cyclic loading. As shown in Fig. C1, a distinct primary crack with considerable width was observed in the joint area. Many fiber pull-outs were identified, with the extracted fibers exhibiting straight configurations and smooth ends, while no significant fiber twisting or fiber-end fracture was detected. Due to the relatively high water-to-cement ratio, the cementitious matrix exhibited reduced stiffness, resulting in fiber–matrix interactions dominated by frictional sliding and fiber pull-out. In addition, most fibers remained bridged across the crack tips in the joint regions. Compared with carbon fibers, a greater number of PVA fibers were involved in crack bridging, which can be attributed to their stronger bridging capability as well as their longer fiber length (8 mm for PVA versus 6 mm for carbon fiber), both of which facilitate more effective crack bridging. Relative to specimen P50, specimen P25 experienced more severe joint cracking, which resulted in a larger crack opening and greater fiber pullout. Consequently, P25 showed the weakest bridging capacity and relatively limited recoverable deformation. However, this severe cracking simultaneously contributed to improved piezoresistive sensitivity in P25. Carbon fiber bundles were also observed, which is associated with the difficulty of achieving uniform dispersion of carbon fibers within the cementitious matrix compared with PVA fibers. Future studies may consider applying surface chemical treatments to carbon fibers to improve their dispersion, thereby enhancing the accuracy and stability of self-sensing performance in cementitious composites.



(a) P50

(b) P25

Fig. C1. Microstructural observations of fiber bridging and pull-out behavior within main crack around the joints of piezoresistive ACCCs after cyclic loading: (a) P50 (images from left to right correspond to the upper joint and lower joint), (b) P25 (images from left to right correspond to the upper joint and lower joint).

Appendix D. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compositesb.2026.114096>.

Data availability

Data will be made available on request.

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