

## Article

# Durability Degradation and Fractal Strength Prediction of Bentonite-Slurry/Steel-Slag Foamed Concrete Under Corrosive Wetting–Drying Exposure

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## Abstract

Bentonite slurry (BS) and steel slag powder (SS) were co-utilized to develop bentonite-slurry/steel-slag foamed concrete (BS-SSFC). The evolution of compressive strength and the associated deterioration mechanisms were examined after repeated wetting–drying exposure in four environments, namely  $H_2O$ ,  $H_2SO_4$ ,  $NaOH$ , and  $Na_2SO_4$ , by combining mechanical testing with microstructural observations. The mix-design results indicate that, for the SS-only mixtures, 20% SS replacement produced a relatively high strength, whereas the binary SS-BS system reached its maximum strength at 10% SS and 5% BS; this combination was consequently adopted for the durability experiments. After 20 cycles, the severity of degradation followed  $Na_2SO_4 > H_2SO_4 > NaOH > H_2O$ . XRD and SEM-EDS evidence shows that sulfate ions in the  $H_2SO_4$  and  $Na_2SO_4$  solutions favored ettringite-type expansive products, and  $Na_2SO_4$  further caused salt-crystallization pressure during drying. For  $NaOH$  exposure, the main damage was related to reduced stability of cementitious phases together with ion redistribution and localized re-precipitation in a strongly alkaline pore environment. Based on fractal theory, an empirical strength–degradation correlation model was established by using SEM-derived two-dimensional apparent areal porosity as a structural parameter and by linking fractal dimension with the number of cycles. Within the scope of the present experiments, the model captures the empirical link between strength loss and apparent pore-structure deterioration in BS-SSFC; however, its use remains dependent on the image-acquisition procedure, thresholding method, and material system considered. The results provide useful support for using BS-SSFC in aggressive engineering settings such as saline ground and acid-rain regions.

**Keywords:** foamed concrete; wetting–drying cycles; steel slag; bentonite; fractal model

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## 1. Introduction

Foamed concrete is valued in engineering because of its low density, thermal-insulation capacity, and potential for incorporating industrial by-products; therefore, it is widely considered for building energy-saving systems, foundation backfill, and lightweight filling applications [1–5]. Its highly porous skeleton, however, also provides pathways for water and aggressive ions, which may accelerate the loss of mechanical performance and durability [6,7]. For backfill and roadbed applications, alternating wetting and drying is a common service condition that should be evaluated [8,9]. During repeated uptake

and evaporation of water, the pore walls experience cyclic swelling and shrinkage; the resulting stress concentration promotes the initiation and growth of microcracks and finally causes a reduction in compressive strength [10–12]. Moreover, foamed concrete used in pipelines, ports, tunnels, subgrades, and industrial-site fills may be exposed to acid rain, sulfate-bearing groundwater, alkaline soils, or alkaline/industrial effluents, all of which can alter its long-term performance [13,14].

Different corrosive media damage foamed concrete through different but coupled processes. Acidic and sulfate solutions can react with cement hydrates and generate expansive phases, while salt solutions may additionally crystallize during the drying stage and impose crystallization pressure. In an alkaline medium, the chemistry of the pore solution and the stability of hydration products may be disturbed. Chemical consumption of binding phases weakens the matrix, and the accompanying expansive or crystallization stresses add physical damage. Once the matrix has been chemically weakened, the following wetting–drying cycle can cause more severe cracking; thus, deterioration accumulates progressively and is expressed macroscopically as a rapid decrease in compressive strength. Madhwani et al. [15] reported that sulfuric acid attack can markedly reduce the compressive strength of foamed concrete, with losses reaching approximately 25%. Li et al. [16] found that 5% dilute hydrochloric acid decreased both mass and strength. Kumar and Chinnaraju [17] observed pronounced expansion of foamed concrete in a sodium hydroxide environment. Bayraktar [18] showed that sulfate exposure induces expansion damage and impairs structural performance. Huang et al. [19] demonstrated that salt erosion affects strength and porosity, with deterioration following the order sulfate > mixed salt > chloride. Chen et al. [20] further reported that salt solutions increase the proportion of large pores and break cementitious products; after 120 days, strength losses in  $\text{Na}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4 + \text{NaCl}$ , and  $\text{NaCl}$  solutions were 18.06%, 12.28%, and 3.58%, respectively.

To improve the service durability of foamed concrete, many studies have introduced composite modifiers [21] or fiber reinforcement [22–25]. For example, Zhang et al. [26] used serpentine in foamed concrete and reported improved resistance to wetting–drying and freeze–thaw actions. Jin et al. [27] showed that hybrid fibers can increase strength, refine the pore system, and enhance frost resistance and performance stability under combined freeze–thaw and wetting–drying actions. Nevertheless, some modification routes rely on additives with complex properties, limited availability, or poor compatibility with resource-saving and environmentally adaptive design.

Adjusting the cementitious system is another effective way to improve concrete strength [28]. Steel slag (SS), a major by-product of steelmaking, has a chemical composition close to that of Portland cement and possesses potential hydraulic activity, making it suitable for partial cement replacement [29–31]. Such utilization can simultaneously improve mechanical performance and recycle industrial solid waste. Previous studies have examined SS in foamed concrete: Liu et al. [32] observed a significant strength increase and smaller strength loss after extensive freeze–thaw cycling; Jiang et al. [33] reported pore-structure refinement and improved compressive strength; Deng et al. [34] found improvements in both strength and volume stability; and Jagadeesan et al. [35] showed that SS-containing foamed concrete had better compressive strength and chloride-penetration resistance than the reference mixture.

Pore-structure regulation is also essential for improving the durability of foamed concrete. Bentonite has a layered mineral structure and swells after absorbing water, allowing it to occupy voids in the cementitious matrix, increase compactness, and reduce permeability [36–40]. Bentonite has therefore been incorporated into foamed concrete in several studies. Xie et al. [41] found that bentonite refined the air-void system and enhanced durability and reliability. Xu et al. [42] reported that bentonite addition optimized the pore

structure and increased compressive strength. Rehman et al. [43] confirmed that bentonite-containing concrete exhibited favorable mechanical properties and better durability than control mixtures. Han et al. [44] showed that the water-absorbing nature of bentonite reduced the expansion ratio and permeability of foamed concrete.

In recent years, the characterization of damage evolution and strength degradation in complex environments has gradually shifted from single empirical fitting to multi-parameter coupled descriptions. Xue et al. [45] proposed a brittleness evaluation method for gas-bearing coal based on the effective-stress principle, the Hoek–Brown criterion, a statistical damage constitutive model, and the energy-evolution mechanism, demonstrating that coupling damage parameters with energy-evolution characteristics can improve the evaluation accuracy of mechanical degradation in complex media. Lin et al. [46] conducted an in situ study on the high-temperature degradation of concrete and, by combining mechanical tests, SEM, XRD, and TG-MS, revealed the relationship among hydrate decomposition, microcrack propagation, and macroscopic strength loss. These studies indicate that material deterioration in complex environments is not controlled by a single factor but by the combined effects of damage accumulation, phase evolution, pore-structure changes, and external media. Therefore, when analyzing the strength degradation of BS-SSFC under corrosive wetting–drying cycles, it is necessary to couple the number of cycles, pore-structure characteristics, and fractal dimension in a strength-degradation calculation model with clearer physical meaning.

Previous studies have separately investigated the effects of steel slag and bentonite on concrete performance. Steel slag, as an industrial solid waste rich in CaO, SiO<sub>2</sub>, and Fe<sub>2</sub>O<sub>3</sub>, has been reported to possess latent hydraulic activity [29–31,47]; at the same time, its powder particles can act as micro-fillers in the cement matrix. The physical filling effect is mainly reflected in particle packing and pore-wall densification, whereas the potential later-age chemical contribution of steel slag can be reasonably interpreted, based on previous studies [29–31,47], as involving the gradual dissolution of reactive phases and the subsequent formation of cementitious products. In the present study, this chemical pathway is discussed as a plausible, literature-supported mechanistic interpretation that is consistent with the experimental observations, rather than as a reaction process directly quantified by the current tests. Bentonite, by contrast, improves foam stability mainly through water absorption, swelling, gel-network formation, and slurry cohesion. Their coupled effects may produce synergy; however, the strength evolution, corrosion-product development, and fractal description of SS-BS binary systems under multi-media wetting–drying cycles remain insufficiently understood. Accordingly, this study investigates the strength response of BS-SSFC subjected to wetting–drying cycles in H<sub>2</sub>O, H<sub>2</sub>SO<sub>4</sub>, NaOH, and Na<sub>2</sub>SO<sub>4</sub> solutions and uses mechanical testing, XRD, SEM-EDS, and image-based fractal analysis to clarify its deterioration mechanism and establish a strength-degradation calculation model.

## 2. Materials and Experimental Methods

### 2.1. Raw Materials and Mix Proportion Design

#### 2.1.1. Raw Materials

- (1) Cement: Anhui (China) Conch's P·O 42.5 ordinary Portland cement was chosen. The measured apparent density was 3100 kg·m<sup>−3</sup> and the specific surface area was 357 m<sup>2</sup>·kg<sup>−1</sup>. Its oxide composition and basic physical–mechanical properties are summarized in Tables 1 and 2.

**Table 1.** Cement chemical constituents.

| Ingredients | K <sub>2</sub> O | SO <sub>3</sub> | TiO <sub>2</sub> | MgO  | Fe <sub>2</sub> O <sub>3</sub> | Al <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> | CaO   |
|-------------|------------------|-----------------|------------------|------|--------------------------------|--------------------------------|------------------|-------|
| content (%) | 0.85             | 2.31            | 0.61             | 2.51 | 4.57                           | 6.12                           | 23.54            | 57.21 |

**Table 2.** Technical parameters of the cement used.

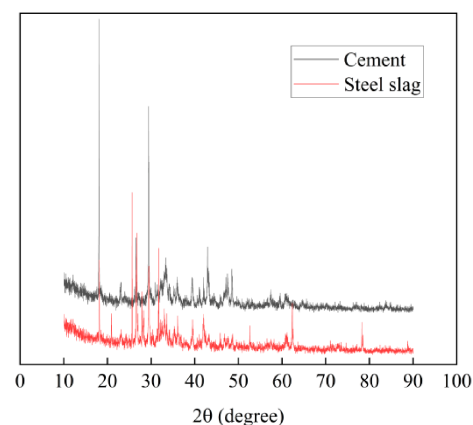
| Setting Time/min     |                    | 3-Day Intensity(MPa) |                   | 28-Day Intensity(MPa) |                   |
|----------------------|--------------------|----------------------|-------------------|-----------------------|-------------------|
| Initial setting time | final setting time | compressive strength | flexural strength | compressive strength  | flexural strength |
| 150                  | 250                | 27.3                 | 5.7               | 55.2                  | 8.5               |

- (2) Steel slag powder: Over-two-year-aged steel slag (SS) was supplied by the Ma Steel Group, Anhui Province (China). Its apparent density and bulk density are  $3400 \text{ kg}\cdot\text{m}^{-3}$  and  $1670 \text{ kg}\cdot\text{m}^{-3}$ , respectively. Table 3 presents the chemical composition of the SS. Measurements indicated a free calcium oxide (f-CaO) content of 2.7% and an expansion rate below 7.8% in the SS, meeting the requirements of the pertinent standards [48,49].

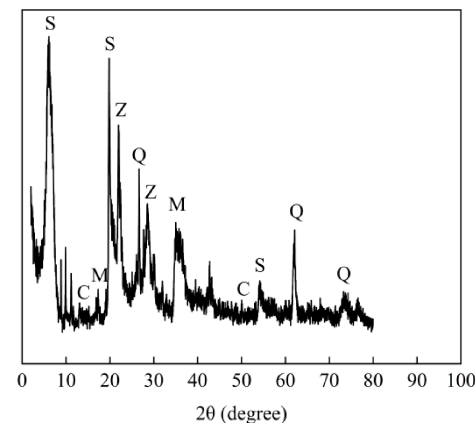
**Table 3.** Chemical composition of SS.

| Ingredients | K <sub>2</sub> O | SO <sub>3</sub> | TiO <sub>2</sub> | MgO  | Fe <sub>2</sub> O <sub>3</sub> | Al <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> | CaO   |
|-------------|------------------|-----------------|------------------|------|--------------------------------|--------------------------------|------------------|-------|
| content (%) | 1.52             | 3.31            | 2.02             | 2.39 | 17.26                          | 4.88                           | 12.53            | 55.78 |

Analysis of Figure 1 (XRD patterns) along with a comparison of the data in Tables 1 and 3 reveals a high degree of similarity in the compositions of cement and SS. This similarity in the proportion of primary cementitious constituents justifies the partial replacement of cement with SS [47].

**Figure 1.** XRD patterns of SS and cement.

- (3) Bentonite: Calcium-based bentonite was selected, presenting as a grayish-white loose powder that forms a gel-like substance upon water absorption and swelling. Its primary component is montmorillonite, and it also contains constituents such as quartz, zeolite, and mica. This phase is montmorillonite, represented by the formula  $(\text{Al}_2\text{Mg}_3)[\text{Si}_4\text{O}_{10}][\text{OH}]_2\cdot n\text{H}_2\text{O}$ , featuring a typical 2:1 T-O-T layered crystal structure where an octahedral alumina layer is interleaved between two tetrahedral silica layers. The XRD pattern is shown in Figure 2.



**Figure 2.** XRD pattern of bentonite (Z—zeolite, M—mica, C—cristobalite, and Q—quartz, S—montmorillonite).

- (4) Foaming agent: An HX-P-type physical foaming agent produced by a company in Tianjin (China) was used. It has a foaming ratio of 28.6, a 1 h settling distance of 7.2 mm, and a bleeding capacity of 62 mL, meeting the requirements of the relevant standard [50].
- (5) Water: The water quality used in all tests strictly complied with the relevant standard for mixing water [51].

To further characterize the physicochemical properties of the steel slag powder and bentonite, their particle-size distribution, specific surface area, and water-absorption/swelling behavior were tested. The particle-size distribution of steel slag powder was measured by laser diffraction, and its specific surface area was determined using the Blaine air-permeability method. For bentonite, particle-size distribution was also obtained by laser diffraction, whereas the specific surface area was measured by the BET method. In addition, its water absorption and free swelling index were tested. The results are listed in Table 4.

**Table 4.** Physical properties of steel slag powder and bentonite.

| Material          | Apparent Density/(kg·m <sup>-3</sup> ) | Bulk Density/(kg·m <sup>-3</sup> ) | D10/μm | D50/μm | D90/μm | Specific Surface Area                 | Water Absorption/% | Free Swelling Index/(mL·2g <sup>-1</sup> ) |
|-------------------|----------------------------------------|------------------------------------|--------|--------|--------|---------------------------------------|--------------------|--------------------------------------------|
| Steel slag powder | 3400                                   | 1670                               | 0.95   | 14.80  | 39.60  | 455 m <sup>2</sup> ·kg <sup>-1</sup>  | —                  | —                                          |
| Calcium bentonite | 2600                                   | 820                                | 1.80   | 11.20  | 42.50  | 38.60 m <sup>2</sup> ·g <sup>-1</sup> | 260                | 13.50                                      |

It should be noted that powder fineness affects both hydration and pore-structure formation in BS-SSFC. Finer particles with larger specific surface areas enhance the physical filling effect and provide additional reaction interfaces that, according to previous studies, favor ion dissolution and hydrate formation [29–31,47]; they can also fill pores in the cement matrix and defects in foam-pore walls, thereby improving pore grading and matrix compactness. Therefore, the influence of steel slag and bentonite on BS-SSFC is not determined solely by their chemical composition but is also closely related to particle-size distribution, specific surface area, and particle-filling effects. The *D*50 and *D*90 values of the steel slag powder were 14.80 μm and 39.60 μm, respectively, which are consistent with its Blaine specific surface area of 455 m<sup>2</sup>·kg<sup>-1</sup>. This particle-size level allows the steel slag powder to serve as a micro-filler and provides a reasonable basis for its potential later-age reaction, as reported in previous studies [29–31,47]. However, different fineness levels of steel slag powder were not separately investigated in this study; therefore, the

independent contribution of steel slag fineness to hydration rate, pore refinement, and strength development requires further study.

### 2.1.2. Mix Proportion Design and Sample Preparation

The main mixture series was designed with a target dry density of  $700 \text{ kg}\cdot\text{m}^{-3}$  and a fixed water-to-binder ratio of 0.45. In this study, the binder was defined as the total mass of cement and steel slag, and the water-to-binder ratio was calculated as the ratio of total water to binder mass:

$$w/b = \frac{m_w}{m_c + m_s} = 0.45 \quad (1)$$

where  $m_w$  is the total water content, including both additional mixing water and the water contained in the bentonite slurry;  $m_c$  is the cement mass; and  $m_s$  is the steel slag mass. The water used for preparing the bentonite slurry was therefore included in the total water content and did not increase the water-to-binder ratio.

Steel slag replaced cement at 0%, 10%, 20%, and 30% by binder mass. Bentonite slurry was added at 1%, 3%, 5%, 7%, 10%, 15%, and 20% of the combined mass of cement, steel slag, and total water. The preliminary optimization showed that, at a soil-to-water ratio of 1:15, a steel slag replacement level of 10%, and a bentonite-slurry dosage of 5%, BS-SSFC exhibited favorable pore structure and mechanical performance; this mixture was therefore used for the subsequent corrosive wetting–drying tests. Taking a target dry density of  $700 \text{ kg}\cdot\text{m}^{-3}$  and a bentonite-slurry soil-to-water ratio of 1:15 as an example, if the steel slag replacement ratio is  $s$  and the bentonite-slurry dosage is  $p$ , the dry binder mass  $B$  is calculated as

$$B = \frac{\rho_d}{1 + \frac{p(1+0.45)}{1+15}} \quad (2)$$

The cement mass is  $B(1 - s)$ , the steel slag mass is  $Bs$ , the total water is  $0.45B$ , the dry bentonite mass is  $p(B + 0.45B)/16$ , the slurry water is 15 times the dry bentonite mass, and the additional mixing water is the difference between the total water and the slurry water. The representative mixture proportions are listed in Table 5.

**Table 5.** Representative mix proportions for the 1:15 bentonite-slurry system at  $700 \text{ kg}\cdot\text{m}^{-3}$ .

| Mixture | SS Replacement/% | BS Dosage/% | Cement/( $\text{kg}\cdot\text{m}^{-3}$ ) | SS/( $\text{kg}\cdot\text{m}^{-3}$ ) | Dry Bentonite/( $\text{kg}\cdot\text{m}^{-3}$ ) | Additional Water/( $\text{kg}\cdot\text{m}^{-3}$ ) | Slurry Water/( $\text{kg}\cdot\text{m}^{-3}$ ) | Total Water/( $\text{kg}\cdot\text{m}^{-3}$ ) | Foam Volume/( $\text{m}^3\cdot\text{m}^{-3}$ ) | Foam/Slurry Volume Ratio |
|---------|------------------|-------------|------------------------------------------|--------------------------------------|-------------------------------------------------|----------------------------------------------------|------------------------------------------------|-----------------------------------------------|------------------------------------------------|--------------------------|
| FC-S0B0 | 0                | 0           | 700.0                                    | 0.0                                  | 0.00                                            | 315.0                                              | 0.0                                            | 315.0                                         | 0.460                                          | 0.85                     |
| S0B5    | 0                | 5           | 696.8                                    | 0.0                                  | 3.16                                            | 266.2                                              | 47.4                                           | 313.6                                         | 0.460                                          | 0.85                     |
| S10B5   | 10               | 5           | 627.2                                    | 69.7                                 | 3.16                                            | 266.2                                              | 47.4                                           | 313.6                                         | 0.462                                          | 0.86                     |
| S20B5   | 20               | 5           | 557.5                                    | 139.4                                | 3.16                                            | 266.2                                              | 47.4                                           | 313.6                                         | 0.464                                          | 0.86                     |
| S30B5   | 30               | 5           | 487.8                                    | 209.1                                | 3.16                                            | 266.2                                              | 47.4                                           | 313.6                                         | 0.466                                          | 0.87                     |

The bentonite slurry was prepared by drying the bentonite to constant mass, passing it through a 200-mesh sieve, and mixing it with water at a soil-to-water ratio of 1:15. The slurry was mechanically stirred until no visible agglomerates remained and then aged for 24 h to ensure uniformity and stability. During specimen preparation, cement and steel slag were dry-mixed for 2 min; the pre-prepared bentonite slurry was then added and mixed for another 3 min to form a homogeneous cementitious slurry.

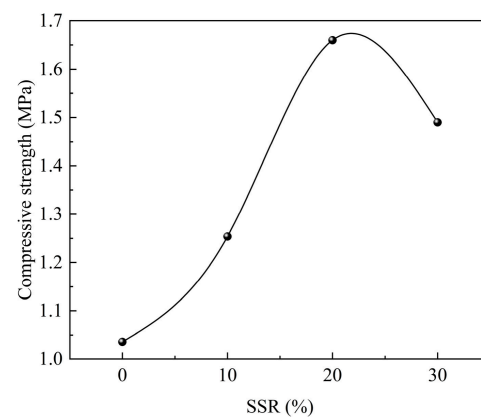
The preformed foam was produced using an HX-P physical foaming agent. The foaming agent was diluted with water at a ratio of 1:30 and foamed using a foaming machine. The measured foaming ratio was 28.6, the foam density was  $35 \pm 3 \text{ kg}\cdot\text{m}^{-3}$ , the 1 h settlement distance was 7.2 mm, and the 1 h bleeding volume was 62 mL. After the cementitious slurry became uniform, the foam was added in batches and mixed at low speed to reduce foam collapse and segregation. The foam dosage was adjusted according to the measured fresh density so that the specimens achieved the target dry

density of  $700 \text{ kg}\cdot\text{m}^{-3}$ . For the optimum S10B5 mixture, the preformed-foam volume was  $0.462 \text{ m}^3\cdot\text{m}^{-3}$ , and the foam/slurry volume ratio was 0.86.

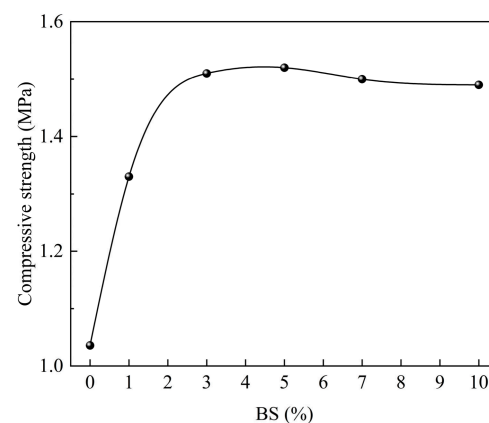
The uniformly mixed foamed-concrete slurry was poured into molds immediately. The surface was carefully leveled with slight compaction, while excessive vibration was avoided to prevent foam collapse. Once placed in the molds, the fresh specimens were sealed with plastic film to limit moisture evaporation, demolded after 24 h, and then transferred to standard curing until the required age.

## 2.2. Determination of Optimal Dosages of BS and SS

Figures 3 and 4 present the compressive strength test results of foamed concrete (FC) with single admixtures of SS and BS, respectively.



**Figure 3.** FC compressive strength versus SSR.



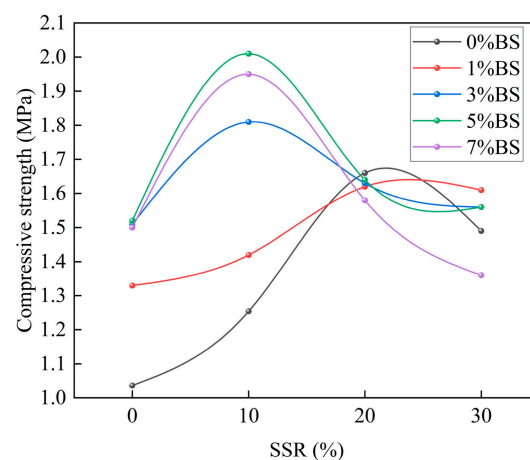
**Figure 4.** Influence of BS content on FC compressive strength.

As shown in Figure 3, the compressive strength initially increases and then decreases with the rise in SS replacement ratio (SSR), a trend consistent with the findings of Chen [52]. The maximum compressive strength of 1.66 MPa is achieved at an SSR of 20%. This variation in compressive strength is closely related to the influence of SS on the paste matrix. When  $\text{SSR} \leq 20\%$ , the appropriate incorporation of SS optimizes the rheological properties of the paste [53]. This results in a more uniform distribution of foam bubbles within the paste, leading to a more homogeneous and denser pore structure in the blocks, which macroscopically manifests as enhanced compressive strength. However, a further increase in SSR leads to a decrease in strength, a trend also reported by Zeng et al. [54]. This reduction may be associated with cement dilution, the relatively low early reactivity of excessive steel slag, and decreased paste cohesion, which can destabilize bubbles and promote local particle settlement [54,55]. The reduction in cohesion makes foam bubbles

more prone to rupture and facilitates the settling of SS particles at the bottom. These phenomena degrade the internal homogeneity of the matrix, consequently leading to the decline in compressive strength.

With increasing BS content, the compressive strength shows an initial increase followed by a decrease (Figure 4), aligning with the observations of Khan [56]. When  $BS \leq 5\%$  (the optimal dosage), the uniformly dispersed BS within the paste fills the microscopic pores [57] and simultaneously enhances the cohesion of the paste [58]. This results in a denser internal structure and more complete bonding of the matrix, manifesting as an improvement in compressive strength. However, when the BS content is further increased, excessive BS competes for free water, which to some extent affects the hydration of the cementitious materials—a phenomenon also noted by Reddy [59]. Concurrently, excessive BS tends to agglomerate into clusters. These agglomerates can easily become stress concentration points, leading to structural damage and ultimately causing a decline in overall strength.

The above discussion indicates that SS and BS affect FC through different mechanisms. In the single-SS system, 20% SS corresponds to a relatively high compressive strength; however, this result applies only to the single-addition system with  $BS = 0$  and cannot be directly used as the optimum mix proportion for the SS-BS binary system. As shown in Figure 5, in the binary system, the combination of 5% BS and 10% SS yields the maximum compressive strength, while further increasing the SS replacement ratio reduces the strength. For clarity, the physical effects of the two modifiers are distinguished here from the potential chemical contribution. At an appropriate dosage, steel slag powder mainly provides a micro-filler effect by filling fine defects in the pore walls and matrix, improving particle packing, and reducing local pore-structure nonuniformity. Bentonite slurry mainly acts through water retention and regulation, enhanced slurry cohesion, foam stabilization, and improved pore-distribution uniformity. Separately, previous studies have shown that reactive Ca-, Si-, and Al-bearing phases in steel slag can gradually dissolve in highly alkaline pore solutions and contribute to later-age cementitious-product formation [29–31,47]. This potential later-age reaction is considered an auxiliary, literature-supported chemical contribution rather than the sole explanation for the observed strength response. When the SS replacement ratio is too high, the cement content decreases and the density difference between SS and slurry increases, which may cause local settlement and reduced forming uniformity. Based on the binary strength response and specimen-forming behavior, 10% SS + 5% BS was selected for subsequent wetting–drying tests.



**Figure 5.** Strength response of mixtures containing both SS and BS.

### 2.3. Wetting–Drying Cycle Test Procedure

For determining the strength degradation of BS-SSFC in different aggressive media, specimens of  $700 \text{ kg}\cdot\text{m}^{-3}$  dry density produced from the adopted mixture (SSR10%, BS5%) were utilized. Deionized water served as the baseline moisture-cycling medium.  $\text{H}_2\text{SO}_4$  represented an acidic environment,  $\text{Na}_2\text{SO}_4$  represented a sulfate saline environment, and NaOH represented a high-pH alkaline environment. The NaOH group was designed for two reasons: BS-SSFC used in backfill, roadbed, or underground filling may encounter alkaline soils, alkaline industrial leachates, or pore solutions from adjacent cement-based materials; together with the  $\text{H}_2\text{SO}_4$  and  $\text{Na}_2\text{SO}_4$  groups, it completes an acid–alkali–salt comparison. Therefore, NaOH exposure was used to assess strength loss and microstructural changes under high-pH conditions. The solution parameters were  $0.01 \text{ mol}\cdot\text{L}^{-1}$   $\text{H}_2\text{SO}_4$  ( $\text{pH} = 2.0 \pm 0.1$ ),  $0.10 \text{ mol}\cdot\text{L}^{-1}$  NaOH ( $\text{pH} = 13.0 \pm 0.1$ ), and 5 wt.%  $\text{Na}_2\text{SO}_4$  ( $\text{pH} = 7.0 \pm 0.2$ ). Before testing, the pH of each solution was calibrated. During cycling, solutions were renewed every five cycles, or earlier if the pH shift exceeded 0.2, to maintain a stable exposure condition. Each test group contained six specimens and the average result was used.

- (1) Initial performance measurement: After curing, the compressive strength of the specimens was measured.
- (2) Cycling process: Upon completion of standard curing (28 d), the specimens were divided into groups of six; each group was then placed in the assigned solution for a 48 h period until they were nearly saturated. Before each cycle, residual surface solution was removed. The specimens were placed in the container with spacing greater than 20 mm between adjacent specimens and at least 20 mm from the container wall; the specimens were submerged such that the solution surface stood at least 30 mm above their tops. One cycle consisted of 5 min immersion, 30 min air drying at room temperature, drying in an oven at  $60 \pm 5^\circ\text{C}$  for 7 h, and 20 min cooling at room temperature. The selected cycle numbers were  $n = 0, 5, 10, 15$ , and 20. The 20-cycle specimens were used for damage and microstructural comparison among media, while all cycle points were used to fit the strength–cycle relationship.
- (3) Performance testing: After the target number of cycles was reached, compressive strength tests were conducted. Each group's compressive strength was computed as the average of six parallel specimens. The results were used to characterize the relative deterioration under the combined action of chemical-medium erosion and wetting–drying cycles.

Cycle regime: After 48 h of pre-saturation, short-term immersion was used to renew the solution within the pores of the low-density foamed concrete during cycling; the subsequent longer drying period was used to intensify crystallization, shrinkage, and ion-migration effects. This regime was adopted to compare the relative deterioration capacity of different media for BS-SSFC.

The  $\text{H}_2\text{SO}_4$  solution was used to simulate acid attack in acid rain, acidic groundwater, or industrial acidic leachate; the  $\text{Na}_2\text{SO}_4$  solution was used to simulate sulfate saline soil, sulfate-bearing groundwater, and coastal saline environments; and the NaOH solution was used to simulate alkaline soil, industrial alkaline wastewater, and the highly alkaline pore solution of cement-based materials. The wetting–drying regime adopted in this study is an accelerated laboratory corrosion test, intended to intensify moisture migration, ion ingress, salt crystallization, and corrosion-product formation so that the relative deterioration of BS-SSFC in different aggressive media can be compared. This regime does not fully reproduce any specific natural field service process; rather, it is used to characterize the relative strength degradation and structural damage of the material under acid, alkaline, and salt environments.

#### 2.4. Scanning Electron Microscopy (SEM)

The SEM samples were prepared from specimens that had been cured to the specified age and subjected to wetting–drying cycles. These samples were subsequently dried in a vacuum oven at 40 °C. Following this, suitably sized fragments were extracted from their interior. To ensure conductivity, the SEM samples were sputter-coated with a layer of gold. SEM microstructural examination was conducted on a JEOL JSM-6490LV instrument (JEOL, Ltd., Tokyo, Japan) following standard imaging procedures. For representative analysis, multiple randomly selected locations ( $\geq 3$  per sample) were imaged.

#### 2.5. X-Ray Diffraction (XRD)

To avoid carbonation and surface contamination, core samples were extracted for testing. To ensure particle size consistency, the material was subjected to pulverization followed by sieving through a 200-mesh standard sieve. A Rigaku SmartLab X-ray diffractometer (Rigaku Corporation, Tokyo, Japan) was employed to perform the XRD analysis.

To further compare the evolution of major crystalline products under different aggressive media, the characteristic peaks of C-(A)-S-H, C-S-H,  $\text{CaCO}_3$ , and Aft were analyzed after phase identification. The peak intensity of each phase in the  $\text{H}_2\text{O}$  group was used as the reference, and the corresponding peak intensities in the corrosive media were normalized to obtain the relative peak-intensity index  $R_i = I_i / I_{\text{H}_2\text{O}}$ . This method reflects the relative variation trend of crystalline products under different media but does not represent absolute phase contents.

#### 2.6. Porosity Determination and Model Data Processing

In this work, porosity was introduced as a structural parameter for the strength model rather than as an independent criterion for mixture optimization. The reported porosity is the SEM-derived two-dimensional apparent areal porosity and is used to characterize the relative change in internal damage under different wetting–drying conditions. The procedure was as follows: internal fragments were sampled and sputter-coated with gold; SEM images were acquired at the same magnification and brightness; at least three representative fields of view were randomly selected for each specimen; the images were calibrated using the scale bar, converted to grayscale, and binarized using the Otsu threshold method; and ImageJ (1.54f)/MATLAB (R2023b) was then used to calculate the ratio of pore-region area to total analyzed area. The average value from multiple images was used for each condition. It should be emphasized that the porosity reported here is not the true three-dimensional volumetric porosity of the material but the SEM-derived two-dimensional apparent areal porosity obtained by threshold segmentation of cross-sectional images. This parameter represents the area fraction of dark regions in the selected SEM field and can be used to describe the relative changes in pores, microcracks, and local spalling areas under the same material system, sampling method, and image-processing procedure. Because SEM images only reflect local cross-sectional morphology, and the binarization result can be affected by sampling position, surface roughness, coating state, brightness, contrast, and the threshold algorithm, this parameter cannot be regarded as the true three-dimensional pore volume fraction. It is used here only as a relative damage index in the fractal model rather than as an absolute porosity.

#### 2.7. Mass Water Absorption, Mass Change, Volume Change, and Strength-Loss Tests

To further evaluate the water-absorption characteristics of BS-SSFC and its apparent deterioration after corrosive wetting–drying cycles, mass water absorption, mass change, volume change, and compressive-strength loss were measured. Mass water absorption was used to characterize pore water uptake and open-pore features; mass change reflected

the combined effects of solution adsorption, corrosion-product formation, salt deposition, and surface spalling; volume change represented macroscopic deformation induced by expansive products, crystallization pressure, and wetting–drying shrinkage; and strength loss was used to quantify the degradation of load-bearing capacity.

For the mass water-absorption test, specimens cured for 28 d were dried to constant mass in an oven at  $60 \pm 5$  °C, and the dry mass  $m_d$  was recorded. The specimens were then immersed in water at  $20 \pm 5$  °C until saturation. After immersion, visible surface water was removed with a damp cloth, and the saturated mass  $m_s$  was immediately measured. The mass water absorption was calculated as follows:

$$W_a = \frac{m_s - m_d}{m_d} \times 100\% \quad (3)$$

where  $W_a$  is the mass water absorption,  $m_d$  is the oven-dry mass, and  $m_s$  is the saturated mass.

During the wetting–drying tests, specimens were removed after the specified number of cycles, residual solution on the surface was wiped off, and the specimens were cooled to room temperature. Their mass and three-dimensional dimensions were then measured. The mass change  $W_m$ , volume change  $W_v$ , and compressive-strength loss  $W_f$  were calculated using Equations (4)–(6):

$$W_m = \frac{m_n - m_0}{m_0} \times 100\% \quad (4)$$

$$W_v = \frac{V_n - V_0}{V_0} \times 100\% \quad (5)$$

$$W_f = \frac{f_0 - f_n}{f_0} \times 100\% \quad (6)$$

where  $m_0$  and  $m_n$  are the masses before cycling and after the  $n$ th cycle,  $V_0$  and  $V_n$  are the corresponding volumes, and  $f_0$  and  $f_n$  are the corresponding compressive strengths. Six parallel specimens were tested for each group, and the average value was used.

It should be noted that mass water absorption reflects the ability of a specimen to absorb water after saturation, whereas mass change describes the change in specimen mass before and after corrosive wetting–drying cycles. The two indices therefore characterize different aspects: the former represents pore water uptake, while the latter reflects the combined effects of corrosion-product formation, salt crystallization, dissolution, and spalling.

## 2.8. Hydration-Heat Test

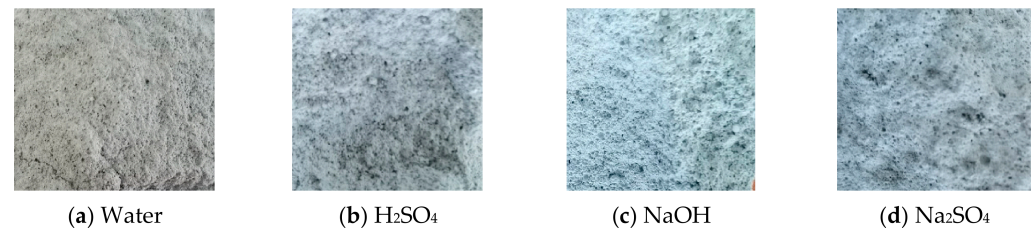
To analyze the influence of steel slag and bentonite slurry on the early hydration process of BS-SSFC, an isothermal calorimeter was used to test the hydration heat of different cementitious systems. Four groups were considered: pure cement (FC), single steel slag addition (S20), single bentonite-slurry addition (B5), and the steel slag–bentonite slurry binary system (S10B5). All samples were prepared at the same water-to-binder ratio, mixed uniformly, and immediately placed in the calorimeter. The tests were conducted continuously for 72 h at  $20 \pm 1$  °C, and the heat-flow rate and cumulative heat release were recorded. Hydration-heat results were normalized by the mass of binder to compare the early hydration process of different systems.

## 3. Results and Discussion

### 3.1. Wetting–Drying Cycle Tests

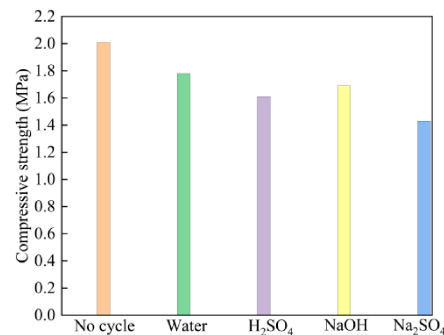
Figure 6 shows the post-failure surface features of BS-SSFC specimens after cyclic exposure, where the target dry density was controlled at  $700 \text{ kg}\cdot\text{m}^{-3}$ . Compared with the water group, the  $\text{H}_2\text{SO}_4$ -,  $\text{NaOH}$ -, and  $\text{Na}_2\text{SO}_4$ -exposed specimens exhibit more pronounced

internal damage, confirming that acid, alkali, and salt species contributed to matrix deterioration. In the  $\text{H}_2\text{SO}_4$  and  $\text{Na}_2\text{SO}_4$  groups,  $\text{SO}_4^{2-}$  can react with cementitious phases to form expansive products such as Aft, and the associated expansion stress weakens the matrix. In the NaOH group, the damage is mainly manifested as local loosening of pore walls and uneven product distribution, which is attributed to partial dissolution of Si-Al phases from SS and bentonite followed by localized re-precipitation.



**Figure 6.** Failure surface morphology after wetting–drying cycles.

Figure 7 presents the compressive strength test results of each group after 20 wetting–drying cycles at a density of  $700 \text{ kg}\cdot\text{m}^{-3}$ .



**Figure 7.** Comparison of compressive strength after wetting–drying cycles.

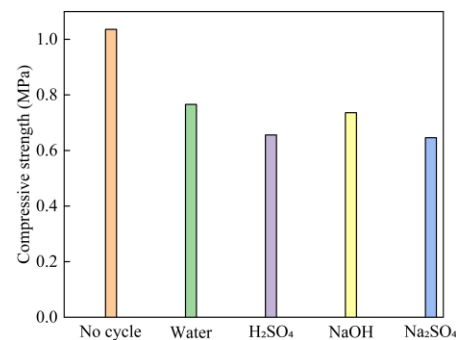
The compressive strengths after cycling in  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{SO}_4$ , NaOH, and  $\text{Na}_2\text{SO}_4$  are 1.78, 1.61, 1.69, and 1.43 MPa, respectively. Relative to the uncycled strength of 2.01 MPa, the corresponding losses are 11.44%, 19.90%, 15.92%, and 28.86%. Thus, the damaging effect increases in the sequence  $\text{H}_2\text{O} < \text{NaOH} < \text{H}_2\text{SO}_4 < \text{Na}_2\text{SO}_4$ . Water cycling mainly causes repeated shrinkage and swelling stresses. In  $\text{H}_2\text{SO}_4$ , this physical damage is coupled with sulfate-induced Aft formation. The NaOH group exhibits less damage than the  $\text{H}_2\text{SO}_4$  group, indicating that alkaline exposure promotes dissolution–re-precipitation of hydration products and local loosening but is less destructive than sulfate reaction and expansive-product formation in acidic solution.  $\text{Na}_2\text{SO}_4$  produces the largest strength reduction because sulfate reaction and salt-crystallization pressure act simultaneously.

### 3.2. Effects of SS and BS on Strength Retention, Water Absorption, and Apparent Deterioration of FC

#### 3.2.1. Strength Improvement

To further quantify the performance improvement of the steel slag–bentonite slurry binary system relative to the reference foamed concrete, a pure cement foamed concrete group without steel slag or bentonite slurry (FC) was used as the control. As shown in Figure 8, the compressive strength of the FC group decreased after 20 wetting–drying cycles in all media. The strengths in  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{SO}_4$ , NaOH, and  $\text{Na}_2\text{SO}_4$  were 0.77, 0.66, 0.74, and 0.65 MPa, respectively, corresponding to strength-loss ratios of 26.35%, 36.92%, 29.23%, and 37.88%. This indicates that water cycling, acid attack, alkaline exposure, and

sulfate salt crystallization all weaken the matrix, with  $\text{H}_2\text{SO}_4$  and  $\text{Na}_2\text{SO}_4$  producing more pronounced deterioration.



**Figure 8.** Compressive strength of pure cement specimens after wetting–drying cycles.

Compared with the FC group, the compressive strengths of BS-SSFC under the uncycled,  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{SO}_4$ , NaOH and  $\text{Na}_2\text{SO}_4$  conditions increased by 93.27%, 132.38%, 145.43%, 129.62%, and 121.36%, respectively, indicating that appropriate co-addition of steel slag and bentonite slurry can improve the initial strength and residual load-bearing capacity after most corrosive wetting–drying cycles. Based on the measured strength and pore-structure results, together with the mechanisms reported in previous studies [29–35,47], this improvement is reasonably interpreted as arising mainly from particle filling, enhanced slurry cohesion, foam stabilization, and pore-structure regulation. The potential later-age reaction of steel slag is considered a plausible, literature-supported auxiliary contribution rather than the sole mechanism responsible for the observed strength improvement.

### 3.2.2. Mass Water-Absorption Analysis

Mass water absorption reflects the water-uptake capacity and open-pore characteristics of foamed concrete and is therefore an important index for evaluating service performance. Table 6 lists the mass water absorption of the pure cement group, 20%SS group, 5%BS group, and S10B5 group. The pure cement group had a mass water absorption of 28.37%, while the 20%SS group, 5%BS group, and S10B5 group showed values of 28.99%, 31.27%, and 30.00%, respectively. The S10B5 group exhibited lower water absorption than the 5%BS group but higher water absorption than the pure cement and 20%SS groups.

**Table 6.** Mass water absorption of different cementitious systems.

| Group       | Mass Water Absorption/% | Change Relative to Pure Cement/% |
|-------------|-------------------------|----------------------------------|
| Pure cement | 28.37                   | —                                |
| 20%SS       | 28.99                   | +2.19                            |
| 5%BS        | 31.27                   | +10.22                           |
| S10B5       | 30.00                   | +5.75                            |

These results show that the addition of steel slag and bentonite slurry changes the water-absorption behavior while improving strength and pore-wall structure. The water absorption of the 20%SS group was only slightly higher than that of the pure cement group, indicating that the micro-filler effect of steel slag can partly improve matrix compactness, although the reduction in cement content may still increase pore connectivity. The 5%BS group showed the highest water absorption, mainly because of the strong water-absorption and water-retention capacity of bentonite. The S10B5 group had a lower water absorption than the 5%BS group, suggesting that the combined steel slag and bentonite slurry addition

can mitigate the excessive water absorption induced by bentonite alone. Nevertheless, the S10B5 value remained higher than that of the pure cement group; thus, the performance advantage of the binary system should be understood mainly in terms of strength improvement and pore-size refinement, rather than comprehensive improvement in all durability indices.

### 3.2.3. Coupled Analysis of Mass Change, Volume Change, and Strength Loss

Mass change and volume change were further introduced together with strength loss to establish a multi-index apparent deterioration evaluation. Mass change reflects the combined effects of solution adsorption, corrosion-product formation, salt deposition, and surface spalling, while volume change represents macroscopic deformation caused by expansive corrosion products, salt crystallization pressure, bentonite swelling, and wetting–drying shrinkage. Table 7 summarizes the mass change, volume change, and strength-loss ratio of BS-SSFC after 20 wetting–drying cycles in the different solutions.

**Table 7.** Multi-index deterioration parameters of BS-SSFC after wetting–drying cycles in different solutions.

| Solution                        | Mass Change/% | Volume Change/% | Compressive-Strength Loss/% | Overall Deterioration |
|---------------------------------|---------------|-----------------|-----------------------------|-----------------------|
| H <sub>2</sub> O                | −0.60         | 0.25            | 11.44                       | Slight                |
| NaOH                            | −1.20         | 0.55            | 15.92                       | Moderate              |
| H <sub>2</sub> SO <sub>4</sub>  | −2.10         | 0.95            | 19.90                       | Severe                |
| Na <sub>2</sub> SO <sub>4</sub> | −3.40         | 1.55            | 28.86                       | Very severe           |

As shown in Table 7, the mass change, volume change, and compressive-strength loss of BS-SSFC differed markedly under different corrosive solutions, and the deterioration degrees reflected by the three indices were generally consistent. The H<sub>2</sub>O group showed the lowest mass loss and volume change, at 0.60% and 0.25%, respectively, with a corresponding compressive-strength loss of 11.44%. This indicates that simple water absorption–evaporation can cause repeated pore-wall shrinkage and local microcrack propagation, but its influence on the overall mass and macroscopic volume of the specimens is relatively limited. Therefore, the deterioration in the H<sub>2</sub>O group was mainly physical wetting–drying damage.

For the NaOH group, the mass loss and volume change increased to 1.20% and 0.55%, respectively, and the compressive-strength loss reached 15.92%, all higher than those of the H<sub>2</sub>O group. This indicates that the high-pH environment could alter the ionic equilibrium of the pore solution in BS-SSFC and may promote the dissolution–migration–re-precipitation of some silicoaluminate phases in steel slag and bentonite, resulting in local loosening of pore walls and reduced continuity of cementitious products. However, compared with acidic and sulfate solutions, the NaOH group did not generate large amounts of sulfate expansive products or salt-crystallization pressure. Therefore, its mass loss, volume change, and strength degradation were lower than those of the H<sub>2</sub>SO<sub>4</sub> and Na<sub>2</sub>SO<sub>4</sub> groups.

In the H<sub>2</sub>SO<sub>4</sub> group, the mass loss and volume change reached 2.10% and 0.95%, respectively, and the compressive-strength loss was 19.90%, indicating that the acidic medium significantly intensified the deterioration of BS-SSFC. On the one hand, H<sup>+</sup> consumed calcium-bearing cementitious products such as Ca(OH)<sub>2</sub> and C-S-H, leading to decalcification, softening, and loosening of the pore walls. On the other hand, SO<sub>4</sub><sup>2−</sup> reacted with aluminate phases to form expansive products such as Aft or gypsum, generating local expansion stress in the pore walls and interfacial regions. The combined effects of cementitious-product loss caused by acid dissolution and local expansion induced by

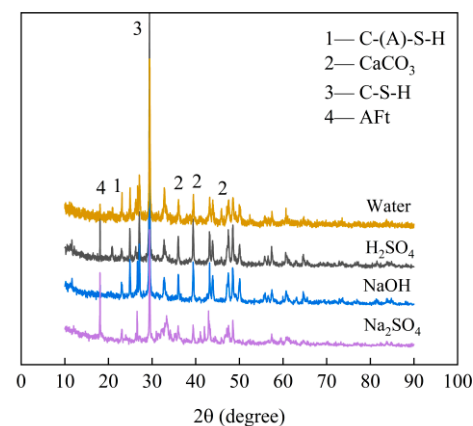
sulfate reaction resulted in relatively high mass loss, volume change, and strength loss in the  $\text{H}_2\text{SO}_4$  group.

The  $\text{Na}_2\text{SO}_4$  group exhibited the most severe deterioration, with mass loss, volume change, and compressive-strength loss of 3.40%, 1.55%, and 28.86%, respectively. Compared with the  $\text{H}_2\text{SO}_4$  group, the  $\text{Na}_2\text{SO}_4$  group was not subjected to strong acid dissolution; however, it was controlled by both sulfate reaction and salt-crystallization pressure during wetting–drying cycles. During the immersion stage,  $\text{SO}_4^{2-}$  entered the pores and participated in the formation of expansive products such as AFt. During the drying stage, salts in the pore solution gradually concentrated and crystallized, and the resulting crystallization pressure further promoted pore-wall cracking and crack propagation. As the number of cycles increased, the accumulation of expansive products, salt-crystallization pressure, and wetting–drying shrinkage stress enhanced pore connectivity and intensified local spalling, eventually leading to the greatest mass loss, volume change, and compressive-strength degradation.

Based on the mass change, volume change, and compressive-strength loss, the overall deterioration degree of BS-SSFC under different media followed the order  $\text{Na}_2\text{SO}_4 > \text{H}_2\text{SO}_4 > \text{NaOH} > \text{H}_2\text{O}$ .

### 3.3. XRD Analysis

Figure 9 shows the XRD patterns of BS-SSFC after 20 wetting–drying cycles in  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{NaOH}$ , and  $\text{Na}_2\text{SO}_4$  solutions. To avoid relying only on qualitative descriptions of peak intensity, representative peaks of C-(A)-S-H, C-S-H,  $\text{CaCO}_3$ , and AFt were selected and normalized. The  $\text{H}_2\text{O}$  group was used as the reference, and the relative peak-intensity indices of the same phases in different media are listed in Table 8.



**Figure 9.** Comparative XRD patterns after wetting–drying cycles.

**Table 8.** Relative peak intensities of main phases after wetting–drying cycles in different solutions.

| Solution                 | C-(A)-S-H | C-S-H | $\text{CaCO}_3$ | AFt  |
|--------------------------|-----------|-------|-----------------|------|
| $\text{H}_2\text{O}$     | 1.00      | 1.00  | 1.00            | 1.00 |
| $\text{H}_2\text{SO}_4$  | 0.82      | 0.78  | 1.16            | 1.45 |
| $\text{NaOH}$            | 0.90      | 0.88  | 1.05            | 1.18 |
| $\text{Na}_2\text{SO}_4$ | 0.70      | 0.72  | 1.22            | 1.70 |

As shown in Table 8, the relative peak intensities of C-(A)-S-H and C-S-H in the  $\text{H}_2\text{O}$  group remained at relatively high levels, while the relative peak intensity of AFt was low. This indicates that pure-water wetting–drying cycles did not significantly change the composition of the main cementitious products, and the deterioration was mainly caused

by pore-wall shrinkage and microcrack propagation induced by repeated water absorption and evaporation.

In the  $\text{H}_2\text{SO}_4$  group, the relative peak intensities of C-(A)-S-H and C-S-H decreased to 0.82 and 0.78, respectively, whereas the relative peak intensity of AFt increased to 1.45, indicating that the acidic environment caused pronounced erosion of the cementitious matrix.  $\text{H}^+$  consumed  $\text{Ca}(\text{OH})_2$  and promoted the decalcification of C-S-H, gradually loosening the matrix. Meanwhile,  $\text{SO}_4^{2-}$  reacted with  $\text{Ca}^{2+}$  and aluminate phases to form expansive products such as AFt. Therefore, the deterioration of the  $\text{H}_2\text{SO}_4$  group was mainly governed by acid neutralization, decalcification dissolution, and sulfate reaction.

In the NaOH group, the relative peak intensities of C-(A)-S-H and C-S-H were 0.90 and 0.88, respectively, showing smaller reductions than those in the  $\text{H}_2\text{SO}_4$  and  $\text{Na}_2\text{SO}_4$  groups. This suggests that the strongly alkaline environment did not induce obvious acid-type decalcification damage, but it could affect the mineral stability of bentonite and steel slag. Montmorillonite in bentonite is a 2:1 layered aluminosilicate. Under high-pH conditions, interlayer cation exchange, compression of the diffuse double layer, and local dissolution of Si–O and Al–O bonds at particle edges may occur, thereby weakening the foam-stabilizing and water-regulating effects of the bentonite slurry. In addition, f-CaO, MgO, and reactive silicoaluminate phases in steel slag may undergo hydration, dissolution, and re-precipitation in the strongly alkaline pore solution, leading to an uneven distribution of products in the interfacial region. Combined with the XRD and SEM-EDS results, the NaOH group did not show typical expansion damage dominated by alkali–aggregate reaction. Its damage was mainly characterized by reduced mineral stability, ion migration, and local loosening of pore walls.

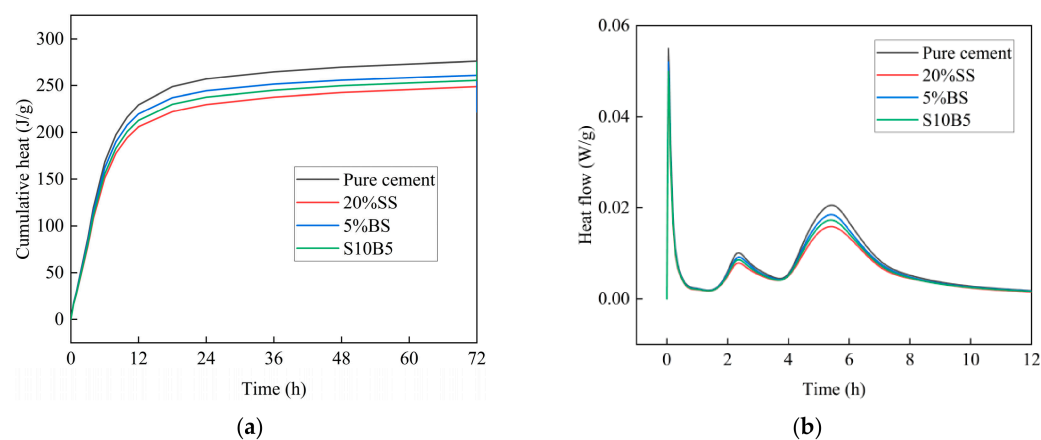
In the  $\text{Na}_2\text{SO}_4$  group, the relative peak intensities of C-(A)-S-H and C-S-H were the lowest, decreasing to 0.70 and 0.72, respectively, while the relative peak intensity of AFt reached the highest value of 1.70. This indicates that  $\text{SO}_4^{2-}$  participated in the reaction and generated more expansive products. Different from the  $\text{H}_2\text{SO}_4$  group, the deterioration of the  $\text{Na}_2\text{SO}_4$  group was not dominated by acid dissolution but by the combined effects of sulfate reaction and salt-crystallization pressure during drying. During the immersion stage,  $\text{SO}_4^{2-}$  penetrated into the pores and promoted AFt formation; during the drying stage,  $\text{Na}_2\text{SO}_4$  crystallization generated crystallization pressure. These two effects jointly caused pore-wall cracking and crack propagation.

Overall, the deterioration pathways of BS-SSFC differed markedly under different aggressive media. The  $\text{H}_2\text{O}$  group was dominated by physical wetting–drying damage; the  $\text{H}_2\text{SO}_4$  group was mainly controlled by acid neutralization, decalcification dissolution, and sulfate reaction; the NaOH group was mainly affected by mineral-stability changes of bentonite and steel slag as well as local dissolution–re-precipitation; and the  $\text{Na}_2\text{SO}_4$  group was dominated by the coupled damage of sulfate reaction and salt-crystallization pressure. The overall deterioration degree followed the order  $\text{Na}_2\text{SO}_4 > \text{H}_2\text{SO}_4 > \text{NaOH} > \text{H}_2\text{O}$ .

### 3.4. Hydration-Heat Analysis

Figure 10 shows the hydration-heat curves of the pure cement group, 20%SS group, 5%BS group, and S10B5 group. As shown in Figure 10a, the cumulative heat release of all groups increased rapidly with hydration time and gradually tended to stabilize after 24 h. At 72 h, the cumulative heat release followed the order pure cement group > 5%BS group > S10B5 group > 20%SS group. The pure cement group exhibited the highest cumulative heat release, indicating the most sufficient early clinker hydration. In contrast, the 20%SS group showed the lowest cumulative heat release, a trend consistent with the clinker-dilution effect and the lower early-age reactivity of steel slag relative to cement clinker reported in previous studies [29–31,47]. The cumulative heat release of

the 5%BS group was slightly lower than that of the pure cement group, suggesting that bentonite slurry had a certain adsorption and regulation effect on free water and delayed the early hydration process to some extent.



**Figure 10.** Hydration-heat characteristics of different cementitious systems. (a) Cumulative heat release. (b) Rate of hydration heat release.

As shown in Figure 10b, the heat-flow curves of all groups exhibited an obvious initial dissolution peak and a main hydration peak. The initial peak was mainly associated with rapid wetting of cement particles, ion dissolution, and early aluminate reactions. The system then entered a relatively stable stage, followed by a main hydration peak at approximately 5–6 h, which mainly corresponded to  $C_3S$  hydration and the rapid formation of C-S-H gel and  $Ca(OH)_2$ . Compared with the pure cement group, the main peak intensity of the 20%SS and S10B5 groups decreased, indicating that steel slag incorporation weakened the early hydration heat release. The main peak of the 5%BS group was slightly lower than that of the pure cement group, suggesting that a small amount of bentonite slurry exerted a certain slow-release effect on hydration.

It should be noted that the S10B5 group did not exhibit the highest heat-flow peak or cumulative heat release, although it showed relatively high macroscopic compressive strength and residual strength after wetting–drying cycles. This indicates that the strength improvement of the binary system cannot be simply attributed to enhanced early hydration. The combined results support a predominant physical contribution from steel slag particle filling, improved particle packing, and pore-size refinement. Previous studies have further shown that reactive phases in steel slag can gradually participate in later-age reactions and cementitious-product formation under alkaline conditions [29–31,47]. Accordingly, the later-age chemical contribution is considered here as a plausible, literature-supported interpretation consistent with the observed material behavior, whereas the physical filling and pore-structure effects constitute the principal explanation directly supported by the present results. As shown in Figure 10, the early cumulative heat release of both the 20%SS and S10B5 groups was lower than that of the pure cement group, indicating that steel slag incorporation did not enhance early hydration heat release. Therefore, in the absence of quantitative measurements of the steel slag reaction degree, steel slag hydration is not regarded as the dominant mechanism for strength improvement in this study.

Considering the hydration-heat, compressive-strength, and pore-structure results together, the contributions to the performance improvement of S10B5 can be separated into physical and potential chemical components. Physically, steel slag provides micro-filler and particle-packing effects, while bentonite slurry enhances slurry cohesion, regulates free water, and stabilizes the foam; their combined action promotes the refinement of the

pore-wall and interfacial structures. Chemically, the potential later-age reactivity of steel slag is considered an additional contribution supported by previous studies [29–31,47].

### 3.5. Summary Analysis of Mixture Composition, Performance, and Main Products

Table 9 summarizes the mixture composition, compressive strength, mass water absorption, pore-size characteristics, and main products of the different cementitious systems. The results show that S10B5 had the highest compressive strength (2.01 MPa) and an average pore diameter of 127.42  $\mu\text{m}$ , lower than that of the 5%BS group (133.96  $\mu\text{m}$ ), with the proportion of pores smaller than 100  $\mu\text{m}$  increasing to 48.00%. This indicates that the binary addition of 10% SS and 5% BS refined the pore structure and improved matrix integrity.

**Table 9.** Summary of mixture composition, compressive strength, mass water absorption, and average pore diameter of different cementitious systems.

| Group       | SS Replacement/% | BS Dosage/% | Compressive Strength/MPa | Mass Water Absorption/% | Average Pore Diameter/ $\mu\text{m}$ |
|-------------|------------------|-------------|--------------------------|-------------------------|--------------------------------------|
| Pure cement | 0                | 0           | 1.04                     | 28.37                   | 181.22                               |
| 20%SS       | 20               | 0           | 1.66                     | 28.99                   | 169.74                               |
| 5%BS        | 0                | 5           | 1.52                     | 31.27                   | 133.96                               |
| S10B5       | 10               | 5           | 2.01                     | 30.00                   | 127.42                               |

The 5%BS group had the highest mass water absorption (31.27%), indicating that although bentonite slurry can improve slurry cohesion and foam stability, its own water-retention characteristics also increase the water-uptake capacity of the specimen. The S10B5 group had a mass water absorption of 30.00%, which was lower than that of the 5%BS group but higher than that of FC, showing that the advantage of the binary system is mainly reflected in strength improvement and pore-size refinement, rather than simultaneous improvement of all durability indices. Therefore, the effect of steel slag and bentonite slurry on BS-SSFC should be understood as a combination of direct experimental observations and mechanistic inference. Based on the strength, mass water absorption, pore-size distribution, and hydration-heat results, the physical contributions can be clearly divided into two parts: (i) the micro-filler, particle-packing, and pore-wall densification effects of steel slag; and (ii) the slurry-cohesion, water-regulation, foam-stabilization, and pore-uniformity effects of bentonite slurry. These physical effects jointly provide the principal explanation for the measured pore-size refinement and strength improvement of S10B5. Separately, the XRD and SEM-EDS observations, together with the reaction mechanisms reported in previous studies [29–31,47], provide a reasonable basis for considering the potential later-age reaction of steel slag as an additional chemical contribution.

### 3.6. SEM Analysis

The strength of FC is governed by both pore characteristics and the distribution of hydration products [60]. To clarify how different wetting–drying media influenced BS-SSFC degradation, SEM-EDS observations were carried out after 20 cycles in  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{NaOH}$ , and  $\text{Na}_2\text{SO}_4$ . The results are presented in Figure 11. The EDS mapping focused mainly on O and Si because they are key elements of C-S-H gel, and O is also a major constituent of Aft. Combining elemental maps with SEM morphology allows the compactness of the matrix and the spatial distribution of reaction products to be evaluated.

The SEM-EDS images show that, after 20 wetting–drying cycles, the BS-SSFC specimens in water already exhibit certain damage, but the elemental distribution remains relatively uniform, indicating that the water group is mainly affected by physical stresses caused by water absorption and loss. The structural damage in the  $\text{H}_2\text{SO}_4$  group is greater than that in the water group; local elemental distribution is uneven, and products such

as AFt can be observed, indicating that  $\text{SO}_4^{2-}$  consumes cementitious components and generates expansion stress. The damage degree in the NaOH group lies between those of the water and  $\text{H}_2\text{SO}_4$  groups. Local loosening of pore walls and a certain nonuniformity in EDS elemental distribution indicate that the high-pH medium weakens the local compactness of the matrix. The  $\text{Na}_2\text{SO}_4$  group shows the most severe deterioration: AFt and a small amount of salt crystals are visible in SEM images, and EDS also reflects a more uneven distribution of O and Si. These results indicate that, in  $\text{Na}_2\text{SO}_4$  solution, water-cycling stress, AFt-related expansion caused by  $\text{SO}_4^{2-}$  reactions, and salt crystallization pressure jointly intensify internal damage, thereby loosening the matrix structure and weakening its load-bearing capacity.

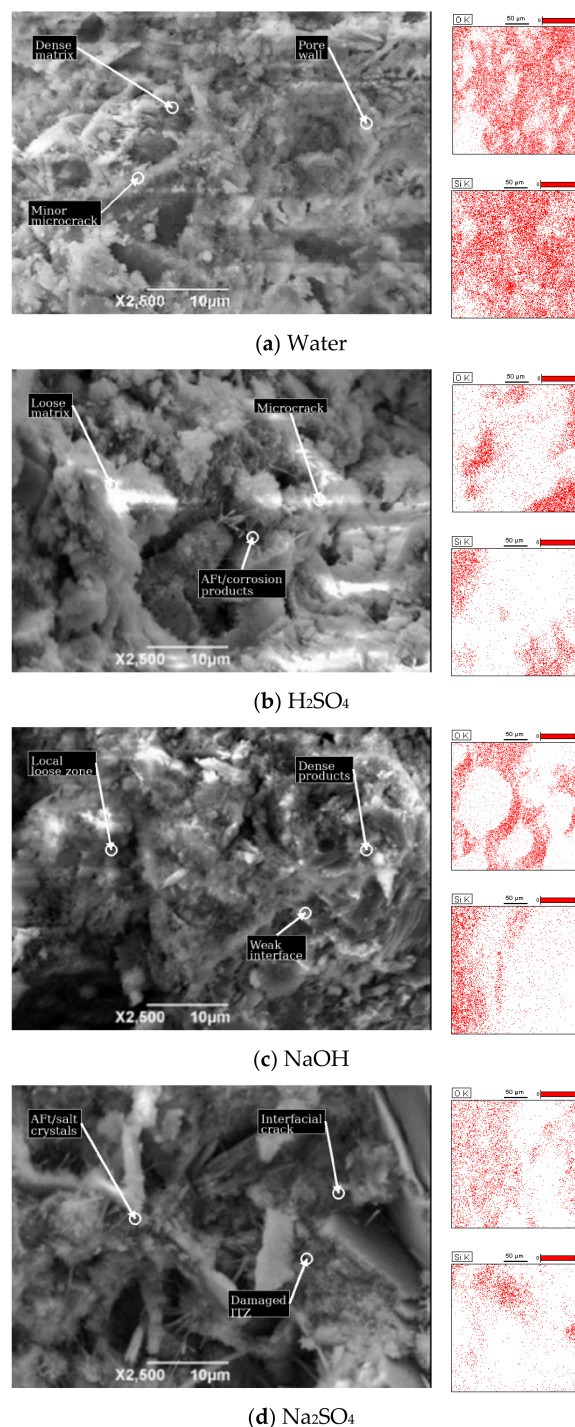


Figure 11. SEM-EDS images of different solutions after 20 wetting–drying cycles.

As shown in Figure 11, the H<sub>2</sub>O group retained a relatively dense matrix with only minor wetting–drying shrinkage microcracks. The H<sub>2</sub>SO<sub>4</sub> group showed a looser matrix and interfacial cracks, indicating that acid neutralization and decalcification weakened the bonding capacity. The NaOH group exhibited local looseness and uneven interfacial-product distribution, implying that changes in the mineral stability of bentonite and steel slag under highly alkaline conditions can affect the interfacial structure. In the Na<sub>2</sub>SO<sub>4</sub> group, AFt/salt-crystallization products and interfacial cracks were more evident, indicating that sulfate reaction and crystallization pressure jointly promoted crack propagation along the ITZ and pore walls. Overall, the deterioration path of BS-SSFC can be summarized as local loosening of pore walls or ITZ, microcrack initiation, crack propagation along interfaces and connected pores, and final macroscopic strength loss.

#### 4. Compressive Strength Calculation Model Under Wetting–Drying Cycles

Based on fractal theory, porosity, fractal dimension, and cycle number were coupled to establish a compressive strength calculation model for BS-SSFC under wetting–drying cycles in multiple media. The model parameters were determined from test data obtained using the same raw materials, similar dry density, and the wetting–drying cycle range considered in this study.

To avoid limiting the model to empirical fitting, the physical meanings of the model parameters are clarified in this study. The cycle number  $n$  represents the cumulative degree of external wetting–drying action. The SEM-derived two-dimensional apparent areal porosity  $\varphi$  reflects the proportion of pores, cracks, and local spalling regions in the SEM images and can be used to characterize the internal damage degree of the material after corrosive wetting–drying cycles. The fractal dimension  $D$  characterizes the complexity of pore boundaries and the heterogeneity of the pore structure. The zero-porosity strength  $M_0$  represents the theoretical matrix strength after excluding the weakening effect of pores within the same material system. The empirical exponent  $b$  reflects the sensitivity of strength reduction to pore-structure complexity. Therefore, the proposed model is not a simple empirical fitting model based only on cycle number but a calculation model coupling the external action history, pore-structure damage, and strength degradation.

In foamed concrete, the pore structure exhibits a strong correlation with its compressive strength. This study investigates the relationship between porosity and compressive strength for BS-SSFC [61], as follows:

$$M_f = M_0(1 - \varphi)^b \quad (7)$$

Here,  $M_f$  represents the compressive strength of BS-SSFC at a given pore condition, while  $M_0$  is the theoretical strength extrapolated to a pore-free state. The symbol  $\varphi$  denotes the measured porosity, and  $b$  is an empirical parameter obtained from fitting. Reference [61] further relates  $b$  to the fractal dimension  $D$  as follows:

$$b = \frac{D - 1}{3(3 - D)} \quad (8)$$

The fractal dimension can be obtained from SEM images. According to fractal theory, Otsu's method is first applied to binarize the SEM images. The binarized image is then covered with non-overlapping squares of side length  $\varepsilon$  (typically  $\varepsilon = 1, 2, 4, \dots, 2^i$  pixels). In the binary image, let 1 represent black and 0 represent white. Denote  $N(\varepsilon)$  as the number of boxes (of side length  $\varepsilon$ ) containing either black or white pixels. Usually, box sizes are taken

as  $\varepsilon = 1, 2, 4, \dots, 2^i$  pixels. As  $\varepsilon \rightarrow 0$ , the fractal dimension  $D$  based on the box-counting method is calculated by the following formula:

$$D_c = \lim_{\varepsilon \rightarrow 0} \frac{\ln N(\varepsilon)}{\ln \varepsilon} \quad (9)$$

Therefore, a smaller  $\varepsilon$  yields a more precise fractal dimension, with the lower limit of  $\varepsilon$  being defined by the physical dimension of a single pixel. Let the pixel size be defined as  $\delta = L/N$ , where  $L$  is the image length and  $N$  is the number of pixels per column. The side length  $a$  of a square box is then given by  $a = \varepsilon\delta$  with  $\varepsilon$  taking values of  $1, 2, 4, \dots, 2^i$ . The following relationship was obtained by fitting the  $\varepsilon$  and  $N(\varepsilon)$  data and applying the least squares method:

$$\ln N(\varepsilon) = D_c * \ln \varepsilon + h \quad (10)$$

Since SEM images provide only two-dimensional sectional pore structures, whereas the real pore system of foamed concrete is a three-dimensional spatial structure, the fractal dimension obtained from the two-dimensional section needs to be converted into an equivalent three-dimensional fractal dimension. According to the sectional fractal theory, when the internal pore structure of a porous material is approximately isotropic and spatially continuous in a statistical sense, the fractal dimension of the three-dimensional pore structure can be approximately estimated by adding 1 to the fractal dimension of the two-dimensional section, as follows [62]:

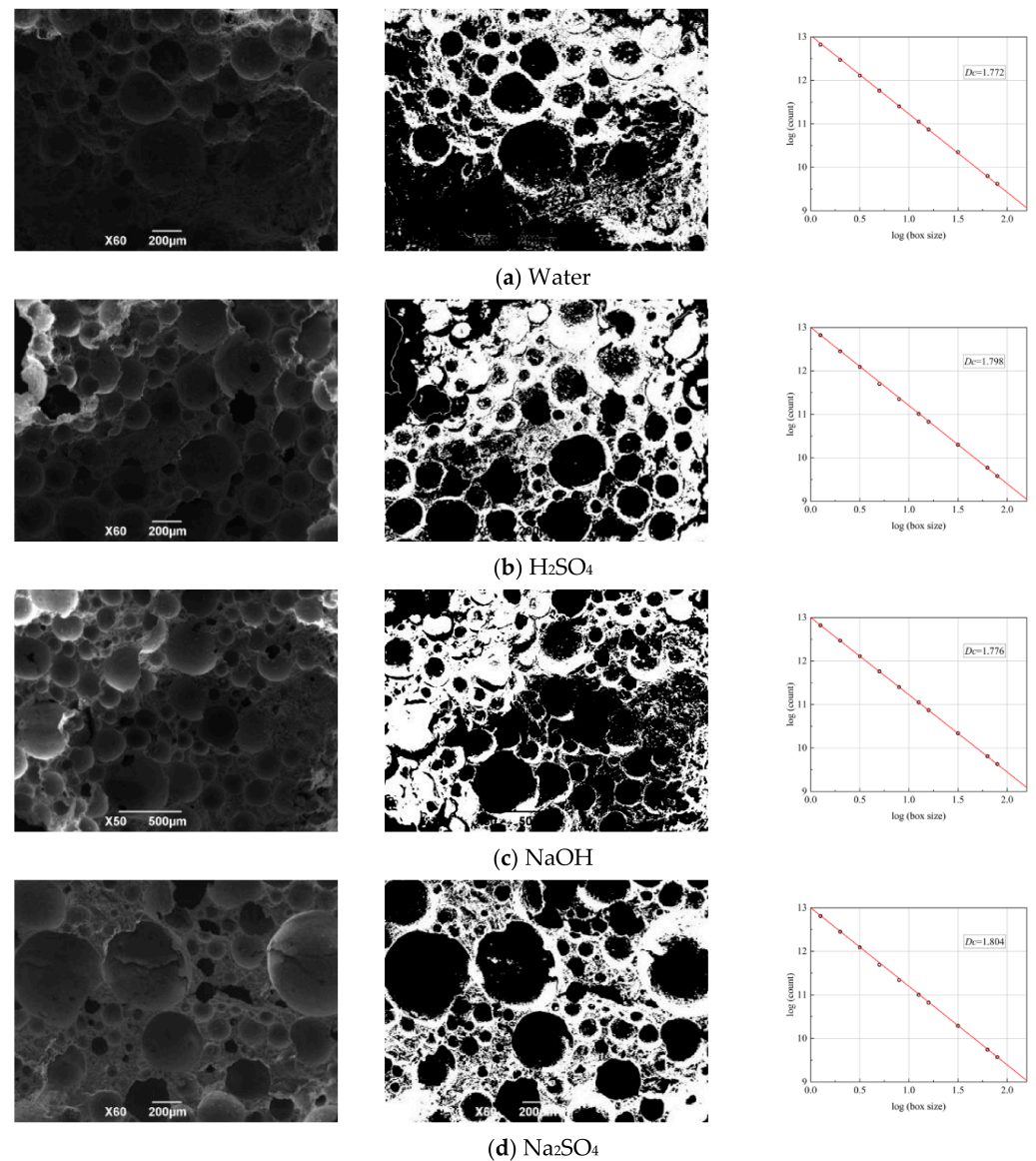
$$D = D_c + 1 \quad (11)$$

where  $D_c$  is the planar fractal dimension obtained from SEM two-dimensional images using the box-counting method, and  $D$  is the equivalent three-dimensional fractal dimension. Foamed concrete consists of a large number of closed pores, connected pores, and pore-wall defects, and the complexity of pore boundaries observed in cross-sections can reflect changes in the heterogeneity of the three-dimensional pore structure. In this study, pore-structure changes under different wetting–drying conditions were compared using the same magnification, the same threshold segmentation method, and the same sampling-area principle. Therefore, this conversion can be used for relative comparison within the same material system and for constructing the strength calculation model. However, it should be noted that the value obtained by this method is an equivalent three-dimensional fractal dimension and cannot fully replace three-dimensional pore-structure characterization methods such as micro-CT.

For the recommended mix, SEM images after cycling were binarized to calculate both the fractal dimension and SEM-derived two-dimensional apparent areal porosity. Figure 12 presents the fractal-analysis images after 20 cycles. The final results are shown in Table 10.

**Table 10.** Relationship between wetting–drying cycles and fractal dimension under different solutions.

| Type of Solution                        | Water             | H <sub>2</sub> SO <sub>4</sub> | NaOH              | Na <sub>2</sub> SO <sub>4</sub> |
|-----------------------------------------|-------------------|--------------------------------|-------------------|---------------------------------|
| two-dimensional fractal dimension $D_c$ | $1.772 \pm 0.012$ | $1.798 \pm 0.015$              | $1.776 \pm 0.011$ | $1.804 \pm 0.018$               |
| Three-dimensional fractal dimension $D$ | 2.772             | 2.798                          | 2.776             | 2.804                           |



**Figure 12.** Binarized images of specimens subjected to 20 wetting–drying cycles under different solution environments.

The two-dimensional fractal dimension  $D_c$  of the SSFC in this experiment was calculated using the box-counting method. In Equation (11),  $D$  represents the three-dimensional fractal dimension, which is 1 greater than the two-dimensional fractal dimension  $D_c$ . The parameter  $b$  can be obtained from Equation (8). Subsequently, the compressive strength at zero porosity was determined through experiments, leading to the derivation of the empirical formula relating compressive strength to porosity (Table 11).

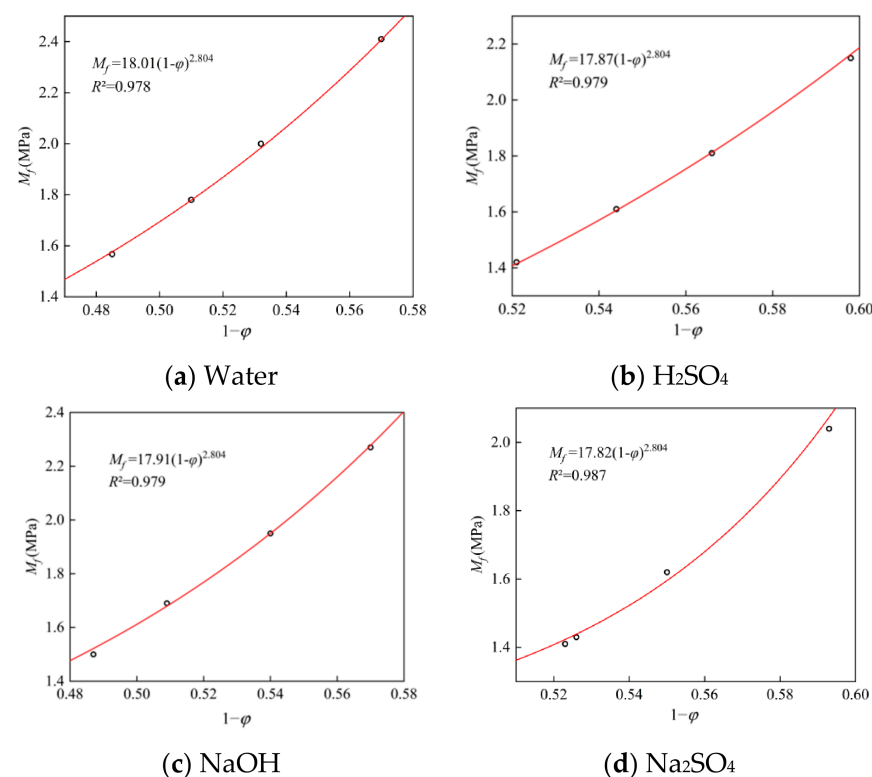
**Table 11.** Relationship between porosity and compressive strength under wetting–drying cycles.

| Solution Type            | $M_0/\text{MPa}$ | Fractal Dimension $D$ | $b$   | $M_f$ - $\varphi$ Relationship Formula | $R^2$ |
|--------------------------|------------------|-----------------------|-------|----------------------------------------|-------|
| Water                    | 18.01            | 2.772                 | 2.591 | $M_f = 18.01(1 - \varphi)^{2.591}$     | 0.970 |
| $\text{H}_2\text{SO}_4$  | 17.87            | 2.798                 | 2.967 | $M_f = 17.87(1 - \varphi)^{2.967}$     | 0.983 |
| NaOH                     | 17.91            | 2.776                 | 2.643 | $M_f = 17.91(1 - \varphi)^{2.643}$     | 0.975 |
| $\text{Na}_2\text{SO}_4$ | 17.82            | 2.804                 | 3.068 | $M_f = 17.82(1 - \varphi)^{3.068}$     | 0.987 |

During wetting–drying cycles in different solutions, the variation range of fractal dimension  $D$  is relatively limited. Therefore, the average value of  $D$  can be used to establish a unified strength–porosity relationship. The empirical constant  $b$  is then calculated from the average value, yielding the relationship shown in Equation (12):

$$M_f = M_0(1 - \phi)^{2.804} \quad (12)$$

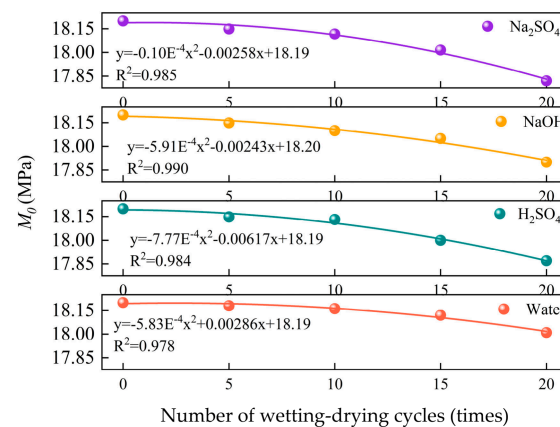
The suitability of using the average fractal dimension was checked by comparing the strengths predicted from Equation (12) with the measured results (Figure 13). For the cycle-related fitting, an additional error analysis was performed. Taking the 700 kg·m<sup>−3</sup> specimens at  $n = 0, 5, 10, 15$ , and 20 as an example, leave-one-cycle-point-out validation produced RMSE values of 0.015–0.132 MPa and MAPE values of 0.72–6.12%. These errors indicate that the model captures the degradation trend of BS-SSFC within the considered cycling range.



**Figure 13.** Compressive strength–porosity correlation in BS-SSFC after 20 wetting–drying cycles in varied solutions.

Equation (12) still contains  $M_0$ . By fitting  $M_0$  (Figure 14), a general expression for  $M_0$  at zero porosity can be obtained. In this expression,  $\alpha$  and  $\beta$  are correlation coefficients associated with the solution type and wetting–drying conditions, respectively, while  $\gamma$  is the strength of foamed concrete before wetting–drying cycles. The fitted equation follows a quadratic parabolic trend, which is generally consistent with existing findings on the damage characteristics of concrete materials in wetting–drying environments [63]:

$$M_0 = \alpha n^2 + \beta n + \gamma \quad (13)$$

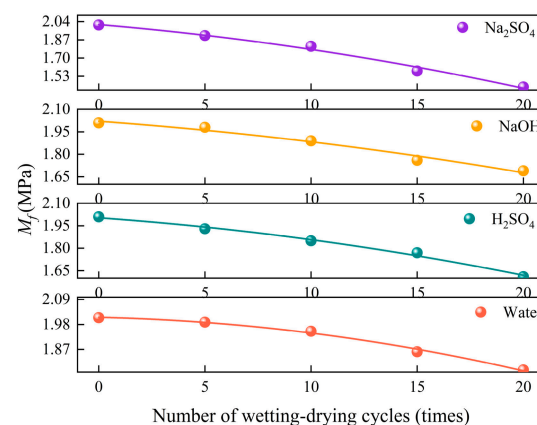


**Figure 14.** Fitted variation of zero-porosity strength with cycle number.

Combining the unified strength–porosity equation with the  $M_0$ -cycle relationship yields the following expression for compressive strength as a function of cycle number:

$$M_f = (\alpha n^2 + \beta n + \gamma)(1 - \phi)^b \quad (14)$$

Model verification was performed by comparing calculated and measured strengths. Figure 15 and Table 12 show that the fitted curves closely follow the experimental data, supporting the rationality and applicability of the proposed calculation framework.

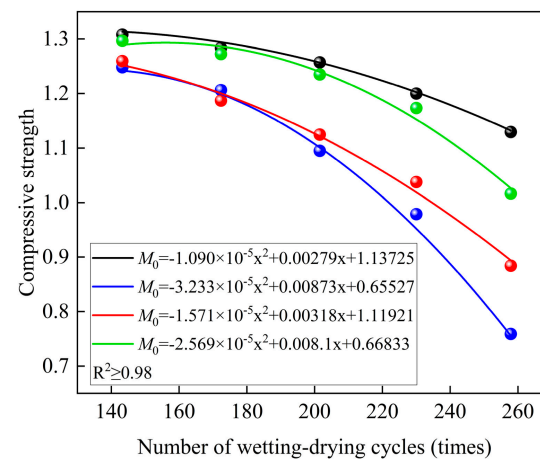


**Figure 15.** Comparison between measured compressive strengths and predicted curves.

**Table 12.** Relationships between compressive strength and the number of wetting–drying cycles.

| Solution Type            | $M_f$ - $n$ Relationship                                               | $1 - \phi$ |
|--------------------------|------------------------------------------------------------------------|------------|
| Water                    | $M_f = (-5.83 \times 10^{-4}n^2 + 0.00286n + 18.19)(1 - \phi)^{2.804}$ | 0.46880    |
| $\text{H}_2\text{SO}_4$  | $M_f = (-7.77 \times 10^{-4}n^2 - 0.00617n + 18.19)(1 - \phi)^{2.804}$ | 0.46390    |
| $\text{NaOH}$            | $M_f = (-5.91 \times 10^{-4}n^2 - 0.00243n + 18.20)(1 - \phi)^{2.804}$ | 0.46370    |
| $\text{Na}_2\text{SO}_4$ | $M_f = (-0.10 \times 10^{-4}n^2 - 0.00258n + 18.19)(1 - \phi)^{2.804}$ | 0.46678    |

An additional validation was conducted using data from Reference [64]. As shown in Figure 16, the predicted curves agree well with the literature results, which further supports the transferability of the proposed model within comparable wetting–drying conditions.



**Figure 16.** Comparison between literature data and predicted curves.

#### 4.1. Comparison with Classical Strength-Degradation Models

To further evaluate the calculation accuracy of the proposed model, it was compared with three commonly used degradation models: linear, exponential, and power-law models. The forms of each model are as follows:

$$f_n = an + c \quad (15)$$

$$f_n = ce^{-kn} \quad (16)$$

$$f_n = cn^{-k} \quad (17)$$

$$f_n = (\alpha n^2 + \beta n + \gamma)(1 - \varphi)^b \quad (18)$$

The first three models mainly use the number of cycles as the independent variable and reflect empirical strength degradation with increasing wetting–drying cycles, whereas the proposed model additionally introduces SEM-derived two-dimensional apparent areal porosity and fractal dimension to link cyclic damage with pore-structure degradation. The model accuracy was evaluated using  $R^2$ , RMSE, and MAPE, as summarized in Table 13.

**Table 13.** Comparison of prediction accuracy among different strength-degradation models.

| Model                  | Control Variables | $R^2$ | RMSE  | MAPE/% |
|------------------------|-------------------|-------|-------|--------|
| Linear model           | $n$               | 0.932 | 0.083 | 4.78   |
| Exponential model      | $n$               | 0.947 | 0.074 | 4.21   |
| Power-law model        | $n$               | 0.951 | 0.069 | 3.98   |
| Proposed fractal model | $n, \varphi, D$   | 0.982 | 0.036 | 1.93   |

As shown in Table 13, the linear, exponential, and power-law models can describe the decreasing trend of compressive strength with increasing wetting–drying cycles to some extent, but they use only the number of cycles as the controlling variable and do not account for differences in pore-structure damage under different aggressive media. By introducing SEM-derived two-dimensional apparent areal porosity and fractal dimension, the proposed model simultaneously considers cycle number, pore expansion, and pore-structure complexity, leading to a higher  $R^2$  and lower RMSE and MAPE values. This indicates that incorporating pore-structure parameters improves the description of BS-SSFC strength degradation under corrosive wetting–drying cycles.

#### 4.2. Model Applicability and Limitations

The proposed model is an empirical correlation established from experimental data, SEM-derived two-dimensional apparent areal porosity, and fractal dimension, rather than a universally applicable model. The porosity parameter represents the area fraction of pores, cracks, and local spalling within selected SEM fields. It is affected by sampling position, fracture-surface morphology, imaging conditions, and threshold segmentation and is not equivalent to true three-dimensional volumetric porosity. Accordingly, it is used only for relative damage comparison under a consistent sampling and image-processing procedure.

True three-dimensional volumetric porosity additionally characterizes closed and connected pores and their spatial distribution. To clarify this distinction, Table 14 compares SEM image analysis with MIP, X-ray micro-CT, and open-porosity testing. SEM-derived two-dimensional apparent areal porosity is suitable for comparing apparent damage within the present test system, but it cannot replace these methods for evaluating true pore volume and connectivity.

**Table 14.** Characterization features and limitations of different porosity testing methods.

| Method                             | Object Characterized                                      | Advantages                                                                                                | Limitations                                                                                                                           |
|------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| SEM two-dimensional image analysis | 2D apparent areal pores, cracks, and local spalling areas | Can be combined with morphology observation and fractal analysis; suitable for relative damage comparison | Cannot represent true 3D volumetric porosity; affected by sampling, surface roughness, imaging conditions, and threshold segmentation |
| MIP                                | Connected pore-size distribution and pore-throat features | Quantitative analysis of connected pores                                                                  | Difficult to characterize closed pores; high pressure may alter fragile pore walls                                                    |
| X-ray micro-CT                     | 3D spatial pore structure                                 | Can characterize pore connectivity and spatial distribution                                               | High cost; resolution limits identification of fine pores and microcracks                                                             |
| Open porosity test                 | Total open-pore volume                                    | Simple operation; suitable for macroscopic porosity comparison                                            | Cannot provide pore-size distribution or closed-pore information                                                                      |

From the perspective of applicability, the model parameters in this study were determined from the test data obtained under the current raw-material composition, dry-density grade, mix proportion, aggressive medium type, and wetting–drying regime. For material systems with substantially different raw materials, foam density, pore-structure formation process, aggressive-medium concentration, or image-processing method, the model parameters need to be recalibrated and should be verified with independent experimental data. Therefore, the proposed model is mainly applicable to the BS-SSFC system used in this study and to the relative evaluation of strength degradation in similar porous cement-based materials.

In summary, the proposed model describes the empirical relationship among wetting–drying cycle number, SEM-derived two-dimensional apparent areal porosity, fractal dimension, and compressive-strength degradation within the present test system. Its results represent relative image-based damage rather than true volumetric porosity. Future MIP, X-ray micro-CT, and open-porosity measurements can provide multiscale calibration of the model parameters.

## 5. Conclusions

This study examined the strength degradation of BS-SSFC subjected to cyclic wetting–drying in water, acid, alkali, and sulfate salt media. After the optimum mixture was selected from compressive-strength tests, mechanical testing, SEM-EDS, XRD, and fractal analysis were combined to clarify the degradation mechanism and to construct a strength calculation model. The main conclusions are as follows:

- (1) In the single-addition system, the 20%SS group showed a relatively high compressive strength of 1.66 MPa. In the binary SS-BS system, the 10%SS and 5%BS mixture achieved the highest strength of 2.01 MPa. The mass water absorption of S10B5 was 30.00%, lower than that of the 5%BS group but higher than that of the pure cement group, indicating that the binary system mainly improved strength and pore structure.
- (2) Hydration-heat results showed that the early heat release of both the 20%SS and S10B5 groups was lower than that of pure cement, indicating that steel slag did not significantly enhance early hydration. Combined with the pore-size distribution and strength results, the performance improvement of S10B5 was primarily associated with two physical pathways: the micro-filler and particle-packing effects of steel slag, and the slurry-cohesion, water-regulation, and foam-stabilization effects of bentonite slurry. These effects jointly promoted pore-structure refinement, while the potential later-age reaction of steel slag was considered an auxiliary chemical contribution supported by previous studies.
- (3) After 20 wetting–drying cycles, the strength-loss ratios of S10B5 in H<sub>2</sub>O, H<sub>2</sub>SO<sub>4</sub>, NaOH, and Na<sub>2</sub>SO<sub>4</sub> solutions were 11.44%, 19.90%, 15.92%, and 28.86%, respectively. Together with mass and volume changes, the apparent deterioration severity followed Na<sub>2</sub>SO<sub>4</sub> > H<sub>2</sub>SO<sub>4</sub> > NaOH > H<sub>2</sub>O, with Na<sub>2</sub>SO<sub>4</sub> causing the most severe degradation due to the combined action of sulfate reaction and salt-crystallization pressure.
- (4) XRD semi-quantitative analysis and SEM-EDS results indicated different deterioration pathways in different media. The H<sub>2</sub>O group was dominated by physical wetting–drying damage; the H<sub>2</sub>SO<sub>4</sub> group by acid neutralization, decalcification, and sulfate reaction; the NaOH group by mineral-stability changes and local dissolution–re-precipitation under strong alkalinity; and the Na<sub>2</sub>SO<sub>4</sub> group by coupled sulfate reaction and crystallization-pressure damage.
- (5) A strength-degradation calculation model based on SEM-derived two-dimensional apparent areal porosity, fractal dimension, and cycle number described the empirical correlation between apparent pore-structure damage and strength loss within the present test system.

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