

Article

Performance Analysis and Mix Proportion Optimization of Coal Gangue Concrete Under Sulfate Dry–Wet Cycling Conditions

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Abstract

The performance degradation of concrete structures in underground water sumps within the Ordos mining area has become increasingly prominent due to environmental factors, particularly the sulfate-induced dry–wet cycles. These conditions lead to the development of cracks, spalling, and structural instability, which poses significant safety risks. This issue must be addressed with consideration of the regional hydrogeological characteristics and the current requirements for safe, sustainable, and environmentally responsible coal mining practices. The study investigates the concrete employed in the underground central water reservoir of Bulianta Coal Mine in the Ordos mining area. A novel approach is proposed for developing sulfate-resistant concrete capable of withstanding dry–wet cyclic conditions in underground environments through the utilization of coal gangue sourced from the same mining operation. Considering concrete performance, cost-effectiveness, and coal gangue utilization, a laboratory mix optimization study was conducted and the optimal mixture proportion was determined to be a 60% gangue content, a 30% fly ash content, a water–binder ratio of 0.38, which produced concrete with a compressive strength of 31 MPa. Sulfate resistance tests were conducted on the optimal mixture of dry–wet cycle-resistant concrete. The effect of different dry–wet cycle counts on the compressive strength of the coal gangue concrete was investigated, and the evolution patterns of the ascending segment shape coefficient a and descending segment shape coefficient b under sulfate-induced dry–wet cycling were analyzed. Combining the Guo Zhenhai concrete constitutive model, a concrete constitutive model suitable for the dry–wet cycle conditions of sulfate was established. Based on the proposed constitutive model, the uniaxial compressive mechanical behavior of coal gangue concrete subjected to sulfate attack was investigated through numerical simulations using the Abaqus (2020) software. The simulation results are basically consistent with the laboratory results, which proves the applicability of the constitutive model and confirms the performance of the optimal proportioning scheme for preparing sulfate-resistant dry–wet cycle concrete using coal gangue from underground mines. This study provides a new type of concrete for similar underground conditions in this mining area and offers a new approach for the comprehensive utilization of coal gangue.



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Keywords: coal gangue concrete; sulfate erosion resistance; constitutive model; optimal ratio

1. Introduction

Coal gangue is a primary industrial solid waste generated during coal mining and processing operations, representing approximately 10% to 20% of the waste from raw coal production [1]. To date, the total accumulated coal gangue in China has reached 7 billion tons, with an annual increase of 300 to 350 million tons [2]. The accumulation of coal gangue occupies a large amount of land and poses a potential threat to the safety and environment of the surrounding areas [3]. The growing annual consumption of concrete in China has led to a steady increase in the demand for natural sand and gravel [4]. The utilization of coal gangue as a substitute for natural crushed stone in concrete production [5,6] represents an effective strategy for addressing coal gangue accumulation and mitigating the growing scarcity of natural sand and gravel resources [7]. The utilization of coal gangue as a substitute for natural gravel in the preparation of concrete is also another effective approach for realizing the reuse of solid waste coal gangue [8–10].

The principal components of coal gangue are quartz and calcite, which are similar to natural aggregates. Coal gangue can be employed as coarse and fine aggregates in concrete [11–14]. Numerous studies have been carried out by both domestic and international researchers on the application of coal gangue as a partial or full replacement for natural aggregates in concrete. Behnoosh et al. [15] studied the application of coal gangue aggregates in concrete and their influence on the mechanical properties of concrete. The results indicated that coal gangue has certain development potential in the construction application and economy of concrete. Yao et al. [16] carried out experimental investigations into the static and dynamic properties of coal gangue concrete, demonstrating that C30 and C40 grade coal gangue concrete can be successfully prepared using coal gangue as coarse and fine aggregates. Gao et al. [17] prepared coal gangue concrete specimens with varying substitution levels. The results showed that full replacement led to a reduction in compressive strength of over 50%. Zhang et al. [18] investigated the influence of the replacement rate for coal gangue coarse aggregate on the uniaxial mechanical properties of concrete. Zhou et al. [19] fabricated concrete by substituting natural gravel with self-combusted coal gangue and rock-type coal gangue at 25% replacement intervals. The experimental results indicated that the peak stress and initial slope of the stress–strain curve decreased and the peak strain exhibited an increasing trend as the coal gangue replacement level increased. Wang et al. [20] prepared coal gangue concrete with the replacement rate of coal gangue as the variable. The results showed that the elastic modulus of the concrete decreased and the drying shrinkage rate increased as the replacement rate increased. Liu et al. [21] proposed an elastic modulus prediction model for coal gangue concrete based on the compressive strength and density of the concrete as the dominant factors. Qiu et al. [22] found that an appropriate incorporation of fly ash can improve the mechanical properties of coal gangue concrete. The improvement is attributed to the secondary hydration of fly ash, which alters the microstructure of both the mortar matrix and the interfacial transition zone. Yu et al. [23] and Ma et al. [24] found that activated SiO_2 and Al_2O_3 in coal gangue can participate in the hydration reaction of coal gangue concrete, which enhances the sulfate resistance of coal gangue concrete. Zhuo Tang et al. [25] developed a corrosion-resistant concrete by incorporating waste glass, coal gangue, and fly ash, revealing that the dosage of waste glass exerted the most significant influence on corrosion resistance, followed by the proportion of coal gangue. Wu Hailei et al. [26] established a model for water and chloride ion diffusion and clearly determined that the coal gangue spray concrete with a

water–cement ratio of 0.4 and a coal gangue substitution rate of 40% had the best resistance to chloride ion erosion. Ling Qin et al. [27] demonstrated that carbonation treatment effectively enhances the sulfate attack resistance of coal gangue concrete. Bo Wen et al. [28] investigated the size effect on the compressive strength of coal gangue concrete through numerical simulations, showing that this effect is more pronounced compared to the effect on conventional concrete. Jiuyang Li et al. [29] employed finite element analysis to study the failure behavior of steel tubular columns filled with coal gangue concrete, finding that ductility gradually decreases as the coal gangue replacement ratio is reduced.

This study is based on the underground concrete application conditions at Bulianta Coal Mine, with coal gangue sampled from the gangue disposal site of Bulianta Coal Mine selected as the research subject. Coal gangue concrete was prepared by incorporating fly ash and coal gangue aggregate. The influence of the fly ash content, water–binder ratio, and coal gangue replacement level on the mechanical properties of the resulting concrete was systematically investigated. In consideration of the actual service environment at Bulianta, the sulfate resistance of the concrete was evaluated through exposure testing under dry–wet cyclic conditions. Uniaxial compressive tests were conducted to assess the mechanical performance and evolution of stress–strain behavior at various stages of sulfate attack. Based on experimental data, the classical Guo Zhenhai [30] concrete constitutive model was modified to account for degradation under sulfate-induced dry–wet cycles, leading to the development of a new constitutive model specifically applicable to such environmental conditions. Using this revised model, numerical simulations in Abaqus were performed to analyze the mechanical property degradation of coal gangue concrete under long-term sulfate exposure. The simulation results validated the applicability of the proposed constitutive model and confirmed the rationality of the optimal mix design for producing sulfate-resistant concrete using underground coal gangue in practical engineering applications.

2. Concrete Mix Proportion Experiment

2.1. Main Experimental Materials

Coal gangue was sourced from the spoil heap of Bulianta Coal Mine in the Shendong Mining Area and classified as sandstone-type gangue. The material was processed through crushing, screening, washing, and air-drying to produce coal gangue coarse aggregate that conformed to specified gradation requirements. The physical properties of the resulting coarse aggregate are summarized in Table 1.

Table 1. Performance indicators of coal gangue concrete.

Property of Aggregate	Gravel	Gangue Coarse Aggregate	Building Machine-Made Sand
Apparent density (kg/m ³)	2635	2440	2610
Loose bulk density (kg/m ³)	1364	1330	1600
Tap bulk density (kg/m ³)	1583	1560	1780
Loose porosity (%)	48.24	45.55	38.70
Tap porosity (%)	39.93	36.14	31.81
silt Content (%)	0.32	0.62	0.5
Water absorption (%)	0.46	7.05	0.78
Crushde value (%)	6.7	23.04	—
Modulus of fineness	—	—	3.05

The cement used is ordinary P.O 42.5 Portland cement that was purchased near the laboratory, which has a specific surface area of 367 m²/kg [31]. The fly ash is grade I fly ash produced by a nearby thermal power plant of the Bulianta mine [32]. The fine aggregate

was purchased from a nearby construction sand-making plant, and has a fineness modulus of 3.05. The water used for mixing was local domestic water from the laboratory, which met the requirements of the “Standard for Water Used in Concrete Mixtures (JGJ63-2006)” [33]. The water-reducing agent is a high-efficiency polycarboxylate water-reducing agent with a water reduction rate of 20% [34]. The chemical composition of the coal gangue was analyzed by X-ray fluorescence spectrometry, as shown in Table 2. The phase composition of the coal gangue is shown in Figure 1, and the microstructure morphology is shown in Figure 2.

Table 2. Factor levels for orthogonal design.

Experimental Level	Factor		
	A—Fly Ash Content/%	B—Water–Cementitious Materials Ratio	C—Coal Gangue Content/%
1	10	0.38	40
2	20	0.42	50
3	30	0.46	60

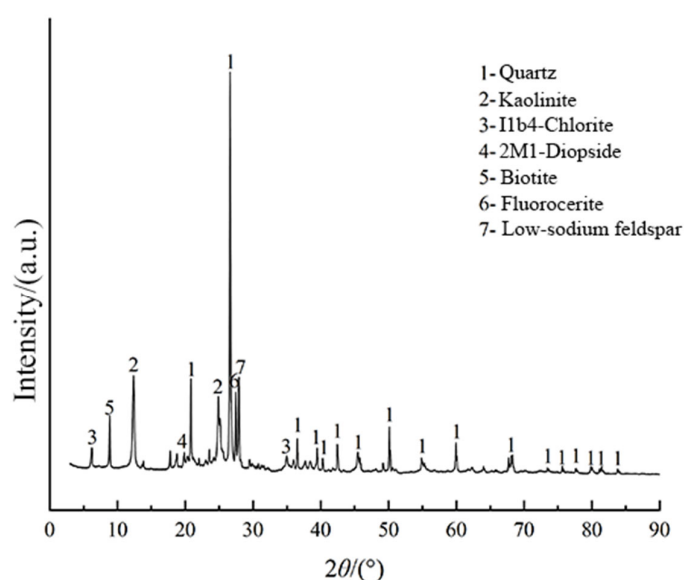


Figure 1. X-ray diffraction (XRD) pattern of coal gangue.

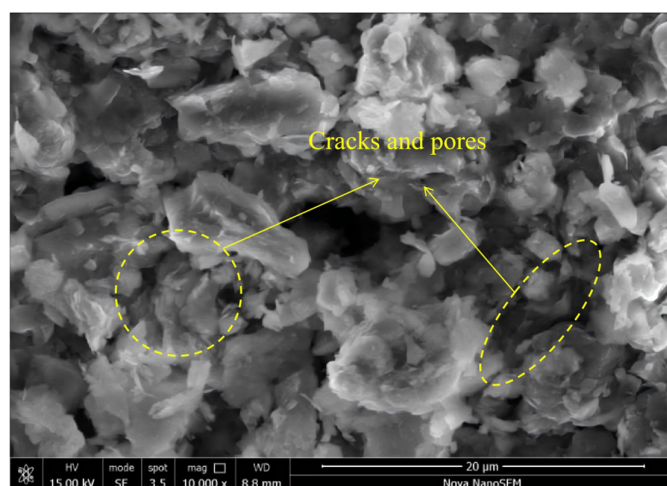


Figure 2. Microstructural morphology of coal gangue.

2.2. Mix Proportion Design

Based on extensive preliminary exploratory testing, three key factors for the orthogonal experimental design were identified: fly ash content (A), water–binder ratio (B), and coal gangue content (C). Each factor was assigned three distinct levels, as detailed in Table 2.

Concrete mixtures were prepared in accordance with the JGJ55-2011 “Code for Design of Mix Proportions of Ordinary Concrete” [35] and the orthogonal design factor levels specified in Table 2. Based on prior research by the research group, coal gangue exhibits a high water absorption capacity. If the mixing water content is not increased, the resulting concrete will exhibit a low slump; however, directly increasing the mixing water risks inducing segregation in the fresh concrete. To address this issue, coal gangue aggregate was pre-wetted prior to specimen preparation, with the pre-wetting water amount set at 50% of the aggregate’s maximum water absorption capacity.

2.3. Specimen Preparation and Curing

All raw materials were introduced into a mixer and blended until uniform before being cast into 100 mm × 100 mm × 100 mm plastic molds, followed by vibration compaction to ensure full consolidation. After 24 h of indoor natural curing, the specimens were demolded and transferred to a standard curing chamber maintained at 20 ± 2 °C and a relative humidity $\geq 95\%$ for subsequent curing.

2.4. Test Methods

Mechanical property testing: Compressive strength tests were performed in accordance with GB/T 50081-2019 “Standard for Test Methods of Mechanical Properties of Normal Concrete” [36]. The tests were conducted using the coal-rock rheological testing system developed by the Key Laboratory of Mine Filling Safety Mining under the National Mine Safety Supervision Bureau, using a constant loading rate of 2 mm/min. Strength measurements were taken after 7 and 28 days of curing. Three replicate specimens were tested per mix group, and the average of the three results was recorded as the final compressive strength value. The detailed procedure is illustrated in Figure 3, and the experimental results are presented in Table 3.

Table 3. Orthogonal experimental results for coal gangue concrete.

Test Group Number	Factor			Compressive Strength/MPa	
	A	B	C	7 d	28 d
A1B1C1	10	0.38	40	25.86	40.80
A2B1C2	20	0.38	50	24.38	36.67
A3B1C3	30	0.38	60	21.59	31.30
A1B2C2	10	0.42	50	24.14	34.34
A2B2C3	20	0.42	60	22.25	32.27
A3B2C1	30	0.42	40	24.37	34.93
A1B3C3	10	0.46	60	22.24	25.69
A2B3C1	20	0.46	40	24.12	30.61
A3B3C2	30	0.46	50	22.96	27.49
A3B3C2	30	0.46	50	22.96	27.49

Sulfate dry–wet cycle testing: Dry–wet cyclic exposure tests were carried out using an automated dry–wet cycle apparatus. A 10% sodium sulfate (Na_2SO_4) solution was prepared as the corrosive medium, and a total of 60 designed cycles were performed. Prior to testing, the initial mass of each concrete specimen was recorded. The corrosion resistance

coefficient was evaluated after the 7th, 10th, 15th, 30th, 45th, 60th, 75th, and 90th cycles. The complete test protocol is outlined in Figure 3.

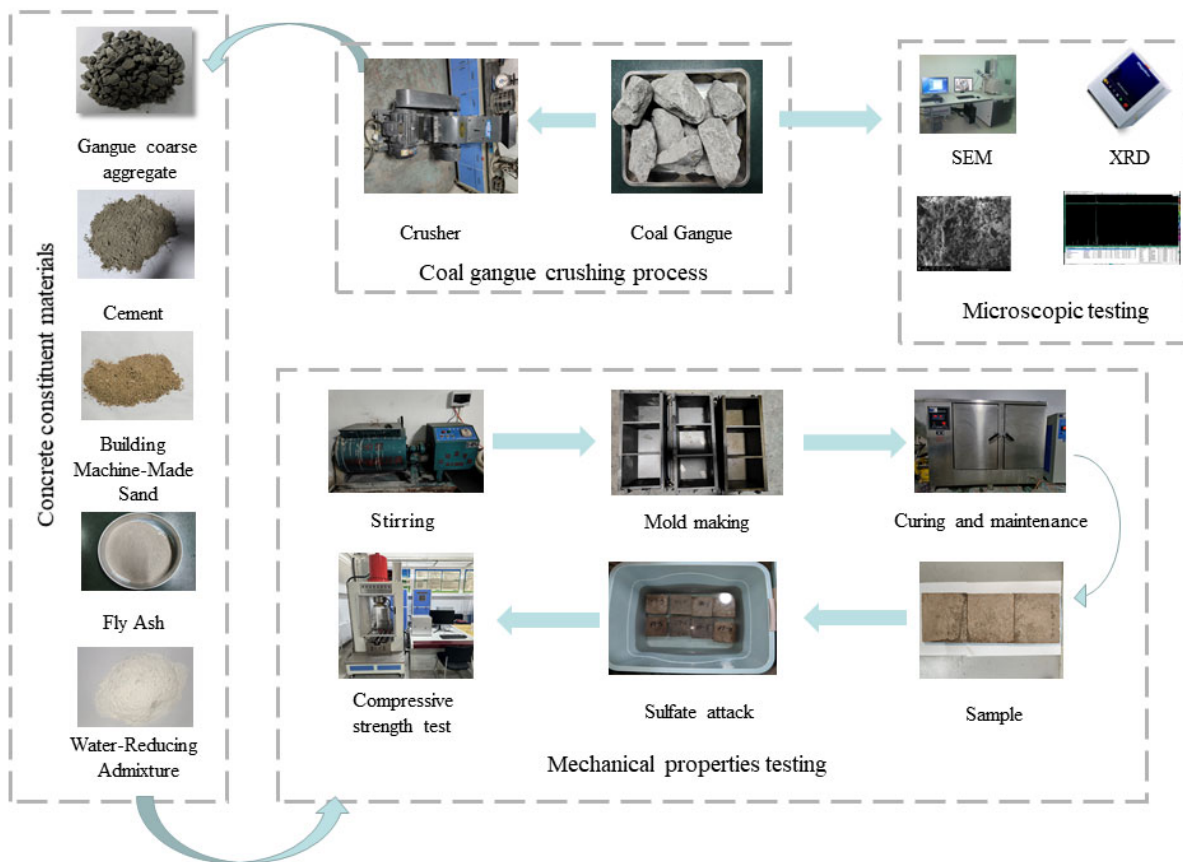


Figure 3. Preparation and testing process for coal gangue concrete.

3. Results and Discussion

3.1. Range Analysis

Range analysis was conducted on the compressive strength values of concrete after 7 and 28 days of curing (Table 3), with the results summarized in Table 4. A larger range value indicates a greater influence of the corresponding factor on concrete compressive strength. As shown in Table 4, when $C > A > B$, coal gangue content (C) was the dominant factor influencing 7-day compressive strength, while fly ash content (A) and water–binder ratio (B) were secondary factors. The underlying mechanisms are as follows:

Table 4. Range analysis results.

Analysis Target	Factor	A	B	C	Significance Order
7-Day Compressive Strength /MPa	k1	24.08	23.94	24.79	$C > A > B$
	k2	23.58	23.59	23.83	
	k3	22.97	23.11	22.03	
	R	1.11	0.83	2.76	
	Optimal Level	A1	B1	C1	
28-Day Compressive Strength /MPa	k1	33.61	36.26	35.44	$B > C > A$
	k2	33.18	33.85	32.83	
	k3	31.24	27.93	29.75	
	R	2.37	8.33	5.69	
	Optimal Level	A1	B1	C1	

(1) Coal gangue exhibits a water absorption capacity more than 15 times higher than that of natural crushed stone due to its loose and porous internal structure. After casting, it rapidly absorbs free water from the cement paste, leading to a sharp decrease in the water–binder ratio within the interfacial transition zone (ITZ). This results in incomplete hydration, and by 7 days, numerous microcracks developed in the ITZ, acting as stress concentration sites. Under compressive loading, cracks propagated preferentially along the aggregate–matrix interface.

(2) At the 7-day curing stage, only 60–70% of cement hydration was completed, and the amount of generated C-S-H gel was insufficient to fill the pores within the coal gangue aggregate or bridge the microcracks at the interface.

As shown in Table 4, when $B > C > A$, the water–binder ratio was the dominant factor influencing the 28-day compressive strength of concrete, followed by coal gangue content as a secondary factor, while fly ash content had the least influence. The underlying mechanisms are as follows:

(1) A higher water–binder ratio led to a lower 28-day compressive strength. This is because the amount of bound water required for hydration per unit volume of cementitious materials is fixed. When the water–binder ratio exceeds the optimal level, excess free water accumulates in the system. Upon evaporation, this water leaves behind numerous capillary voids, creating internal defects that compromise the structural integrity of the concrete matrix.

(2) The effect of the water–binder ratio on later-age strength was more pronounced than on early-age strength. This is attributed to the fact that a lower water–binder ratio results in finer capillary pores after water evaporation, which enhances the efficiency with which subsequent hydration products—such as C-S-H gel—can fill these pores during continued curing.

(3) By 28 days, when the concrete strength reached approximately 40 MPa, aggregate failure began to occur. The crushing value of coal gangue was 23.04%, significantly higher than that of natural crushed stone (6.7%), indicating inferior mechanical strength. As coal gangue exhibits much lower compressive resistance compared to natural aggregates, increasing its substitution ratio in the mixture reduces the overall compressive strength of the concrete.

3.2. Variance Analysis

To further determine the influence of the above factors on the compressive strength at 7 days and 28 days, variance analysis was conducted on the experimental results in Table 3. The analysis results are presented in Tables 5 and 6. In Tables 5 and 6, “*” denotes a relatively significant effect, “[*]” denotes a certain degree of effect, and blank entries indicate no effect.

Table 5. Analysis of variance for 7-day compressive strength.

Factor	Sum of Squared Deviations	Degrees of Freedom	F	F-Critical Value	Significance
Fly Ash Content	1.85	2	5.95	19	[*]
Water–Cementitious Materials Ratio	1.04	2	3.37	19	[*]
Coal Gangue Content	11.79	2	37.96	19	*
Error	0.31	2			

Table 6. Analysis of variance for 28-day compressive strength.

Factor	Sum of Squared Deviations	Degrees of Freedom	F	F-Critical Value	Significance
Fly Ash Content	9.56	2	2.84	19	[*]
water-cementitious Materials Ratio	110.27	2	32.73	19	*
Coal Gangue Content	48.65	2	14.44	19	[*]
Error	3.37				

As shown in Tables 5 and 6, factors B and C exerted significant effects on the 28-day compressive strength of coal gangue concrete, while factor A had a moderate influence. The combined results of range and variance analyses indicate that the order of influence is $B > C > A$. The combination A1B1C1 was identified as the optimal mix in terms of mechanical performance. However, considering both coal gangue utilization efficiency and concrete production cost, the A3B1C3 mixture was selected as the recommended formulation, which achieved a 28-day compressive strength of 31.30 MPa.

4. Sulfate Resistance Testing

4.1. Design of the Concrete Sulfate Resistance Test

To meet the underground service performance requirements at Bulianta Coal Mine, sulfate resistance durability tests were conducted on the A3B1C3 mixture. Six specimens were prepared for each test group. In accordance with the Standard Test Methods for Long-Term Performance and Durability of Ordinary Concrete (GB/T 50082–2024) [37], the specimens were cured for 26 days and then dried at 80 ± 5 °C for 48 h until a constant mass was reached; these served as the initial reference specimens for sulfate attack evaluation. Each dry–wet cycle was set to 24 h: specimens were immersed in a sulfate solution for 16 h, followed by drying at 80 ± 5 °C for 6 h and subsequent cooling at room temperature for 2 h. To ensure consistent and reliable test conditions, the specimens were spaced apart to prevent contact during testing.

4.2. Sulfate Resistance Analysis

As shown in Figure 4, the compressive strength of coal gangue concrete initially increased and then decreased with increasing dry–wet cycles. The maximum strength was achieved at the 15th cycle. Between the 15th and 45th cycles, the strength declined rapidly, while from the 45th to the 90th cycle, the rate of strength reduction gradually stabilized. The mass change trend followed a similar pattern: the mass reached its peak after 30 cycles of sulfate exposure and subsequently decreased. By the 90th cycle, the mass change rate reached -1.4% . The underlying mechanisms are as follows:

(1) During the first 15 dry–wet cycles, the compressive strength increased by an average of 8–10%. This is attributed to the hydration of cement during curing, which produces $\text{Ca}(\text{OH})_2$. In the presence of sulfate ions (SO_4^{2-}) in the solution, $\text{Ca}(\text{OH})_2$ undergoes a series of chemical reactions to form secondary hydration products such as gypsum (dihydrate calcium sulfate) and ettringite. The expansive nature of ettringite contributes to pore refinement and densification of the matrix, thereby enhancing the compressive strength.

(2) Active aluminosilicate components in coal gangue exhibit pozzolanic activity under alkaline conditions, reacting with hydroxide ions (OH^-) to form additional cementitious phases, including sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H), which further improve the microstructure and durability.



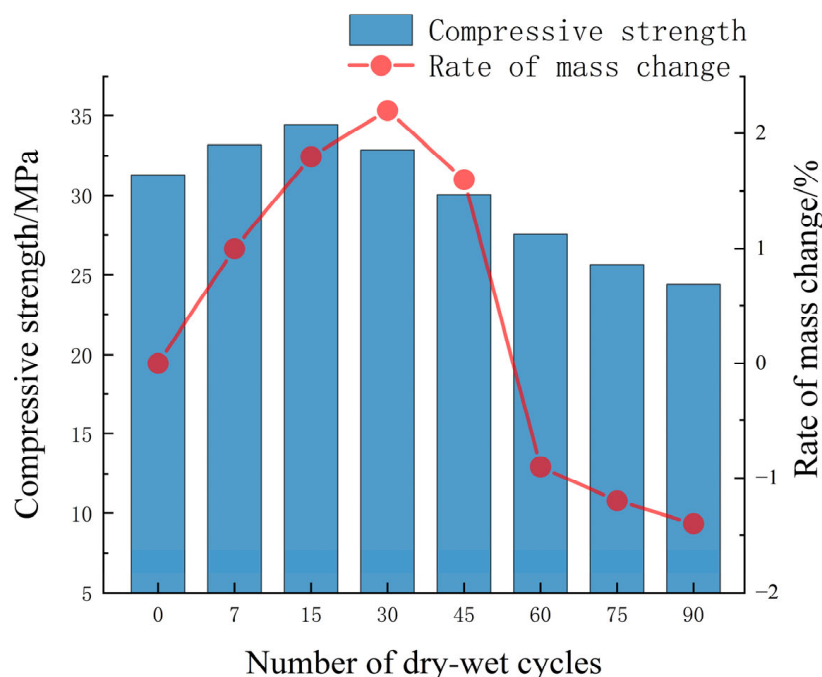


Figure 4. Experimental results on sulfate resistance.

(3) The decline in concrete strength began after 10 dry–wet cycles, primarily due to the progressive formation of ettringite and gypsum. As these expansive products accumulate, their internal expansion stress eventually reaches the tensile strength limit of the concrete matrix, initiating numerous microcracks that may coalesce into cracks and lead to structural deterioration. During repeated wetting and drying cycles, the concrete undergoes cyclic swelling upon water absorption and shrinkage upon dehydration, promoting the initiation and propagation of internal microcracks. These cracks serve as preferential pathways for sulfate ingress, accelerating the penetration of aggressive ions. As illustrated in Figure 1, kaolinite present in coal gangue can exacerbate this degradation process due to its potential to participate in secondary reactions under sulfate-rich conditions. During the drying phase, infiltrated sulfate solutions become concentrated, leading to salt crystallization within capillary pores and existing microcracks. The growth of crystals generates significant crystallization pressure, which further widens and extends cracks, ultimately resulting in the evolution of micro-damage into macroscopic failure.

4.3. Stress–Strain Curve

The full stress–strain curves of coal gangue concrete under the action of sulfate dry–wet cycles are shown in Figure 5. It can be seen that the stress–strain variation trends of coal gangue concrete under different cycle numbers were mostly similar. When the cycle number was less than 30, the stress–strain curve changes were not obvious compared with that of the un-eroded state. As the cycle number increased, the slope of the ascending section of the stress–strain curve of coal gangue concrete continuously decreased, the peak point of the curve continuously dropped and shifted to the right, the peak stress decreased, and the peak strain increased. The curve became wider and flatter, which is particularly obvious after 90 cycles. The reason is that in the later stage of erosion, the internal microcracks and pores of coal gangue concrete increase, and the degree of structural looseness increases. Therefore, under a very small stress, a large deformation can be produced.

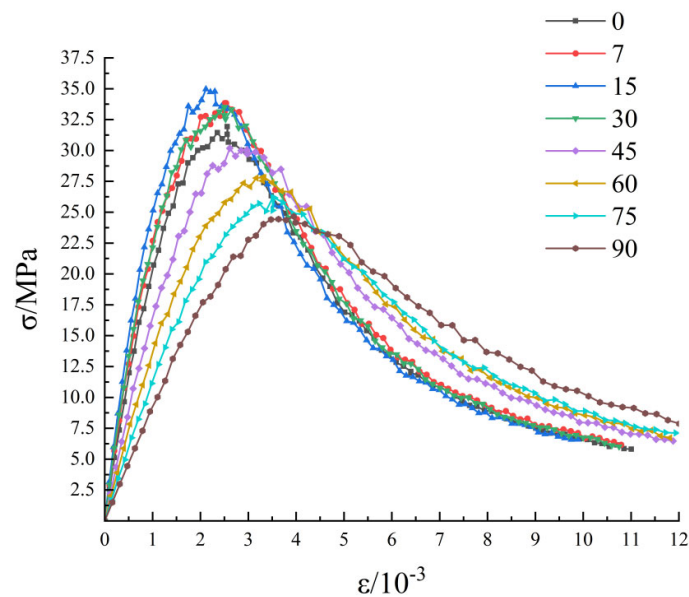


Figure 5. Stress–strain curve diagram.

In this study, the uniaxial compression piecewise constitutive equation of concrete suggested in reference [30] was adopted, as shown in Equation (1), and the calculated values of the parameters of the full uniaxial compression stress–strain curve of coal gangue concrete under the action of sulfate erosion and dry–wet cycles were obtained, as shown in Table 7.

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

Table 7. Shape parameters of the stress–strain curve for coal gangue concrete.

Number of cycles	0	7	15	30	45	60	75	90
Ascending branch parameter <i>a</i>	2.15	2.21	2.32	2.33	1.92	1.86	1.67	1.57
Descending branch parameter <i>b</i>	1.74	1.71	1.69	1.72	1.64	1.62	1.58	1.49

In the equation, $x = \varepsilon/\varepsilon_p$, $y = \sigma/f_p$, f_p , and ε_p represent the peak stress and peak strain of concrete, respectively; a and b are the control parameters of the ascending and descending segments related to the material. The parameters a and b of the full stress–strain curve of concrete under uniaxial compression have clear physical and geometric meanings. If the value of a is smaller and the value of b is larger, the curve will be narrower, the area under the curve will be smaller, and its ductility and plastic deformation capacity will be poorer. Therefore, the difference in the mechanical properties of concrete can be compared or measured by parameters a and b . As shown in Table 7, in the early stage of erosion, a slightly increased in the sodium sulfate solution, and the corresponding changes can also be seen in the stress–strain curve. As the number of cycles increased, a gradually decreased after 30 cycles. When the number of cycles was 90, a decreased by 27%. As the number of cycles increased, b showed an overall downward trend. When the number of cycles was 90, b was 1.49, a decrease of 14%.

Based on statistical regression analysis of the experimental data, the relationships between parameter a (ascending branch) and parameter b (descending branch) of the

stress–strain curve of coal gangue concrete under sulfate dry–wet cyclic conditions, and the number of cycles t are as follows:

$$\begin{aligned} a &= 2.329 - 7.65 \times 10^{-5}t - 9.03 \times 10^{-5}t^2 \\ b &= 1.721 - 2.04 \times 10^{-4}t - 2.51 \times 10^{-5}t^2 \end{aligned} \quad (3)$$

Based on Equations (2) and (3), the stress–strain fitting curves of coal gangue concrete under different cycle numbers can be obtained. Figure 6 shows the comparison between the fitting curves and the test results, from which it can be seen that the two are in good agreement.

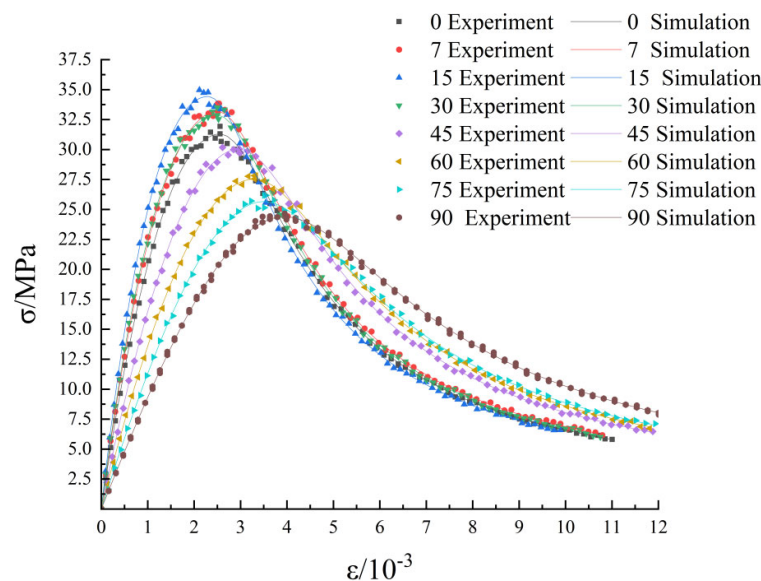


Figure 6. Stress–strain fitting curve.

5. Numerical Simulation

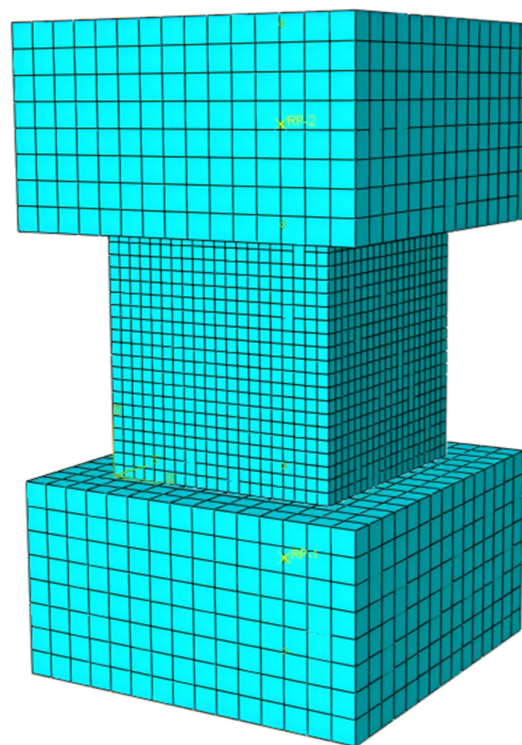
5.1. Model Development

Abaqus is an engineering simulation platform based on finite element analysis technology that is equipped with comprehensive pre- and post-processing modules and robust nonlinear solving capabilities. It has been extensively employed in numerical simulations of concrete structures. This study conducts the relevant simulation analyses using this platform. Abaqus offers three constitutive models for simulating concrete material behavior: the brittle fracture model, the smeared crack model, and the concrete damage plasticity model (CDP). Among these, the concrete damage plasticity model can accurately capture the mechanical response of concrete throughout the entire loading process and was therefore adopted as the primary constitutive model in this study. This model effectively characterizes both compressive crushing and tensile cracking behaviors of concrete and has been widely validated in structural simulation applications. For coal gangue concrete, the strength and elastic modulus were derived from experimental measurements, the Poisson's ratio was set to 0.22, and the plastic parameters were determined according to recommended values reported in the literature [38]. The specific parameter values are listed in Table 8.

Table 8. Material parameter selection for plastic damage model.

Parameter	Expansion Angle ψ	Eccentricity c	f_{b0}/f_{c0}	K	Viscosity Coefficient μ
Value	30	0.1	1.15	0.667	0.0005

The three-dimensional model of the concrete specimen, with dimensions of 100 mm $\times$ 100 mm $\times$ 100 mm, is illustrated in Figure 7. The compressive constitutive relationship was derived from analytical results based on Equations (2) and (3), incorporating a coal gangue concrete model that accounts for sulfate attack effects. Using this constitutive model, the required Concrete Damage Plasticity (CDP) parameters— $\sigma_{\max}$, ϵ^{in} , and d_c —were determined for the numerical simulation. The tensile constitutive behavior was defined according to the relevant provisions of the “Code for Design of Concrete Structures” (GB 50010–2010) [39]. The concrete was discretized using C3D8R elements (eight-node linear brick elements with reduced integration and hourglass control), and a uniform mesh size of 5 mm was adopted. Numerical analysis was performed using a Static, General step with automatic time incrementation. Loading was applied through rigid platens with a high elastic modulus to simulate compression tests. A surface-based interaction with a friction coefficient of 0.2 was employed to model the contact between the rigid platens and the prism specimen. The top and bottom surfaces of the rigid platens were kinematically coupled to reference points 1 and 2, respectively, enabling the application of boundary conditions. The bottom surface of the specimen was fully fixed, while the top surface served as the loading end, where a downward displacement was imposed in the vertical direction; lateral displacements at the top were constrained to simulate uniaxial compression conditions.

**Figure 7.** Cube compression simulation model.

5.2. Analysis of Simulation Results

The failure patterns of coal gangue concrete specimens under uniaxial compression following sulfate-induced dry–wet cycles are presented in Figure 8. As observed in Figure 8,

the overall failure mode of specimens subjected to sulfate attack was generally similar to that of the unattacked specimens, exhibiting an inverted triangular shape. However, when the number of cycles reached 90, the extent of sulfate deterioration became more severe, and the failure pattern of the coal gangue concrete gradually transitioned toward shear failure.

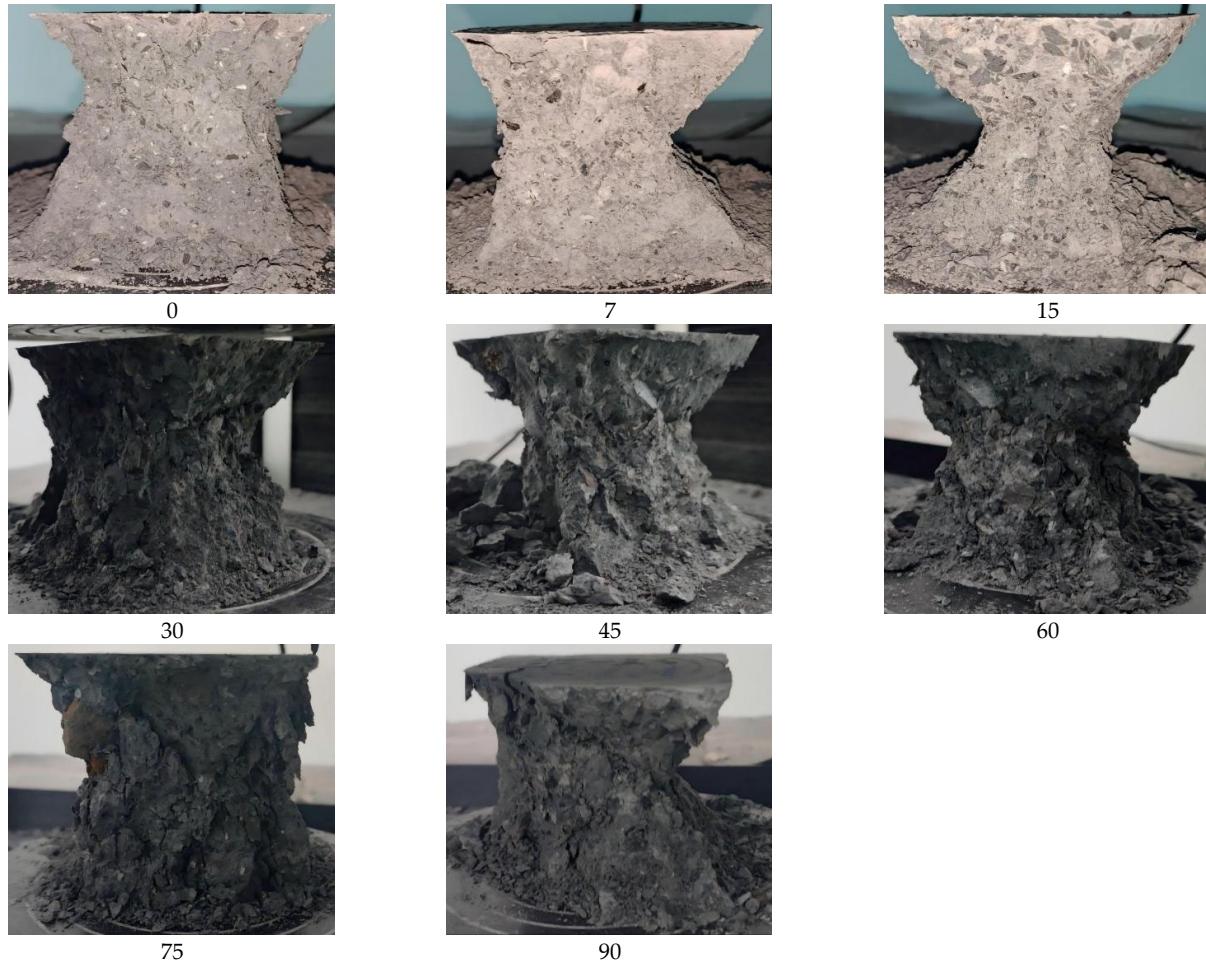


Figure 8. Apparent damage characteristics of coal gangue concrete specimens.

According to the criteria specified in Reference [23], the ultimate strain ϵ_{cu} is defined as the strain corresponding to a value of $0.5 f_c$ on the descending branch of the concrete stress-strain curve. The failure pattern of the concrete finite element model was analyzed by examining the cloud diagram of damage distribution on the longitudinal cross-section. The compressive damage factor distribution is presented in Figure 9. As shown in Figure 9, for the coal gangue concrete specimen at $t = 0$, the maximum compressive damage was primarily localized in the four edge regions near the mid-height of the specimen. With increasing cycle numbers ($t = 15, 30$), the zone of maximum compressive damage gradually shifted toward the central region, and its spatial extent progressively expanded. At a high number of dry–wet cycles ($t = 90$), the maximum compressive damage was distributed across the entire central cross-section. This simulated damage evolution is consistent with the observed macroscopic failure patterns in the experimental results shown in Figure 8.

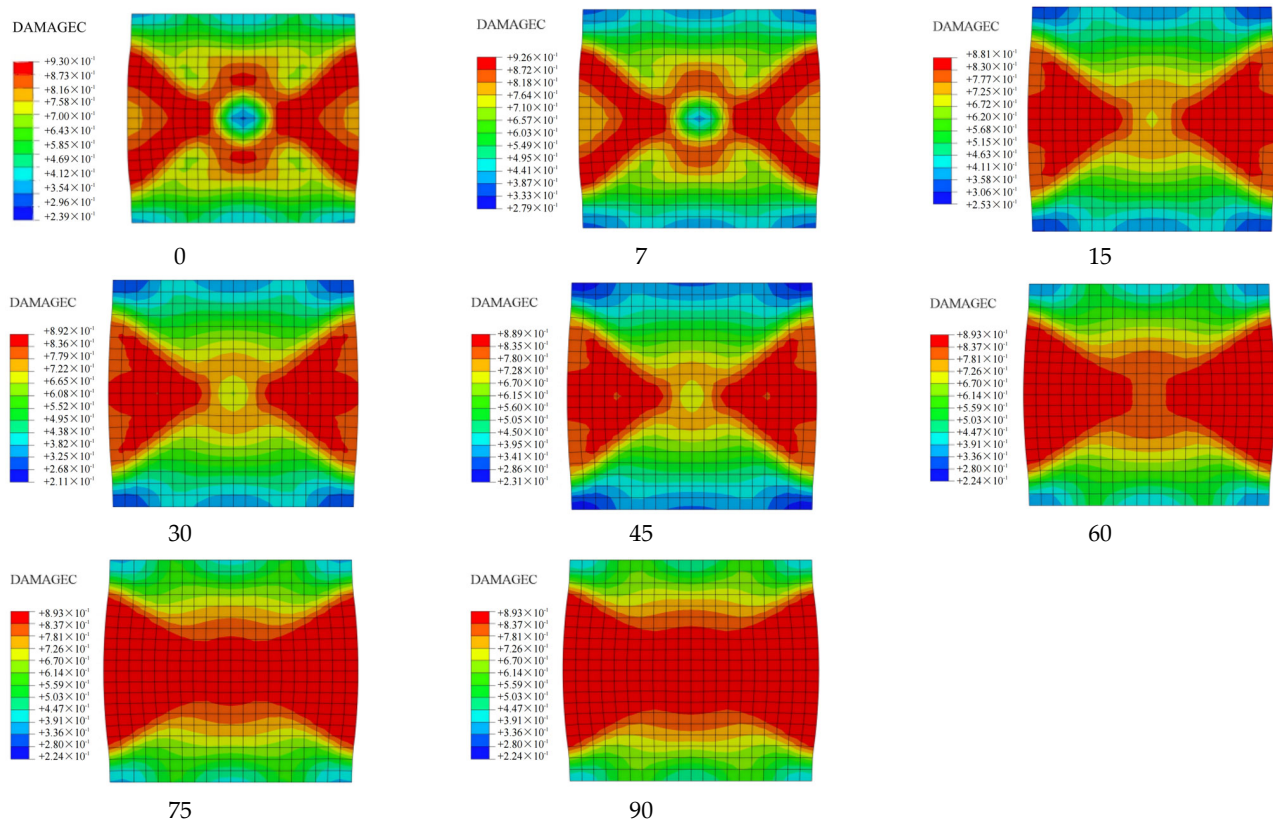


Figure 9. Numerical simulation of damage behavior in coal gangue concrete specimens.

The equivalent plastic strain contour of the concrete cubic finite element model is presented in Figure 10. As shown in the figure, the region of maximum plastic strain was symmetrically distributed along a 45-degree inclination on both sides of the specimen, indicating that during the loading process, the accumulation, release, and transmission of stress led to the formation of a pair of symmetric shear failure zones oriented at approximately 45 degrees. Under axial loading, initial micro-cracks developed within the concrete specimen, accompanied by stress-induced damage and pronounced stress concentration. Stress relaxation occurred at the crack tips, driving the cracks to propagate symmetrically along the 45-degree direction until macroscopic failure of the specimen was achieved. This simulated failure pattern aligns well with the experimental observations: as illustrated in Figure 8, the specimen ultimately fractured into two opposing regular tetrahedral cones, thereby validating the accuracy and reliability of the numerical simulation.

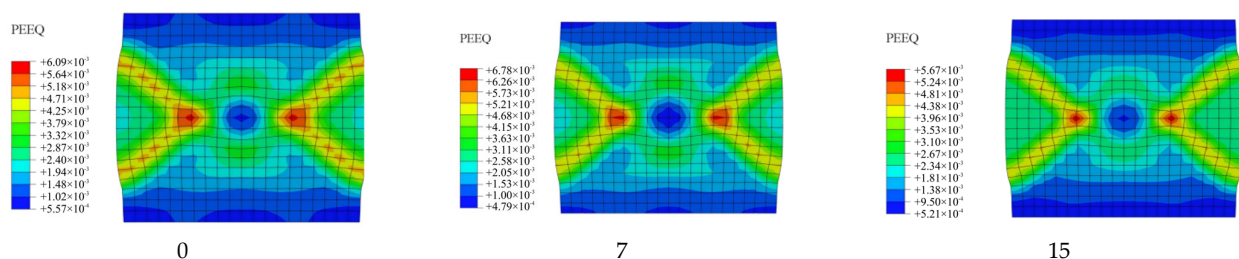


Figure 10. Cont.

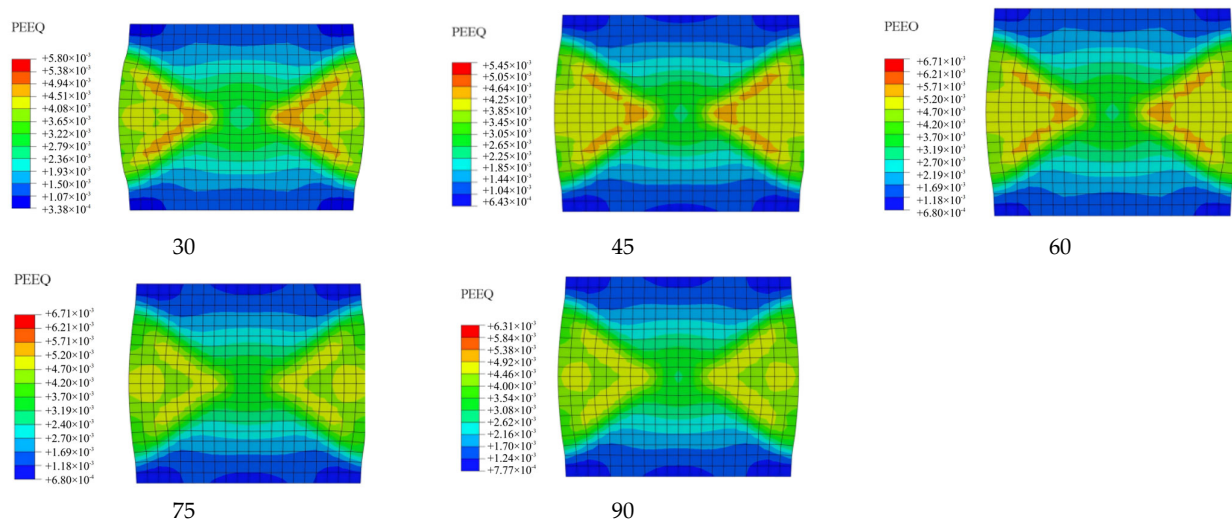


Figure 10. Numerical simulation of equivalent plastic strain in coal gangue concrete specimens.

6. Conclusions

The study proposes a coal gangue-based concrete specifically designed for underground sulfate erosion environments at Bulianta Coal Mine, which is based on conventional concrete. A sulfate erosion constitutive model tailored to the mixture proportion was established through experimental data fitting, and the constitutive model rationality was validated using numerical simulations in Abaqus.

(1) This study investigated the concrete used in the underground central water sump at Bulianta Coal Mine in the Ordos mining region. A novel approach for developing sulfate-resistant dry–wet cycle concrete utilizing underground coal gangue is proposed, based on the characteristic sulfate-laden dry–wet cycling conditions encountered in underground environments. Considering key factors such as concrete performance, cost-effectiveness, and coal gangue utilization, a comprehensive laboratory mix design study was conducted. The optimal mixture proportion was determined to be 60% coal gangue, 30% fly ash, and a water–binder ratio of 0.38, which achieved a compressive strength of 31 MPa.

(2) The sulfate solution initially enhanced and subsequently reduced the strength of the coal gangue concrete. The behavior is primarily attributed to the reaction between sulfate ions in the solution and the hydration product $\text{Ca}(\text{OH})_2$ in the concrete, which generates secondary products such as gypsum dihydrate. These products fill internal pores, leading to a denser microstructure and initial strength gain. However, with prolonged exposure, the continued formation and accumulation of expansive products induce internal stresses that eventually exceed the tensile capacity of the concrete, resulting in microcracking and strength deterioration. Nevertheless, within the tested exposure range, the overall degradation remains limited, and the material maintains sufficient durability to meet the operational requirements in the underground environment of Bulianta Coal Mine [37].

(3) A sulfate resistance test was conducted on the optimally proportioned sulfate-resistant concrete subjected to dry–wet cycles. The experimental results revealed that, with increasing numbers of sulfate-laden dry–wet cycles, the constitutive model proposed by Guo Zhenhai in Reference [30] exhibited limited applicability under the studied conditions. To address this limitation, the original model was modified and a new constitutive model tailored for concrete under sulfate-induced dry–wet cyclic environments was developed. The proposed constitutive model was subsequently implemented in Abaqus for numerical simulation studies.

(4) The constitutive model proposed in this study can be effectively integrated with the built-in Concrete Damaged Plasticity (CDP) model in Abaqus. Using this combined

framework, numerical simulations of the mechanical property degradation of coal gangue concrete under sulfate-induced dry–wet cycles were conducted within the Abaqus platform. The simulation accurately captured the uniaxial compressive behavior of coal gangue concrete under such environmental conditions, revealing the evolution of damage during the loading process and thereby validating the applicability of the proposed constitutive model. This approach establishes a novel methodology for future numerical analysis of coal gangue concrete in sulfate-laden dry–wet environments and further confirms the rationality of the optimal mixture proportion for producing sulfate-resistant dry–wet cycle concrete using underground coal gangue.

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