

Article

Study on the Attack of Concrete by External Sulfate under Electric Fields

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Abstract: The research on and application of electric fields to promote the rapid infiltration of ions into cement concrete have been widely explored. Still, there are few studies on the migration of sulfate ions using electric fields. In this paper, a new test method is designed using the principle of electric fields, that is, to accelerate the attack of sulfate into concrete under the action of the electric field, to test the resistance of concrete to sulfate attack. By testing different water–cement ratios, different pulse frequencies, different ages, and different soaking environments, the influence of the electric field on the sulfate resistance of concrete was analyzed. The results show that the compressive strength of concrete in a sulfate attack environment is smaller than that of conventional attack and water immersion environment when the water–cement ratio is 0.3, 0.4, and 0.5 under the action of the electric field and increases with the increase of water in the water–cement ratio. Compared with a 14 day test, the compressive strength of concrete in a sulfate attack environment decreased by 1.9%, 8.6%, and 2.9%, respectively, at 28 days, which was faster than that of conventional attack and water immersion. The compressive strength of the concrete in the sulfate attack environment during the full immersion test and the semi-immersion test is smaller than that of the conventional attack and water immersion, and the semi-immersion test method is more obvious than the full immersion test method. The microscopic morphology of the test group, the water group, and the solution group were compared. From the microscopic morphology comparison, it can be seen that the electric field accelerates the diffusion of sulfate ions into the cement concrete and accelerates the reaction of sulfate ions with the relevant components in the cement concrete. Given the demand for concrete to resist sulfate attack under the action of the electric field, developing new and efficient protective materials is an important research direction. At present, the market lacks protective materials specifically for such an attack environment. This paper provides the theoretical basis and technical support for improving the effectiveness of concrete surface protection technology and engineering practices.

Keywords: electric field; concrete; sulfate resistance; microscopic morphology



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1. Introduction

As a main building material widely used in civil engineering, the durability of concrete is very important for the long-term stability of engineering structures. Sulfate attack is an important field in the study of concrete durability. It not only affects the physical and mechanical properties of concrete, but also leads to serious deterioration of the structure. In terms of attack mechanism and performance impact, Lawrence, D.C. et al.'s research deeply explored the attack of sulfate on concrete, analyzed the attack mechanism and its impact on concrete performance in detail, and provided a solid scientific basis for understanding and preventing sulfate attack [1]. On the electric field effect, Juan and Rui Zhao studied the role of the electric field in promoting the removal of chemically bound chloride ions in concrete, which is crucial to improving the long-term stability and prolonging the service life of concrete structures [2]. Xie, Xiaoli, and others have deepened this field and revealed

the complex physical and chemical interaction mechanism induced by the electric field by analyzing the distribution of chloride ions and the change of microstructures in concrete with mineral admixtures under the action of the electric field [3]. In the study of the interaction between electric field and sulfate attack, Chen Li et al. invented a new way to focus on the specific response of Portland cement-based materials to sulfate attack in an electric field environment, including the unique mode of mineral phase transition and ion migration, which provides a new perspective for understanding the process of sulfate attack under electric field regulation [4]. In the field of durability evaluation, Wang, Zhao, et al. verified the spatial averaging phenomenon of the electric field associated with steel attack by using an innovative pseudo-concrete model and explored its application prospects in actual concrete structures, which opened up a new method for durability prediction [5]. Yin and others comprehensively analyzed the deterioration process of concrete under sodium sulfate attack through finite element analysis and construction of a macro–micro integrated model, which provided a powerful tool for evaluation [6]. In the research and development of protective technologies and materials, Martins, M.C. et al. systematically evaluated the attack effect of ammonium sulfate, reflected on the existing methods, and laid a foundation for scientific protection strategies. Durgun, M.Y. et al. evaluated the attack resistance of various mineral admixtures by the Taguchi method, which provided data support for material selection [7–11]. Huang, Q. et al. and Silva, D. et al. explored new ways to improve the sulfate resistance of concrete from the perspective of surface treatment of nano-silica and silicon-based nanoparticles, respectively, providing an experimental basis for environmentally friendly and efficient protection technology [8–15]. In terms of test method innovation, Esselami, R. et al. proposed a new method of using an induction period and hot drying to accelerate the sulfate attack test, which significantly shortened the test time and was successfully applied to a variety of concrete materials [16–19]. It opened up an efficient channel for rapid assessment of concrete durability, promoted the deep integration of research and engineering practice, and promoted the sustainable development of concrete technology [19–21]. An in-depth study of the sulfate resistance of concrete not only helps to improve the durability of building materials, and reduce maintenance costs, but also improves the safety and service life of engineering structures [22,23].

Early research mainly focused on the chemical reaction mechanisms and physical damage modes of sulfate attack on concrete [17,24]. Studies have shown that sulfate reacts with calcium hydroxide and tricalcium aluminate in concrete to form an expansion product, ettringite, resulting in expansion and cracking of the internal structure of concrete [25,26]. With the deepening of research, scholars began to pay attention to the sulfate attack behavior of concrete under complex environmental conditions, such as the dry–wet cycle, freeze–thaw cycle, and sulfate attack under a high-temperature environment [27]. Zhang Shaohui et al. [28] found that the increase in temperature will lead to a change in the pore structure of concrete, which will affect its sulfate resistance. Many scholars have also carried out in-depth research on the application of electric fields in concrete. As an effective accelerated test method, the electric field is widely used to study the migration and diffusion process of ions in concrete. Carrión A. et al. [29] studied the migration behavior of cations such as Cl, Na, and Ca under an electric field, and found that an electric field can significantly accelerate the penetration process of ions, which helps evaluate the durability of concrete more quickly [30,31]. However, most studies mainly focus on chloride ion migration and electric field acceleration test methods, and less on the migration behavior of sulfate ions and their mechanism of action in concrete [32,33]. Therefore, this paper studies the law of sulfate attack on concrete under the action of electric field, aiming at filling the research gap of sulfate ion migration, deepening the understanding of concrete durability, revealing the influence mechanism of electric fields on the sulfate attack process, providing a theoretical basis of external electric field accelerated sulfate attack tests, guiding the protection of underground engineering structures such as subways, and promoting the improvement of concrete durability evaluation and design methods. In practical engineering, structures like underground metros, tunnels, and wastewater treatment plants

face accelerated concrete degradation due to sulfate-rich environments combined with electric fields. Understanding and mitigating this sulfate attack is crucial for the durability and longevity of these structures

2. Materials and Methods

2.1. Experimental Raw Materials

2.1.1. Cement

The cement used is P.O 42.5R ordinary Portland cement produced by Lafarge Cement Co., Ltd. (Dujiangyan City, China). Its chemical composition is shown in Table 1, and its physical and mechanical properties are shown in Table 2:

Table 1. Chemical components of ordinary Portland cement.

Materials	SiO ₂ (%)	Fe ₂ O ₃ (%)	Al ₂ O ₃ (%)	CaO (%)	MgO (%)	SO ₃ (%)	Total Alkali Content (%)	Ignition Loss
Ordinary 42.5R	21.3	2.53	5.79	60.15	2.35	2.54	0.72	3.66

Table 2. Physical and mechanical properties of ordinary Portland cement.

Standard Consistency (%)	Initial Setting Time (min)	Final Setting Time (min)	Stability (Slump Test)	Compressive Strength (MPa)		Flexural Strength (MPa)	
				3 d	28 d	3 d	28 d
28.4	179	239	No cracks observed No warping observed	5.5	27.6	8.8	53.0

2.1.2. Coarse Aggregate

Coarse aggregate is sourced from Gele Mountain Quarry. The composition of the coarse aggregate consists of 5–10 mm crushed stones and 10–20 mm crushed stones mixed in a 3:7 ratio. The main properties of the crushed stones are shown in Table 3. The grain size distribution curve in Figure 1 illustrates the particle size distribution of two different ranges of crushed stones: 5–10 mm and 10–20 mm.

Table 3. Performance of gravel.

Particle Size (mm)	Bulk Density (g/cm ³)	Particle Density (g/cm ³)		Porosity (%)	
		Loose	Dense	Loose	Dense
5~10	2670	1380	1470	48.3	44.9
10~20	2670	1400	1520	47.6	43.1

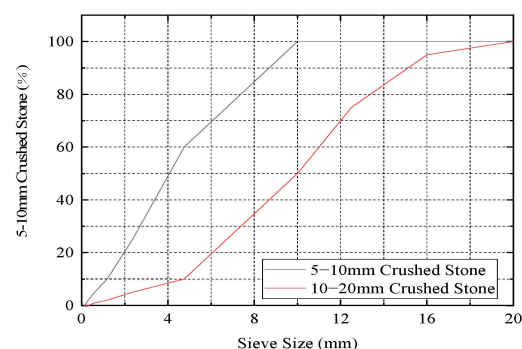


Figure 1. Grain size distribution curve of coarse aggregate.

2.1.3. Fine Aggregate

Medium sand from Jianyang, Sichuan is used. The sand has a mud content of 1.2%, a fineness modulus of 2.4, and moisture content of 2%.

2.1.4. Chemical Reagents

Sodium hydroxide: 95% purity, industrial reagent, provided by Dongfang Huabo Co., Ltd. (Dongfang, China).

Anhydrous sodium sulfate: 95% purity, industrial reagent, provided by Dongfang Huabo Co., Ltd.

2.1.5. Concrete Mix Proportion

The quantities of each raw material used in the experiment are shown in Table 4. The water–cement ratio is the mass ratio of water to cementitious materials.

Table 4. Mix ratio of ordinary concrete.

Water–Cement Ratio	Water/kg·m ^{−3}	Cement/kg·m ^{−3}	Sand/kg·m ^{−3}	Crushed Stone/kg·m ^{−3}
0.3	190	633	602	1025
0.4	190	475	660	1125
0.5	190	380	696	1184

2.2. Experimental Methods

2.2.1. Experimental Equipment

- (1) The mold of the water group and sulfate solution is a laboratory plastic triple mold, specification 100 mm × 100 mm; after the improvement of the standard triple mold, it becomes the mold used for the electro-osmotic pulse group specimen. The middle baffle is sawed into a comb shape, the seam depth is about 90 mm, the seam width is 2~3 mm, and 9 seams are evenly sawed on each plate (Figure 1).
- (2) The white iron sheet, specification 100 mm × 120 mm, is mainly used for the test group to prevent cement slurry seepage during concrete molding; the perforated white iron sheet (Figure 2), 95 mm × 100 mm, is used as the electrode plate.



Figure 2. Experimental mold.

- (3) In the mold of the electro-osmotic pulse group, only one specimen is formed in the middle, and the solution is on both sides. The electrode plate is inserted into the solution and connected to the pulse generator. Pulse electro-osmotic device (Figure 3), test group device schematic (Figure 4), pulse waveform schematic (Figure 5).



Figure 3. Electrode plates.

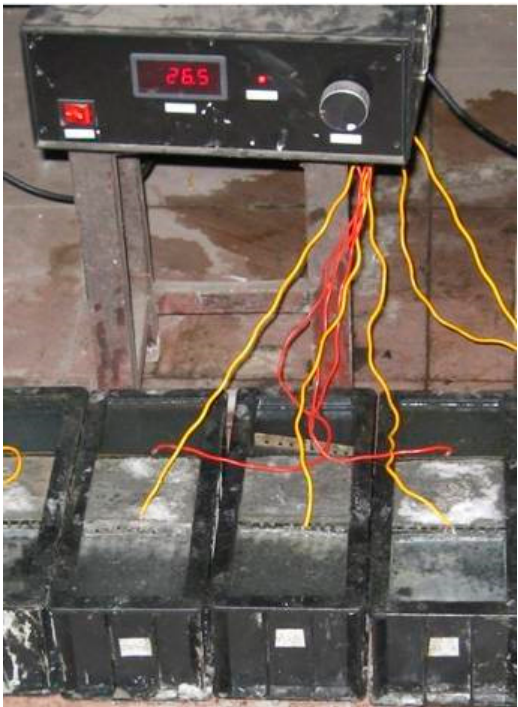


Figure 4. Electric field electro-osmotic device.

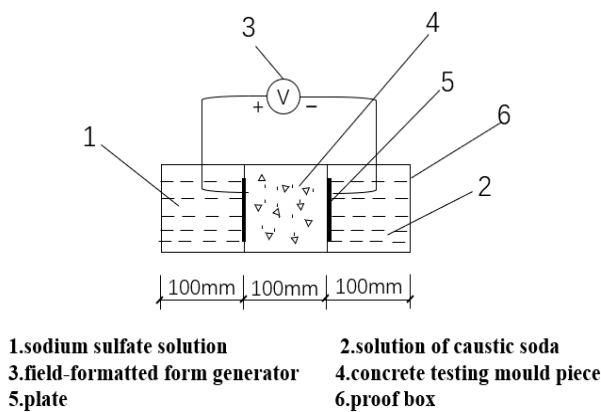


Figure 5. Schematic diagram of sulfate attack resistance test device for concrete.

2.2.2. Experimental Procedures

The sulfate resistance test of concrete with different water–cement ratios, different ages, different electric field frequencies, and different soaking methods under the action of the electric field was carried out. The proposed test voltage is 30 V, the water–cement ratios of concrete are 0.3, 0.4, and 0.5 respectively, the electric field frequency is 10 s–20 s, the mass fraction of sodium sulfate solution is 5%, and the test ages are 14 days and 28 days.

Concrete specimens were molded at three different water–cement ratios: 0.3, 0.4, and 0.5. This experiment uses these water-to-cement ratios based on actual concrete in common engineering projects and referencing the standards of the ‘Concrete Design Code’ (GB/T 50081-2019) [34]. The selection of water-to-cement ratios aims to study the impact of different densities on sulfate attack. Both the electric field group and the sodium sulfate solution group used the same concentration of sodium sulfate solution. The specimen with a water–cement ratio of 0.4 uses 10 s and 20 s frequencies to compare the influence of the electric field frequency. Each mix proportion had three groups, with three samples in each group, totaling 9 samples. The preparation and testing of the samples in this experiment were carried out by the Standard Test Methods for Long-Term Performance and Durability of Ordinary Concrete (GB/T 50082-2009) [35]. Each method involved molding three specimens, and the compressive strength was calculated as the average of the three specimens. The specimens were molded according to standard curing conditions and tested for compressive strength after specific immersion periods. To ensure consistency and minimize external influences, three specimens were molded for each method, and the compressive strength was calculated as the average of the three specimens.

2.2.3. Specimen Molding

The specimens were molded according to the mix ratio in Table 4, with dimensions of $100 \times 100 \times 100$. They were cured under standard curing conditions for 7 days, soaked in sodium sulfate solution for 14 days, and then removed for testing. The specimens subjected to full immersion were tested for compressive strength after 7 and 21 days, while those subjected to partial immersion were tested for compressive strength after 21 days. Full immersion means the specimens were completely submerged in the test solutions. Partial immersion indicates that only half of the specimen was submerged. Each group consisted of three specimens, and the compressive strength was taken as the average of the three specimens. The arrangement of specimens is shown in Table 5.

Table 5. The number of concrete specimen models.

Group		Water Group		Sodium Sulfate Solution Group		Electric Field Group (10 s)		Electric Field Group (20 s)	
Immersion Method		Full Im-mersion	Partial Im-mersion	Full Im-mersion	Partial Im-mersion	Full Im-mersion	Partial Im-mersion	Full Im-mersion	Partial Im-mersion
Water–Cement Ratio	0.3	6	3	6	3	6	3	0	0
	0.4	6	3	6	3	6	3	6	3
	0.5	6	3	6	3	6	3	0	0

2.2.4. Evaluation Criteria

In this experiment, mass loss rate and compressive strength are used as the evaluation criteria for the test of electric field on concrete resistance to sulfate attack.

The expression for mass loss rate is:

$$K = (M_2 - M_1) / M_1 \quad (1)$$

K is the mass loss rate (positive value indicates mass increase, negative value indicates mass decrease), %;

M_1 is the initial mass of the specimen before testing, kg;

M_2 is the mass of the specimen at a certain age of testing, kg;
The expression for the relative attack resistance coefficient is:

$$K = R_2/R_1 \quad (2)$$

K is the relative attack resistance coefficient;

R_2 is the compressive strength of the specimen immersed in the attack solution for a certain age, MPa;

R_1 is the compressive strength of the specimen immersed in water for the same age, MPa;

The mass M_1 and M_2 of each concrete specimen before and after the test, as well as the compressive strength R before and after the test, are measured in the experiment.

2.2.5. Scanning Electron Microscopy (SEM) Test

For the SEM test, 9 samples were selected. During sample preparation, the samples were first soaked in ethanol solution for seven hours, then removed and placed in a 60 °C oven for three hours. Afterwards, the samples were taken out and a conductive metal film was coated on their surface for observation under the electron microscope.

3. Results

3.1. Surface Characteristics

Figure 6 illustrates a specimen immersed in water, showing no apparent changes such as peeling, cracking, or spalling on the surface. Figure 7, depicting a specimen eroded by sodium sulfate solution, shows a small amount of white sulfate crystals. The surface of the specimen does not exhibit significant changes, with no spalling, peeling, or cracking observed. Figure 8 is the specimen under the action of the electric field. After the electric field is introduced, under the action of external voltage, through the observation of the whole test process, white sulfate crystals are continuously precipitated on the surface of the specimen. Until the end of the test, there is no obvious change in the apparent characteristics of the specimen in the test group, and the phenomena of desizing, slagging, and cracking of the epidermis are not obvious. The conductor iron sheet used has a very serious attack phenomenon (Figure 9).

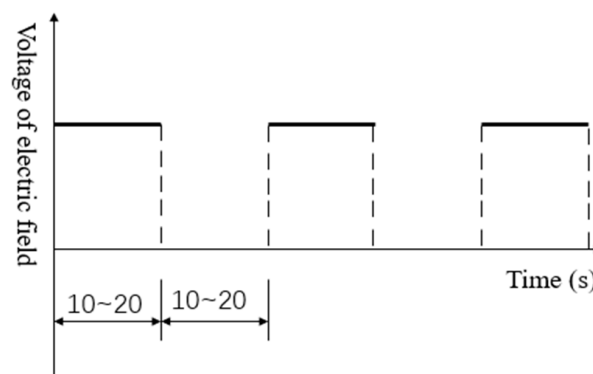


Figure 6. Electric field waveform diagram.

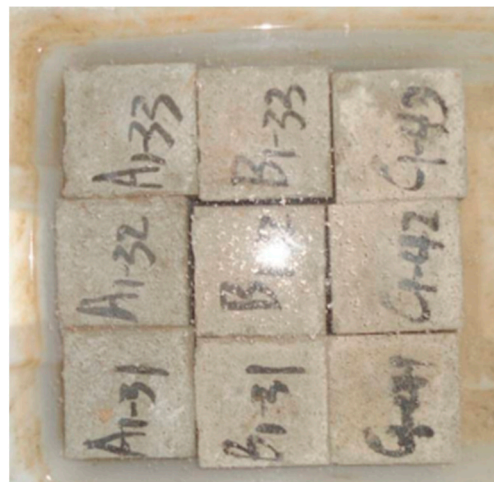


Figure 7. The specimen was soaked in water.



Figure 8. The specimen was soaked in a sodium sulfate solution.

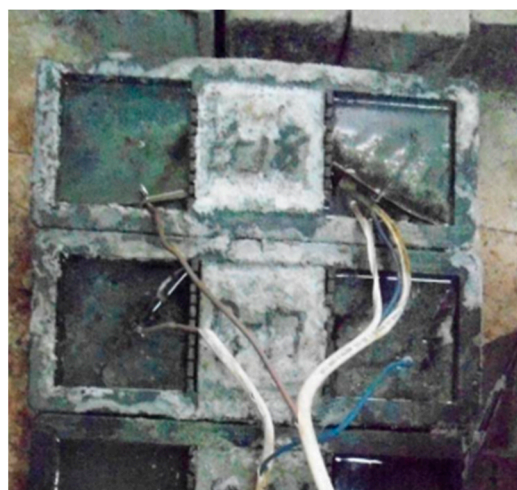


Figure 9. Fourteen days in the experimental group specimens.

3.2. Mass Loss

The sulfate resistance test of concrete with different water–cement ratios, different ages, different electric field frequencies, and different soaking methods under the action of the

electric field was carried out. The proposed test voltage is 30 V, the water–cement ratio of the concrete is 0.3, 0.4, and 0.5, respectively, the electric field frequency is 10–20 s, the mass fraction of sodium sulfate solution is 5%, and the test age is 14 days and 28 days. Table 6, Table 7, and Table 8, respectively, reflect the mass loss of full immersion for 14 days, full immersion for 28 days, and half immersion for 28 days under the action of the electric field.

Table 6. Quality changes under different conditions of ordinary concrete in 14 days.

Water–Cement Ratio		Average Mass of Specimens (kg)	Average Mass of Specimens (kg)	Mass Loss Rate k (%)
0.3	Water Group	2.50	2.51	0.53
	Sodium Sulfate Solution Group	2.53	2.55	1.06
	Electric field group (10 s)	2.43	2.45	0.55
0.4	Water Group	2.44	2.46	0.82
	Sodium Sulfate Solution Group	2.45	2.46	0.54
	Electric field group (10 s)	2.42	2.44	0.83
	Electric field group (20 s)	2.47	2.49	0.81
0.5	Water Group	2.53	2.55	0.79
	Sodium Sulfate Solution Group	2.55	2.56	0.52
	Electric field group (10 s)	2.47	2.50	1.35

Table 7. Full soaking of ordinary concrete under different conditions, mass loss of 28 days.

Water–Cement Ratio		Average Mass of Specimens (kg)	Average Mass of Specimens (kg)	Mass Loss Rate k (%)
0.3	Water Group	2.46	2.45	−0.41
	Sodium Sulfate Solution Group	2.45	2.45	0
	Electric field group (10 s)	3.57	3.52	−1.40
0.4	Water Group	2.48	2.46	−0.81
	Sodium Sulfate Solution Group	2.47	2.48	0.41
	Electric field group (10 s)	3.45	3.42	−0.87
	Electric field group (20 s)	3.43	3.40	−0.87
0.5	Water Group	2.41	2.39	−0.83
	Sodium Sulfate Solution Group	2.42	2.42	0
	Electric field group (10 s)	3.35	3.4	−1.65

Table 8. Semi-soaked plain concrete under different conditions, mass loss of 28 days.

Water–Cement Ratio		Average Mass of Specimens (kg)	Average Mass of Specimens (kg)	Mass Loss Rate k (%)
0.3	Water Group	2.45	2.44	−0.41
	Sodium Sulfate Solution Group	2.43	2.43	0
	Electric field group (10 s)	3.42	3.41	−0.30
0.4	Water Group	2.46	2.46	0
	Sodium Sulfate Solution Group	2.46	2.44	−0.81
	Electric field group (10 s)	3.45	3.42	−0.87
	Electric field Group (20 s)	3.39	3.39	0
0.5	Water Group	2.41	2.39	−0.83
	Sodium Sulfate Solution Group	2.42	2.38	−1.65
	Electric field group (10 s)	3.35	3.35	0

Table 6 shows that after 14 days of full immersion, all groups of specimens showed no mass loss, and an increase in mass. The reason for this result may be that in the initial stage of attack, the generated ettringite and gypsum only fill the pores of the concrete, thereby increasing its mass.

Tables 7 and 8 show that the mass loss rate of sulfate attack under an electric field is greater than that of conventional attack and water immersion after 28 days of test; that is, the physical damage degree of sulfate attack under an electric field is greater than that of conventional attack and water immersion. It can be said that the introduction of the electric field in the test increases the damage of sulfate to concrete; that is, the electric field plays a certain accelerative role in the attack of sulfate to concrete. However, due to the short specimen time of the attack test, the mass loss is not obvious.

3.3. Analysis of Experimental Results on Sulfate Attack on Concrete under Electric Field

The experimental results for compressive strength and attack resistance coefficients are shown in Tables 9–11.

Table 9. Fourteenth day compressive strength of ordinary concrete under different conditions.

Water–Cement Ratio	Group	Compressive Strength (Mpa)	Relative Attack Resistance Coefficient K
0.3	Water Group	60.7	1
	Sodium Sulfate Solution Group	60.6	0.99
	Electric field group (10 s)	56.5	0.94
0.4	Water Group	50.3	1
	Sodium Sulfate Solution Group	47.8	0.94
	Electric field group (10 s)	45.3	0.90
	Electric field group (20 s)	45.3	0.90
0.5	Water Group	35.8	1
	Sodium Sulfate Solution Group	34.4	0.96
	Electric field group (10 s)	30.8	0.88

Table 10. Twenty-eighth day compressive strength of ordinary concrete under different soaking conditions.

Water–Cement Ratio	Group	Compressive Strength (Mpa)	Relative Attack Resistance Coefficient K
0.3	Water Group	61	1
	Sodium Sulfate Solution Group	59	0.97
	Electric field group (10 s)	57.6	0.944
0.4	Water Group	53.5	1
	Sodium Sulfate Solution Group	50.7	0.95
	Electric field group (10 s)	49.2	0.92
	Electric field group (20 s)	48.1	0.90
0.5	Water Group	36.1	1
	Sodium Sulfate Solution Group	35.2	0.98
	Electric field group (10 s)	31.7	0.88

Table 11. Twenty-eighth day strength of ordinary concrete, semi-soaked.

Water–Cement Ratio	Group	Compressive Strength (Mpa)	Relative Attack Resistance Coefficient K
0.3	Water Group	60.7	1
	Sodium Sulfate Solution Group	60.6	0.99
	Electric field group (10 s)	56.5	0.94
0.4	Water Group	50.3	1
	Sodium Sulfate Solution Group	47.8	0.94
	Electric field group (10 s)	45.3	0.90
	Electric field group (20 s)	45.3	0.90

Table 11. Cont.

Water–Cement Ratio	Group	Compressive Strength (Mpa)	Relative Attack Resistance Coefficient K
0.5	Water Group	35.8	1
	Sodium Sulfate Solution Group	34.4	0.96
	Electric field group (10 s)	30.8	0.86

4. Discussion

4.1. Experimental Results Analysis

4.1.1. Influence of Water–Cement Ratio on the Experiment

(1) Influence of Water–Cement Ratio at 14 Days

Figures 10 and 11 illustrate that as the water–cement ratio goes from 0.3 to 0.5, the attack resistance coefficient follows the trend: water group > test group > test group, indicating a clear decrease in the compressive strength of concrete under the action of the electric field. However, there is some fluctuation in the relative attack resistance coefficient with the change in water–cement ratio. This result may be attributed to three reasons: (1) the introduction of the electric field in the sodium sulfate attack test accelerates the attack of concrete by sodium sulfate; (2) the attack and damage of concrete by sodium sulfate is a complex physicochemical process; (3) the attack time of sodium sulfate on concrete is relatively short, and the strength development of concrete has not yet reached a stable state, resulting in the phenomenon presented in the figure.

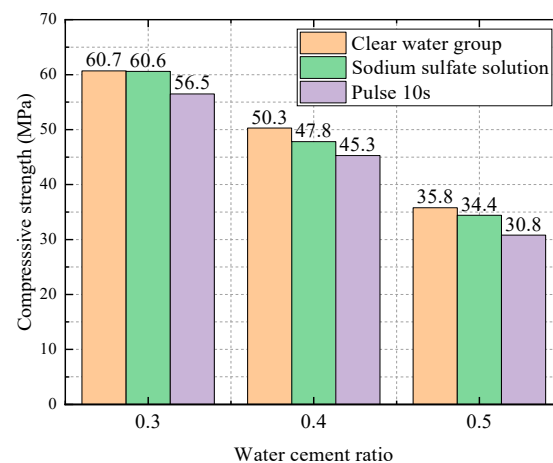


Figure 10. Full immersion 14 day compressive strength.

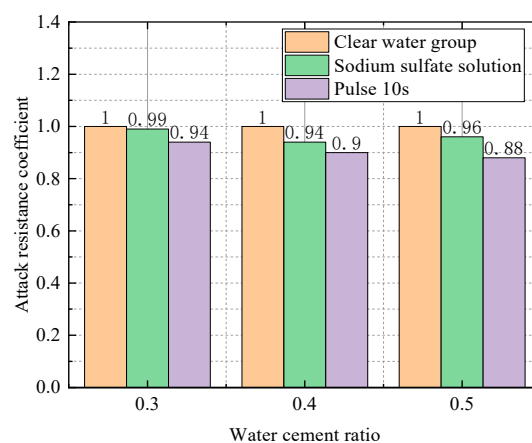


Figure 11. Attack resistance coefficient of full immersion for 14 days.

(2) Influence of Water–Cement Ratio at 28 Days

The data in Figures 12–15 show the attack resistance coefficients of concrete tested after 28 days of exposure to sodium sulfate. The attack resistance coefficients of the specimens are all less than one, indicating that the specimens have entered a period of strength decline, making it reasonable to evaluate the attack resistance performance of the specimens. From the figures, it can be seen that the decrease in attack resistance coefficient of specimens under an electric field, compared to conventional attack, increases with the increase in water–cement ratio. This suggests that under the action of the electric field, the higher the water–cement ratio, the more pronounced the acceleration of attack by an electric field. This is because the water–cement ratio is an important factor affecting the compactness of concrete. The damage of concrete by the sulfate is mainly due to the sulfate ions in the external environment entering the concrete through connected pores and reacting with the hydration products of cement to form expansive substances or crystals, which generate expansion stress or crystallization stress. When the expansion stress or crystallization stress exceeds the tensile strength of concrete, damage occurs. The larger the water–cement ratio of the specimen, the higher the capillary porosity of the cement stone, the more large and connected pores there are, the better the permeability, and the easier it is for sulfate to penetrate into the interior of the concrete. The higher the water–cement ratio, the faster the penetration rate, resulting in concrete damage. The speed and quantity of calcium aluminate and gypsum formation inside will be faster and greater, and the speed of sulfate attack damage will be accelerated.

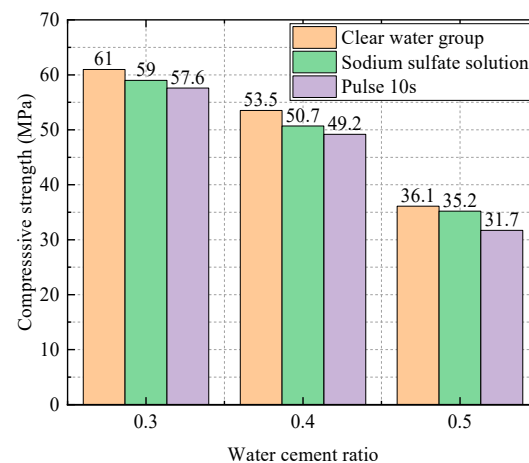


Figure 12. Full immersion 28 day compressive strength.

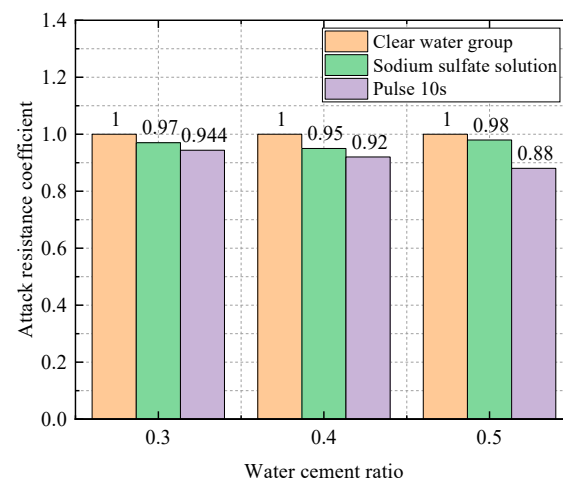


Figure 13. Attack resistance coefficient of full immersion for 28 days.

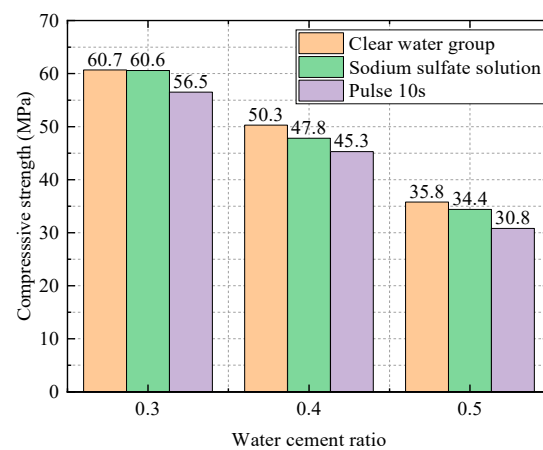


Figure 14. Semi-immersed 28 day compressive strength.

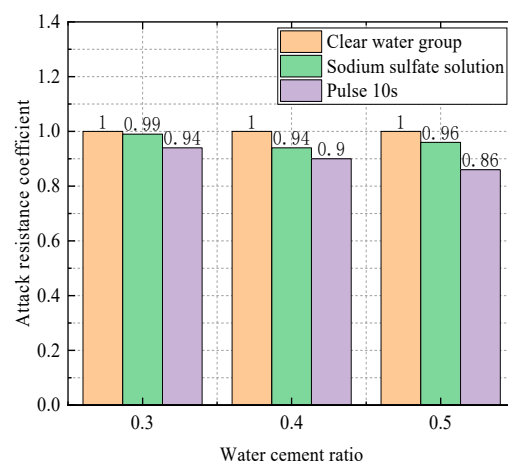


Figure 15. Semi-immersed 28 day attack resistance coefficient.

4.1.2. Impact of the Frequency of Electric Field on the Experiment

Figures 16 and 17 illustrate that when the water–cement ratio, age, and immersion method are the same, the compressive strengths of the 10 s and 20 s electric field groups are almost equal. For a water–cement ratio of 0.4, an age of 28 days, and full immersion, the attack coefficients are 0.92 and 0.9, respectively. Therefore, it shows that the influence of electric field frequency on compressive strength is not obvious.

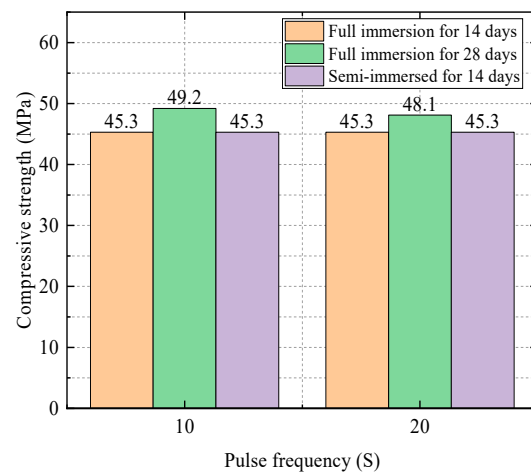


Figure 16. Compressive strength of different pulse frequencies with water–cement ratio of 0.4.

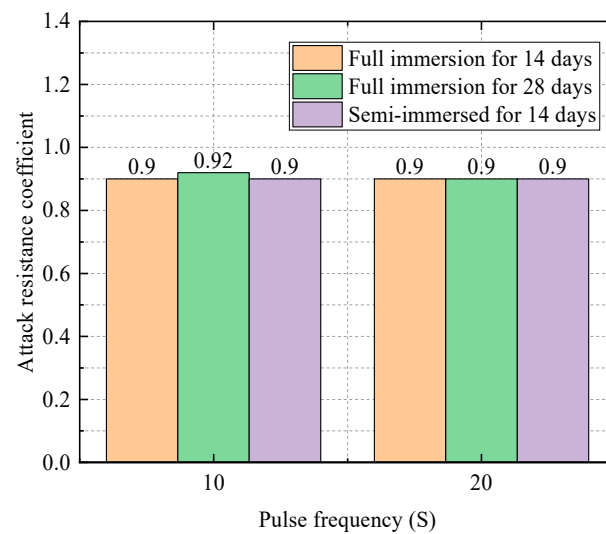


Figure 17. Attack resistance coefficient of different pulse frequencies with water–cement ratio of 0.4.

4.1.3. Impact of Age on the Experiment

(1) When the water–cement ratio is 0.3:

The above figures show that under conventional attack, the attack resistance coefficients at 14 and 28 days are 0.99 and 0.97, respectively. Under the attack of the electric field, the attack resistance coefficients at 14 and 28 days are 0.94 and 0.944, respectively. This means that with increasing time, the attack under the action of the electric field becomes more pronounced. It can be indirectly inferred that an electric field promotes the attack of concrete by sulfate (Figures 18 and 19).

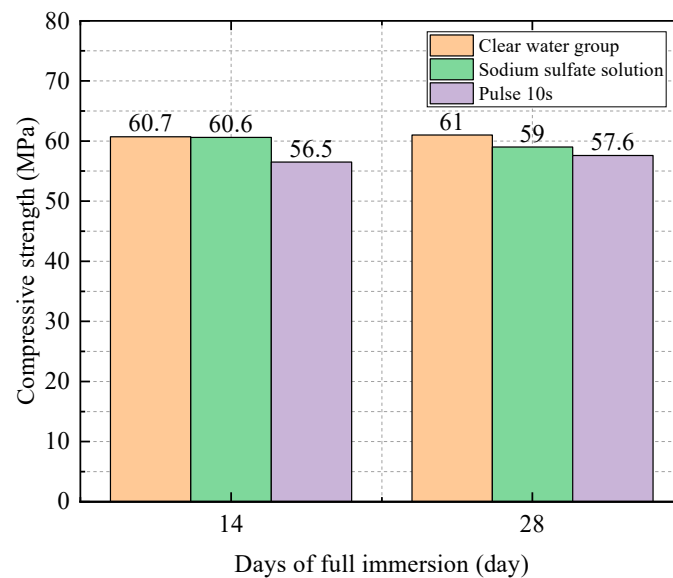


Figure 18. Compressive strength of full immersion resistance with water–cement ratio of 0.3.

(2) When the water–cement ratio is 0.4:

Figures 20 and 21 indicate that in the sodium sulfate solution group, the attack resistance coefficient at 14 days is 0.94, and at 28 days is 0.95. Under the attack of an electric field, the attack resistance coefficient at 14 days is 0.96, and at 28 days is 0.92. This indicates that in the sodium sulfate solution group, there is little change in the attack resistance coefficient with increasing time. Under the attack of the electric field, the attack resistance

coefficient decreases significantly with increasing time and an increasing water–cement ratio. It can be considered that an electric field promotes the attack of concrete by sulfate.

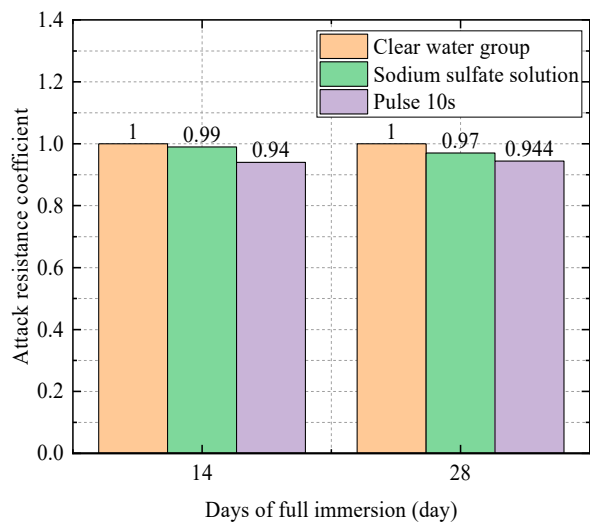


Figure 19. Attack resistance coefficient of full immersion resistance with water–cement ratio of 0.3.

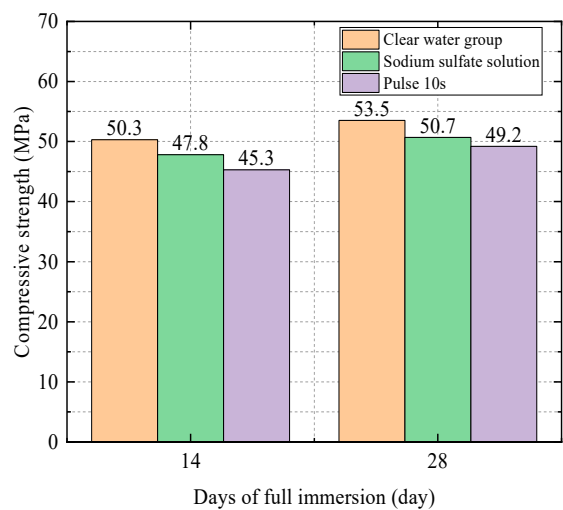


Figure 20. Compressive strength of full immersion resistance with water cement ratio of 0.4.

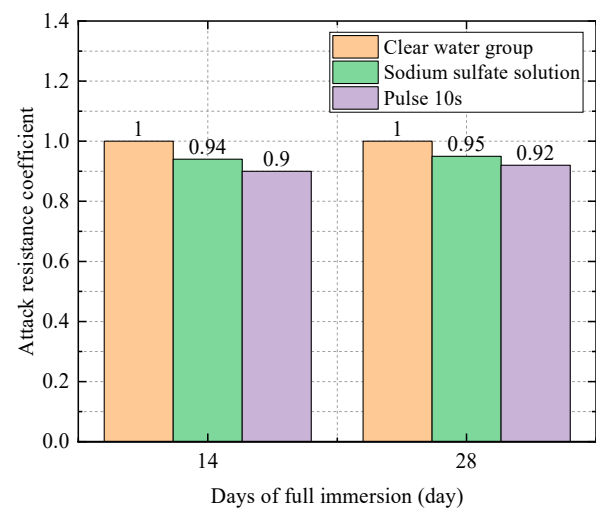


Figure 21. Attack resistance coefficient of full immersion resistance with water cement ratio of 0.4.

(3) When the water–cement ratio is 0.5:

Figures 22 and 23 show that in the sodium sulfate solution group the attack resistance coefficients at 14 and 28 days are 0.96 and 0.98, respectively. In the electric field group, the attack resistance coefficients at 14 and 28 days are 0.88 and 0.88, respectively. This indicates that there is little change in the attack resistance coefficient with increasing time.

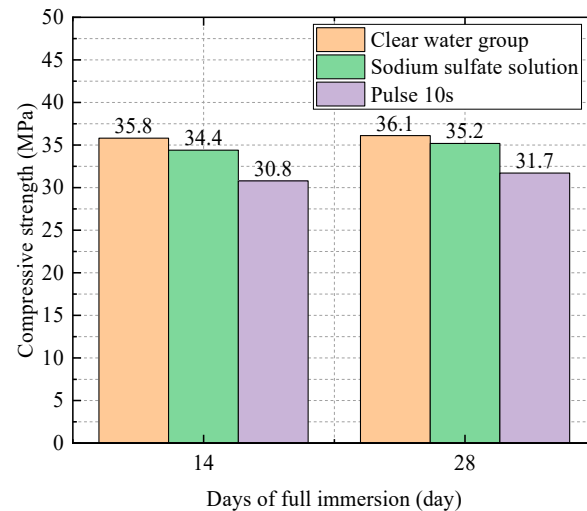


Figure 22. Compressive strength of full immersion resistance with water–cement ratio of 0.5.

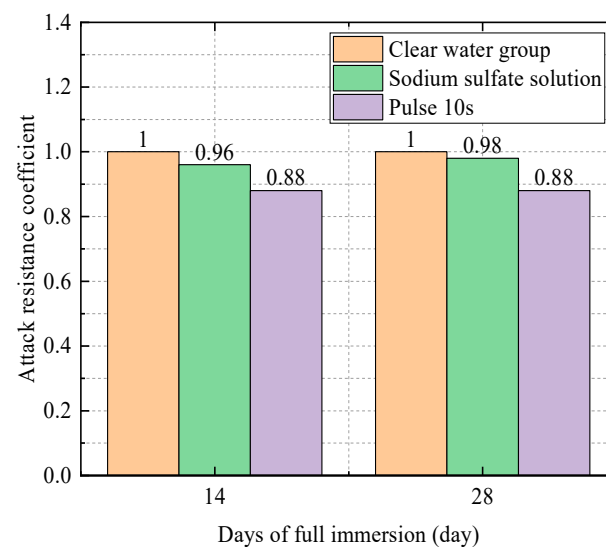


Figure 23. Attack resistance coefficient of full immersion resistance with water–cement ratio of 0.5.

The figures also indicate that under the attack of the electric field at 28 days, the attack is more severe than in the sodium sulfate solution group, and this difference is more significant at a water–cement ratio of 0.5 compared to ratios of 0.3 and 0.4. Therefore, introducing an electric field in the attack of concrete by sulfate increases the attack effect of sulfate on concrete. To more fully reflect the resistance of cement concrete to sulfate attack, the test time should be appropriately extended.

4.1.4. Impact of Different Immersion Methods

(1) When the water–cement ratio is 0.3:

Figures 24 and 25 show that at a water–cement ratio of 0.3, the attack resistance coefficient for full immersion in the sodium sulfate solution group is 0.97, while for partial immersion, it is 0.99. Under the attack of the electric field, the attack resistance coefficient

for full immersion is 0.94, and for partial immersion, it is 0.93. The experimental results indicate that partial immersion causes more severe attack than full immersion.

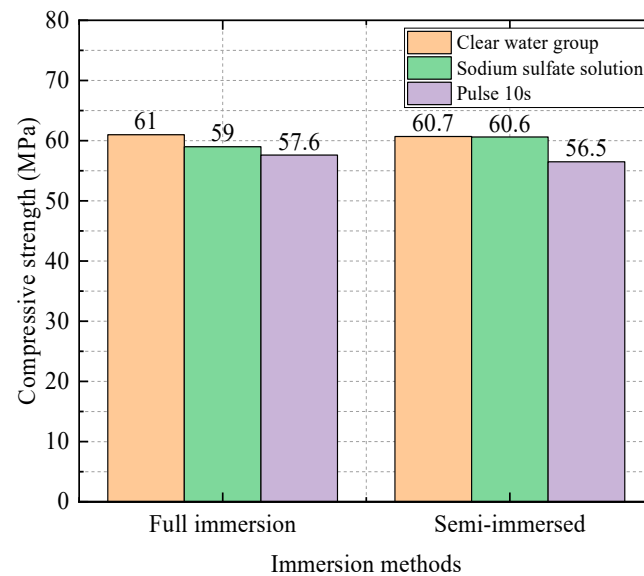


Figure 24. Compressive strength of different immersion methods with water–cement ratio of 0.3.

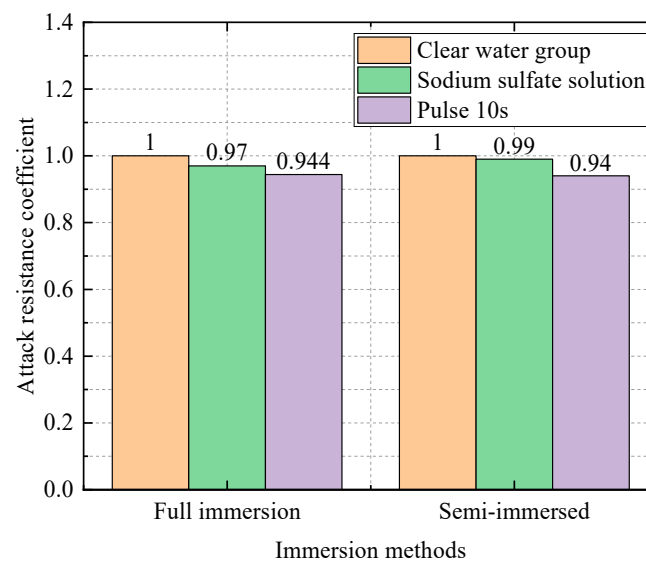


Figure 25. Attack resistance coefficient of different immersion methods with water–cement ratio of 0.3.

(2) When the water–cement ratio is 0.4:

Figures 26 and 27 indicate that at a water–cement ratio of 0.4, the attack resistance coefficient for full immersion in the sodium sulfate solution group is 0.95, while for partial immersion, it is 0.94. Under the attack of the electric field, the attack resistance coefficient for full immersion is 0.92, and for partial immersion, it is 0.90. The study shows that under the attack of an electric field, the attack resistance coefficient for partial immersion is lower than that for full immersion, and the attack resistance coefficient decreases more rapidly for partial immersion under the attack of an electric field. From the perspective of the attack of concrete by sulfate under different immersion methods, it can be concluded that an electric field accelerates the attack of concrete by sulfate to a certain extent.

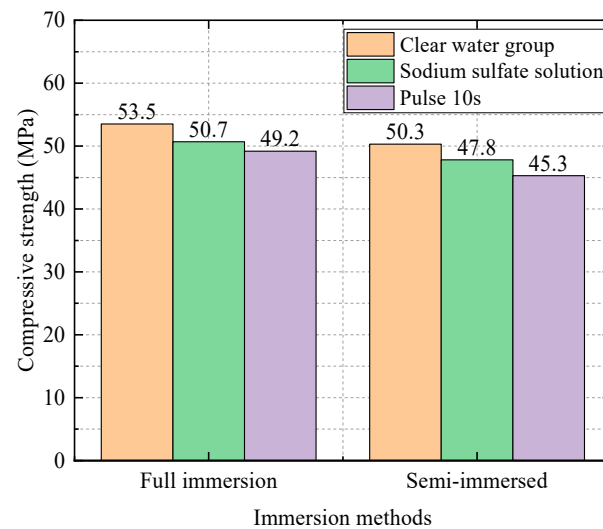


Figure 26. Compressive strength of different immersion methods with water–cement ratio of 0.4.

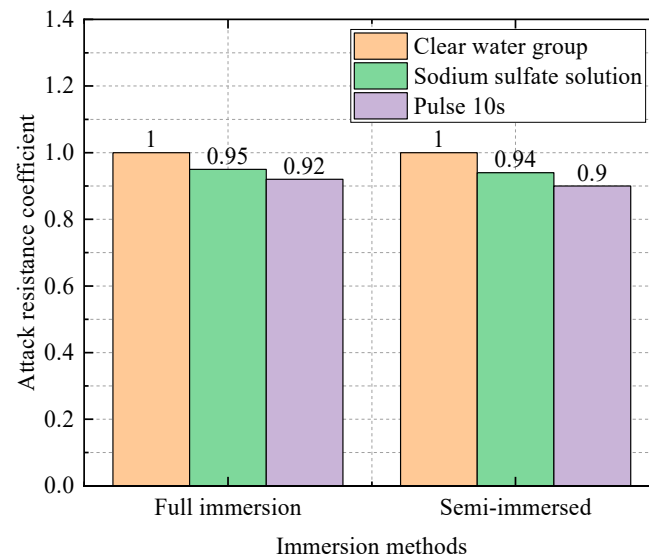


Figure 27. Attack resistance coefficient of different immersion methods with water–cement ratio of 0.4.

(3) When the water–cement ratio is 0.5:

Figures 28 and 29 indicate that at a water–cement ratio of 0.5, the attack resistance coefficient for full immersion in the sodium sulfate solution group is 0.98, while for partial immersion, it is 0.96. Under the attack of the electric field, the attack resistance coefficient for full immersion is 0.88, and for partial immersion, it is 0.88. In the experiments with water–cement ratios of 0.4 and 0.5, the attack resistance coefficient for partial immersion in both the sodium sulfate solution group and under the attack of the electric field is lower than that for full immersion.

Xiao Haiying et al. from the School of Materials, Harbin Institute of Technology have studied the effect of sulfate on the attack of concrete under different immersion methods. In the test, three kinds of horizontal semi-immersion, vertical semi-immersion, and horizontal full-immersion methods were used. In the test, it was concluded that the sensitivity of the three different immersion methods to the bending attack of concrete to a corrosive liquid was the largest under the vertical semi-immersion method. Furthermore, it is concluded that the flexural attack resistance coefficient of concrete under vertical semi-immersion attack can be used to quickly evaluate the attack resistance of concrete. In the tests with

water–cement ratios of 0.4 and 0.5, the attack resistance coefficient of semi-immersion under conventional attack and electro-osmotic pulse attack is smaller than that of full immersion, which is consistent with the results of Xiao Haiying’s research.

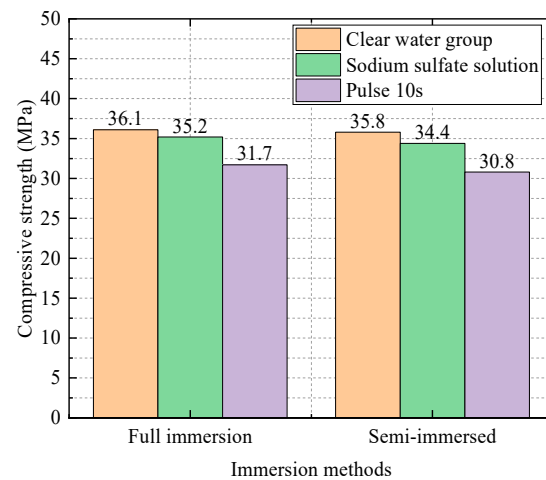


Figure 28. Compressive strength of different immersion methods with water–cement ratio of 0.5.

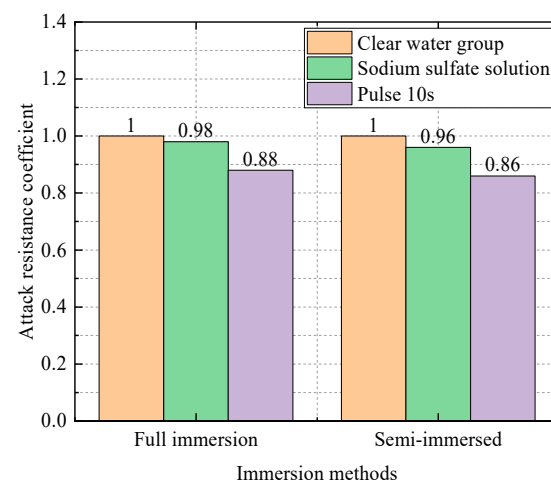


Figure 29. Attack resistance coefficient of different immersion methods with water–cement ratio of 0.5.

4.2. Microscopic Analysis of Ordinary Concrete Specimens

The experimental program included three groups of concrete specimens: the Shimizu group, the solution group, and the test group.

Shimizu group: This refers to the control group samples immersed in water, not exposed to sulfate attack. It serves as a baseline for comparison with other groups.

Solution group: This refers to the samples immersed in a sodium sulfate solution, exposed to sulfate attack but not subjected to an electric field. This group helps evaluate the effect of sulfate attack alone on the concrete specimens.

Test group: This refers to the samples subjected to both sulfate attack and an electric field. This group is used to study the combined effects of the electric field and sulfate attack on the concrete specimens.

Figure 30a, Figure 30b and Figure 30c respectively show the microscopic morphology of cement paste specimens with water–cement ratios of 0.3, 0.4, and 0.5 immersed in water. Since the specimens were immersed in water, they were not eroded. However, these figures reveal that there were initial cracks inside the concrete specimens, and there were some micro-cracks on the surface of the concrete. This indicates that the concrete specimens had

certain defects and damage at the beginning. From these figures, it can also be observed that there were abundant fibrous and flocculent hydrated products (C-S-H) on the surface of the concrete, filling the voids and cracks inside the specimens. Due to the absence of sulfate ions, no significant ettringite crystals or gypsum crystals were observed inside the specimens at this stage.

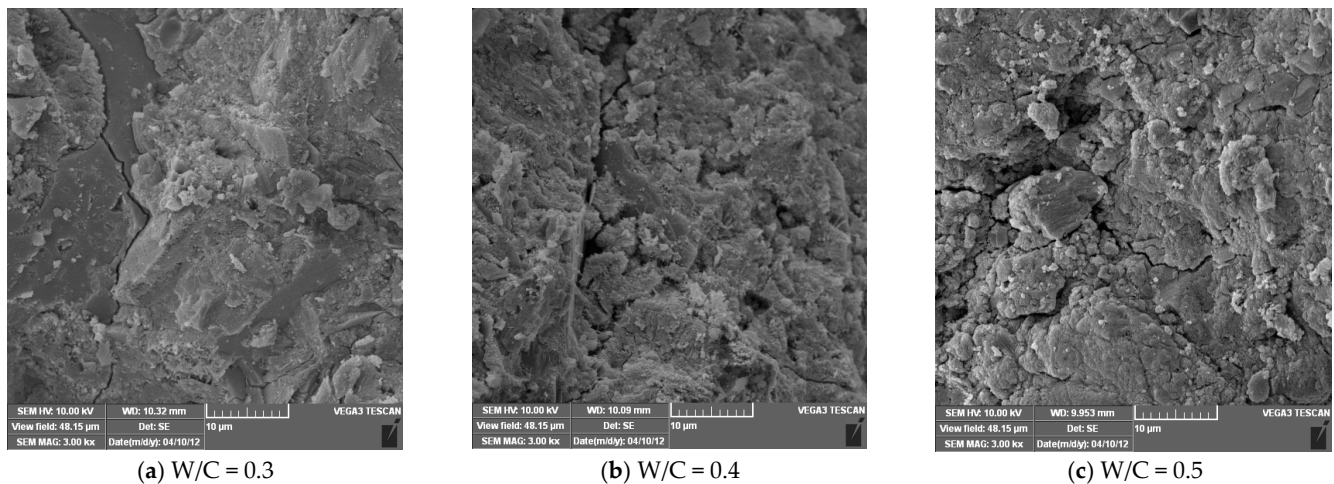


Figure 30. Morphology of Shimizu group at 14 days.

Figure 31a–c show that there were many intact lamellar $\text{Ca}(\text{OH})_2$ crystals, mainly distributed on the surface around the cracks. This indicates that the reaction of sulfate ions on the specimens was not complete, and the reaction products of the concrete specimens immersed in sulfate would also fill the interfaces or pores in the specimens. The figures show that only a small amount of needle-like ettringite crystals filled the smaller pore structures and interface cracks, coexisting with C-S-H gel and surrounded by surrounding gelatinous hydrated materials. Based on this trend, it can be inferred that as the attack time increases, the attack products will increase, continuously generating tensile stress inside the concrete. When this tensile stress exceeds the ultimate tensile strength of the concrete, expansion cracks will occur inside the concrete, indicating that the change in microstructure conforms to the macroscopic mechanical properties.

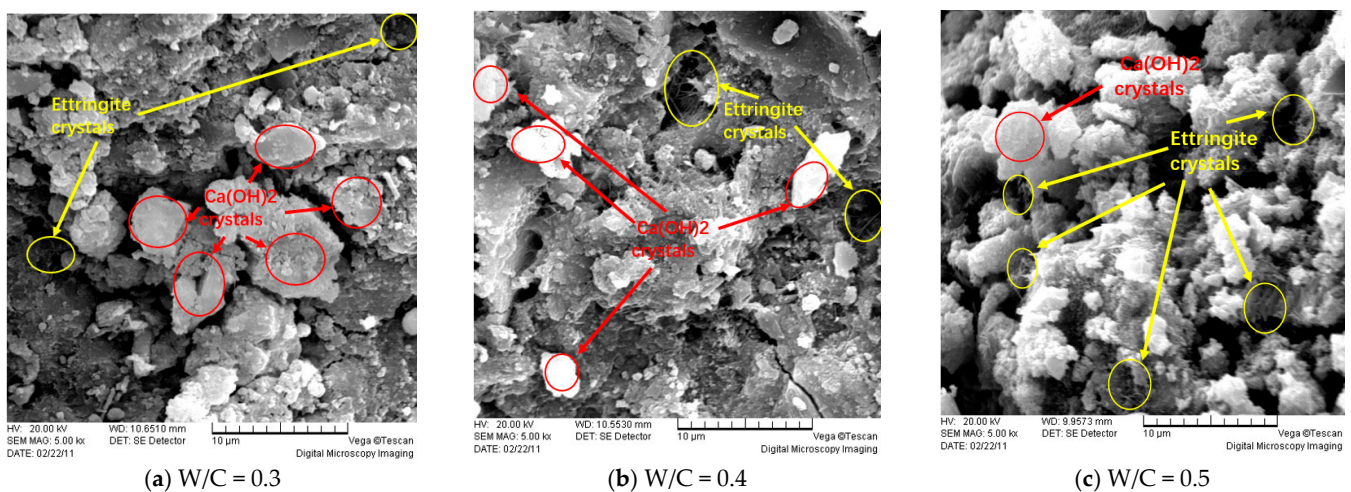


Figure 31. Morphology of solution group at 14 days.

Figure 32a–c shows the microscopic morphology of concrete specimens with the introduction of the electric field in the attack of concrete by sulfate. A large number of fibrous gels and flocculent calcium silicate hydrate gels were generated on the surface

of the concrete, and intact $\text{Ca}(\text{OH})_2$ crystals were hardly visible. This indicates that the attack reaction was relatively thorough. Compared with the microscopic morphology of specimens immersed in water and conventional attack, it can be seen from the microscopic morphology that the introduction of an electric field promoted the migration of sulfate ions into the specimens.

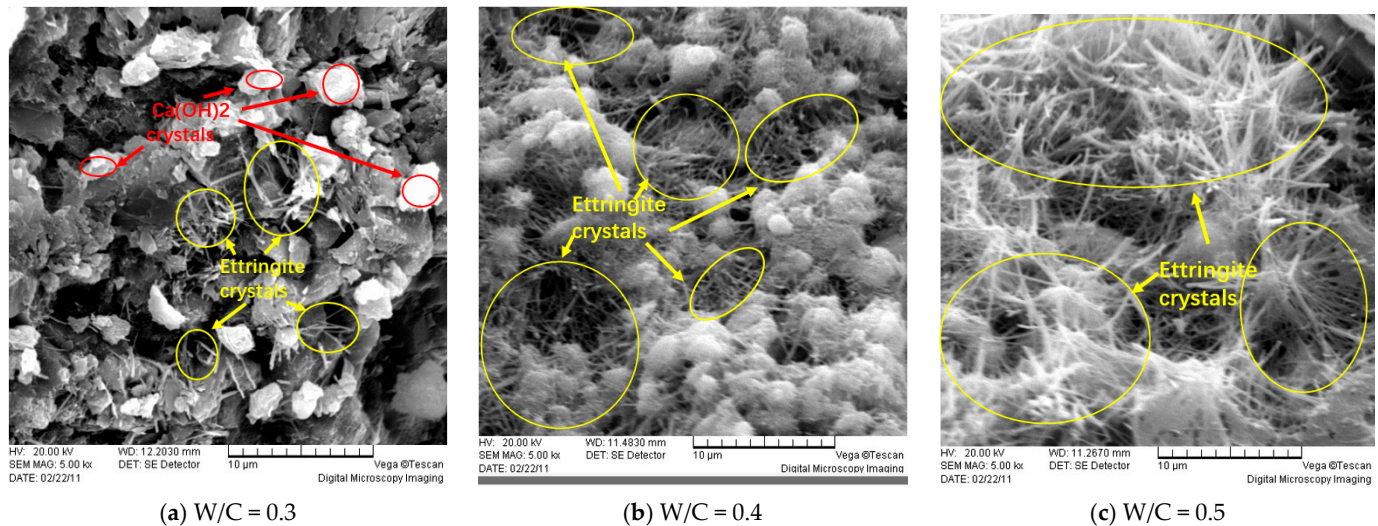


Figure 32. Morphology of test group at 14 days.

5. Conclusions

Through the detection of the mass loss rate and compressive strength of sulfate-eroded concrete under the action of the electric field, and the analysis of the microscopic morphology of each group of concrete, we draw the following conclusions:

- (1) Electric field accelerates sulfate attack: Electric field can significantly accelerate the sulfate attack on concrete, which shows that the compressive strength of concrete in a sulfate environment is significantly reduced, especially in the case of an increasing water–cement ratio.
- (2) Water–cement ratio affects the rate of sulfate attack: Different water–cement ratios have a significant effect on the attack resistance of concrete. The higher the water–cement ratio, the more the porosity and connected pores in the concrete, and the faster the sulfate attack.
- (3) The effect of soaking time is significant: with the increase of soaking time, the mass loss and strength attenuation of concrete is significant, especially at the age of 28 days, when the attack effect of concrete under an electric field is more obvious.
- (4) Semi-immersed attack is more serious: In the sulfate attack environment, the compressive strength of semi-immersed concrete specimens is lower than that of fully immersed specimens, and the attack effect is more obvious.
- (5) Microstructure changes significantly: SEM analysis shows that under the action of the electric field, more cracks and pores are produced in the concrete, and the migration of sulfate ions is accelerated, resulting in the formation of attack products in the concrete structure.
- (6) To further enhance the understanding and practical application of sulfate attack resistance in concrete under electric fields, future research will focus on the impact of power plant sulfate attack on concrete and its protective measures. In particular, the potential application of fly ash in mitigating the attack effect will be emphasized. This research will help develop more durable concrete formulations, improving the long-term reliability and sustainability of infrastructure.

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