

Research Article

Re-Alkalization Effect Experiment and a New Re-Alkalization Control Model of Carbonated Concrete

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The re-alkalization technology of carbonated concrete can effectively restore the alkalinity of concrete, but the effect of re-alkalization is affected by many factors, such as the voltage, electrolyte concentration, and current conduction time. In this paper, the re-alkalization effect of carbonated concrete under different parameter changes is studied, and the feasibility of re-alkalization technology and the selection range of parameters in its application are determined. Results show that the voltage should be controlled below 12 V or above 16 V and can be adjusted properly; the electrolyte concentration should be controlled at 0.5 molL^{-1} ; and the current conduction time is determined according to the control model. Finally, a new re-alkalization control model is obtained by regression of test data to control the re-alkalization process.

1. Introduction

The corrosion of reinforcement is the main reason for the lack of durability of concrete. Therefore, methods for preventing the corrosion of reinforcements are an urgent problem to be solved. One of the main reasons for the corrosion of reinforcement is the carbonation of concrete [1], and the corrosion of reinforcement and the carbonation of concrete structures caused by carbon dioxide is very serious [2]. A new solution to carbonation-induced rebar corrosion is the use of electrochemical methods, which include a cathodic protection method [3–5], an electrochemical chloride extraction treatment [6], and an electrochemical re-alkalization technique [7]. In terms of operation and feasibility, the electrochemical re-alkalization technique is a new and more convenient method for repairing and solving the problem of carbonated concrete [8, 9].

Some studies of electrochemical re-alkalization techniques have focused on transport mechanisms [7, 10, 11] and the effects of concrete materials [12–15]. However, parameters such as the voltage, electrolyte concentration and

type, current conduction time, and steel corrosion level will all influence the re-alkalization effect. To control the re-alkalization process and achieve the best effect, some studies on the process parameters of the re-alkalization effect have been reported.

Matsumoto [16] used Li_3BO_3 and Na_2CO_3 solutions as electrolytes in the re-alkalization test. The results showed that the Na_2CO_3 solution as the electrolyte easily underwent alkali-aggregate reactions, which led to the expansion of concrete in the process of re-alkalization; however, the addition of the Li_3BO_3 solution as the electrolyte could decrease the frequency of alkali-aggregate reactions. González [13] found that compared with other solutions, K_2CO_3 could play an effective role in preventing silicon alkali reactions and maintaining long-term stability after re-alkalization. Bastidas [17] studied whether re-alkalization could prevent the corrosion of steel bars in carbonated concrete and what conditions needed to be achieved to prevent the corrosion of steel bars. The results showed that re-alkalization could prevent the corrosion of the steel bars in concrete, while the carbonation degree was not up to the surface of the steel bars. Therefore, the author thought that re-alkalization technology

could be used as a preventive means and not as a repair method. Zhang [18] studied the electrode reaction and the change in the composition of the rust layer on the surface of steel after re-alkalization by electrochemical testing and scanning electron microscopy. The results showed that additional inhibitors should be added if the surface of the internal rebar of carbonated concrete needs to be passivated by re-alkalization. Redaeli [3] studied the influence of the corrosion level of the steel bar on the re-alkalization effect. The results showed that re-alkalization was beneficial to the restoration and passivation of the corroded steel bar. González [19] systematically studied the influence of rebar corrosion on the re-alkalization effect. The results showed that re-alkalization could only restore the passivation of recently rusted reinforcement and could not repair severely rusted reinforcement. Miranda [20] studied the factors affecting rebalancing, and the results showed that rebar with severe corrosion could not be recovered after rebalancing. Franzoni [12] carried out a re-alkalization test on old concrete and mortar. The results showed that the compressive strength of the old concrete and mortar could be improved after repair by re-alkalization technology, and the remaining service reliability of the improved concrete structure could meet structural requirements. Yeih [21] studied the changes in the physical properties of the mechanical parameters of concrete after re-alkalization, such as the elastic modulus, compressive strength, and pore structure. The results showed that the mechanical parameters of the specimens decreased with increasing electric quantity, and the pore structure of the concrete was concentrated after re-alkalization.

In summary, re-alkalization can make carbonated concrete return to alkaline conditions. However, in the process of re-alkalization, the electrolyte concentration, electrification time, and physical state of the steel bar surface will influence the effect of re-alkalization. To obtain the best effect of re-alkalization, research on the factors affecting the re-alkalization effect should be developed from a qualitative to quantitative standpoint. In addition, re-alkalization can not only restore the alkalinity of carbonated concrete but also produce other effects, such as changes in the mechanical properties of concrete. Therefore, research on the re-alkalization effect should be expanded to a wider range to prevent the possible adverse consequences of re-alkalization.

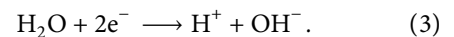
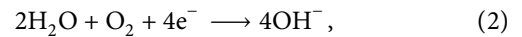
However, the specific influence of parameters on the re-alkalization effect has not been quantitatively studied. In this paper, the influence of voltage, electrolyte concentration and current conduction time on the evaluation indexes of the re-alkalization effect is studied through the re-alkalization test of carbonated concrete specimens, and a new control model for the re-alkalization of carbonated concrete is established.

2. Principle of Re-Alkalization

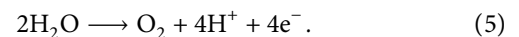
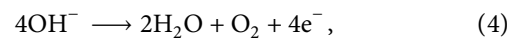
In the process of re-alkalization, the current forces the anodic reaction as given in the following equation on the surface of the reinforcement to stop completely.



As there are only active metal cations with a small algebraic value of electrode potential in the solution, hydrogen ions will preferentially obtain electrons. When oxygen is involved in the reaction, a cathodic reaction (2) will take place on the surface of the reinforcement. If the current between the anode and cathode is too large, a cathodic overprotection phenomenon will occur, and an electrolytic water reaction will occur (3). Part of the OH^{-} generated by (2) and (3) migrates to the anode, and part of the OH^{-} is retained around the reinforcement, which increases the alkalinity of the concrete.



The anions in the anode solution contain carbonate and hydroxide ions. The carbonate ions are not easy to oxidize and will not discharge at the anode, and the hydroxide ions in the solution will preferentially discharge at the anode and produce oxygen, as shown in the following equation. In addition, the electrolytic water reaction is also conducted at the anode (5). Additionally, the highly alkaline electrolyte solution penetrates into the carbonated concrete through the porous concrete matrix under the applied voltage.



As seen from the above, the re-alkalization effect of concrete is mainly based on two aspects: the electrochemical reaction of the cathode and the electro-osmosis of the alkaline solution.

3. Experimental Methods

3.1. Casting and Curing of Concrete Specimens. The cement used in the study was a 42.5R high early strength Portland cement that complies with the Chinese standard GB 175-2007 [22]. The coarse aggregate used was continuously graded crushed gravel with a size from 5 to 20 mm. The fine aggregate used was locally available natural river sand. The properties and chemical components of cement, fine aggregate, and coarse aggregate are shown in Tables 1 to 3.

In this study, the water-binder ratios were set at 0.7, and the subsequent concrete mixtures and properties are presented in Table 4.

Nineteen different batches of specimens, as described in Table 5, were used for the three experiments in this study: specimens for the influence of voltage experiment (V), specimens for the influence of electrolyte concentration experiment (C), and specimens for the influence of current conduction time experiment (T). U4, C3, and T3 in Table 5 are from the same batch. Each batch had three specimens, and there were a total of fifty-seven specimens in this experiment. The mean values of three test specimens were used as the results of each batch.

All test specimens were prisms with dimensions of 100 mm × 100 mm × 400 mm. One rebar with a diameter of

TABLE 1: Properties of the cement.

Type and class	Specific surface area/ $\text{m}^2 \text{kg}^{-1}$	Water requirement for a normal consistency/%	Initial and final setting time/min	Soundness/ mm	3-day compressive and flexural strength/MPa
P.II42.5R	385	30.6	163/223	1.0	28.0/6.0

TABLE 2: Properties of the fine aggregate.

Fineness modulus	Apparent density/ kg m^{-3}	Bulk density/ kg m^{-3}	Mud content/%	Clod content/%	Moisture content/%	Grain grading
2.91	2560	1245	0.2	0	2.24	II

TABLE 3: Properties of the coarse aggregate.

Apparent density/ kg m^{-3}	Bulk density/ kg m^{-3}	Mud content/ %	Clod content/ %	Water absorption/%	Elongated particle contents/%	Crushing value/ %
2583	1296	0.3	0.6	0.82	13	12.5

TABLE 4: Proportions of the concrete mixture (kg m^{-3}).

Number	Water-binder ratio	Cement	Water	Gravel	Sand
All specimens	0.7	190	133	733.4	573.8

TABLE 5: Test specimen batches.

Batch	Voltage/V	Electrolyte concentration/ mol L^{-1}	Current conduction time/day
U1	1	0.5	3
U2	4	0.5	3
U3	7	0.5	3
U4 (C3, T3)	10	0.5	3
U5	13	0.5	3
U6	16	0.5	3
U7	19	0.5	3
C1	10	0.1	3
C2	10	0.3	3
C3 (U4, T3)	10	0.5	3
C4	10	0.7	3
C5	10	0.9	3
C6	10	1.1	3
C7	10	1.3	3
T1	10	0.5	1
T2	10	0.5	2
T3 (U4, C3)	10	0.5	3
T4	10	0.5	4
T5	10	0.5	5
T6	10	0.5	6
T7	10	0.5	7

10 mm and a length of 360 mm was embedded in the specimens. The details of the test specimens are shown in Figure 1. In addition, two control specimens were cubes with dimensions of 100 mm \times 100 mm \times 100 mm to test and compare the carbonation degree in each experiment. The dimensions of the specimen used for the compressive strength test of each batch were 150 mm \times 150 mm \times 150 mm.

3.2. Carbonation Test of Specimens. After the specimens were poured, the mould was removed 24 hours later, and the test and control specimens were placed in a curing room for 7 days of standard curing. Then, the specimens were immediately placed in an oven at 60°C. All the specimens were removed after 48 hours, and the test specimens were sealed with silicone sealant on five of the surfaces, with one surface set apart so that the re-alkalization process only occurred on

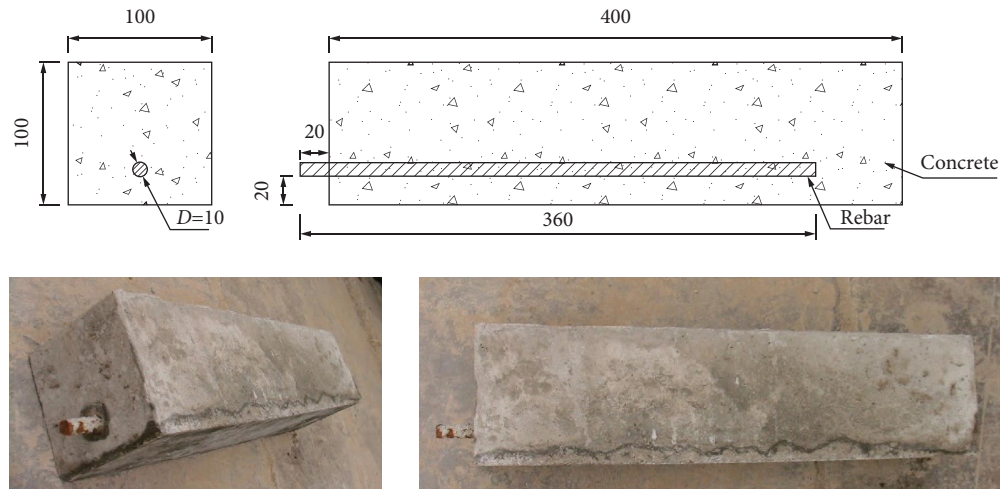


FIGURE 1: Details of the test specimens and the location of rebar.

one surface. After the sealing was completed, all the specimens were placed in a tank for carbonation. The carbon dioxide concentration in the tank was controlled at $(20 \pm 3)\%$, the temperature was controlled at $(20 \pm 2)^\circ\text{C}$, and the relative humidity was controlled at $(70 \pm 5)\%$.

All specimens were removed after 2 months of carbonation, and then the control specimens were split and titrated into split sections with a phenolphthalein reagent. All the control group specimens were completely carbonated, which also indicated that the test specimens were completely carbonated.

3.3. Testing Process. After the carbonation test, the specimens were subjected to re-alkalization. The specimen was laid flat on a foam cushion block in a container with the unsealed surface of the specimen perpendicular to the bottom of the container. The K_2CO_3 solution was injected into the container until the solution submerged a portion of the unsealed surface of the specimen while not coming into contact with the rebar. A wire welded to the rebar was connected to the cathode of a power supply, and the wire attached to the steel wire mesh was connected to the anode of the power supply.

To ensure the reliability of the data obtained during the test, three test specimens in each batch were tested at the same time, and the mean value of the obtained data was taken as the test data.

The whole test process was continuous and uninterrupted, and the current was observed and recorded at appropriate intervals. After current conduction was completed, the test specimens were split vertically on the surface that was not sealed and titrated with a phenolphthalein solution. The re-alkalization depth was measured by observing the depth of the pink area, thus finally obtaining Figure 2 re-alkalization area.

Some phenomena occurred in the testing and are described below:

- (1) The anode of the steel wire mesh was corroded during the test, and the corrosion was more serious

at the location exposed to the solution. The reason was that the location exposed to the solution lost electrons easily and oxidized in the presence of air.

- (2) There were many bubbles in the solution, especially near the wire mesh. According to the principle of re-alkalization, the electrochemical reaction in the process of re-alkalization was the production of electrolytic water, which would inevitably produce gas, especially when the steel wire mesh was used as the anode. During the experiment, the container was hot, and the temperature of the electrolyte solution clearly increased.
- (3) After the test, many white crystals appeared on the realkalized surface of the specimen, as shown in Figure 2(a). This phenomenon was explained as follows: a certain amount of K_2CO_3 solution would be retained on the surface of concrete, and K_2CO_3 would undergo a hydrolysis reaction during the process of re-alkalization and electrification, thereby leading to the formation of crystals.
- (4) For the specimen with a large applied voltage, cracks appeared along the direction of reinforcement on the realkalized surface, as shown in Figure 2(b). The reason was that the larger the applied voltage, the larger the corresponding current. The larger current would result in a greater thermal effect on the steel bar, causing it to expand and causing the concrete to crack along the direction of the steel bar. In this test, only the U7 specimens exhibited small cracks, and no obvious cracks were found on the other specimens.

4. Results and Discussion

4.1. Influences of Voltage on the Re-alkalization Effect. The U1–U7 batches were tested under different voltages, while keeping the same electrolyte concentration and current conduction time. The relationship between the current and time is shown in Figure 3(a).

Figure 3(a) indicates the current change in the whole process of re-alkalization. The curves all show an upward

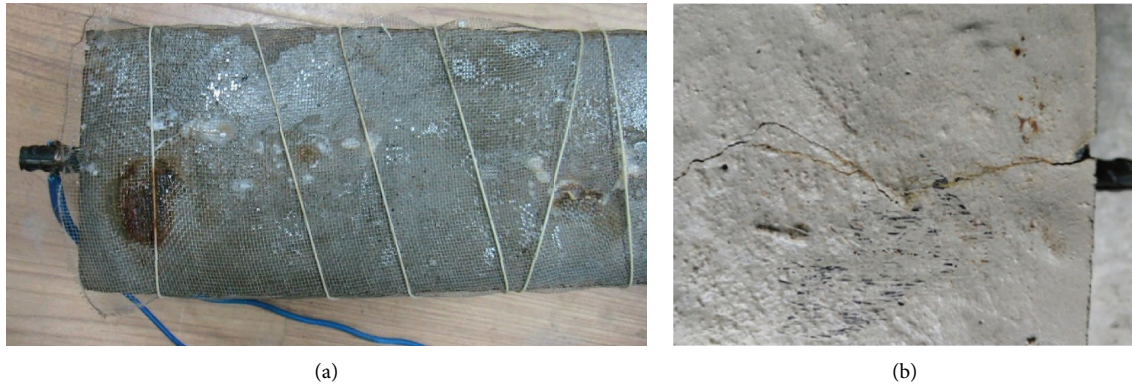


FIGURE 2: Phenomena that occurred in the testing: (a) white crystals on the surface of the specimen and (b) cracks on the surface of the U7 specimen.

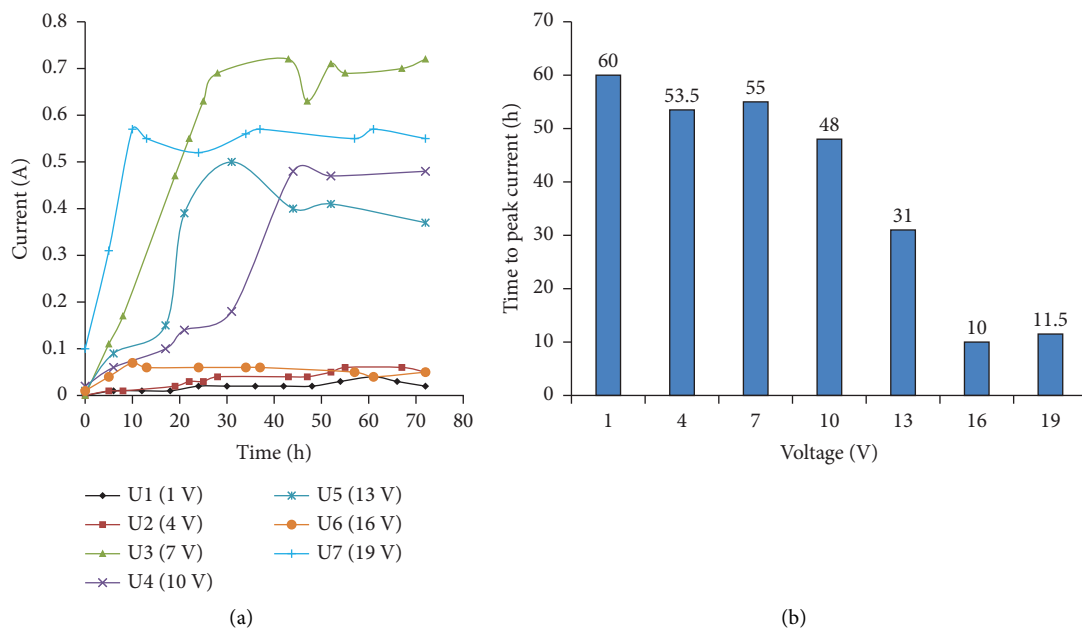


FIGURE 3: Results of the influence of voltage: (a) relationship between the current and time at different voltages and (b) the time to peak current at different voltages.

trend from the beginning and then tend to be stable or slightly decreasing. The reason is that only a small amount of conductive material is present in the concrete before re-alkalization; thus, the current is small at the beginning. As the re-alkalization process progresses, the electrolyte solution slowly penetrates from the surface to the interior of the concrete, resulting in an increase in concrete conductivity. The current gradually increases until the electrolyte in the concrete gradually approaches saturation, which inhibits the resistance from continuing to decrease; thus, the current finally stabilizes at a certain value. The current change trend meets the expected requirements, although the current cannot develop according to the ideal state curve due to the existence of other external factors, such as the temperature and environment.

Figure 3(a) also shows that the current intensity through the specimens reaches a peak value in the process of re-

alkalization. The peak current indicates that the conductive solution penetrating into the concrete of the specimens reaches saturation, and the effect of re-alkalization is best at this point. The times corresponding to the peak current are different for the specimens, indicating that the re-alkalization speeds are different.

To determine the influence of increasing voltage on the re-alkalization speed, the time to reach the peak current is shown in Figure 3(b). The figure shows that the time corresponding to the peak current decreases and the re-alkalization speed increases with an increase in voltage.

In this experiment, the re-alkalization degree was evaluated by using a phenolphthalein indicator and measuring the re-alkalization depth of the specimens. From the centre around the rebar, the larger the re-alkalization area is, the larger degree of re-alkalization. From the concrete surface to the centre of the rebar, the re-alkalization depth

was measured at angles of 0, 45, 90, 135 and 180°, which correspond to points 1, 2, 3, 4 and 5 in Figure 4. The mean value of the five depths is used as the re-alkalization depth of a specimen (s), and the mean value of the results of three specimens is used as the re-alkalization depth of a batch (\bar{s}).

Figure 5 shows the re-alkalization depth of a batch (\bar{s}) at different voltages in the test. Basically, the \bar{s} increases when the voltage is below 12 V or above 16 V, but the re-alkalization depth decreases when the voltage is between 12 and 16 V. The reason is that the electric energy is mainly used for the electrolytic water reaction instead of the other electrochemical reactions when the voltage is more than 12 V according to electrochemical literature. Therefore, only a small portion of the electric energy is used to promote the penetration of the alkaline electrolyte in the concrete when the voltage reaches 12 V; thus, the re-alkalization depth decreases. In addition, the electroosmosis effect is very strong due to the excessive voltage when the voltage increases to more than 16 V because the electrolyzed water reaction is very vigorous, thus promoting the re-alkalization depth to continue increasing. Therefore, the effect of re-alkalization will be enhanced with increasing voltage when the voltage is below 12 V or above 16 V, but the effect of re-alkalization will be lessened when the voltage is between 12 and 16 V. As shown in Figure 5, the voltage should be in the range of 8-12 V after considering the above effects and economic cost.

The points in Figure 4 are connected with straight lines after obtaining the re-alkalization depth to form a closed figure. The area of the closed figure is the re-alkalization area of a specimen (A). The obtained mean re-alkalization areas of batches (\bar{A}) are shown in Table 6.

The re-alkalization area of U1 is basically zero in Table 6, which indicates that there is basically no re-alkalization effect at this voltage, and the change in the re-alkalization area of U2-U7 is similar to the change in the re-alkalization depth. Therefore, the change in re-alkalization depth can essentially reflect the change in re-alkalization area, and only an analysis of the re-alkalization depth is needed when analysing the re-alkalization effect.

4.2. Influences of the Electrolyte Concentration on the Re-alkalization Effect. The C1-C7 batches were at different electrolyte concentrations while keeping the same voltage and current conduction time. The relationship between the current and time is shown in Figure 6(a).

As seen from Figure 6(a), the current change trend of C1-C7 is basically the same as that of U1-U7. The current is small at the beginning and then gradually increases to a certain limit value, at which point the current fluctuates above and below this limit.

The time to reach the peak current for C1-C7 is shown in Figure 6(a). The figure shows that the time corresponding to the peak current decreases and the re-alkalization speed increases with an increase in the electrolyte concentration when the concentration is below 0.7 molL⁻¹. However, electrolyte concentrations above 0.7 molL⁻¹ do not continue to increase the re-alkalization speed.

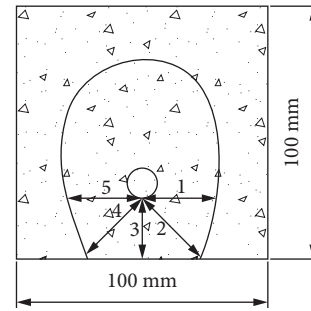


FIGURE 4: Definition of the re-alkalization depth (s).

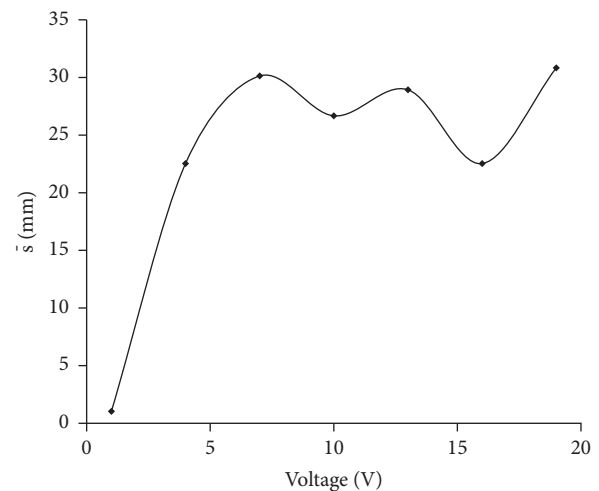


FIGURE 5: Re-alkalization depth of batches at different voltages.

The relationship between the re-alkalization depth and the electrolyte concentration is shown in Figure 8. The figure shows that the higher the electrolyte concentration is, the greater the re-alkalization depth is; thus, the better the effect of re-alkalization is. The figure also shows that the increase in re-alkalization depth decreases and that the re-alkalization effect cannot continue to increase when the electrolyte concentration is above 0.7 molL⁻¹. This result is consistent with the results of the previous current change analysis.

Therefore, the electrolyte concentration should be properly controlled below 0.7 molL⁻¹ in the process of re-alkalization because the re-alkalization effect cannot continue to improve above 0.7 molL⁻¹; thus, the use of additional electrolyte would be uneconomical. As shown in Figure 7, the electrolyte concentration should be between 0.5 and 0.7 molL⁻¹ when considering the above effect and economic cost.

Similar to the voltage, the obtained re-alkalization areas of the C1-C7 batches are shown in Table 7.

4.3. Influences of the Current Conduction Time on the Re-alkalization Effect. The T1-T7 batches are at different current conduction times while keeping the same voltage and electrolyte concentration. The relationship between the current and time is shown in Figure 8(a).

TABLE 6: Re-alkalization depths and the areas of batches at different voltages.

Batch	U1	U2	U3	U4	U5	U6	U7
\bar{s}/mm	1.03	22.53	30.13	26.67	28.93	22.53	30.83
\bar{A}/mm^2	44.13	950.67	1300.33	1118.33	1240.00	929.23	1345.00
\bar{A}/\bar{s}	42.84	42.20	43.16	41.93	42.86	41.24	43.62

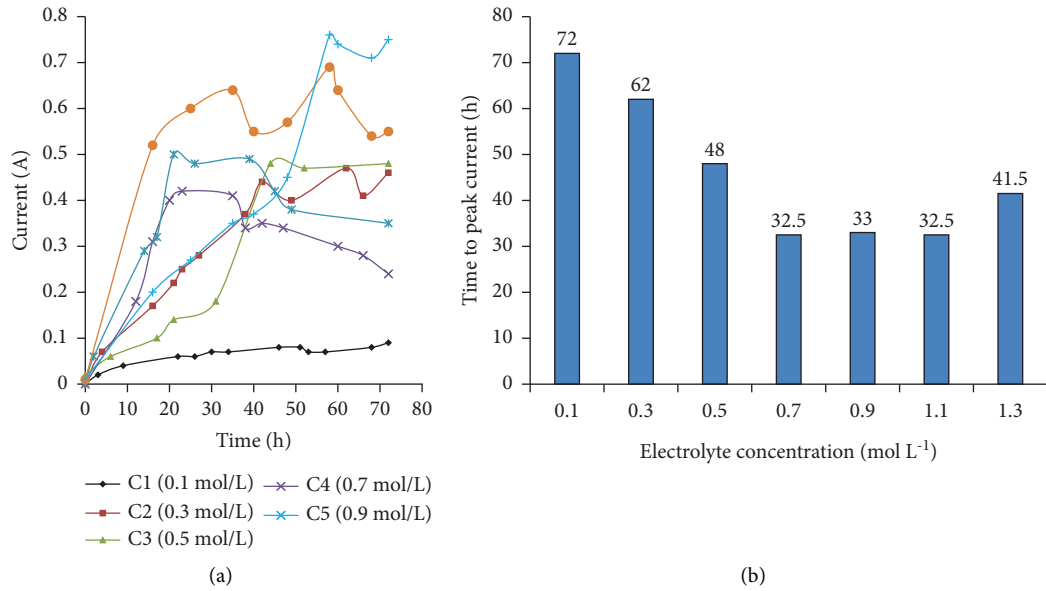


FIGURE 6: Result of the influence of electrolyte concentration: (a) relationship between the current and time at different concentrations and (b) the time to peak current at different concentrations.

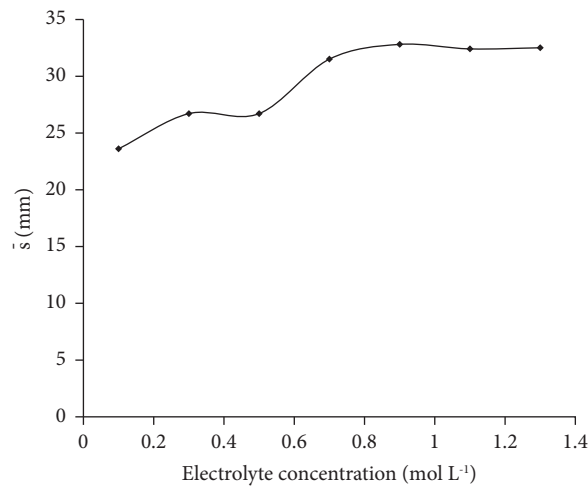


FIGURE 7: Re-alkalization depth of batches at different electrolyte concentration.

TABLE 7: Re-alkalization depths and areas of batches at different electrolyte concentrations.

Batch	C1	C2	C3	C4	C5	C6	C7
\bar{s}/mm	23.63	26.73	26.67	31.53	32.83	32.43	32.53
\bar{A}/mm^2	855.00	1030.13	1118.33	1360.67	1365.23	1425.03	1420.83
\bar{A}/\bar{s}	36.18	38.54	41.93	43.15	41.58	43.94	43.67

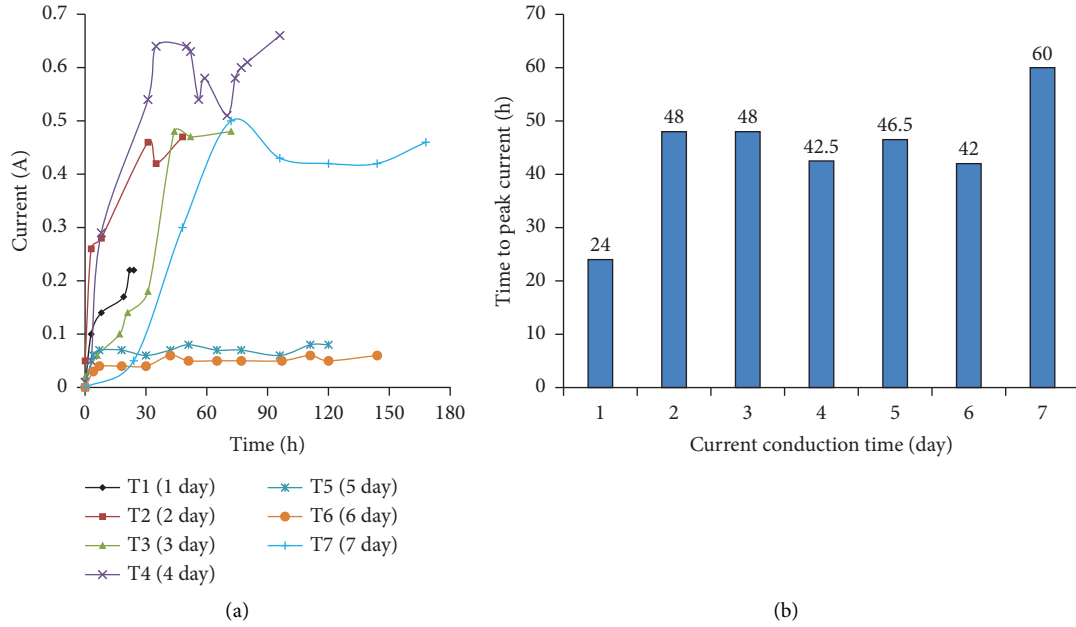


FIGURE 8: Result of the influence of current conduction of time: (a) relationship between the current and different conduction times and (b) the time to peak current at different conduction times.

As shown in Figure 8(a), the current changes in T1, T2 and T3 basically show an upward trend without a downward trend. These results indicate that the alkaline electrolyte solution in the specimen has not reached saturation and that the re-alkalization effect is always increasing when the electrification time is less than three days. However, the current intensity of T4–T7 begins to gradually or slightly decrease upon reaching a certain re-alkalization degree after more than three days of electrification. Therefore, the best re-alkalization effect of the specimen can be achieved only after being electrified for a certain period of time, and the re-alkalization effect cannot increase indefinitely with an extended electrification time.

The time to reach the peak current for T1–T7 is shown in Figure 8(b). The figure shows that the time for each specimen to reach its peak current is mostly within 40–60 hours, except T1. These results show that the solution in the concrete specimen basically reaches saturation when the current conduction time is between 40 and 60 hours.

According to the results, the changes in the re-alkalization depth of the T1–T7 batches at different current conduction times are shown in Figure 9. As seen from the figure, the re-alkalization depth basically shows an upward trend after a few days of electrification but does not continue to increase after four days.

Therefore, as seen from Figure 9, the re-alkalization effect cannot continue to improve after four days; thus, continuing electrification for more than four days is uneconomical. Therefore, the current conduction time should be properly controlled at four days after considering the above effects and economic cost.

Similar to when the voltage was constant, the obtained re-alkalization areas of the T1–T7 batches are shown in Table 8.

4.4. Relationship between Area/Depth (\bar{A}/\bar{s}) and the Parameters. Taking the area/depth (\bar{A}/\bar{s}) at the same electrolyte concentration in Tables 6–8 as the object, the relationships between \bar{A}/\bar{s} and the parameters are shown in Figure 10.

As shown in Figure 10(a), \bar{A}/\bar{s} basically remains unchanged when the voltage changes. Figures 10(b) and 10(c) show that \bar{A}/\bar{s} changes with concentration and time according to (6) and (7). These results indicate that the value of \bar{A}/\bar{s} is independent of the voltage and related to the electrolyte concentration and current conduction time.

$$\bar{A}/\bar{s} = -7.1071C^2 + 15.829C + 34.824, \quad (6)$$

$$\bar{A}/\bar{s} = -0.1393T^2 + 4.9121T + 31.637. \quad (7)$$

4.5. New Control Model of the Carbonated Concrete Re-alkalization. It can be seen from the published literature, the re-alkalization effect is mainly based on two aspects: the electrochemical reaction at the cathode and electroosmosis of the alkaline solution. Zhang [23] studied the influence of electrochemistry and electroosmosis on the re-alkalization of carbonated concrete and established a model of re-alkalization, as shown in (8). In (8), $kI_e T / Fc_{OH^-}$ is the electrochemical effect, $DU\zeta / 4\pi\eta h \cdot A_0 \cdot T$ is the electroosmosis effect, and $\bar{A} \cdot l \cdot \rho / 1 + \rho$ is the expected re-alkalization effect.

$$\frac{DU\zeta}{4\pi\eta h} \cdot A_0 \cdot T + \frac{kI_e T}{Fc_{OH^-}} = \bar{A} \cdot l \cdot \frac{\rho}{1 + \rho}, \quad (8)$$

where D is the relative permittivity of water, U is the loop voltage, ζ is the potential on the shear plane, η is the bond coefficient of water, h is the cover thickness of concrete, k

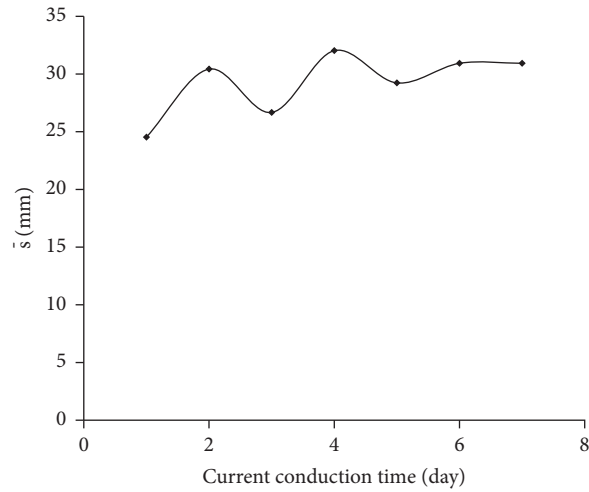
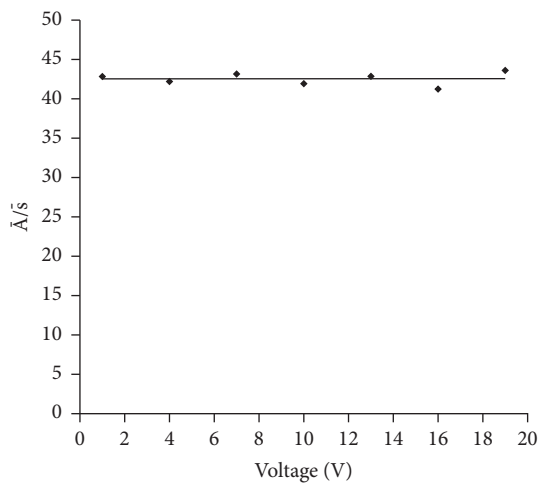


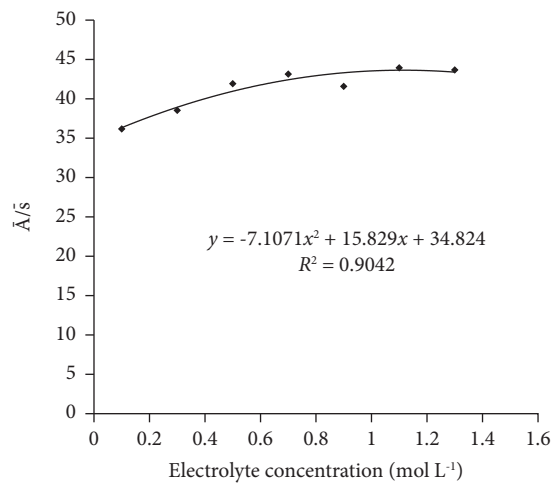
FIGURE 9: Re-alkalization depth of batches at different current conduction times.

TABLE 8: Re-alkalization depths and areas of batches at different current conduction times.

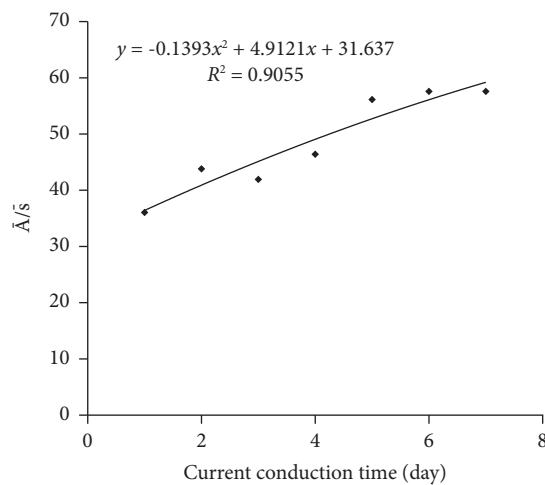
Batch	T1	T2	T3	T4	T5	T6	T7
\bar{s}/mm	24.53	30.43	26.67	32.03	29.23	30.93	30.93
\bar{A}/mm^2	884.33	1333.23	1118.33	1486.67	1641.06	1781.03	1781.03
\bar{A}/\bar{s}	36.05	43.81	41.93	46.41	56.14	57.58	57.58



(a)



(b)



(c)

FIGURE 10: Relationships between \bar{A}^- / \bar{s}^- .

TABLE 9: Re-alkalization depths under different UT values.

UT/V	10	12	20	21	30	39	40	48	50	57	60	70
s/mm	23.61	22.51	26.71	30.11	26.71	28.91	31.51	22.51	32.81	30.81	32.41	32.51

is the retention coefficient of OH^- , I_e is the equivalent current strength, T is the current conduction time, F is the Faraday electrolytic constant, c_{OH^-} is the concentration of OH^- in the electrolyte solution, A_0 is the area of the electroosmosis path, \bar{A} is the re-alkalization area, l is the buried length of the reinforcement, and ρ is the porosity of the concrete.

In this experiment, the restorative effect on the cover thickness of concrete is the main target; thus, only the effect of electroosmosis should be considered, and the model can be further simplified as follows:

$$\frac{DU\zeta}{4\pi\eta h} \cdot A_0 \cdot T = \bar{A} \cdot l \cdot \frac{\rho}{1+\rho}. \quad (9)$$

From (7), the value of \bar{A}/\bar{s} is related to the current conduction time at the same electrolyte concentration; thus, (10) can be obtained.

$$\frac{DU\zeta}{4\pi\eta h} \cdot A_0 \cdot T = (-0.1393T^2 + 4.9121T + 31.637) \cdot \bar{s} \cdot l \cdot \frac{\rho}{1+\rho}. \quad (10)$$

The relation extracted in Section 4.4 is related to the unique mixing ratios and test method of this research, and its use in general relation (8) lead to the extraction of a relation (10) with specified conditions and constraints.

According to the model described by Wu et al. [24], the potential ζ on the shear plane changes with the electrolyte concentration, and the reduction coefficient k_z should be considered in the calculation of the potential ζ ; thus, equation (11) can be obtained.

$$\frac{DUT}{4\pi\eta h} \cdot A_0 \cdot k_z \zeta = (-0.1393T^2 + 4.9121T + 31.637) \cdot \bar{s} \cdot l \cdot \frac{\rho}{1+\rho}. \quad (11)$$

The concrete porosity (ρ) in this experiment can be obtained from the relationship model deduced by Kollas [25] according to (12), and the result is $\rho = 56\%$.

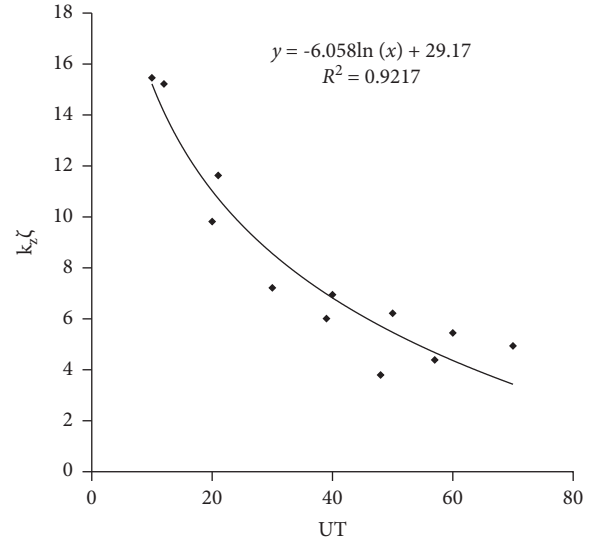
$$\sigma_c = 154.7 - 2.38\rho, \quad (12)$$

where σ_c is the compressive strength of concrete, 21.3 MPa.

The relative permittivity of water (D) and the bond coefficient of water (η) in this experiment can be obtained from Tang [26]; and the results are $D = 72.77 \text{ F/m}$ and $\eta = 1.139 \text{ cP}$. In this experiment, the cover thickness of concrete is $h = 20 \text{ mm}$, the area of the electroosmosis path is $A_0 = 2669 \text{ mm}^2$, and the buried length of the reinforcement is $l = 340 \text{ mm}$. Therefore, the following equation can be obtained.

$$678.82k_z\zeta \cdot UT = 122.05(-0.1393T^2 + 4.9121T + 31.637)\bar{s}. \quad (13)$$

The relationship between $k_z\zeta$ and UT can be obtained by the data in Tables 6–8 and (13), as shown in Table 9 and Figure 11. The figure shows a regression coefficient of

FIGURE 11: Relationship between $k_z\delta$ and UT .

$R^2 = 0.9218$, thereby expressing high reliability. Thus, (11) can be described as (14) according to Figure 11.

$$(-6.058 \ln(UT) + 29.17) \cdot \frac{DUT}{4\pi\eta h} \cdot A_0 = (-0.1393T^2 + 4.9121T + 31.637) \cdot \bar{s} \cdot l \cdot \frac{\rho}{1+\rho}. \quad (14)$$

5. Conclusions

Based on the above study, the following conclusions can be drawn [24, 26].

- (1) The voltage should be between reasonable level after considering the above effect and economic cost.
- (2) The electrolyte concentration should be reasonable level after considering the above effect and economic cost.
- (3) The current conduction time should be properly controlled at four days after considering the above effect and economic cost.
- (4) The re-alkalization area/depth (\bar{A}/\bar{s}) value is independent of the voltage and is related to the electrolyte concentration and current conduction time.
- (5) A new control model for the re-alkalization of carbonated concrete is established.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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