Influence Of Electromagnetic Field On Crystallization Of Tunnel Drainage Pipes

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The salts contained in hard groundwater often lead to crystallization and blockage of tunnel drainage pipes. In this paper, based on the principle of scale removal and inhibition, indoor tests were implemented so as to study the influence law of water filling conditions and different combinations of electromagnetic compound field and the crystallization of tunnel drainage pipes. The results showed that: (1) Under the action of applied electric field, electromagnetic compound field had a certain inhibitory effect on calcium carbonate crystallization process, resulting in changes in crystal structure morphology According to the test, the electromagnetic compound field had significantly greater influence than that of individual electric field or magnetic field under the same test parameters. After electromagnetic compound field treatment, the crystals became loose, unstable and irregular. (2) Different parameter combinations of electromagnetic compound field had different effects on crystallization. Among the parameter combinations, 0.1 T-5 V and 0.2 T-9 V were better parameter combinations, where the effect of 0.2 T is better than that of 0.1 T. (3) The influence of electromagnetic compound field on crystallization was more and more significant with time. After a certain time, new crystals were formed while old crystals were flaked off, the so-called process of “new crystalline matters replacing old ones”. Different combinations of parameters had different effects on crystallization, and the average anti-crystallization efficiency for the best combination of parameters was 46.43%. (4) Crystallization was more likely to occur in the drainage pipe under the “half-filled” condition than that under the “fully filled” condition. This was because the electromagnetic compound field promoted crystallization in the early stage, and gradually inhibited crystallization over time. Regardless of the water filling conditions of the drainage pipe, the electromagnetic compound field has more salient effects on crystallization over time. The study results can provide technical support for preventing crystal blockage of tunnel drainage pipes.

Keywords: Tunnel engineering; Drainage system; Crystal blockage; Model test; Electromagnetic compound field

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1. Introduction

With the development of tunneling and underground engineering construction technology, China has become a tunneling power in the world [1]. Most tunnels in southwest China pass through areas with hard groundwater containing cations Ca^{2+} and Mg^{2+} and anions CO_3^{2-}, HCO^{3-} and SO_4^{2-}. The abundant cations and anions provide a natural basis for the generation of microsoluble, salts like $CaCO_3$ [2, 3]. At the same time, the surrounding rock debris and particles generated from the long-term immersion, erosion and scour by groundwater are carried into the tunnel drainage pipes [4] by the flow of groundwater. In addition, the calcification of tunnel drainage pipes leads to crystal blockage, which causes a series of tunnel defects [5] and seriously affect the tunnel structure and operation safety. Thus, how to reduce or inhibit the crystallization of drainage system is an important way to deal with the tunnel defects.

Regarding the scale removal and inhibition technology in water, a large number of scholars at home and abroad have conducted research by using electric or magnetic fields. In terms of electric field treatment technology, the non-uniform high-voltage electrostatic field has higher the scale inhibition rate than that of uniform high-voltage electrostatic field [6]; The scale after high-voltage electrostatic field treatment is transformed into aragonite-type soft scale and it is easy to remove due to the changes in its crystal structure [7]; Electrostatic field accelerates the formation of $CaCO_3$ and maintains the electrostatic memory [8] for at least 100 h; Electrostatic field promotes calcium carbonate scale to form a typical calcite structure, and the scaling rate of calcium carbonate scale shows a trend of first decreasing and then increasing [9] with the increasing electrostatic field intensity; Electrostatic field affects the molecular structure and crystal shape of calcium carbonate, which can inhibit the formation of stable calcite calcium carbonate or change it into calcium carbonate by destroying its morphology to achieve the effect of descaling and inhibition [10–12].

In terms of magnetic field treatment technology, the magnetic field on $CaCO_3$ crystallization has increasing influence with the increasing magnetic field intensity [13]; Magnetic field treatment, which is affected by water quality parameters, magnetic field intensity and magnetizing time, can transform $CaCO_3$ crystals from calcite to agonite [14]; Magnetic field can change the solubility of $CaCO_3$ in water by acting on the nucleation rate and solution saturation of calcium carbonate in aqueous solution [15]; Magnetic field has a significant scale removal influence, an increase of 46.7% and increasing scale removal to 30% at a magnetic field strength 0.4 T [16]; Calcite crystals are transformed into bundled aragonite crystals under the action of magnetic field [17]; Crystals in hard water after magnetic field treatment are longer compared to the control group [18].

The theoretical basis for treating the crystallization of calcium carbonate based on electromagnetic field is quite mature, but the crystallization of tunnel drainage pipes is affected by various factors, such as, ion mass concentration, flow rate, pH value and temperature because of complex tunnel construction environment [19, 20]. In this paper, an indoor experimental model of electromagnetic compound field on drainage pipe anti-crystallization was designed to study the formation and intensity of magnetic field treatment as well as water filling condition on the crystallization of tunnel drainage pipes. The study results can provide a technical basis for preventing the crystallization of tunnel drainage pipes by electromagnetic composite field.

2. The design of treatment device by electromagnetic compound field

2.1. Treatment device by uniform low-voltage electrostatic field

The schematic diagram of the uniform low-pressure electrostatic field treatment device is shown in Fig. 1. Most tunnels do not have a high-voltage power supply in reality, so the low-voltage electrostatic field was selected for test. Two relatively parallel aluminum plates were connected to direct current (DC), and insulated with high-temperature treated polyester film so as to generate the uniform low-voltage electrostatic field on both sides of the drainage pipes. Different voltage values on both sides of the electrodes can produce electric fields of different strengths.

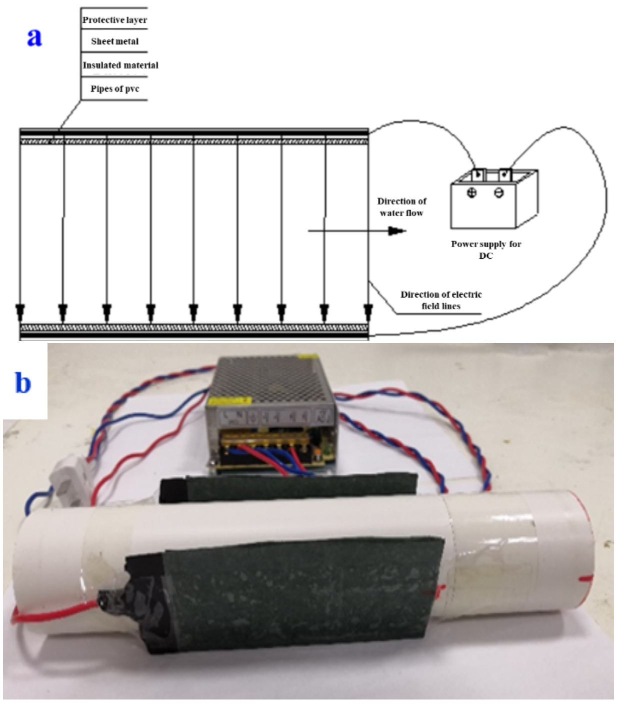


Fig. 1. Treatment device by uniform low-voltage electrostatic field (a: diagram; b: picture)

The principle of the drainage pipe device for the treatment of electrostatic field is shown in Fig. 2. Electric potential difference produces a uniform electric field in the pipe, and water cuts the electric field line when it flows in the pipe. Due to the interaction between charges, anions and cations are distributed on the upper and lower sides of the pipe, making them difficult to be combined to form calcium carbonate and making them prevent the crystal blockage of the pipe.

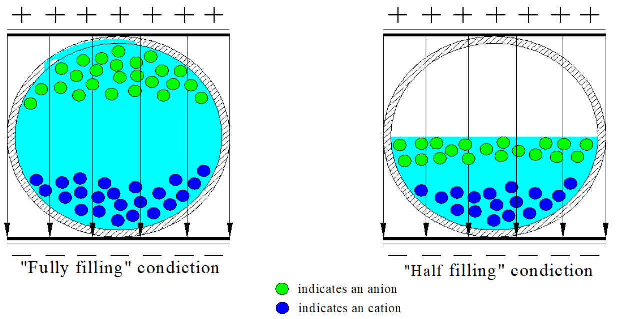


Fig. 2. Diagram of the distribution of anions and cations under uniform electrostatic field

2.2. Treatment device by magnetic field

The diagram of the treatment device by magnetic field is shown in Fig. 3. Similar to the uniform low-pressure electrostatic field treatment device, two permanent magnets (Ndfeb magnet) with a certain magnetic flux density were placed on both sides of the PVC pipe, thus generating a constant magnetic field in the pipe, and cutting the magnetic induction line when water flows through the pipe. When calcium and magnesium ions, carbonate ions and bicarbonate ions form hydrated ions in water, the Lorentz force and orientation of the magnetic field are used to reduce the crystallization of calcium carbonate.

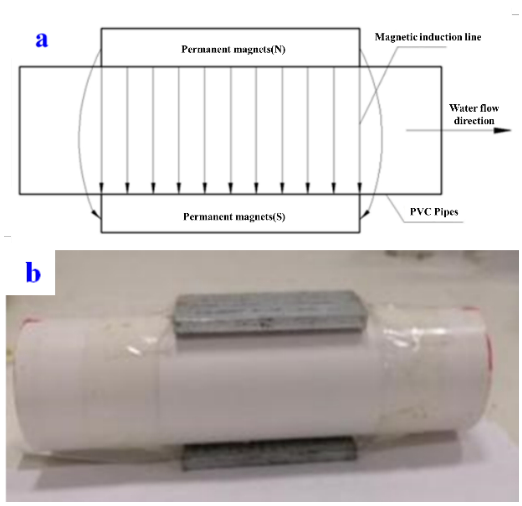


Fig. 3. Diagram of the treatment device by magnetic field (a: diagram; b: picture).

2.3. Treatment device by electromagnetic compound field

The diagram of the treatment device by electromagnetic compound field is shown in Fig. 4. The device is a combination of the two devices as described above. Under the combined effects of electrostatic field and magnetic field, $CaCO_3$ is "wrapped" in water molecules at the initial stage of formation, so that it cannot move freely and cannot interact with each other to form crystals. At the same time, the ions with different charges are subject to electric field force and Lorentz force under the action of the compound field, so each ion moves in opposite direction and follows a certain trajectory, the chance of collision and interact with each other is reduced, avoiding the reaction.

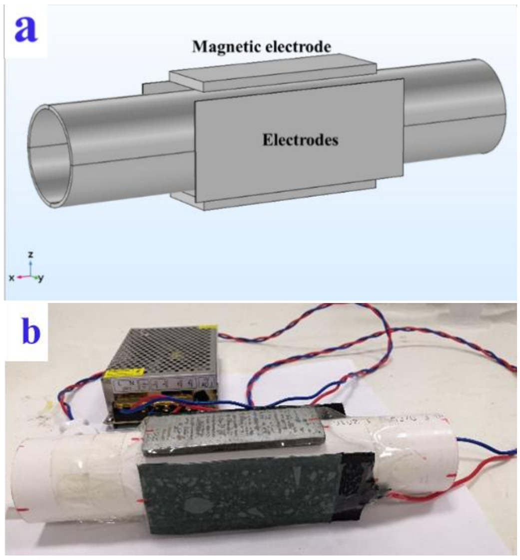


Fig. 4. Diagram of the treatment device by electromagnetic compound field (a: diagram; b: picture).

3. Test of the crystallization law of the drainage pipes under electromagnetic compound field

3.1. Design of the test system

The test system is shown in Fig. 5. It is composed of a 740 mm×535 mm×415 mm plastic water tank, a water pump, a U-PVC ball valve, a test pipe (non-treatment PVC pipe, three treatment devices) and joints. The test system is powered by the pump and the water flow is adjusted and controlled by the U-PVC ball valve. The water flows through the test pipe and then flows back to the water tank. During the experiment, the room temperature should be kept at normal temperature to avoid the influence of ambient temperature on crystallization. The test can be divided into three parts: (1) Pre-test exploration of the influence of electromagnetic compound field on crystallization; (2)

Optimization analysis of the combined parameters of electromagnetic compound field; (3) Test of the influence law of electromagnetic compound field on the crystallization of drainage pipes under "full filled" and "half filled" conditions.

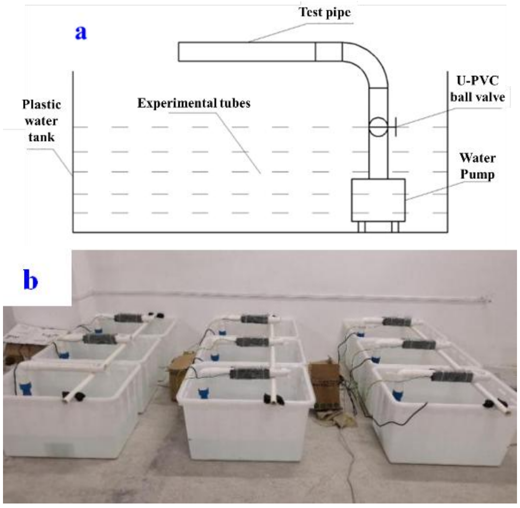


Fig. 5. Diagram of the indoor test model (a: diagram; b: picture).

3.2. Preparation of the test solution

According to the characteristics of general tunnel groundwater, the composition of tap water did not greatly affect Ca^{2+}, CO_3^{2-} and HCO_3^-, and the ion concentration in tap water is very low compared with the experimental ion concentration, so the ion content can be ignored. At the same time, taking the groundwater quality analysis and detection results of a certain section of the Reservoir tunnel on the Bijie-Weining expressway in Guizhou Province in a hard water environment as an example, it is found that the water sample ion composition is the same, and the detection results are shown in Table 1. Therefore, sodium bicarbonate ($NaHCO_3$) and anhydrous calcium chloride ($CaCl_2$) were used and they were mixed together with tap water to prepare the test solution according to a certain proportion. CAS number of chemical reagent: 144-55-8,3-140-8; Company: Tianjin Zhiyuan Chemical Reagent Co., LTD. The preparation process of the test solution is as follows:

(1) A 140 L plastic water tank was filled with an appropriate amount of clean tap water.

(2) A certain amount of analytically pure $NaHCO_3$ and $CaCl_{2-}$ was weighed in according with the ratio of sodium bicarbonate to calcium chloride (2:1).

(3) The weighed solute was added to the water, and another solute was added after one solute was completely dissolved according to the principle of dissolution item by item. The solution was constantly stirred during the dissolution to ensure complete uniform dissolution. The tap water was poured into the water tank of each group constantly till it reached 60 L. After the prepared solution was left static for 12 h, power supply was turned on to run the test of all groups at the same time.

3.3. Selection of the test parameters

In the first part of the test, a DC power supply voltage of 5 V was selected and a NdFeB magnet with magnetic induction strength of 0.1 T was used. The parameters are shown in Table 2.

In the second part of the test, the parameter combinations of electromagnetic compound field are shown in Table 3.

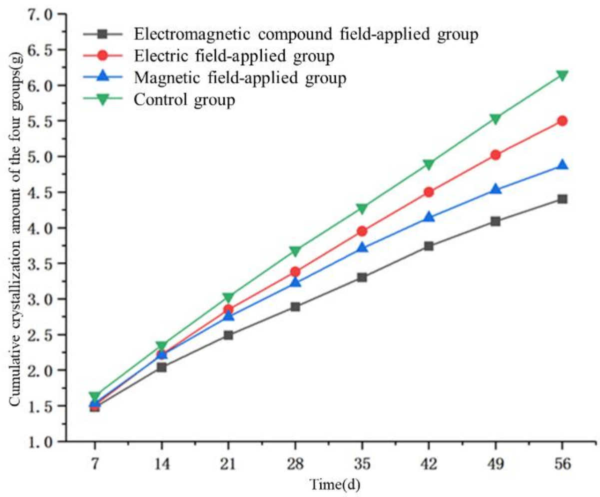


Fig. 6. Changes of the number of cumulative crystalline matter of the four groups over time.

3.4. Test steps

All test conditions were the same except for parameters. The test steps were as follows:

1. After the solution was prepared, the test device was used to check for water leakage;
2. A 25 cm long PVC pipe was taken to make the treatment devices by electric field, magnetic field, and electromagnetic compound field, which were numbered. The power and voltage value of the aluminum sheets were checked with a universal electric meter to see if the voltage reached the design voltage.
3. The initial weight of each test pipe was weighed and recorded.

Table 1. Water quality test results.

Ion species	Ion	Concentration (mmol/L)	Percentage (%)
Positive ion	K^{+}+Na^{+}	0.122	7.22
	Ca^{2+}	1.171	69.29
	Mg^{2+}	0.397	23.49
Negative ion	Cl^{-}	0.255	15.09
	SO_4^{2-}	0.399	23.61
	HCO_3^{-}	0.676	40.00
	CO_3^{2-}	0.360	21.30

Table 2. Parameters for individual electric field and magnetic field.

Group	Voltage intensity of electric field	Voltage intensity of magnetic field
Electric field	5 V	-
Magnetic field	-	0.1 T
Electromagnetic compound field	5 V	0.1 T
Control group	-	-

Table 3. Parameter combinations of electromagnetic compound field.

Group	Voltage intensity	Magnetic field	Electromagnetic compound field	Group	Voltage intensity	Magnetic field	Electromagnetic compound field
1	5 V		0.1 T-5 V	5	5 V		0.2 T-5 V
2	9 V	0.1T	0.1 T-9 V	6	9 V	0.2T	0.2 T-9 V
3	12 V		0.1 T-12 V	7	12 V		0.2 T-12 V
4	24 V		0.1 T-24 V	8	24 V		0.2 T-24 V
Control group	-	-	-	-	-	-	-

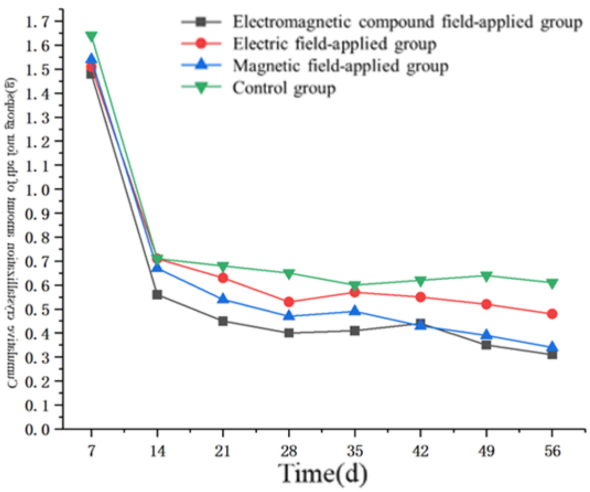


Fig. 7. Changes of the number of crystalline matter the four groups per cycle over time.

4. The water flow rate in the pipe was controlled so that the pipe in each group was in a "half filled" condition, that is, the water flow rate of 0.26 L/s.

5. The test was run for 8 cycles, with each cycle of 7 days and a total of 56 days. After the end of each cycle, the test was suspended temporarily, and the test pipe was dried in a 45°C oven for 12 h. After the dry weight of the test pipe was weighed and recorded, the next cycle started.

6. During the experiment, the concentration of liquid ions should be kept basically unchanged. Therefore, an equal amount of test solution was continuously added to the test box of each group. After the test, the circulating water tank was cleaned before the other tests.

7. The optimal parameter combinations of electromagnetic compound field were selected for the test of the crystallization law of drainage pipes under the "full filled" and "half-filled" conditions by repeating the previous steps.

4. Analysis of test results

4.1. Changes of the crystal amount of the drainage pipes under electric and magnetic field

The cumulative dry weight of crystals in four groups in each cycle is shown in Fig. 6. The crystal increment of each cycle was expressed as the difference between the dry weight of crystals in each cycle and the dry weight of crystals in the previous cycle (Fig. 7). The following conclusions were drawn:

1. With the increasing test cycles, the cumulative crystallization amount of electromagnetic compound field-applied group, electric field-applied group, magnetic field-applied group and control group increased from 1.48 g, 1.51 g, 1.54 g, 1.64 g at 7 d to 4.4 g, 5.5 g, 4.87 g, 6.15 g respectively, and the gap of crystallization amount of each group increased over time.

2. The crystallization increment gradually reduced in the treatment groups per unit time, and the effect of electromagnetic compound field-applied group was the most obvious. The amount of crystallization of the control group per cycle was basically the same, and its growth trend increased approximately linearly.

3. The change trend of the cumulative crystallization amount of electromagnetic compound field-applied group was similar to that of the magnetic field-applied group, with a difference of only 0.47 g, indicating that the influence of electromagnetic compound field was greater than that of magnetic field.

4. The cumulative amount and change of crystals of electromagnetic compound field-applied group was lower than those of other groups, indicating that the electromagnetic compound field had more significant effects than individual electric field or magnetic field under the same test parameters.

In order to analyze the influence of electromagnetic compound field, the anti-crystallization efficiency η of each group was obtained based on Formula 1.

$$\eta = \frac{M_0 - M}{M_0} \times 100\% \tag{1}$$

Where: M_0 — crystallization amount of the drainage pipe of the control group (g); M — crystallization amount of the drainage pipe of the treatment groups (g).

Thus, the changes of anti-crystallization efficiency of the treatment groups per cycle over time are shown in Fig. 8. In the first cycle of the test, there was a small difference in the anti-crystallization efficiency among all the treatment groups, which was 9.76%, 7.93% and 6.1%, respectively. With the increasing test time, the anti-crystallization efficiency finally increased to 28.46%, 10.57% and 20.81%, respectively. From 28 d to 35 d, the anti-crystallization efficiency growth was slow or reduced, showing that there was a relative saturation of crystal amount change during this cycle. The trend of the anti-crystallization efficiency of the three treatments was basically similar, with the electromagnetic compound field-applied group significantly higher than the electric and magnetic fields-applied groups.

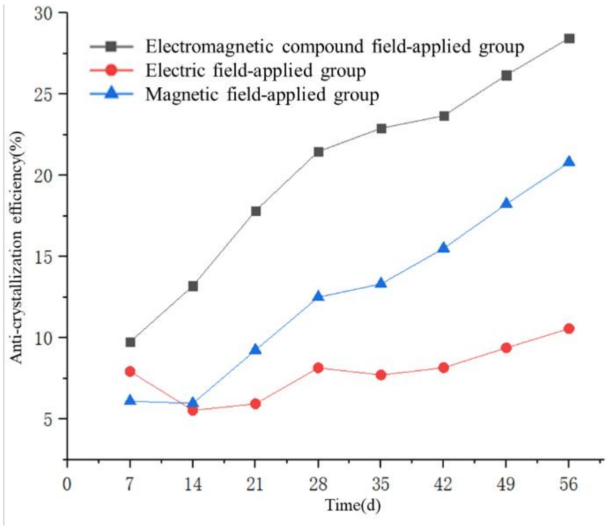


Fig. 8. Changes of anti-crystallization efficiency of the four groups per cycle over time.

4.2. Optimization analysis of the parameters of electromagnetic compound field

because the unstable calcium carbonate precipitation in the test solution led to insignificant influence of electromagnetic compound field. (2) With the increasing test time, the crystallization of the drainage pipe under different parameter combinations all grew in an alternating fashion. (3) The slope of growth of crystallization matter in each group of pipes was almost unchanged due to the continuous addition of the same amount of test solution to the test box of each group during the test, but it became flat in the 7th cycle (48 56 days). (4) During the whole test, the crystal growth remained at the highest level in the control group, and in the treatment group with a parameter combination of 0.2 T-9 V at the lowest level.

As there were a large number of combinations of electromagnetic compound field parameters, this study kept the parameters of magnetic field changed (Fig. 10). (1) During the whole test cycle, the crystallization amount of the drainage pipe of electromagnetic compound field-applied group was lower than that of the control group, and the average influence under the parameter of 0.2 T was greater than that under the parameter of 0.1 T. Among the parameter combinations, 0.1 T-5 V and 0.2 T-9 V were better parameter combinations. (2) The incremental change of pipe crystallization per cycle was changed in a stable manner per cycle, but it decreased significantly in the 7^{th} cycle (48∼56 days), which varied for different parameter combinations. This was mainly because the electromagnetic compound field changed the morphology of calcium carbonate crystals and loosened their structure, making

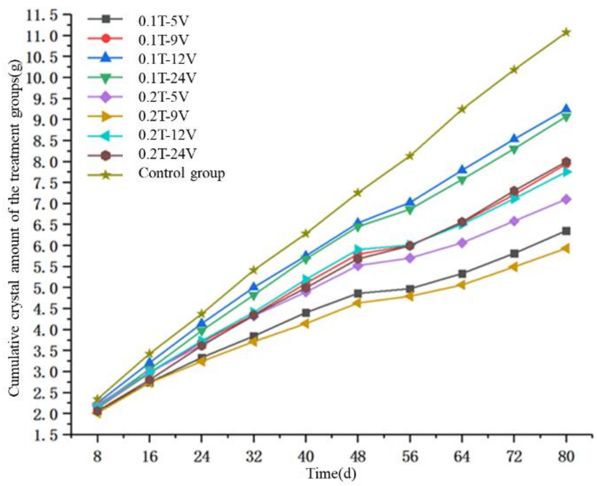


Fig. 9. Changes of the number of cumulative crystalline matter of the treatment groups under electric and magnetic fields over time.

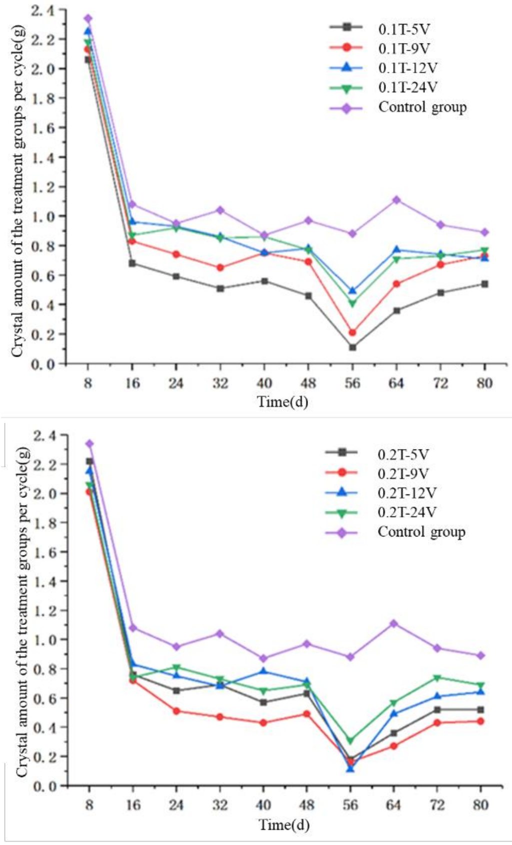


Fig. 10. Changes of the number of cumulative crystalline matters of the treatment groups under electric and magnetic fields per cycle over time.

them difficult to attach firmly to the inner wall of the pipe. However, new crystals formed during this process, and the increment was greater than the amount of peeling crystalline matters, so there was no negative increment. This process can be called the process of "the new crystalline matters replacing the old ones". (3) The crystallization rate under different parameter combinations was different, and the decrease in crystallization rate was greater under the 0.2 T condition with the action of electromagnetic compound field.

The anti-crystallization efficiency of electromagnetic compound field under different combinations of parameters is shown in Fig. 11. Throughout the whole test, the anti-crystallization efficiency under different parameter combinations showed the changes of oscillatory change-peak-rapid decline, with the peak appearing in the 7th cycle. Among them, 0.1 T-5 V and 0.2 T-9 V were better parameter combinations, with the average anti-crystallization efficiency of 42.64% and 46.43%, respectively.

4.3. Analysis on the influence of electromagnetic compound field on crystallization under different water filling conditions

The influence of electromagnetic compound field on the crystal amount of the drainage pipe under two different "full filed" and "half filled" conditions is shown in Figs. 12 and 13. The following conclusions were drawn:

1. The cumulative amount of crystalline matters under the "full filled" condition was significantly less than that under the "half filled" condition, because the large water impact force in the pipe center under the "full filled" condition made the crystalline matters difficult to attach to the inner wall of the pipe. When the aqueous solution full filled the pipe, the distribution of electric and magnetic fields in the pipe was more uniform, achieving better anti-crystallization effects. In addition, the aqueous solution in the pipe under the "half filled" condition had a larger contact surface with the CO2 in the air, making it easier to form CaCO3 crystals.
2. The electromagnetic compound field-applied group under both the "full filled" and "half filled" conditions had greater crystallization increment than the control group in the early stage, and decreased in the later stage. This showed that the electromagnetic compound field promoted crystallization in the early stage, but inhibited the increase of crystalline matters or cause crystalline matters to peel off in the later stage.

The changes of anti-crystallization efficiency of electromagnetic compound field under the "full filled" and

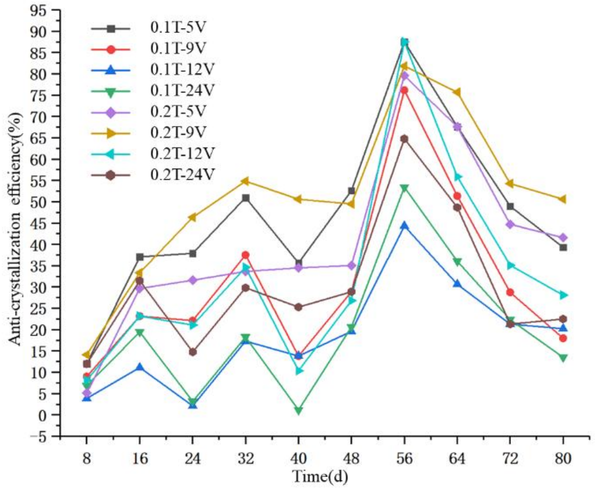
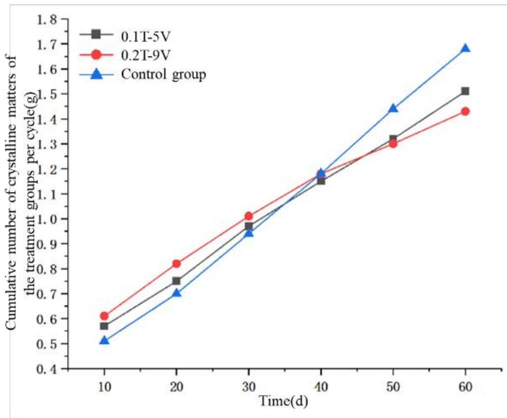
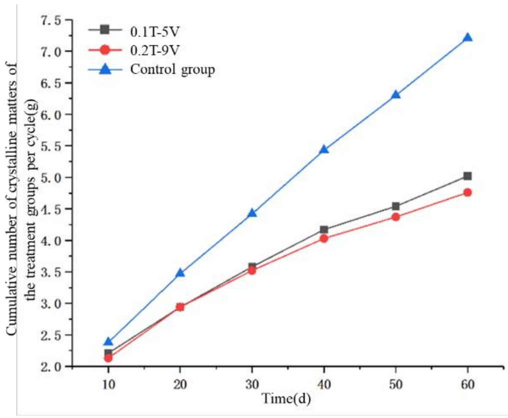


Fig. 11. Changes of anti-crystallization efficiency of the treatment groups under electric and magnetic fields per cycle over time.



(a) "full filled" condition



(b) "half filled" condition

Fig. 12. Changes of the number of cumulative crystalline matters of the treatment groups under the water filling condition over time.

"half filled" conditions is shown in Fig. 14. The anti-crystallization efficiency of electromagnetic compound field under both the "full filled" and "half filled" conditions increased with time and reached a maximum at the 5th cycle. However, the anti-crystallization efficiency of electromagnetic compound field under the "full filled" condition was negative in the early stage, indicating that the anti-crystallization efficiency of electromagnetic compound field under the "full filled" condition was not stable in the early stage. The influence of electromagnetic compound field on crystallization under both water filling conditions was more and more significant over time.

4.4. Microscopic morphological analysis of crystals

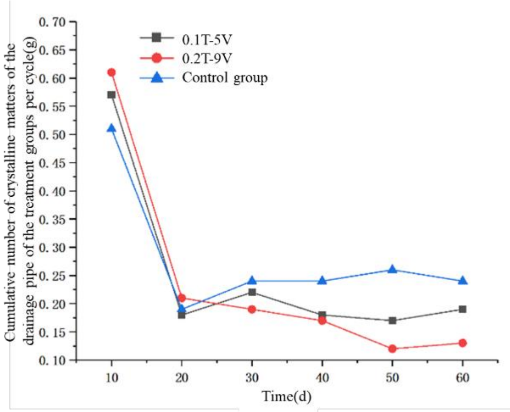
The crystalline matters of the inner wall of each test group was sampled by SEM, and the SEM images of the crystalline material of the four test groups with different treatments were taken with 1,000 or 7,000 times magnification as shown in Fig. 15. It can be found that the calcium carbonate crystals after applied field treatment became loose, unstable and irregular small particles and clusters; the calcium carbonate crystals after magnetic field treatment had a needle tip; the calcium carbonate crystals of the control group were tight and stable. Therefore, the binding ability of calcium carbonate crystals after applied field treatment was weakened, so they cannot attach to the inner wall of the pipe firmly, indicating that the applied electric field, magnetic field and electromagnetic compound field all played a role in preventing and removing crystalline matters.

Meanwhile, it can be found that the calcium carbonate crystals without any treatment were regular and cube blocks with clear edges, having the structure characteristics of calcite calcium carbonate crystals: close structure and sound stability. By contrast, the calcium carbonate crystals after electromagnetic compound field treatment had an irregular shape, with a looser structure and poor tightness.

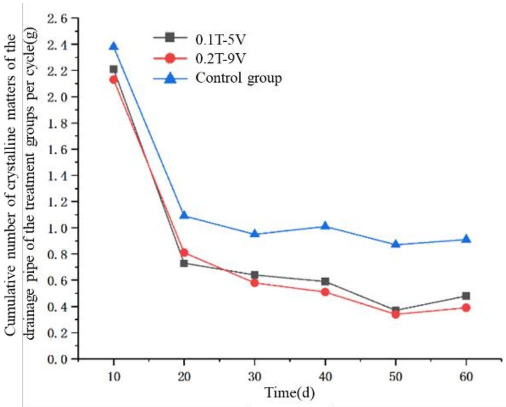
In summary, the crystalline matters after electromagnetic compound field treatment became loose, unstable and irregular, showing that the electromagnetic compound field had an influence on the crystallization of calcium carbonate.

5. Conclusions

1. Under the action of applied electric field, magnetic field and electromagnetic compound field, the crystallization process of calcium carbonate in the drainage pipe was inhibited, and the crystal structure was changed. The influence of electromagnetic compound field was significantly greater than that of individual

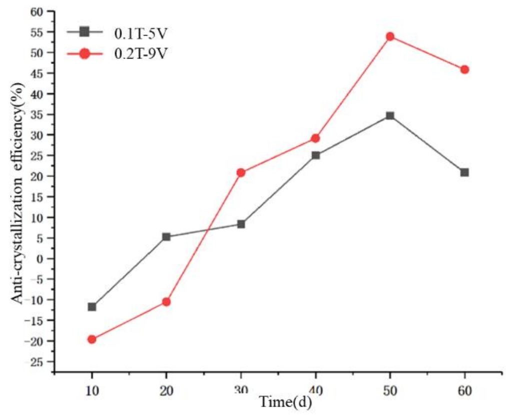


(a) "full filled" condition

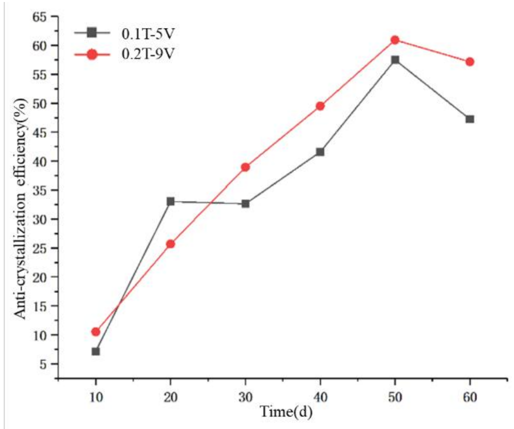


(b) "half filled" condition

Fig. 13. Changes of the number of cumulative crystalline matters the treatment groups under the water filling condition over time.



(a) "full filled" condition



(b) "half filled" condition

Fig. 14. Anti-crystallization efficiency of electromagnetic compound field under the water filling condition over time.

electric field or magnetic field under the same test parameters. After electromagnetic compound field treatment, the crystals became loose, unstable and irregular.

2. The influence of different parameter combinations of electromagnetic compound field on crystallization was different. Among the parameter combinations, 0.1 T-5 V and 0.2 T-9 V were better parameter combinations, with the influence of 0.2 T better than that of 0.1 T.

3. The influence of electromagnetic compound field on crystallization was more and more significant over time. After a certain period of time, the new crystalline matters were formed while the old crystalline matters peeled off, known as the process of "the new crystalline matters replacing the old crystalline matters". The influence of different parameter combinations on crystallization was different, with the average anti-crystallization efficiency of optimal parameter combination of 46.43%.

4. Crystallization was more likely to occur in the drainage pipe under the "half filled" condition than that under the "full filled" condition. This was because the electromagnetic compound field promoted crystallization in the early stage, and gradually inhibited crystallization over time. Regardless of the water filling conditions of the drainage pipe, the electromagnetic compound field had increasingly significant influence on crystallization with time.

Acknowledgements

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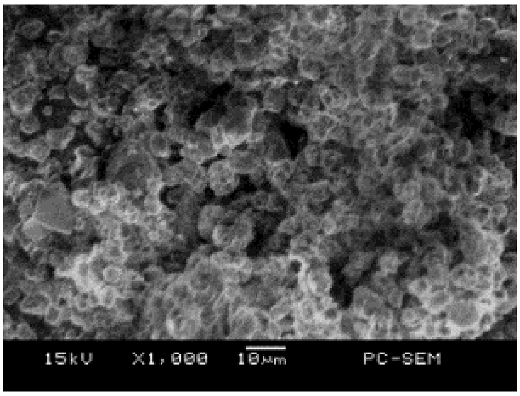
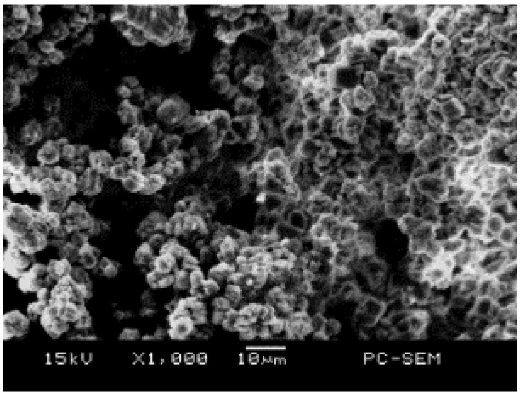
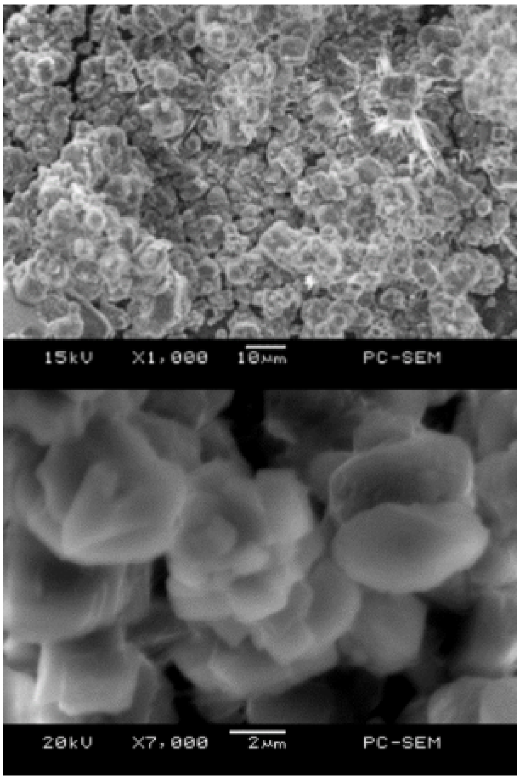
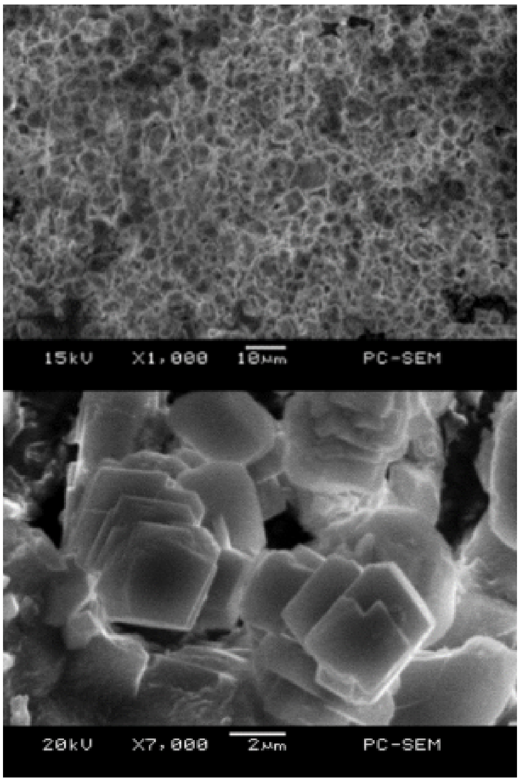




(a) Magnetic field-applied group **(b)** Electric field-applied group





(c) Electromagnetic compound field-applied group **(d)** Control group

Fig. 15. SEM images of crystals (-1000X or -7000X).

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