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Research Article

Investigation and Analysis on Crystallization of Tunnel Drainage Pipes in Chongqing

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A lot of crystallizations exist on the inner wall of tunnel drainage pipes in Chongqing. Tunnel support structure often bears larger load than usual because the tunnel drainage pipes are blocked easily by the crystals and the groundwater level would rise. In order to investigate what the crystals are, site investigations and laboratory tests of crystals and groundwater were completed. Some valuable results have been obtained. Firstly, the crystallizations are usually discovered in drainage pipe exits of tunnels which are under construction in Chongqing. Furthermore, the results of XRD have confirmed that the crystals are calcite. And calcite morphology could be found in most SEM images. But there are other morphologies in these images other than calcite because calcite is often influenced by some factors, such as important ions in groundwater, pH of groundwater, kinetics effect, and so on. Finally, some steps and solutions to solve blocking of tunnel drainage pipes caused by crystallization are suggested. One of the best solutions is that some special materials which could prevent crystals from being attached to pipes are coated on the inner surface of drainage pipes. The results could contribute to understand the crystallization phenomenon profoundly and help solve the similar situations of tunnel drainage pipe blocking.

1. Introduction

A lot of crystallization phenomena on the inner wall of tunnel drainage pipes are often found in Chongqing, and drainage function is gradually invalid. Some drainage pipes of railway tunnels and subway tunnels are also blocked seriously in Korea [1–3]. The ground load would increase if the groundwater could not flow out along the tunnel drainage system [4–6]. Some researchers have found that the crystals from the old tunnel are calcium carbonate by microanalysis [1–3]. Plenty of researchers focus on influence factors of calcium carbonate crystallization and how to prevent and remove calcium carbonate crystallization in recent years. Thus, many achievements about crystallization impacts are obtained, such as water hardness, alkalinity, saturation index, salinity, temperature, pH, hydraulic gradient, flow rate, thickness of diffusion boundary layer, and so on [7–12]. Another popular topic is that how the magnetic field influences on calcium carbonate crystallization [13–19]. Reis et al. [20] proposed a two-fluid model of homogeneous crystallization of calcium carbonate in highly supersaturated solutions. Liu et al. [21] found that carboxymethyl cellulose could slow down the growth rate and crystallinity of $CaCO_3$ crystals but did not affect the polymorph of $CaCO_3$ crystals. These latest research studies could provide help to prevent calcium carbonate crystals blocking drainage pipes.

In fact, the crystals may be different from each tunnel because the characters of surrounding rock and groundwater are not the same everywhere. Thus, what the crystals are is very important for understanding the blocking problem. And, some solutions should be obtained.

In order to investigate what the crystals from tunnels are in Chongqing, site investigations and laboratory tests have been fulfilled. Firstly, crystallization phenomena of some tunnel drainage pipes which are under construction were surveyed in Chongqing. The statuses of crystallizations and environment were investigated. Then, the properties of water samples were tested, and the XRD and SEM of crystals were analyzed in the laboratory. This study mainly contributes to understand the crystallization phenomenon in the tunnels of Chongqing and to get some solution ideas.

2. Crystallization Phenomena and Environment Temperature Investigation

2.1. Crystallization Phenomena. There are a lot of crystallization phenomena on the inner wall of tunnel drainage pipes in Chongqing. Some tunnels are investigated such as the tunnel between Chongqing North Railway Station and Yulu Station, tunnel between Danzishi Station and Tushan Station, tunnel between Wutong Road Station and Wulidian Station, tunnel between Min'an Avenue Station and Chongqing North Railway Station, and New Zhongliang Mountain tunnel. The investigations include 336 drainage pipe exits in these tunnels which are under construction. The results are shown in Table 1. The crystallization ratio of New Zhongliang Mountain is the largest. The crystallization ratio of the right tunnel of tunnel between Min'an Avenue Station and Chongqing North Railway Station is the smallest. Both survey locations are less than the other tunnels because the investigation conditions are very difficult to satisfy in some sites. Small data could result in larger or smaller crystallization ratio than large data. The average crystallization ratio is up to 69.3% in every tunnel. It indicates that crystallization is a universal and objective phenomenon in the tunnels of Chongqing.

In 62.8% of the drainage pipe exits, groundwater could be found. In general, the crystallization would probably accompany groundwater. However, there is less water in the tunnel between Wutong Road Station and Wulidian Station and the right tunnel of New Zhongliang Mountain than the other tunnels. In fact, there was much groundwater in the investigation locations when the rock was excavated. Groundwater could decrease less and less with time increasing because it always flows out of the tunnel. So, some locations had no water while they were investigating. Thus, crystallization is severely affected by groundwater.

Groundwater and crystals are very important research objects in this study. Some typical groundwater and crystal samples were taken from the investigation locations which are listed in Table 2. The lithology of every investigation location was also obtained. The surrounding rock types contain sand mudstone, sandstone, limestone, dolomitic limestone, flint limestone, and so on. It indicates that crystallization is not related to a particular lithology.

Every drainage pipe exit reveals different crystallization situations (shown in Figure 1). However, all exits of tunnel drainage pipes are close to be completely blocked by crystals in these pictures. The obvious appearance feature of crystals is that they have different colors. For example, the crystals in site 1 and site 8 are white, and they are white with a little yellow in site 5 and site 6. But colors of crystals in site 2, site 4, and site 7 are light yellow. What is surprising is that the crystal from site 3 is black. Are they the same substance? The answer would be gained by XRD and SEM in next sections.

2.2. Environment Temperature. The crystal is generated by some chemical reactions. Generally, temperature is an important factor for a chemical reaction. Thus, water and air temperatures were obtained when the crystals were sampling. The results are shown in Table 3. The average water temperature is 22.5°C, and the maximum and minimum are 25.0°C and 20.3°C, respectively. The average air temperature is 24.9°C, and the maximum and minimum values are 29.0°C and 22.6°C, respectively. All the air temperatures are larger than water temperatures because a lot of heat is caused by construction and it is released to air firstly. And then, the water temperature changes with the air temperature.

3. Results of XRD and SEM Tests

Calcite, aragonite, and vaterite are the main polymorphic forms of calcium carbonate. And they have different features of diffractograms and morphologies [17, 22, 23]. So, the composition and microscopic characteristics of crystal samples were studied by XRD and SEM. The results of XRD indicate that all samples exhibit the largest peaks centered at $2\theta = 29.4^\circ$ assigned to the (1 0 4) plane of the calcite and other larger peaks centered at 23°, 36°, 39°, 43°, 47°, and 48° (shown in Figure 2). The distributions of the largest peak and other larger peaks are the same as JCPDS file 00-005-0586 and the results of some literatures [2, 13, 17, 22, 23]. These diffractograms have shown that all crystals are composed of calcite although their colors are different.

All morphologies of samples were investigated by SEM at an electron energy of 5.0 keV. A series of SEM images have been obtained. Both of sample 4 and sample 7 are composed of rhombohedral particles (shown in Figures 3(d) and 3(g)). It is clear that they are calcite based on the results of literatures [9, 13, 15, 17, 23]. Some rhombohedral particles (circled in images with red line) could also be found in Figures 3(a), 3(b), 3(c), 3(f), and 3(h). In addition, bar-like particles (circled in images with red line) could be discovered in Figures 3(f) and 3(h). The particles in Figure 3(e) are similar to spherical. The morphology of calcite could be changed by the magnetic field [13, 15]. Actually, there is usually no magnetic field in tunnel engineering. So, the crystal morphologies may be affected by magnesium ions, potassium ions, sodium ions, sulfate ions and chloride ions, humic acid, and so on [9, 17, 22, 23]. Anyway, all results prove that the crystals are calcium carbonate.

4. Water Quality Analysis

In order to investigate whether there are some ions which could influence crystal morphologies in water samples, water quality were analyzed when the air temperature was 22.0°C and water temperature was 21.0°C. As Table 4 shows, the concentrations of calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), sodium ions (Na^{+}), potassium ions (K^{+}), chloride ions (Cl^{-}), sulfate ions (SO_4^{2-}), carbonate ions (CO_3^{2-}), bicarbonate ions (HCO_3^{-}), and hydroxide ions (HO^{-}) were obtained by laboratory tests. All ions are contained in water samples except carbonate ions, bicarbonate ions, and hydroxide ions. Some samples include carbonate ions, and the others include bicarbonate ions and hydroxide ions. Obviously, calcium ions and carbonate ions or bicarbonate ions

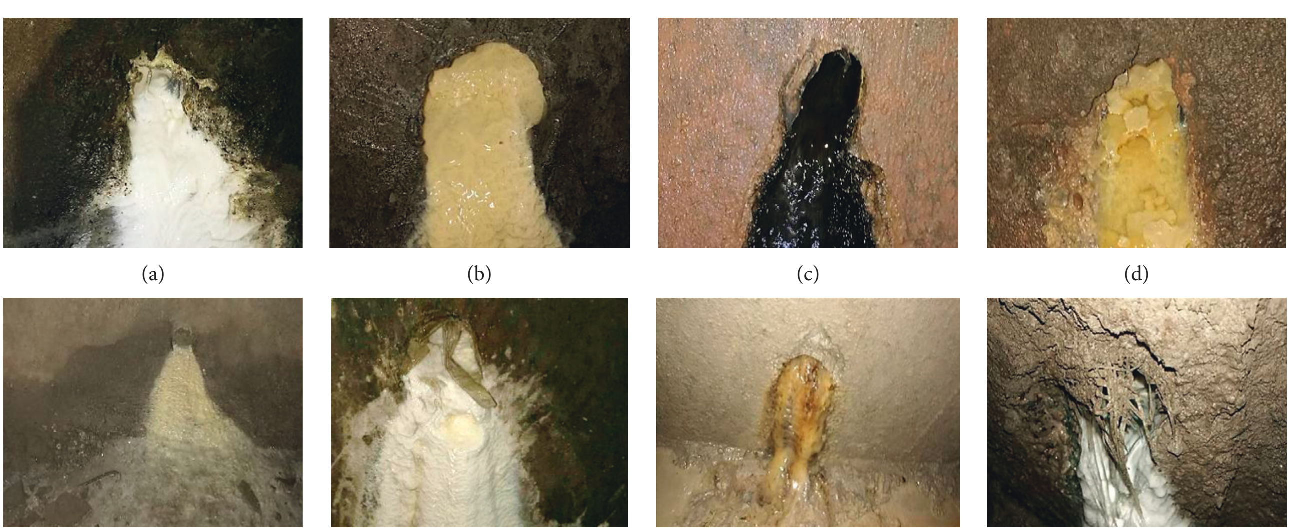
Table 1: Statistics of crystallization surveys on some tunnels under construction in Chongqing.

Projects	Number of locations				Crystallization (%)	Groundwater (%)
	Crystallization	Groundwater	No groundwater	Total		
Tunnel between Chongqing North Railway Station and Yulu Station	72	82	10	92	78.3	89.1
Right tunnel between Danzishi Station and Tushan Station	42	48	22	70	60.0	68.6
Left tunnel between Danzishi Station and Tushan Station	28	37	2	39	71.8	94.9
Tunnel between Wutong Road Station and Wulidian Station	60	14	61	75	80.0	18.7
Tunnel between Min'an Avenue Station and Chongqing North Railway Station	8	14	6	20	40.0	70.0
Right tunnel of New Zhongliang Mountain	9	2	8	10	90.0	20.0
Left tunnel of New Zhongliang Mountain	14	14	16	30	46.7	46.7
Total	233	211	125	336	69.3	62.8

Note: all data in Table 1 only reflect the states when the sites were surveying.

Table 2: Investigation locations and samples.

Investigation locations	Number			Lithology
	Locations	Water samples	Crystal samples	
Tunnel between Chongqing North Railway Station and Yulu Station K21+772	Site 1	Water 1	Sample 1	Sand mudstone and sandstone
Tunnel between Chongqing North Railway Station and Yulu Station K21+610	Site 2	Water 2	Sample 2	Sand mudstone and sandstone
Tunnel between Danzishi Station and Tushan Station YDK28+285	Site 3	Water 3	Sample 3	Sand mudstone
Tunnel between Danzishi Station and Tushan Station YDK28+180	Site 4	Water 4	Sample 4	Sand mudstone
Tunnel between Wutong Road Station and Wulidian Station YDK23+920	Site 5	Water 5	Sample 5	Sand mudstone
Tunnel between Min'an Avenue Station and Chongqing North Railway Station K20+200	Site 6	Water 6	Sample 6	Sand mudstone and sandstone
Right tunnel of New Zhongliang Moutain YK3+144	Site 7	Water 7	Sample 7	Limestone and dolomitic limestone
Left tunnel of New Zhongliang Moutain ZK4+120	Site 8	Water 8	Sample 8	Flint limestone



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 1: Situations of drainage pipe exits. (a) Site 1. (b) Site 2. (c) Site 3. (d) Site 4. (e) Site 5. (f) Site 6. (g) Site 7. (h) Site 8.

Table 3: Water and air temperatures at investigation locations.

Number	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Average
Water temperature (°C)	23.0	23.3	20.4	20.4	25.0	24.8	22.8	20.3	22.5
Air temperature (°C)	24.9	24.9	22.7	22.6	29.0	27.0	24.3	23.8	24.9

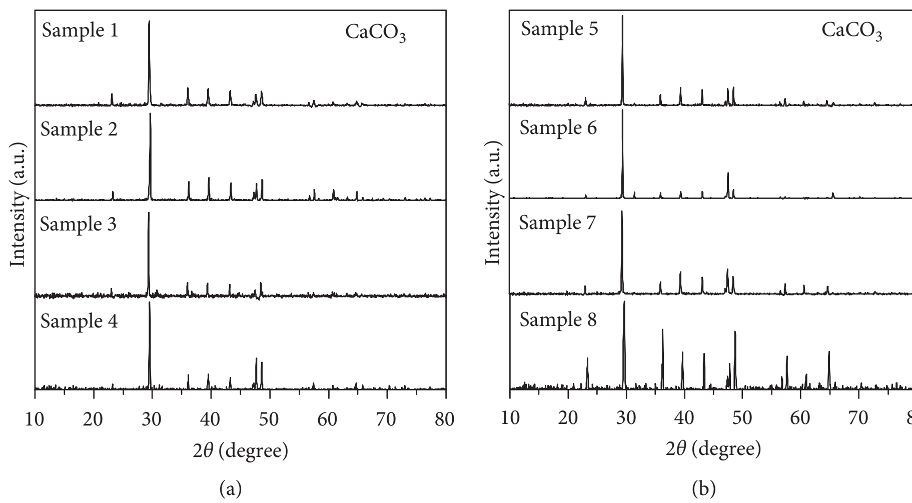


Figure 2: Diffractograms of crystal samples.

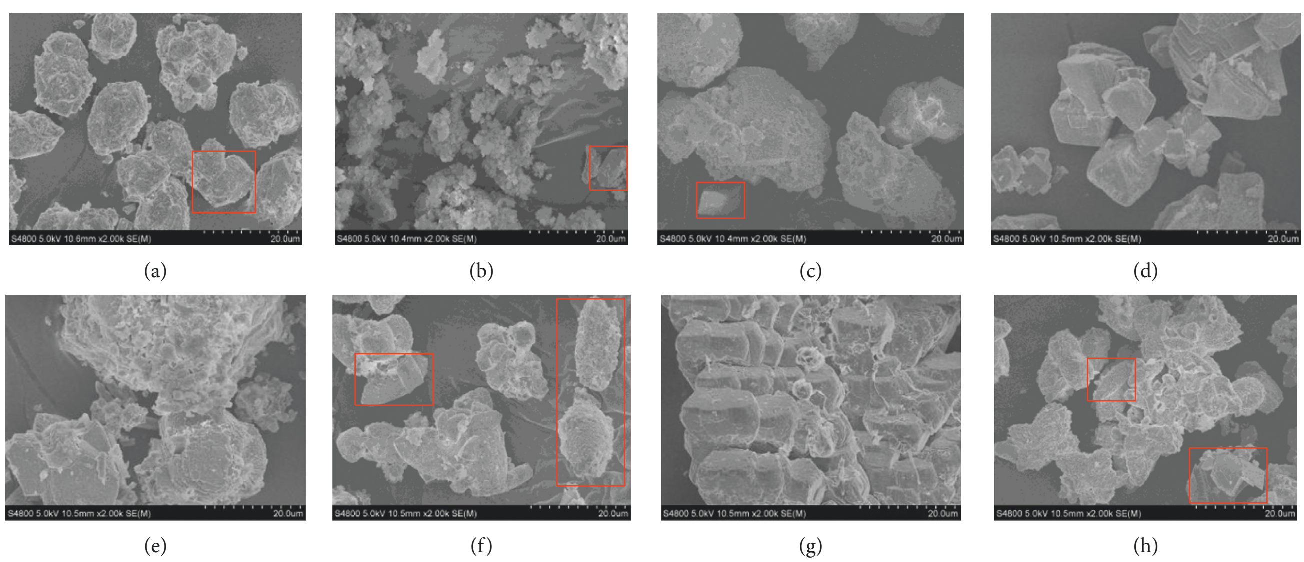


Figure 3: Typical SEM images of crystal samples. (a) Sample 1. (b) Sample 2. (c) Sample 3. (d) Sample 4. (e) Sample 5. (f) Sample 6. (g) Sample 7. (h) Sample 8.

of the samples are the most significant condition to precipitate calcium carbonate.

Total hardness, total alkalinity, salinity, and pH of water samples have been also obtained in laboratory. The total hardness of some samples is very high, such as water 3, 4, 5, and 7. But the hardness of other samples is far less than these samples. The total alkalinities of all samples are high, and the maximum and minimum values are 515.8 and 103.1, respectively. The salinities of all water samples are low because they are all smaller than 1000. All samples are of alkaline water since the pH of all samples is larger than 7. There are carbonate ions in the water sample when the pH is larger than 11. Otherwise, there are bicarbonate ions but no carbonate ions in water samples.

5. Discussion

If the crystals are not tested by XRD, we may believe that the crystals are different because they have different colors. The crystal color may be affected by the hydrogeological environment. In fact, the results of XRD show that all crystals are calcite. However, the SEM images show that the crystals are

Table 4: Water quality analysis of samples (mg/L).

Parameters	Water 1	Water 2	Water 3	Water 4	Water 5	Water 6	Water 7	Water 8
Ca^{2+}	10.4	8.66	113.87	122.91	127.8	2.24	134.71	5.01
Mg^{2+}	1.2	4.22	25.02	8.45	12.66	0.61	35.58	1.2
Na^{+}	77.64	84.87	54.23	90.28	84.72	132.22	37.66	105.21
K^{+}	33.49	22.35	1.83	61.13	39.66	27.45	17.56	24.66
Cl^{-}	31.66	31.8	63.32	9.04	18.08	5.67	97.25	7.91
SO_4^{2-}	107.15	121.37	113.59	142.02	139.43	163.97	139.43	60.66
HCO_3^{-}	0	0	406.37	0	0	0	416.01	0
CO_3^{2-}	33.36	38.1	0	28.58	23.83	50.03	0	121.49
OH^{-}	16.16	18.19	0	148.22	161.7	34.37	0	0
Total hardness	30.93	38.99	387.4	341.71	371.28	8.11	482.93	17.47
Total alkalinity	103.14	117.01	333.3	484.04	515.81	184.52	358.67	202.33
Salinity	311.07	329.56	575.05	610.63	607.88	416.57	670.2	326.14
pH	11.21	11.69	7.77	12.26	12.35	11.26	7.03	11.5

a little different from each other since the morphologies of crystals are different (shown in Figure 3). Figures 3(d) and 3(g) show that the crystals are calcite which is composed of rhombohedral particles. Some calcite morphologies could be found in Figure 3 except for Figure 3(e) although the other images are different from Figures 3(d) and 3(g). It seems that the results contradict each other.

Most crystals would be calcite because the groundwater temperature is between 20.3°C and 25.0°C [22]. The calcite morphology could be influenced by the magnesium ion of groundwater. Aragonite may appear if there are magnesium ions in groundwater. And the amount of aragonite would increase with the magnesium ion concentration increase [9, 17, 22, 23]. In addition, the morphology of calcite crystals is also affected by potassium ions, sulfate ions, temperature, pH, and kinetics effect [9, 23]. In summary, many different ions, pH, and kinetics effect could result in changes of crystal morphologies and make us misunderstand the essence of the crystal. The crystal morphologies are studied to investigate the essence of the crystals, and it could be contributed to get some ideas to prevent crystallizing.

There are many chemical reactions among the ions in water, such as

$$\begin{aligned}
Ca^{2+} + CO_3^{2-} &\longrightarrow CaCO_3\\
Mg^{2+} + CO_3^{2-} &\longrightarrow MgCO_3\\
MgCO_3 + Ca^{2+} &\longrightarrow CaCO_3 + Mg^{2+}\\
Ca^{2+} + SO_4^{2-} &\longrightarrow CaSO_4\\
CaSO_4 + CO_3^{2-} &\longrightarrow CaCO_3 + SO_4^{2-}\\
Ca^{2+} + HCO_3^{-} &\longleftrightarrow CaCO_3 + H^{+}\\
Ca^{2+} + 2HCO_3^{-} &\longleftrightarrow CaCO_3 + CO_2 + H_2O\\
Mg^{2+} + 2HCO_3^{-} &\longleftrightarrow MgCO_3 + CO_2 + H_2O\\
Ca^{2+} + CO_2 + H_2O &\longleftrightarrow CaCO_3 + 2H^{+}\\
Ca^{2+} + HCO_3^{-} + OH^{-} &\longrightarrow CaCO_3 + H_2O
\end{aligned} \tag{1}$$

Thus, there would be many crystals in drainage pipes of tunnels because of these chemical reactions. Finally, the crystals tightly were attached to pipes. This process will be studied in future.

Based on field investigations, laboratory tests, chemical reactions, and other research studies, some methods could prevent drainage pipes blocking by calcium carbonate. For example, crystals could be prevented by putting some acidic chemical materials into groundwater. But it may not be a good method because it may pollute environment. It had been proved that electromagnetic field could solve this problem. However, electromagnetic field would consume much electric energy. If there are some special materials on the inner surface of drainage pipes so that crystals could not be attached to pipes, maybe it is one of the best methods.

6. Conclusions

Some investigations and laboratory tests are taken, and some valuable conclusions could be obtained as follows:

(1) A lot of site investigations show that crystallization phenomena on the inner wall of tunnel drainage pipes are often present in Chongqing. The groundwater level could rise if the tunnel drainage pipes are seriously blocked by the crystals. The support structure of tunnels may receive larger load than before. So the safety of tunnel support structure is critically threatened by crystallization. Thus, we should pay more attention to this problem than before.

(2) Most of the crystals are calcite when the air and groundwater temperatures are between 20°C and 30°C. The results of XRD and SEM also confirm that the main composition of crystals is calcite. But their morphologies may be changed by some ions of groundwater, such as magnesium ions, sodium ions, potassium ions, chloride ions, sulfate ions, pH, kinetics effect, and so on.

(3) How to solve the problems when drainage pipes of tunnels are blocked. Firstly, site investigation should be taken, and every crystal should be tested in the laboratory. And then the morphologies of crystals should be gained. Finally, we could get the reasonable

solutions according to these results. For example, some special materials which could prevent crystals from being attached to pipes are coated on the inner surface of drainage pipes.

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 there are no conflicts of interest regarding the publication of this paper.

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