Experimental investigation of the engineering properties of coarse grain embankment fill material with accumulative salt effect by adding on-site brine groundwater

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Abstract

The purpose of this research is to study the accumulative effect of repetitively adding groundwater on the engineering properties of coarse grain salinized embankment fill material. Large-scale compression and engineering characteristics tests were carried out on different salt content samples. Based on the laboratory test results, the influence factors on the engineering properties by repetitively adding groundwater with SO_4^{2-} or CL^- were analyzed. With the increasing times of added water containing SO_4^{2-} or CL^-, the compressive deformation of tested samples showed a trend of dramatically increasing at the beginning followed by gradually decreasing, while the collapse deformation of the samples increased continuously. Its coefficient of compressibility showed a typical three-stage variation law, regardless of the salt types of added water. With the decrease of the temperature (simulating the cooling period during construction), the excessive content of SO_4^{2-} in the water resulted in an increase of salt expansion of samples, while the shrinkage behaviour was observed with the excessive content of CL^- in the water. Thus, an obvious accumulative effect in the salt expansion of the sample was observed. With the increasing times of added water containing SO_4^{2-} or CL^-, the collapse deformation of the samples increased continuously. Besides, the mechanisms of added water with SO_4^{2-} or CL^- on the engineering characteristics of the samples were discussed from the following perspectives: the salt accumulation, the distribution of salt in the soil, the interaction of salt ions, and the dissolution of soluble salt. It is further shown that even a small amount of the soluble salt in groundwater, will have a significant impact on the engineering properties of the coarse grain saline soil with the accumulative effect by repetitively adding groundwater.

Keywords: Embankment fill material, Corse grain saline soil, Sodium sulfate, Ground Water, Salt content

1. Introduction

Saline soil widely distributes in the arid and semi-arid regions with a total area accounting for 6.5% of the global land area. There is a significant amount of saline soil distribution in China, Pakistan, Saudi Arabia, Iraq, Egypt, Iran, and many other countries, especially Middle East area in which the percentage of saline soil area is far larger than the world's average level (FAO 2002). As increasing demands for highway and highspeed railway, some construction projects have to cross through the saline soil areas considering the construction cost. There is a detrimental effect of salt crystallization due to reduction of ambient temperature, while in a warm condition, the water of crystallization in the saline soil may be released, resulting in a soil volume contraction (Gao et al. 1997b; Wu et al. 2002; Zhang et al. 2020). The salt expansion of sulfate saline soil is one of the most critical factors that cause engineering damage in the saline soil areas (Gao et al. 1997a; Liu et al. 2019; Zhang et al. 2020). It was found that the rate of cooling, salt content, water content, ion sort and types of soils had an impact on the crystal of sodium sulfate, thus, could influence the salt expansion of sulfate saline soils (Bing and Ma 2011; Lai et al. 2016). Wan et al. (2017b) and Xiao and Lai (2017) also confirmed the influence of initial supersaturate ratio on the amount of salt expansion and the inhibiting effect of chloride ion on the salt expansion. Durotoye T.O et al. (2016) confirmed that adding sodium chloride to expansive soils can reduce its free swell index and increase its strength characteristics. Wu et al. (2002) found that the salt expansion amount was related to a sensible temperature range, which was from -7℃ to 0℃ for the coarse grain saline soil.

Soil subsidence, caused by dissolving the soluble salts in saline soils (Zhang et al. 2019), could also lead to the damage of embankment structure. In order to study the factors that influence the collapsibility of coarse saline soils, a site collapse experiment was performed by Cheng et al. (2013), which found that not only the water and salt content but also the content of coarse particle, the soil density, and the permeability quotient had an impact on the collapsibility of coarse saline soils. Some scholars (Wang 2009; Song 2017) found that the collapse coefficient increased with the increasing salt content at the same water content level, whereas the collapse coefficient decreased with the increasing water content at the same salt content level (K. Abbeche et al. 2010).

To avoid the saline soil induced engineering hazards, several soil stabilization techniques were developed to treat salinized soils by use of sodium chloride , fly ash or lime(Sivapullaiah et al. 2009; Durotoye T.O et al. 2016; Zhang et al. 2020; Consoli et al. 2019a). In addition, when those soils were treated by lime or calcium-based stabilizers, the existing sulfate in the soils reacts with the calcium from stabilizers and the free reactive alumina from soils to form a crystalline mineral as ettringite which would result in heaving in the soils, known as sulfate-induced heave (Puppala et al. 2004; Consoli et al. 2019b). Besides, dispersive clay particles come apart and get progressively eroded when subjected to water containing reduced quantities of salt as a large amount of dispersed sodium exist in pore water of dispersive clays (Consoli et al. 2016). It was proved that the adding of fly ash could improve engineering properties of dispersive clays which was treated by lime initially (Consoli et al. 2019c).

In general, the groundwater in the saline soil areas often contains a certain amount of soluble salt, which is not high enough to cause damage to the subgrade, as the salt content meets the requirement of construction standards by the water examining. However, due to the lack of accumulative salt content effect awareness, those soluble salt in groundwater may cause potential damage to some subgrades when using this local groundwater during the embankment construction. A recently on-going construction project in the Middle East area (Zhang et al. 2019) reported that because of the dry climate and high evaporation capacity on the construction site, the subgrade filling speed was slow. To maintain the water content of the subgrade, the local groundwater containing soluble salt was added several times during the filling process. This repetitively added groundwater resulted in an increase of soluble salt content in the subgrade fillers due to the accumulative effect, leading to potential salt-expansion damage hazards on the constructing subgrade.

Although replacing the local groundwater with the pure water for the subgrade construction could avoid potential hazards, this will cause a steep increase in the construction cost. Currently, there is no study on the accumulative effect of salt in coarse grain soils caused by repetitively adding brine groundwater. Thus, to reduce the construction cost while ensuring the stability of subgrade in the saline soil areas, a study on the accumulative effect of groundwater in the saline soil areas on the coarse grain embankment fill materials needs to be carried out.

This study reveals the influence law and mechanism of repetitively added groundwater on the engineering properties of coarse grain saline soil. Therefore, based on the engineering problems existing in the construction project in the saline soil areas, two types of water were prepared in the laboratory: sulfate solution and chlorine solution, simulating the two main types of soluble salt existing in the groundwater of Middle East saline soil areas. The coarse grain saline materials were mixed with these prepared water for 0, 1, 2, 3, 4, 5 times to simulate the on-site subgrade construction process (e.g. in the Middle East construction project), in which the groundwater was added several times to maintain a certain water content for compaction due to the high level of evaporation. Then, large-scale compression tests, salt expansion tests, and collapsible tests were performed on these samples to study the effect of repetitively adding brine water on the engineering characteristics of coarse grain saline materials.

2. Fundamental engineering property of experiment materials

2.1. Materials

The materials used in this experiment were obtained from Hosi Corridor, Gansu province, China. Fig. 1 (Google map 2019) shows a satellite map of the sample collection location. According to the standard method (the Code for Civil Engineering Experiment of Railway Project (MOR 2010)), which is the same as (BSI 1990a), the particle size distribution test was performed on the collected samples. The particle size distribution curves of samples, named as TL-1 and TL-2, are shown in Fig. 2. According to the classification standard in the Code for design on subgrade of the railway (MOR 2005), the test samples are classified as well-gradation fine round gravel, which is a good subgrade aggregate.

According to the standard method (MOR 2010), which is the same as (BSI 1990b), the optimum water content and the largest dry density of the soil sample TL-1 are 6.7% and 2.22 g/cm^3, while they are 6.4% and 2.24 g/cm^3 for the soil sample TL-2. The salt content analysis was performed on test samples based on the standard methods (MOHURD 2014) and (BSI 2018), giving the results that show a relatively low salt content compared with soils that collected from the highspeed railway project in the Middle East area mentioned in the introduction. To present the on-site soil condition, sodium chloride and sodium sulfate were added to the test samples. The salt contents of these two types of samples were set as the typical salt content level in the Middle East coarse grain saline soil areas (Zhang et al. 2019; William D. 2014). The soluble salt assay result of test samples is presented in Table 1.

2.2. Groundwater

According to the standard method (MOR 2003), the ion analysis was carried out on the groundwater samples collected in the saline soil areas from the Middle East high-speed railway project. The results showed that the highest ion concentrations of SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, K^+, and Na^+ were 96.53 g/L, 133.13 g/L, 11.00 g/L, 4.80 g/L, and 63.01 g/L, respectively. The ion concentration of HCO_3^- was 0 while the highest ion concentration of CO_3^{2-} was 0.48 g/L in most of the water samples. PH value ranged from 7 to 9, while the highest content of free-state carbon dioxide was 0.04 g/L.

To obtain more representative experiment results, based on the ion analysis result, two common types of water samples with medium salt content were chosen. As there is a relatively low ion concentration of HCO_3^- and CO_3^{2-} in the water samples, and the damage of saline soil is mainly related to SO_4^{2-} and Cl^-, the effects of other ions can be ignored (Gao et al. 1997a). Thus, the test water sample-A was prepared in the laboratory by mixing potassium sulfate and sodium sulfate with pure water, while the test water sample-B was prepared by mixing potassium chloride and sodium chloride with pure water. The ion analysis results of these two types of test water samples are shown in Table 2.

3. The design of the experiment scheme

3.1. Sample preparation

In order to study the effect of repetitively adding brine groundwater on the engineering properties of coarse grain sulfate saline fill materials, large-scale compression tests, salt expansion tests, and collapse tests were carried out. The test sample preparing details are shown as follow. When preparing test samples, the total times of added water was 5 to reach the optimum water content, in another word, that is adding the test water for n (n=0,1,2,3,4,5) times, while the pure water was added (5-n) times. For instance, if the test brine water is added for 0 times, then the pure water should be added 5 times to reach the optimum water content. To be specific, the TL-1 test sample was prepared by adding the test water-A for 0, 1, 2, 3, 4, and 5 times, while the pure water was added for 5, 4, 3, 2, 1, and 0 times, numbered as S0–S5, respectively. The test sample TL-2 was prepared by adding the test water-B for 0, 1, 2, 3, 4, and 5 times, while the pure water was added for 5, 4, 3, 2, 1, and 0 times, numbered as C0–C5, respectively. The test samples were cured for 24 h so that the test water could evenly distribute within the soil samples. Then, the test samples were placed into the corresponding test container according to the requirement of each test. Table 3 presents the design scheme of adding test water.

3.2. Large-scale compression test

Large-scale compression tests were carried out based on the standard method (MOHURD 2019), by using a 1000 kN large-scale consolidometer. The instrument is designed for testing the coarse grain soil, with an allowed maximum particle size of 60 mm. The deformation sensor ranges from 0 mm to 50 mm, with an accuracy of 0.2% F.S (full scale). The pressure sensor ranges from 0 kN to 1000 kN, with a stability accuracy of 1% making it suitable for testing.

Test samples were compacted dynamically and evenly into the test container in three layers with the compactness of 92% which is determined by the compaction requirement of the highspeed railway subgrade according to the Code for design on subgrade of the railway (MOR 2005). The dimension of the cylinder test container was Φ500 mm (inner diameter) × 250 mm (height). After compaction, the container with samples was placed into the instrument. The soil samples were first pre-loaded and then loaded from 0 kPa to 50 kPa. The next stage load was applied when the specimen deformation was stabilized under the current stage load, which gave the deformation rate no greater than 0.05 mm/h. This procedure was repeated at 100 kPa, 200 kPa, 300 kPa until the designed load 400 kPa was reached. After the deformation of the soil samples was stabilized again at 400 kPa, the unload program was then performed.

3.3. Salt expansion test

The cooling equipment used in the salt expansion test was a bespoke simple temperature control test box (temperature ranges from -15°C to 50°C). Figure 3 shows the photograph and principle diagram of the temperature control test box. This instrument has two main advantages to ensure the accuracy of the test results compared to other test devices. The temperature inside the test box was maintained stable as the reading could be done outside the instrument without opening the test box. Besides, the dial was placed outside the thermal insulation to ensure the accuracy regardless of the low-temperature influence inside the instrument. The test container used in the salt expansion test is a bespoke organic glass barrel (Fig.3c) with the dimension of Φ240 mm (inner diameter) × 250 mm (height). The soil samples were compacted dynamically into the test container in three even layers with the compactness of 92%. After the container was placed into the test box, the temperature control system was turned on. The initial temperature was set as 25°C with a cooling rate of 5°C/60 min. The temperature was kept at the same level for an hour at each cooling stage. When reached the designed lowest temperature (-15°C), the temperature was kept constant at -15°C for 5 hours. The amount of salt expansion at each cooling stage was recorded. According to the expansion law of sodium sulfate crystallization, the temperature around -10°C and a cooling rate of 0.1°C/min met the temperature requirements for salt expansion (Lai et al.2016; Xiao et al.2017).

3.4. Collapse test

The test device used in the collapse experiments is shown in Figure 4. The collapse tests were carried out at room temperature (about 20°C). The soil samples were compacted dynamically into the test container in three even layers with the compactness of 92%. The test container was a specially designed barrel made from acrylic glass with the dimension of Φ280 mm (inner diameter) × 70 mm (height). The upper and lower sides can drain freely, and there is a steel drainage plate placed on the upper surface of the barrel. This steel plate allows the load applied uniformly towards the soil sample. There are removable iron hoops around the barrel to limit horizontal displacement of the soil sample.

The collapse test was followed to the Code for Civil Engineering Experiment of Railway Project (MOR 2010).The collapse test procedure was determined using the single-line method described as follow. The soil samples were loaded to 200 kPa step by step at an interval of 50 kPa without adding water. The pure water was added to the soil samples from top to bottom after the deformation of samples stabilized at 200 kPa. When the deformation of the soil samples reached a stable state after adding the pure water, the load was then increased to 300 kPa. The stable state mentioned hereby is defined as the deformation rate of the soil samples is no greater than 0.01 mm per hour. The designated amount of added water in the collapse test was calculated based on the largest precipitation level of 40mm, which was observed on-site from the Middle East high-speed railway project. The total amount of added water = cross-section area of soil sample × precipitation quality = $S.H = \pi.R^2.H = 3.14 \times (\frac{28}{2})^2 \times 4 = 2461.8\ mL.$

4. Results and discussion

4.1. The results and analysis of compression tests

4.1.1. The results of compression tests

The result of the compression tests is shown in Figures 5, 6 and 7. Fig. 5 shows the variation of the void ratio of samples S0–S5, C0–C5 with the load increasing from 0 kPa to 400 kPa. From Fig. 5, with the increase of loading, the void ratio of the sample decreases in all tested samples. It is interesting to see from Table 4 that the volume changes of samples are the largest with values of 0.010 in TL-1 and 0.006 in TL-2 at 400 kPa when adding the brine water for 3 times regardless of the salt types.

Fig. 6 shows the variation of compression deformation of the samples with the varied times of adding the brine water under the condition of load increased from 300 kPa to 400 kPa. From Fig. 6, the average total amount of deformation increased gradually from 212 mm to 266 mm upon adding the test water for 0 to 2 times, with a sudden increase to 419 mm when adding the test water for 3 times. After adding the test water for 4-5 times, the total amount of deformation decreased gradually from 311 mm to 298 mm, nearly to the level of that (266mm) when adding the test water for 2 times.

From Table 5, compared with the deformation when adding the pure water for 5 times, the maximum stabilized deformation increments of coarse sulfate saline fill materials vary from 10.27% to 116.73%, with the maximum values of 116.73% and 79.01% when adding the sulfate and chloride water 3 times respectively.

Fig. 7 shows the variation of the compression coefficient of compressibility ($a_{100\text{-}200}$) with the increasing times of adding the test water. From Fig. 7, with the increasing times of adding the test water, the coefficient of compressibility showed a three-stage variation trend regardless of the salt types. It decreased slightly followed by dramatically increasing to the maximum, and then decreased gradually until stabilization. The coefficient of compressibility of the sample when adding the brine water for 3 times is about 62% higher than that with only pure water added. Compared with the samples that adding the pure water for 5 times, the coefficient of compressibility of the sample that mixed with the sulfate water for 5 times increased about 0.5 times, while the coefficient of compressibility of the sample that mixed with the chloride water for 5 times increased about 0.4 times. This fact illustrates that the times of adding the brine water have an impact on the compression characteristics of coarse sulfate saline fill materials.

4.1.2. The analysis of compression tests

The volume of the test container used in the compression tests was fixed. And according to the test water adding scheme, the total water content of each soil sample was the same. Thus, the soluble salt content in the samples increased upon adding the brine water. In the condition of adding the brine water for 0 times, the pure water was added for 5 times to reach the optimum water content. Under this condition (S0 or C0), the largest dry density and optimum water content of the samples were obtained by the heavy compact tests, resulting in the highest density of the soil sample. Thus, the lowest compressive deformation was observed under this condition. In the other conditions (S1-S3 or C1-C3) when adding the brine water from 1 to 3 times to reach the so-called optimum water content, the real optimum water content of the samples increased with the increase of the soluble salt content, in the same manner as Zhang and Yang (2019), which has been proved by an experimental contacted by Zhang. Thus, in the process of adding the brine water for 1 to 3 times, the water content of samples decreased compared to the real optimum water content, resulting in a decreased dry density and an increased compressive deformation.

Meanwhile, at certain temperatures with small temperature variation, the solubility of soluble salt in water was constant. Fig. 8 shows the variation of the solubility (g/100g water) of NaCl and Na_2SO_4 with temperature (Lai et al. 2017; Wan et al. 2017a). From Fig. 8, the solubilities of NaCl and Na_2SO_4 were 36 g and 19.5 g, respectively, when the temperature was about 20°C, as the same as that when the Large-scale compression test was performed in this study. Based on this concept and the result of this compression test, it may be deduced that most the soluble salts that initially acted as the binder of soil skeleton (Zhang et al. 2020) and the pore fillers in the soil samples were dissolved by the process of the first 3 times of adding the brine water. Meanwhile, the density of the samples gradually decreased with the increasing times of adding the brine water, which resulted in an increased compressive deformation. Especially when adding the brine water 3 times, the soluble salt reached its maximum solubility, resulting in the weakest soil structure and the maximum stabilized compressive deformation compared with that in the condition of adding the brine water for 1 and 2 times. When adding the brine water for 4 times, the soluble salt content in the soil samples was too high for the water in the soil samples to dissolve all of them. Therefore, parts of soluble salt crystal-separation acted as the binder of the soil skeleton and the pore filler in the soil again. This crystal-separation due to the accumulative effect of adding the brine water enhanced the soil structure. Thus, the amount of the compressive deformation decreased and the compression modulus increased when adding the brine water for 4 and 5 times.

4.2. The results and analysis of salt expansion tests

4.2.1. The results of salt expansion tests

Fig. 9 shows the variation of salt expansion of the sample TL-1 mixed with the test water-A (sulfate) and the sample TL-2 mixed with the test water-B (chloride) under the influence of cooling. The temperature gradient was 25°C→20°C→15°C→10°C→5°C→0°C→-5°C→-10°C→-15°C. Fig. 10 shows the samples that had been cured for 12 hours under the room temperature of 25°C after the test finished.

From Fig. 9, adding the brine water for 1 time had a limited influence on the salt expansion characteristic of the samples. With the increasing times of adding the brine water, the salt expansion characteristic of the samples changed significantly. After adding the brine water for 2 times, the results showed that the amount of salt expansion of the samples mixed with the sulfate brine water increased dramatically from 0.685 mm to 3.964 mm, while the samples mixed with the chloride brine water decreased obviously from 0.495 mm to 0.146 mm, with the shrinkage occurred at the beginning of cooling. As the times of adding the brine water continued to increase, the total amount of salt expansion of the samples mixed with the sulfate brine water continued to increase gradually from 5.594 mm to 6.120 mm. Meanwhile, the total amount of salt expansion of the samples mixed with the chloride brine water continued to decrease gradually from 0.130 mm to 0.037 mm, with the shrinkage increasing gradually at the beginning of cooling.

In comparison with the samples that added pure water for 5 times, the increasing times of adding the sulfate brine water increased the salt expansion amount, with a maximum salt expansion increasement of 7.9 times. While the primary effect of adding the chloride brine water on the samples was to increase the shrinkage, this decreased the amount of salt expansion to some extent, with a maximum salt expansion reduction of 12.4 times.

4.2.2. The analysis of salt expansion tests

The reason for this phenomenon found from Fig. 9 is discussed as follow. The Na_2SO_4 that initially dissolved in the water would absorb the water molecule to form $Na_2SO_4{\cdot}10H_2O$ under the condition of cooling as presented in Fig. 8 resulting in the salt expansion (Wan et al. 2017a). The chemical formulation of this process is $2Na^+ + SO_4^{2-} + 10H_2O = Na_2SO_4{\cdot}10H_2O$. There was a minimum salt content for the salt expansion to occur in the sulfate saline soils (Gao et al. 1997a). Because the samples used in this experiment contained a certain level of chloride salt, which can inhibit the salt expansion of the sulfate saline soil (Xiao et al. 2017), while the sulfate salt content in the soil samples was relatively low after adding the test water-A (sulfate brine water) for one time. Therefore, the amount of salt expansion was relatively low after adding the test water-A (sulfate brine water) for one time. However, the sulfate salt was accumulated to a relatively higher level after adding the test water-A (sulfate brine water) for 2 to 3 times with sufficient water content. Thus, the Na_2SO_4 phased to $Na_2SO_4{\cdot}10H_2O$ under the condition of cooling, which resulted in the salt expansion amount increased obviously after adding the test water-A (sulfate brine water) for 2 to 3 times. As the sulfate salt content in the soil samples increased after adding the test water-A (sulfate brine water) for 4 to 5 times, the total amount of water was insufficient for Na_2SO_4 to crystallize to $Na_2SO_4{\cdot}10H_2O$. Thus the amount of salt expansion became stable (Figure 9a).

With the test water-B (chloride brine water) added, the Cl^-/SO_4^{2-} ratio in the samples continued to increase, the common ion effect of NaCl on Na_2SO_4 reduced the amount of water for Na_2SO_4 crystallization, which resulted in a decreased amount of crystallized $Na_2SO_4{\cdot}10H_2O$. Thus the amount of salt expansion gradually decreased, which was proved by (Lai et al. 2017). Besides, chloride sodium in the test sample reduced the freezing point of water, the higher the concentration of chloride sodium, the more obvious the effect of reducing the freezing point. This effect of lowering the freezing point is much stronger than sulfate sodium (Wan et al. 2017a). Thus, the added chloride sodium reduced the minimum temperature that salt expansion needed, which also inhibited the salt expansion (Figure 9b).

4.3. The results and analysis of collapse tests

4.3.1. The results of collapse tests

The result of the collapse tests is shown in Figures 11 and 12. From Fig. 11, the rule of the final deformation of collapse test is presented as follows: by adding of the brine water, the final deformation increased dramatically at first and reached the largest deformation when added the brine water for three times, and then gradually decrease until stable. This rule is independent of the types of brine water.

From Fig. 11, with an increased amount of the brine water added, the collapse deformation of the soil samples increased continuously from 0.198 mm to 1.074 mm and 0.133 mm to 1.204 mm for the sulfate water and the chloride water respectively. From Fig. 12, with the addition of the brine water, no matter what kind of brine water, the collapse deformation of the samples increased continuously. However, the collapse deformation of the soil sample C5 (adding the chloride water for 5 times) was greater than that of the soil sample S5 (adding the sulfate water for 5 times). This result is consistent with that of Wang (2017) and Song (2007). Compared with the samples in which the pure water was added for 5 times, the collapse deformation of coarse grain sulfate saline increased by 4.464 times when adding the sulfate water, while that was 8.052 times when adding the chloride water.

4.3.2. The analysis of collapse tests

In the samples that mixed with the brine water for 0 to 3 times, as the water within the soil samples dissolved all the soluble salt, there was no crystal salt left to act as a pore filler or binder among soil particles. Meanwhile, the soil structure was weakened in the process of adding the brine water. Thus, the collapse deformation increased gradually with the increase of the load.

In the samples that added the brine water for 4 to 5 times, the water within the soil samples failed to dissolve all the soluble salt, resulted in that some contents of soluble salt were in the form of crystallization in the soil samples and acted as a pore filler and binder among soil particles. After adding the pure water at 200kPa (Corresponding to rainfall in nature enviornment), all the soluble salt was dissolved immediately, which weaken the soil structure as the loss of the crystallized soluble salt that acted as a pore filler and binder among soil particles. Thus, a sudden deformation increase was observed at 200 kPa for all samples and the collapse deformation increased continually after adding the brine water for 4-5 times.

The final deformation of the collapse test included three parts: the deformation before adding the pure water, the collapse deformation, and the deformation after the pure water was added. From the results, the deformation before adding the pure water was the same as the compression deformation. In the comparison of the collapse deformation and the deformation after the pure water was added, the deformation before the pure water added was higher. Thus, the final deformation behaviour is similar to that of compression deformation. No matter what kind of brine water was added to the soil samples, the undissolved sulfate and chloride salt acted as a binder or pore filler among soil particles which could all be dissolved in the process of adding the pure water at 200 kPa, resulting in the weakening of the soil structure. Thus, the collapse is occurring independently of salt types. However, as chloride is more soluble in the water than sulfate, the amount of collapse deformation is related to the salt types.

When the collapse tests were performed, the environment temperature was approximately 20°C, with the same amount of pure water added to test containers for the samples added with TL-1 and TL-2. At this temperature, the solubility of NaCl (36g/100 g water) was higher than that of Na_2SO_4 (19.5 g/100 g water), which means that more amount of NaCl can be dissolved. Therefore, the increased collapse deformation (1.071 mm) of soil sample mixed with the chloride brine water was higher than that (0.876 mm) of soil sample mixed with the sulfate brine water.

5. Conclusion

This study investigated the influence of adding different times of brine groundwater on the engineering characteristics of coarse grain embankment fill material through the large-scale consolidation compression tests, the salt expansion tests and the collapse tests . The conclusions are summarized as follow:

(1) Upon adding the brine water, the compression deformation of coarse gain sulfate saline materials showed a trend of gradual stability after the increased deformation at the beginning. The variation of the compression coefficient presented a typical three-stage law which is independent of the primary ion type in the brine water: 1) decreased stage; 2) increased stage; 3) stabilised stage. The compression coefficient of the sample that adding the brine water for 3 times is highest compared with other conditions. The accumulative effect of adding the brine water on the compression characteristics of coarse grain sulfate soil was evident and mainly related to the cumulative salt amount in the soil samples and the distribution form of crystallized salt among soil particles.

(2) Under the condition of cooling, with the sulfate brine water added, the salt expansion of coarse grain sulfate saline fill materials showed a trend of a noticeable increase at the beginning followed with a stabilized deformation. The amount of salt expansion increased by 7.9 times at most compared with the samples that added the pure water only. When the salt content in the soil sample reached a certain level—about 2% (after adding the sulfate brine water 4 times), limited by the amount of water to dissolve the soluble salt, the salt expansion tended to be stabilized.

(3) Under the condition of cooling, with the chloride brine water added, there was shrinkage behaviour observed in the coarse grain sulfate saline fill materials, which inhibited the salt expansion. The salt expansion deformation was significantly reduced and then stabilized. The salt expansion deformation was reduced by 12.4 times at most compared with the samples that added the pure water only. The inhibition effect of chlorine salt on the salt expansion of coarse grain sulfate saline fill materials was mainly related to the relative content of NaCl and Na_2SO_4 accumulated in the soil after the brine water added.

(4) With the brine water added, the collapse deformation of coarse grain sulfate saline fill materials showed a trend of continuous increase, which increased the collapse deformation by 8.05 times at most compared with the samples that added the pure water only. The accumulative effect of adding the brine water on the collapse characteristics of coarse grain sulfate saline fill materials was evident and mainly related to the cumulated salt amount in the soil and the

distribution form of crystallized salt among soil particles.

According to this study, it is further shown that even a small amount of the soluble salt in groundwater may have a greater impact on the engineering properties of coarse grain embankment fill materials considering the cumulative effect of the soluble salt. It is recommended that preventive measures should be carried out during the construction process for safety consideration in the saline soil areas.

Conflict of interest

There are no conflicts of interest.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. (1) Ion assay results of soil samples collected along D-Y highspeed railway. (2) Ion assay results of the groundwater samples collected along D-Y highspeed railway project. (3) Other data can be obtained from submitted paper.

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Table 1 Soluble salt content of test samples

Test sample	Natural soil sample /%				After adding salt /%			
	SO_4^{2-}	Cl^-	HCO_3^-	Total content of soluble salt	SO_4^{2-}	Cl^-	HCO_3^-	Total content of soluble salt
TL-1	0.09	0.02	0.01	0.16	0.16	0.02	0.01	0.36
TL-2	0.10	0.02	0.01	0.18	0.34	0.04	0.01	0.77

Table 2 The main ion contents of test water samples

Test water	Positive ions (g/L)		Negative ions (g/L)		Total mineralization (g/L)
	Na^+	K^+	SO_4^{2-}	Cl^-	
Test water-A	9.70	20.11	45.00	0.00	74.81
Test water-B	9.97	21.45	0.00	35.00	66.42

Table 3 Design scheme of adding test water

Types of test water	Test samples	number	Time of adding test water	Times of adding pure water
Test water-A	TL-1	S0	0	5
		S1	1	4
		S2	2	3
		S3	3	2
		S4	4	1
		S5	5	0
Test water-B	TL-2	C0	0	5
		C1	1	4
		C2	2	3
		C3	3	2
		C4	4	1
		C5	5	0

Table 4 Changes of the void ratio of samples added brine water 1-5 times compared with that of adding pure water under the load of 400 kPa

Times of adding brine water / Samples	1	2	3	4	5
TL-1	-0.001	-0.002	-0.010	-0.006	-0.007
TL-2	-0.001	-0.002	-0.006	-0.004	-0.004

Table 5 Stable deformation amount and ratio (compared with samples added pure water for 5 times) of samples mixed with brine water for 0-5 times

Times of adding brine water (Times)	0	1	2	3	4	5
Stable deformation of TL-1(mm)	-203.25	-234.25	-265.25	-440.50	-340.40	-321.63
Stable deformation of TL-2(mm)	-221.50	-244.25	-267.00	-396.50	-281.67	-274.80
Average stable deformation of TL-1 and TL-2(mm)	-212.375	-239.25	-266.125	-418.5	-311.034	-298.214
Deformation ratio of TL-1(%)	0%	15.25%	30.50%	116.73%	67.48%	58.24%
Deformation ratio of TL-2(%)	0%	10.27%	20.54%	79.01%	27.16%	24.06%

Figure Captions list

Fig. 1 Sampling location（https://www.google.com/maps/place）

Fig. 2 The particle size distribution of samples

Fig. 3 Self-made temperature controlling test box. (a) Temperature controlling test box. (b) principle diagram of the temperature control test box. (c) The test container that put inside the test box

Fig. 4 Test device for collapsibility test

Fig. 5 e-p curve of the whole compression process. (a) TL-1 with test water sample-A (sulfate) (b) TL-2 with test water sample-B (chloride)

Fig. 6 The change of soil deformation with the times of adding brine water

Fig. 7 Changes in the coefficient of compressibility (100-200kPa)

Fig. 8 Solubility curve of soluble salt (Lai et al. 2017; Wan et al. 2017)

Fig. 9 The relationship between the sample deformations and cooling time with different added salt types and different added times when temperature reduce from 25°C to -15°C. (a) TL-1 with test water sample-A (b) TL-2 with test water sample-B

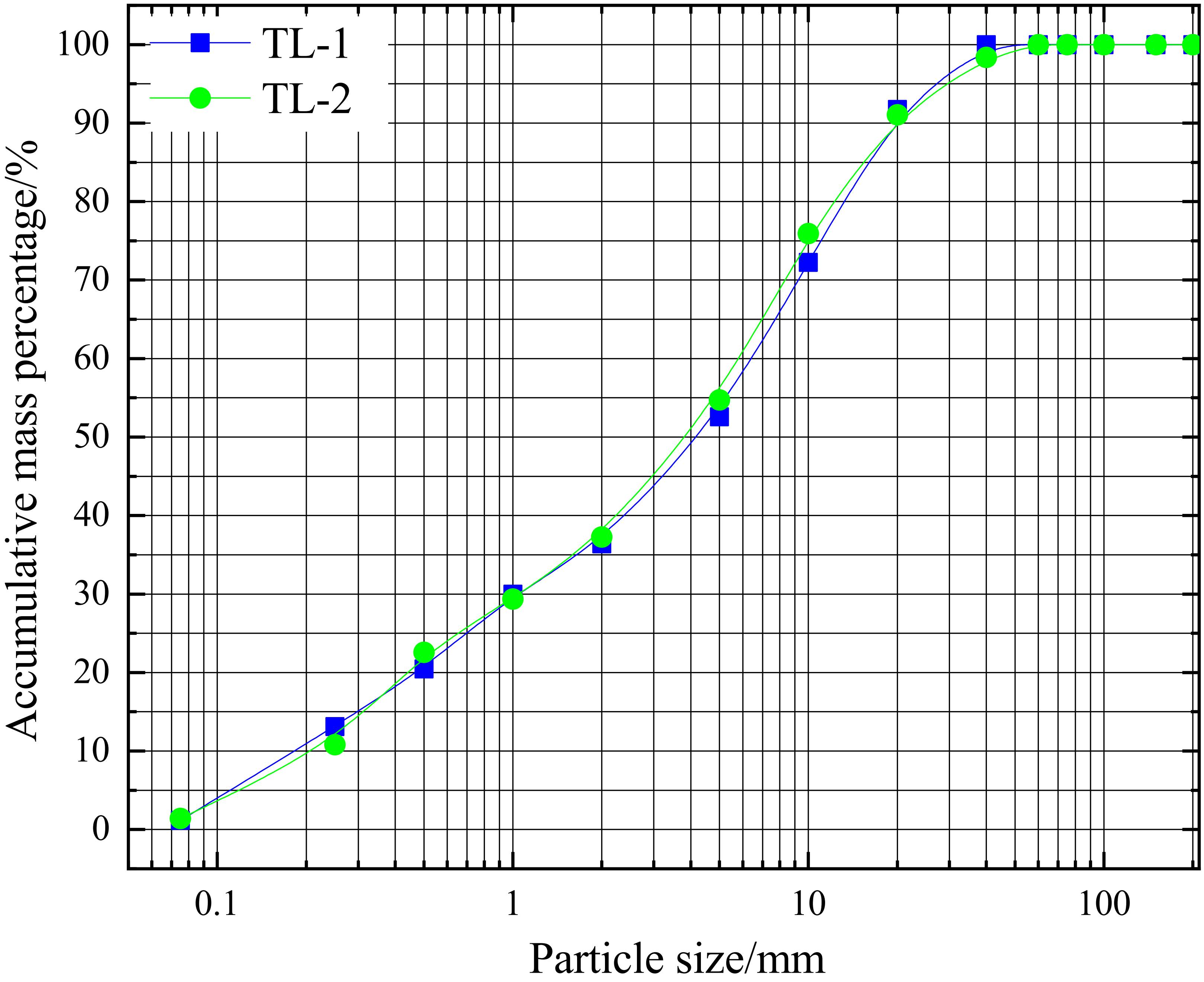
Fig. 10 Samples after cooling

Fig. 11 Load-deformation-relation curve of the sample with brine water added times. (a) TL-1 with test water sample-A (sulfate) (b) TL-2 with test water sample-B (chloride)

Fig. 12 Variation of collapse deformation with the times of adding brine water

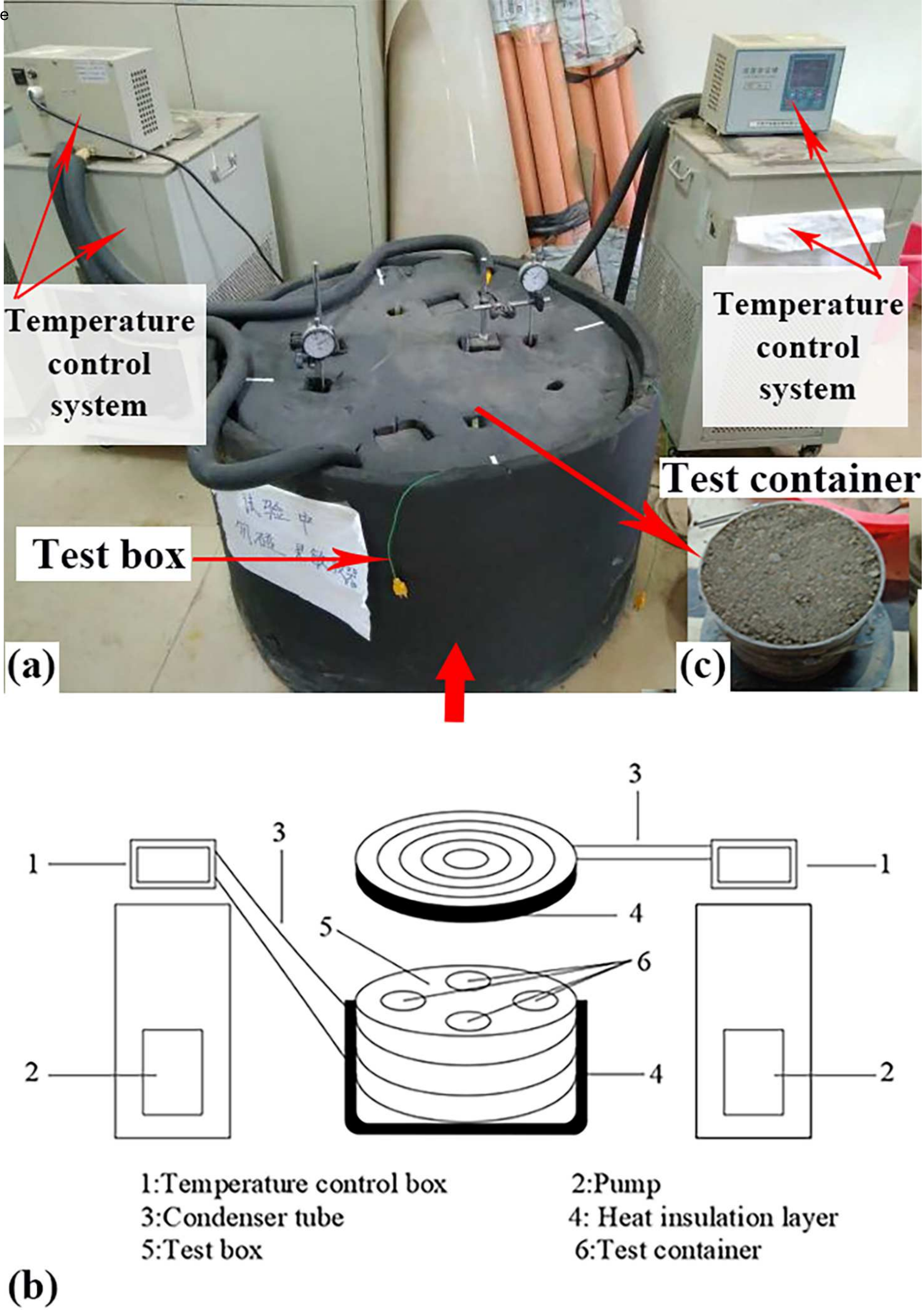
Figure

Figure

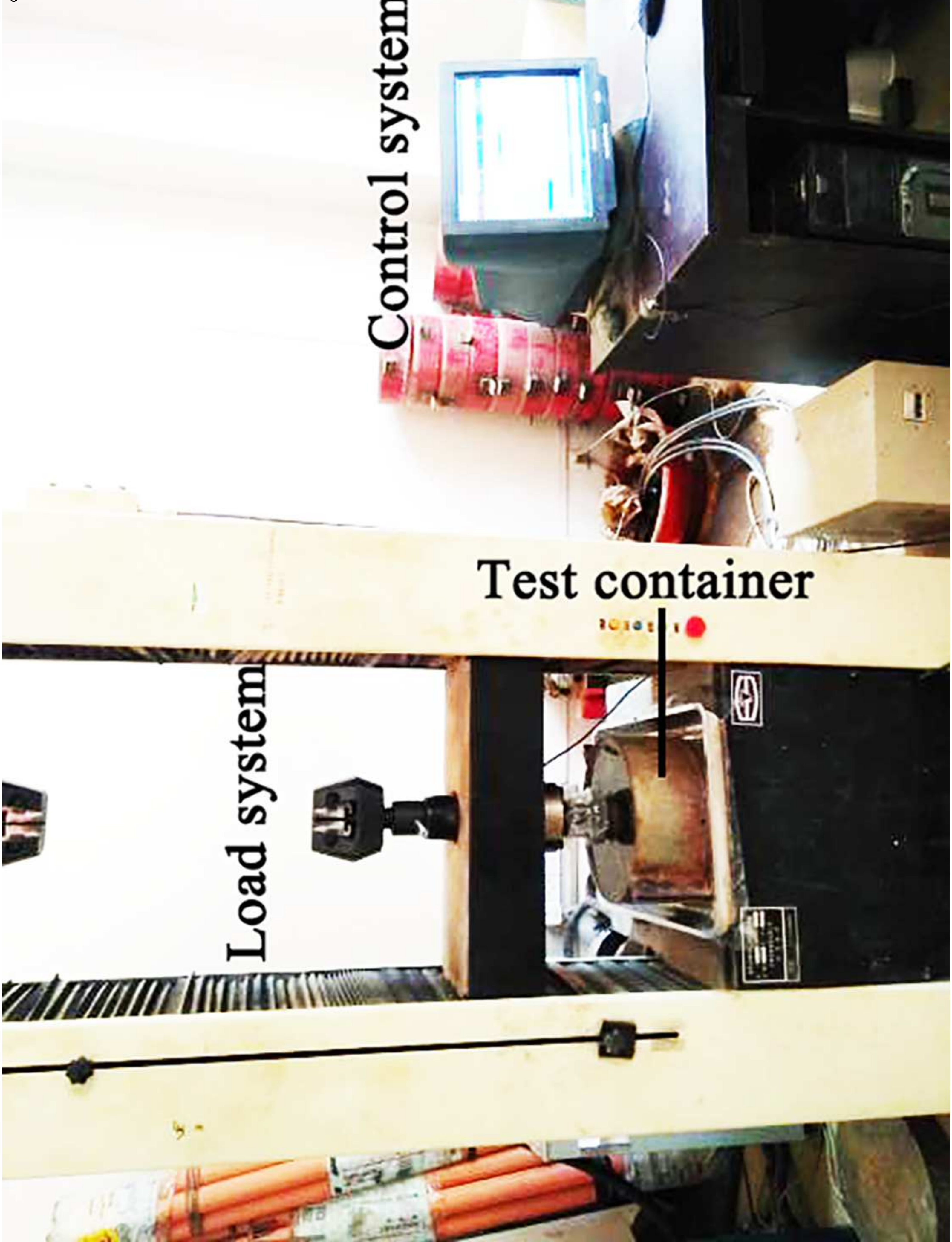


TL-1
TL-2
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Accumulative mass percentage/%
Particle size/mm

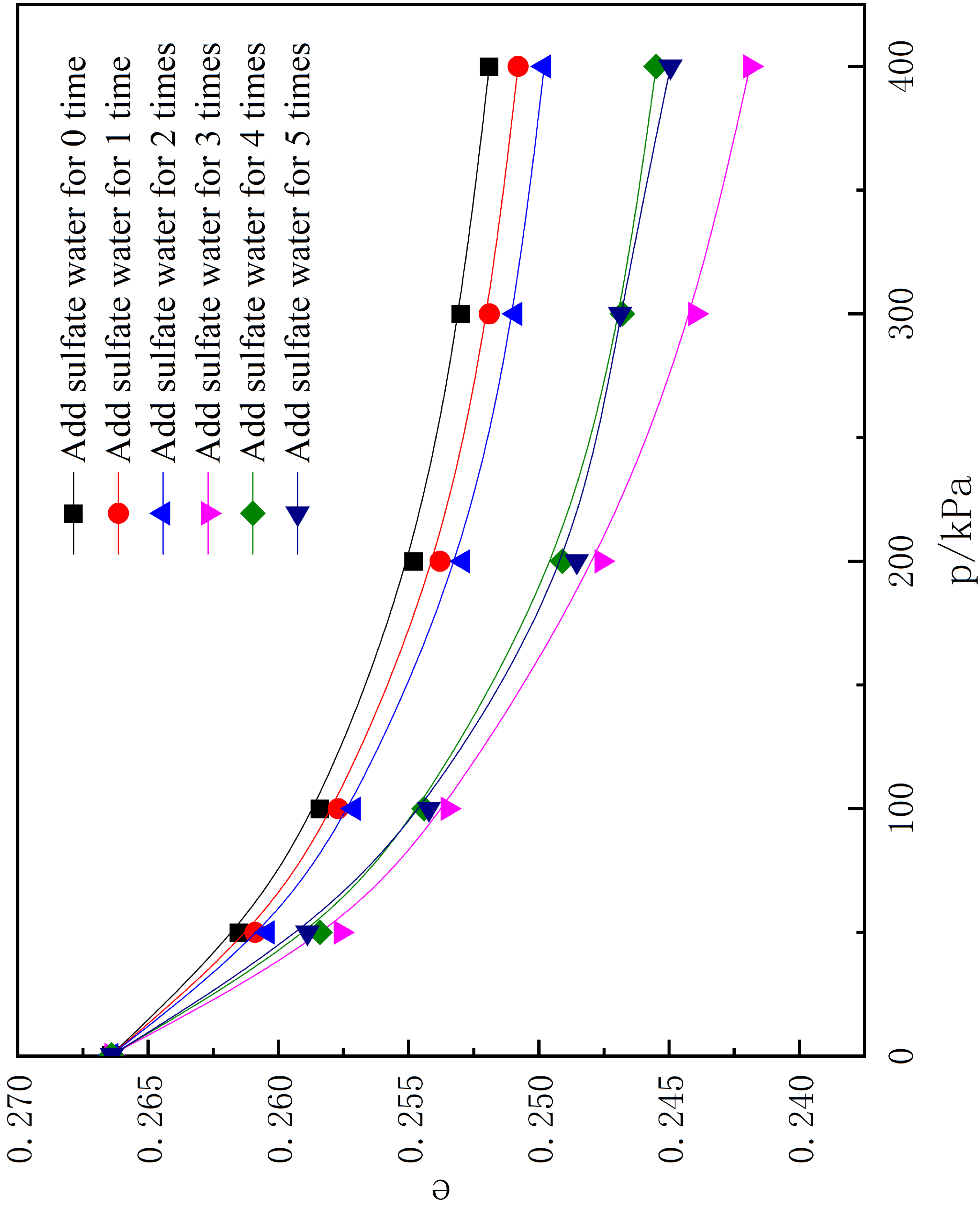
Figure


Temperature control system
Temperature control system
Test container
Test box
(a)
(c)
1
1
2
2
3
3
3
4
4
5
6
1:Temperature control box
2:Pump
3:Condenser tube
4: Heat insulation layer
5:Test box
6:Test container
(b)

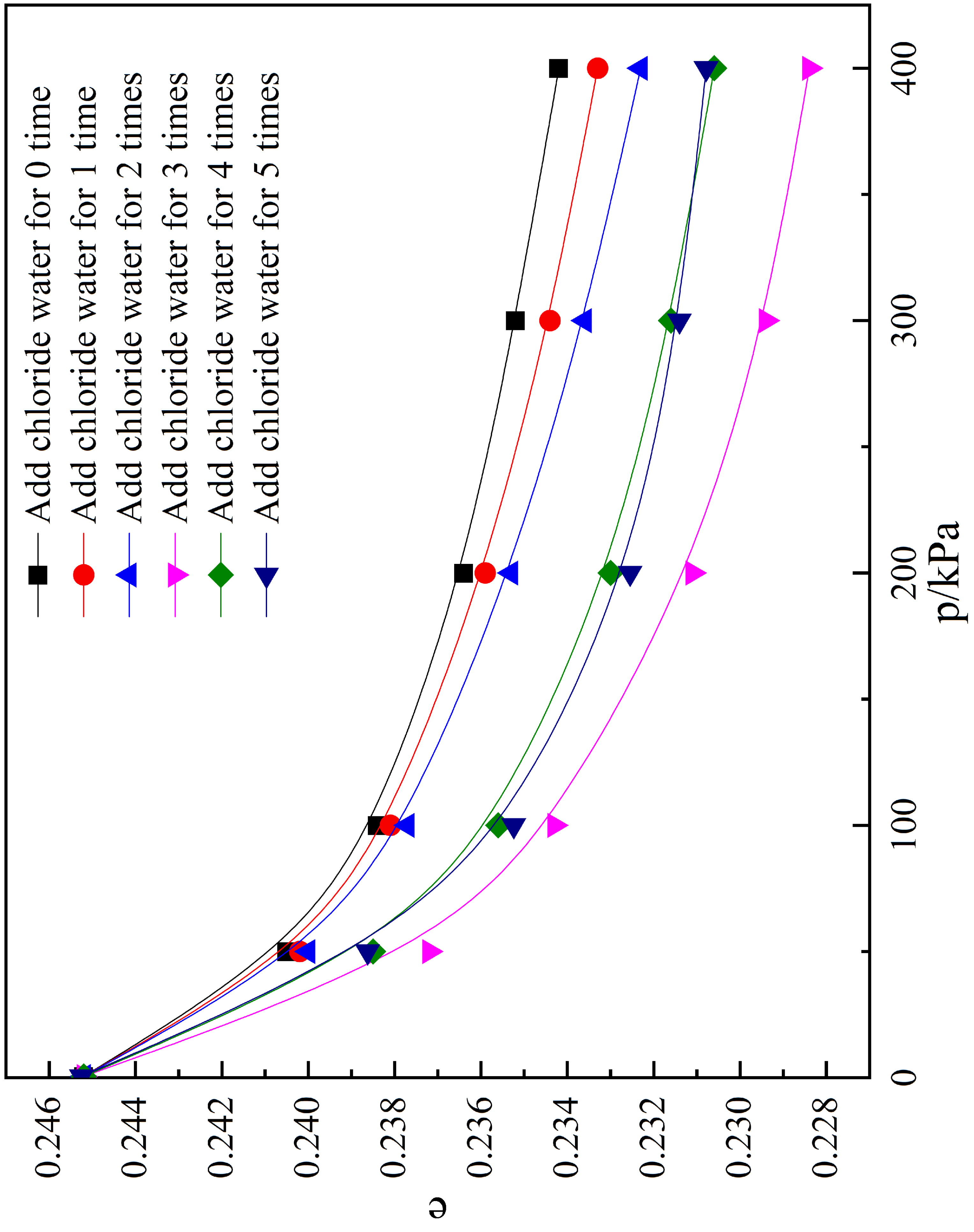
Figure



Figure

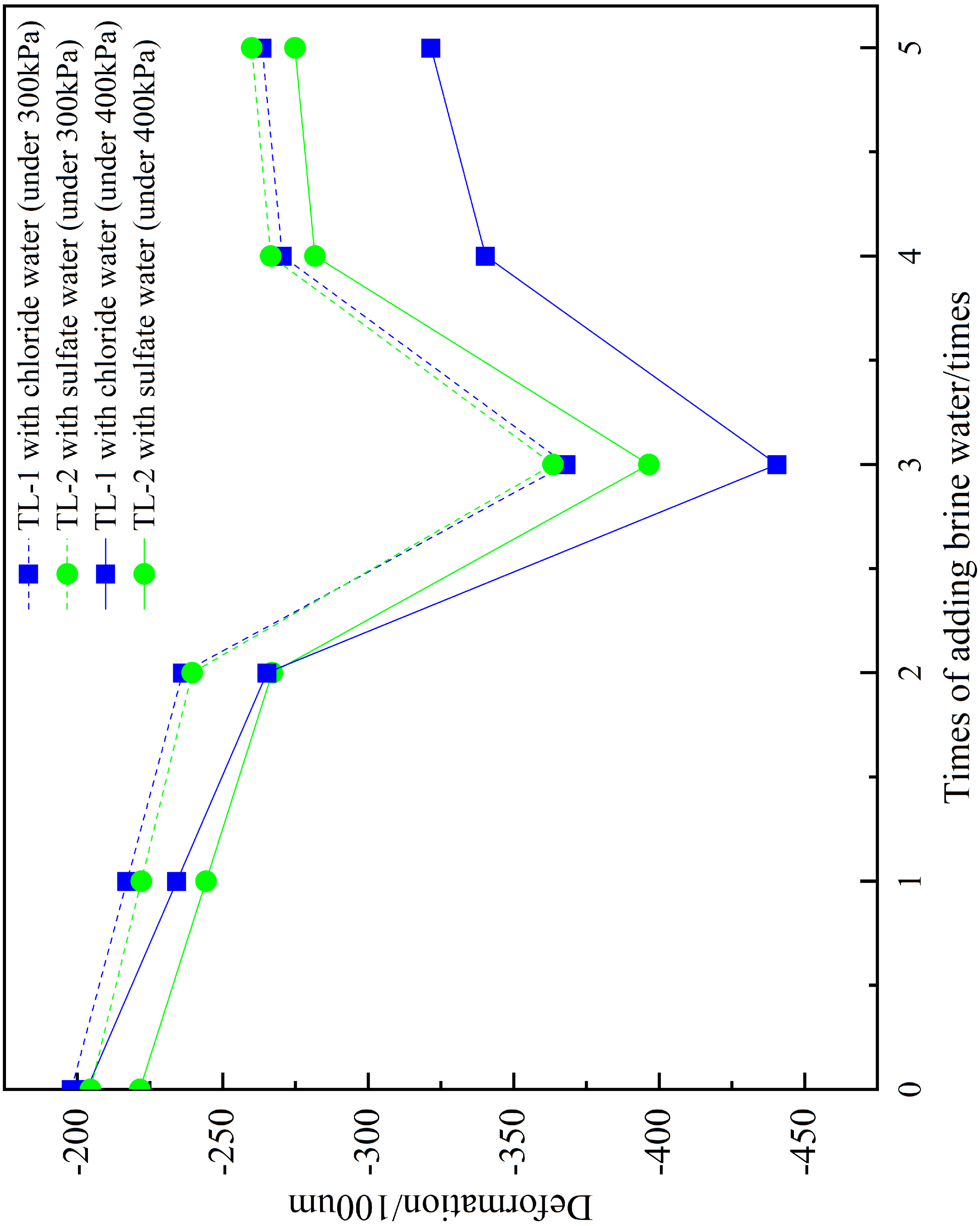

Add sulfate water for 0 time
Add sulfate water for 1 time
Add sulfate water for 2 times
Add sulfate water for 3 times
Add sulfate water for 4 times
Add sulfate water for 5 times
e
0. 270
0. 265
0. 260
0. 255
0. 250
0. 245
0. 240
p/kPa
0
100
200
300
400

Figure

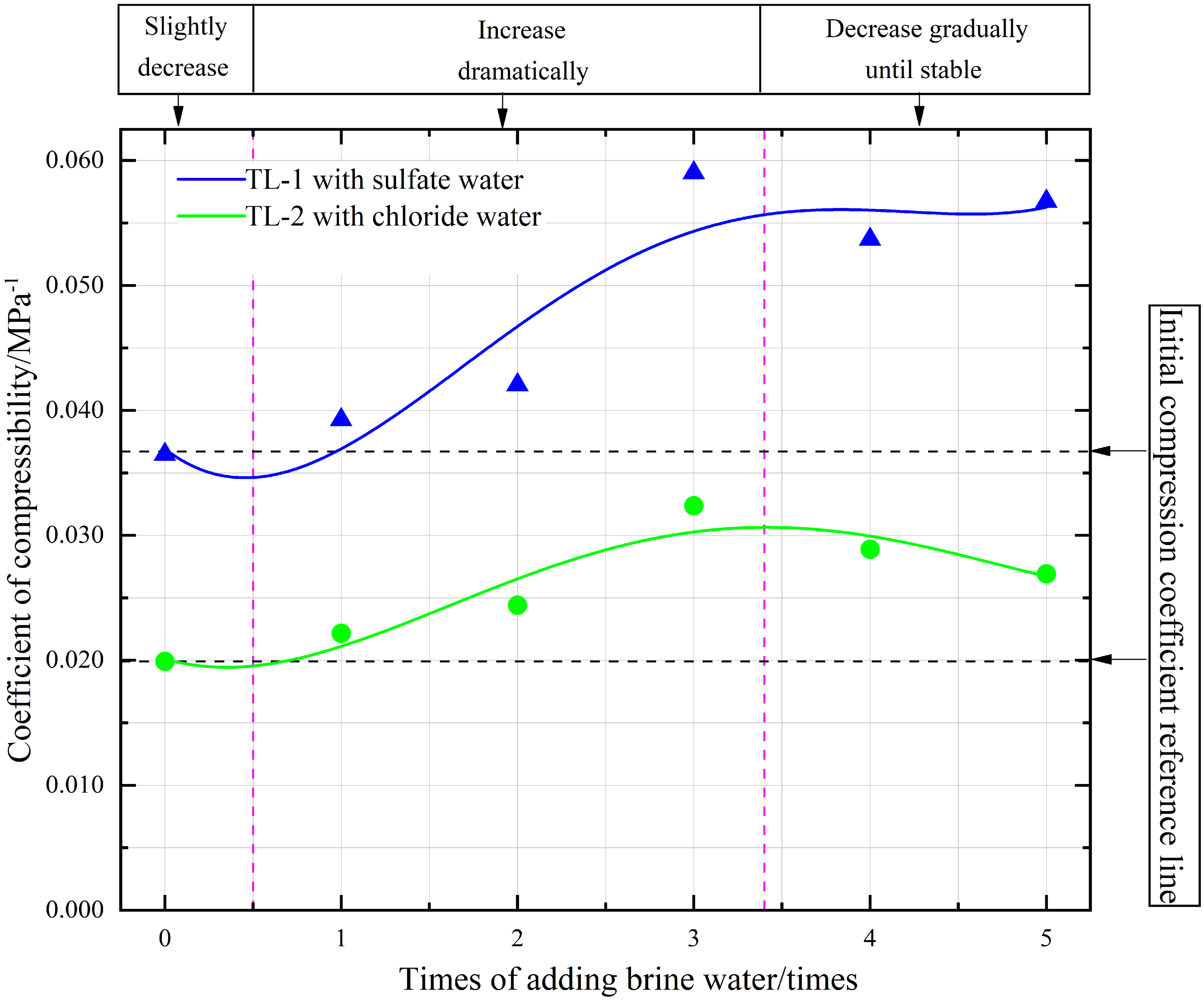


■ Add chloride water for 0 time
● Add chloride water for 1 time
◀ Add chloride water for 2 times
▶ Add chloride water for 3 times
◆ Add chloride water for 4 times
▼ Add chloride water for 5 times
e
p/kPa
0
100
200
300
400
0.246
0.244
0.242
0.240
0.238
0.236
0.234
0.232
0.230
0.228

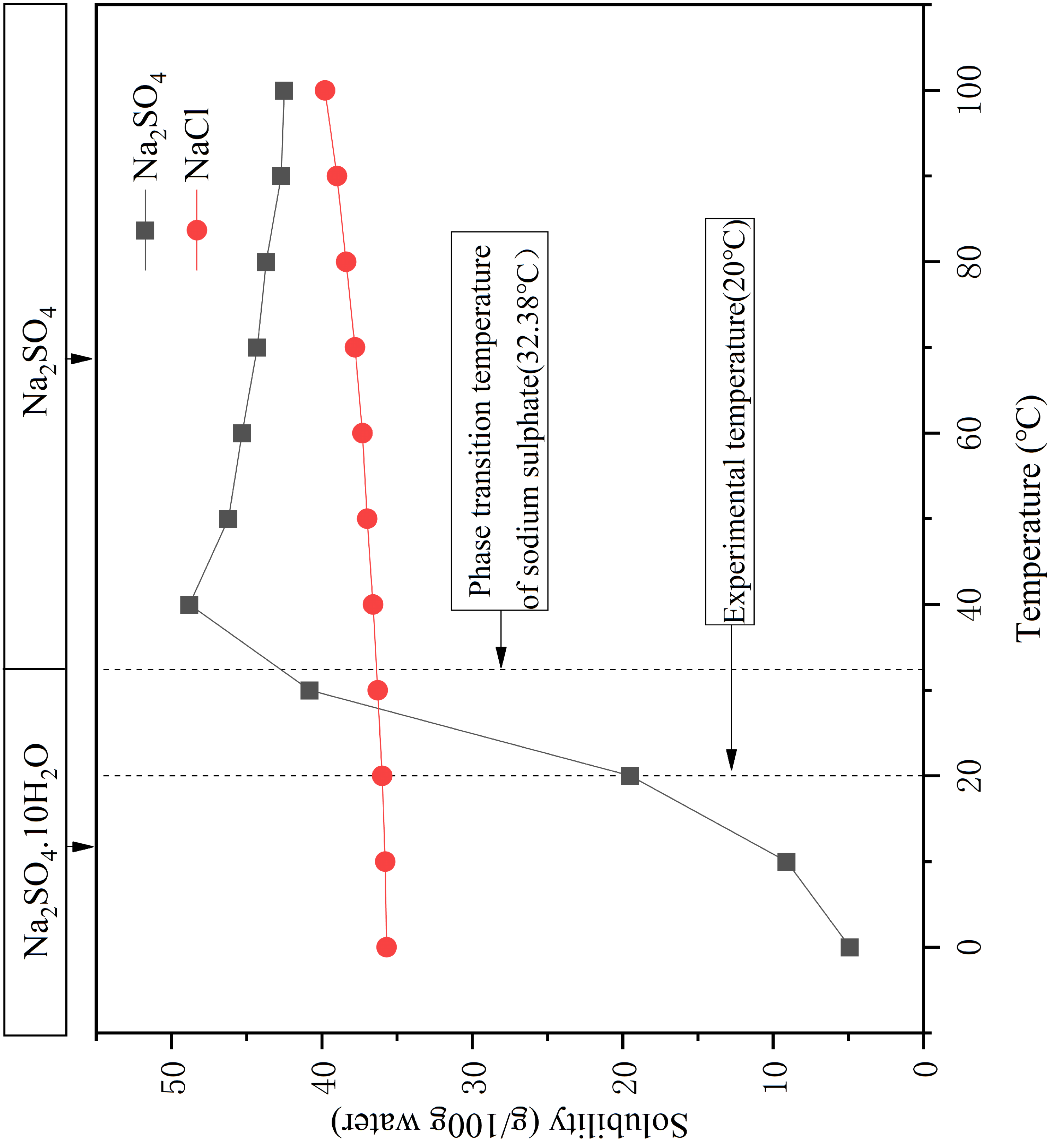
Figure


TL-1 with chloride water (under 300kPa)
TL-2 with sulfate water (under 300kPa)
TL-1 with chloride water (under 400kPa)
TL-2 with sulfate water (under 400kPa)
Times of adding brine water/times
0
1
2
3
4
5
Deformation/100um
-200
-250
-300
-350
-400
-450

Figure

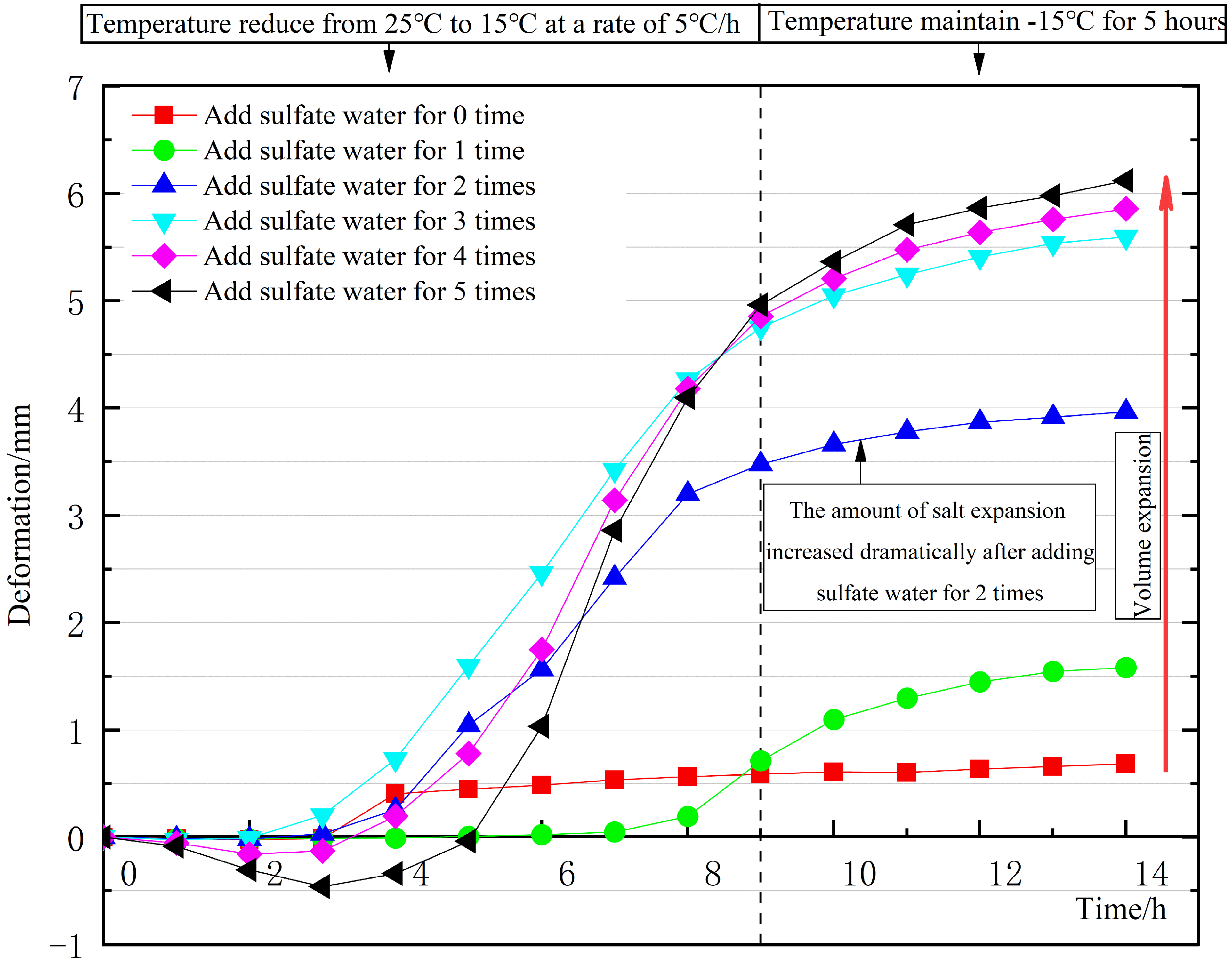

Slightly decrease
Increase dramatically
Decrease gradually until stable
TL-1 with sulfate water
TL-2 with chloride water
Initial compression coefficient reference line
Coefficient of compressibility/MPa^{-1}
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0
1
2
3
4
5
Times of adding brine water/times

Figure

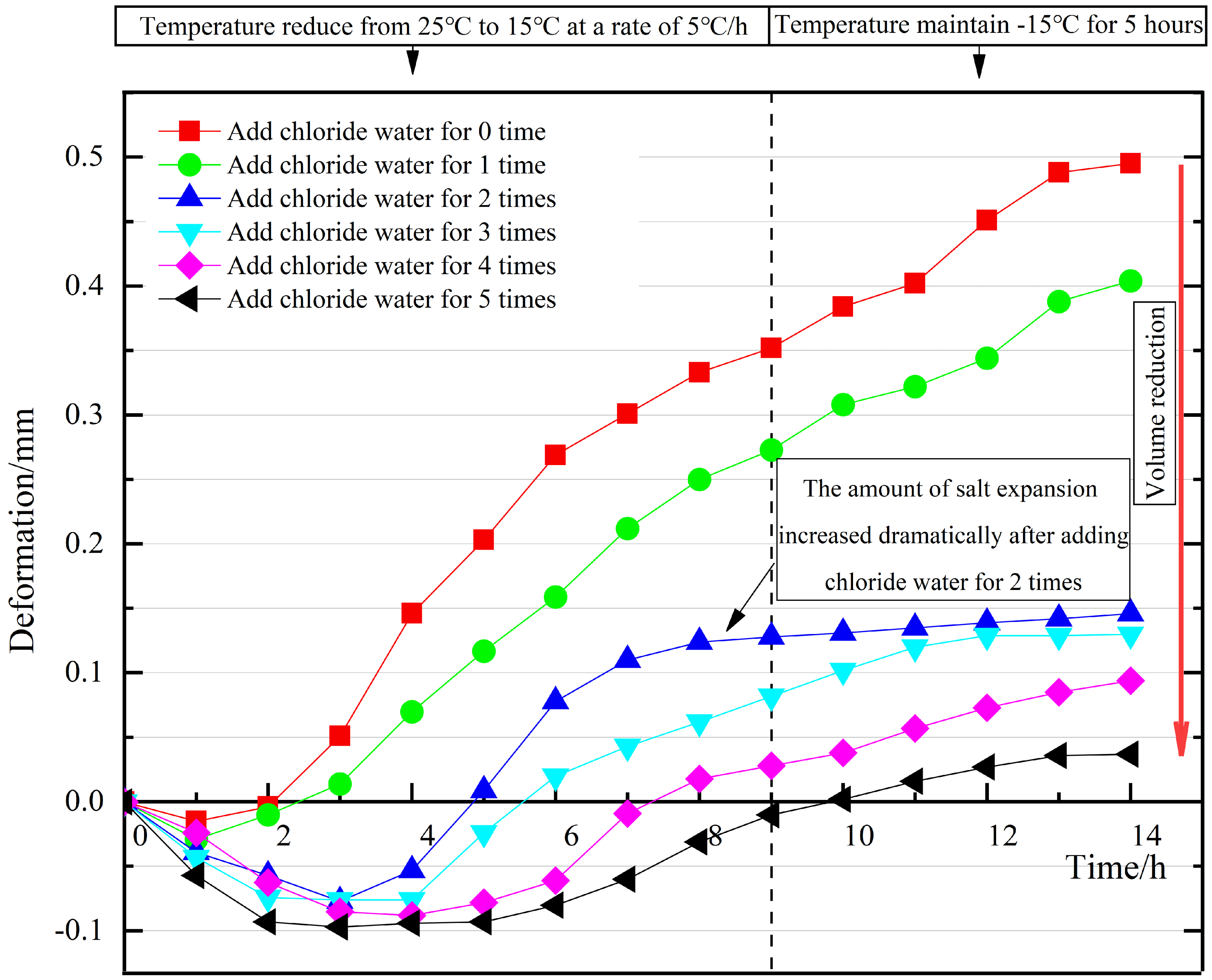


$Na_2SO_4.10H_2O$
Na_2SO_4
Na_2SO_4
NaCl
Phase transition temperature of sodium sulphate(32.38°C)
Experimental temperature(20°C)
Solubility (g/100g water)
Temperature (°C)
0
10
20
30
40
50
0
20
40
60
80
100

Figure

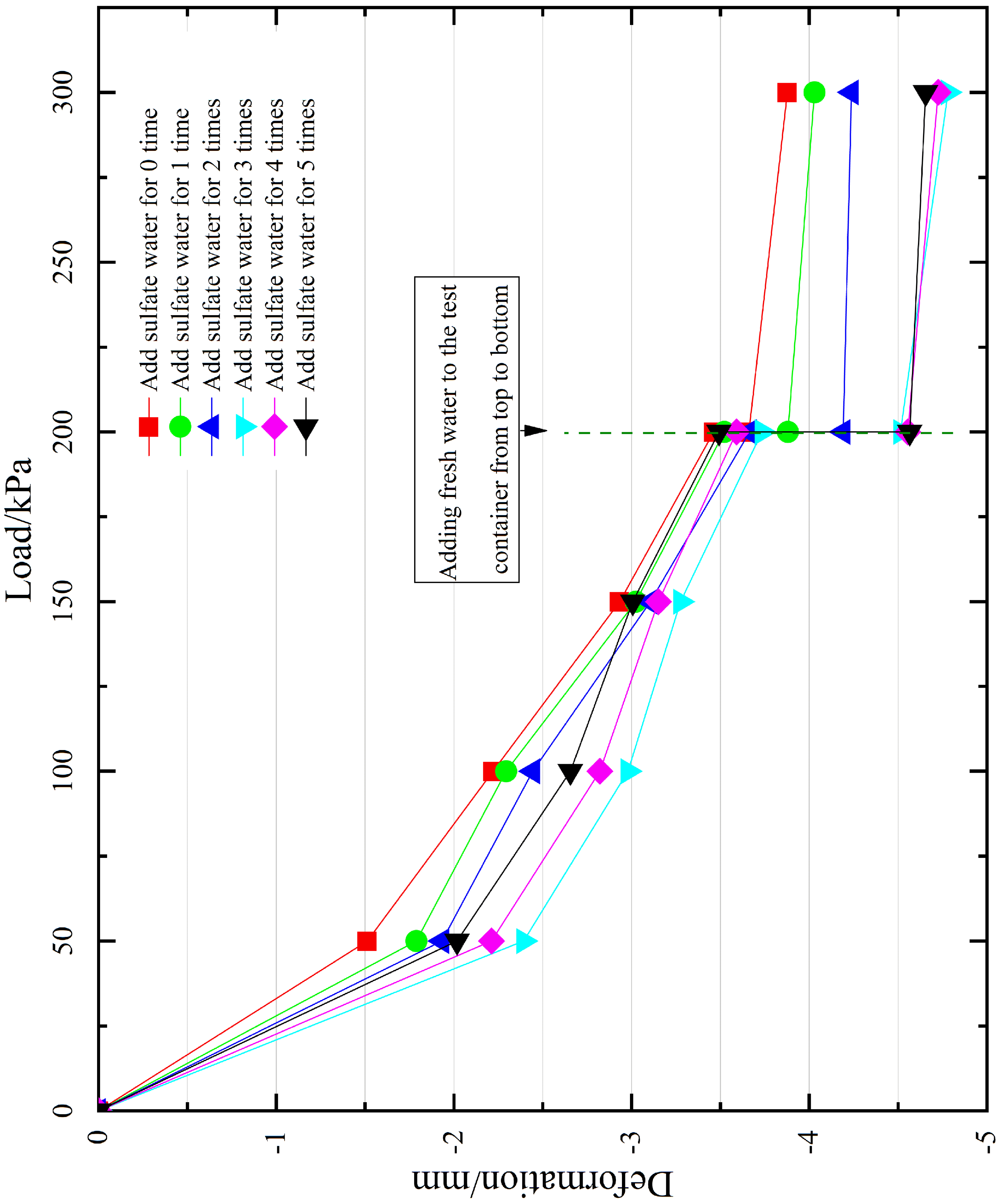

Temperature reduce from 25°C to 15°C at a rate of 5°C/h
Temperature maintain -15°C for 5 hours
Add sulfate water for 0 time
Add sulfate water for 1 time
Add sulfate water for 2 times
Add sulfate water for 3 times
Add sulfate water for 4 times
Add sulfate water for 5 times
The amount of salt expansion increased dramatically after adding sulfate water for 2 times
Volume expansion
Deformation/mm
Time/h
7
6
5
4
3
2
1
0
−1
0
2
4
6
8
10
12
14

Figure


Temperature reduce from 25℃ to 15℃ at a rate of 5℃/h
Temperature maintain -15℃ for 5 hours
Add chloride water for 0 time
Add chloride water for 1 time
Add chloride water for 2 times
Add chloride water for 3 times
Add chloride water for 4 times
Add chloride water for 5 times
The amount of salt expansion increased dramatically after adding chloride water for 2 times
Volume reduction
Deformation/mm
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
2
4
6
8
10
12
14
Time/h

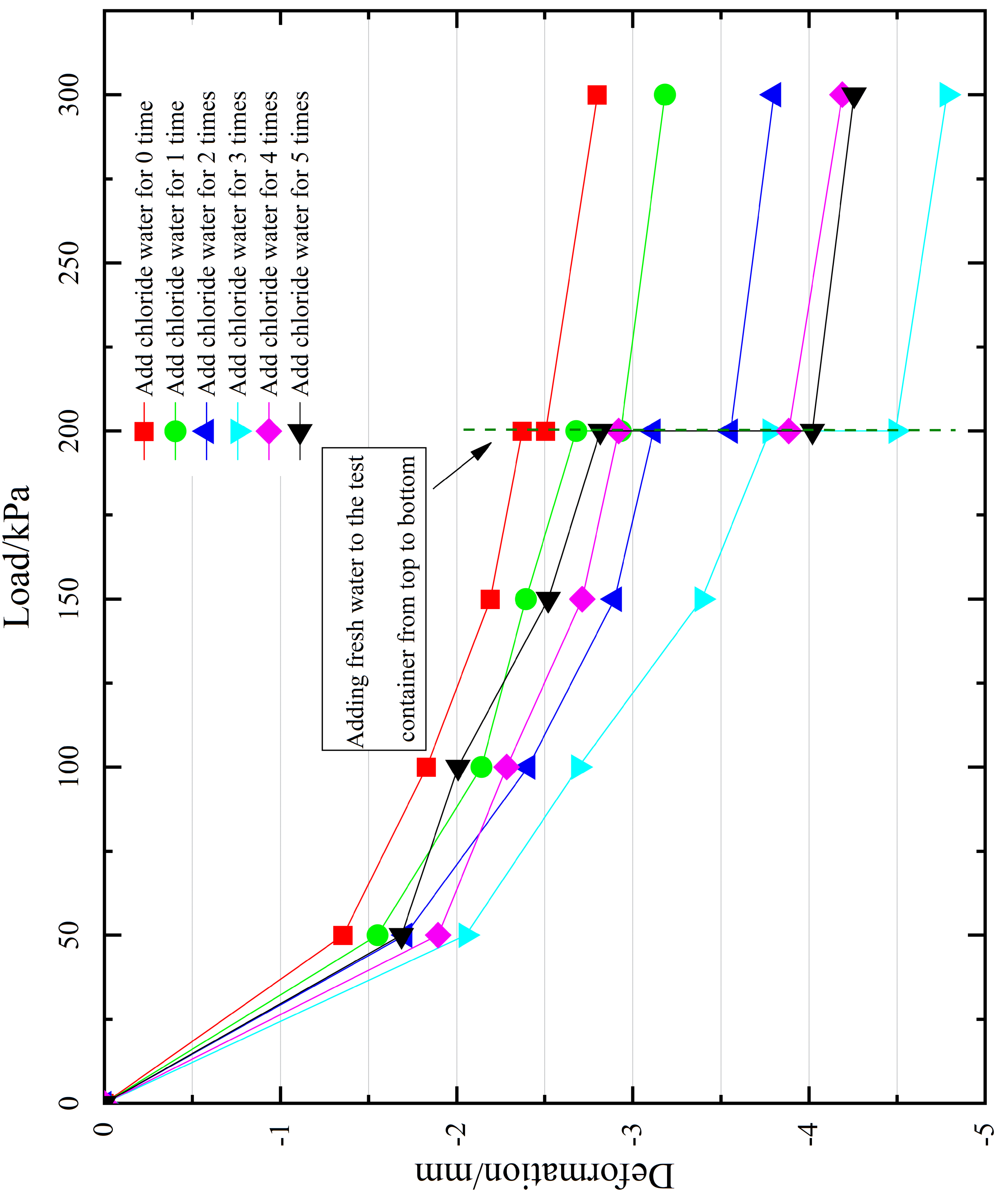
Figure

Figure



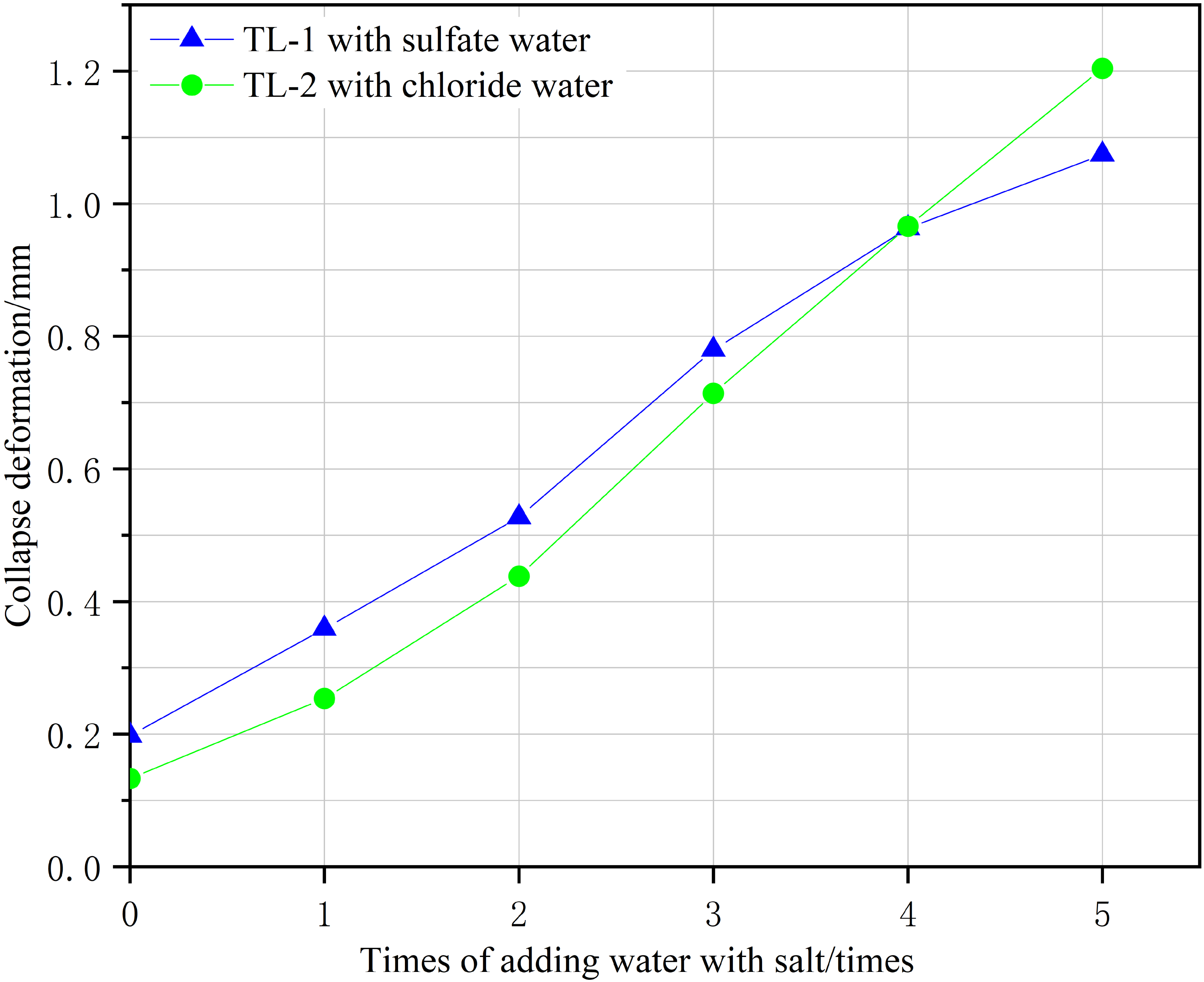
Load/kPa
Deformation/mm
0
50
100
150
200
250
300
0
-1
-2
-3
-4
-5
Add sulfate water for 0 time
Add sulfate water for 1 time
Add sulfate water for 2 times
Add sulfate water for 3 times
Add sulfate water for 4 times
Add sulfate water for 5 times
Adding fresh water to the test
container from top to bottom

Figure



Load/kPa
Deformation/mm
0
50
100
150
200
250
300
0
-1
-2
-3
-4
-5
Add chloride water for 0 time
Add chloride water for 1 time
Add chloride water for 2 times
Add chloride water for 3 times
Add chloride water for 4 times
Add chloride water for 5 times
Adding fresh water to the test container from top to bottom

Figure


TL-1 with sulfate water
TL-2 with chloride water
Collapse deformation/mm
0. 0
0. 2
0. 4
0. 6
0. 8
1. 0
1. 2
0
1
2
3
4
5
Times of adding water with salt/times