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An experimental study on the influence of cooling rates on salt expansion in sodium sulfate soils

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ABSTRACT

This experimental study examined salt expansion in sodium sulfate soils. The results indicated that salt expansion was caused by the crystallization of sodium sulfate decahydrate when the supersaturation ratio of the sodium sulfate solution in the soil reached a maximum value. The maximum supersaturation ratio of the sodium sulfate solution decreased as the sodium sulfate content increased, and the supersaturation ratio decreased as crystals continued to precipitate. The total amount of crystal generation was related to the crystal growth rate. The rate of crystal growth decreased exponentially as temperature decreased. The formation of crystals was influenced by the rate of cooling. When mirabilite began to precipitate, the supersaturation rate was reduced versus the rate of cooling, whereas the salt expansion rate of the soil increased. When the salt content of sodium sulfate was less than 1.5%, salt crystals began to form after the phase change of the solution from water to ice, but salt expansion did not occur. When salt content of sodium sulfate was less than 0.7%, the precipitation of salt crystals was minimal or did not occur.

1. Introduction

Saline soils cover 2% of the total land area in China, and are widely distributed in Sinkiang, Qinghai, Gansu, Ningxia, Inner Mongolia, and other locales (Luo, 1980). These soils are problematic to the development of farms, and also to the construction and engineering of roads, channels, and airports, because of the swelling of salt crystals when the sodium sulfate soil freezes. Studies on salt expansion in sodium sulfate soils in China have mainly focused on measuring the expansion ratios of soils with different salt contents (Chen et al., 1989; Wang et al., 2006; Zhang and Gao, 2010). Factors that affect salt expansion include water content, salt content, the initial dry density, and the overlying load (Gao et al., 1996; Gu et al., 2009). The calculation of salt expansion and the precipitation of salt crystals in soils are usually based on the phase diagram for the corresponding solution (Niu and Gao, 2008). However, the calculation by Niu and Gao (2008) may have had a lower degree of accuracy because there was little discussion of the solution's properties in the unsteady-state, and no consideration of the metastable phase. In addition, there was very little investigation into the process and timing of salt crystal precipitation. When the supersaturation rate of the sodium sulfate solution causes crystal precipitation, salt heaving of the soil will occur, and sodium sulfate decahydrate or heptahydrate is formed as the sodium sulfate combines with either ten or seven water molecules, respectively (Steiger and Asumssen, 2008). Very few studies have discussed the influences of the rate of cooling on the supersaturation rate of sodium sulfate solutions when crystals initially precipitate at low temperatures.

Most studies concerning salt expansion from outside China have examined the supersaturation rate of solutions in brick, concrete, rock, and other building materials, and have discussed the salt heaving force generated when different salt solutions begin to crystallize (Robert, 2002; Steiger, 2005; Espinosa et al., 2008; Koniorczyk, 2010). However, few studies have investigated the initiation and growth of salt crystals in natural soils, and when soil has been involved, salt expansion has only been studied at room temperature (Mokni et al., 2010). Salt expansion at lower and negative temperatures remains uninvestigated.

Sulfate saline soils are widespread in the western cold region of China. The damage to roads caused by salt expansion and frost heave remains an ongoing problem. Research on sulfate saline soil in cold regions faces urgent questions due to the large temperature variations in these environments, such as: at what supersaturation rate will salt crystallization occur in soils, how does the maximum supersaturation rate of solutions in soil vary at different cooling rates, and what influences will salt crystallization exert on salt expansion? This paper focuses on the influence of different cooling rates on salt crystallization and expansion in sodium sulfate saline soils, which can cause serious damage to infrastructure on Qinghai–Tibet Plateau.

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2. Experimental design

Silty clay from the Qinghai–Tibet Plateau was sampled in the laboratory. The measured plastic and liquid limit for this soil was 16.4% and 27.9%, respectively (Bin and He, 2011). The sample was desalinated, dried, and pulverized. Then, five samples with 18% gravimetric water content and different salt contents (the ratio of the mass of salt to the mass of water-free soil) (0%, 2.1%, 2.6%, 3.2%, 3.8%) were made and sealed at room temperature for 24 h for uniformization. Next, the samples were placed in plastic cups and compacted in five layers to make samples of 6.3 cm in diameter and 7.5 cm in height. The dry density and porosity of the desalinated samples were 1.711 g/cm^3 and 0.37, respectively.

A Stevens Hydra Probe (SDI-12) (Fig. 1a) manufactured by Stevens Water Monitoring Systems, Inc., accurate to ±0.0014S/m, operating temperature: −30 ~ 65 °C and measurement range: 0.01 ~ 1.5 S/m; a thermistor with ±0.01 °C accuracy, and a NS-WY02 displacement sensor (Fig. 1b) manufactured by Shanghai TM Automation Instruments Co., Ltd., accurate to ±0.001 mm and measurement range: 0.001 ~ 50 mm, were installed into the soil samples to monitor variations in conductivity, temperature, and displacement. The thermistors and Stevens Hydra Probes were inserted into samples encased by waterproof plastic sheets, and the displacement sensors were set to contact the top surface of soil samples. A programmable ultra-low temperature chamber (manufactured by Dongguan Terchy Test Equipment Co., Ltd. in China, Fig. 1c) was also used to vary conditions to simulate the temperature regime of cold regions. The data acquisition system was a date taker CR3000 (Fig. 1d) with intervals set to 10 s, which was manufactured by Campbell Scientific headquarters, Logan, UT, USA. It supports complex applications with many sensors, so the test results could be stored in CR3000. The experimental setup is shown in Fig.2. After installing the experimental apparatus, the temperature chamber was held at 25 °C for 30 min to eliminate measurement errors caused by any temperature differences of the samples. The temperature was then decreased at a rate of 0.02 °C/min and then held steady at 0 °C.

3. Crystal precipitation in sodium sulfate saline soil at positive temperatures

3.1. Supersaturation ratio of sodium sulfate solution

The experimental data were analyzed to describe the internal temperature variations of the soil samples (Fig. 3). One sodium sulfate molecule and ten water molecules combine to form sodium sulfate decahydrate when the supersaturation ratio of the solution reaches a maximum value. When crystals began to precipitate, the temperature increased, due to the exothermic nature of the precipitation reaction. This caused small increases or 'jumps' in temperature along the cooling curve (Wan et al., 2015), which were less pronounced at lower salt contents (Fig. 3). We considered the point at which the temperature rises as the initial temperature of salt precipitation. Therefore, the initial precipitation temperatures of different solution concentrations were determined. The experimental results showed that as salt content decreased, the initial precipitation temperature also decreased. It is commonly the supersaturation ratio of the solution that determines the range of metastable solutions in which salt crystallization may occur. The differences in the maximum supersaturation ratios observed when solutions with different salt contents begin to crystallize are discussed below.

a) Stevens Hydra Probe (SDI-12) b) NS-WY02 displacement sensor

c) The programmable ultra-low temperature chamber d) Date Taker CR3000

Fig. 1. The diagram of test sensors and equipment.