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Mechanisms During Formation of Ice Lenses and Suction in Freezing Soils

Les mécanismes de la formation des lentilles de glace et de succion au cours de la congélation du sol

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ABSTRACT: In the course of frost penetration in the soil the formation of ice lenses may result under certain boundary conditions. Due to the development of suction, water is drawn from unfrozen parts to the frost line. In this paper an apparatus for conducting experiments is presented which serves to determine the ice lens building process as well as the suction. Within the scope of the test program different dependencies are analyzed for understanding the mechanisms of suction development and for making predictions on the formation of ice lenses possible. The test results show the connection between suction development and ice lens formation. It also shows that even without external water supply reallocation processes take place.

RÉSUMÉ : La pénétration du givre dans le sol contribue, sous certaines conditions limites, à la formation de lentilles de glace. A cause du développement du processus de succion, l'eau des parties non gelées migre vers le front de gel. Cet article présente un centre d'essai, qui permet, d'une part, d'effectuer les tests sur la formation de lentilles de glace et, d'autre part, d'analyser le processus de succion. Dans le cadre du programme expérimental, plusieurs dépendances ont été analysées afin de mieux comprendre les mécanismes de formation de succion et d'améliorer les prédictions sur la formation de lentilles de glace. Les résultats de ses expériences montrent un lien entre le développement du processus de succion et la formation des lentilles de gel, et que, sans apport supplémentaire d'eau en dehors de l'échantillon, le processus de migration peut avoir lieu.

KEYWORDS: frozen soil, ice lenses, suction, frost heave

1 INTRODUCTION

In the course of artificial and natural ground freezing, when the frost penetrates into the ground, in many cases, frost heaves occur. If they are not well controlled (Kellner et all 2006) they may lead to damages to buildings that are close by. Thus, the objective is to predict frost heaves and preferably to minimize them.

Depending on the existing boundary conditions, the heaves are caused for two different reasons. Generally, there is an increase in volume of 9 % caused by the transformation of water into ice. Moreover, ice lenses may develop for fine-grained soils. During the frost penetration into the ground water migrates from the unfrozen areas of the soil towards the frost line. There, the water is accumulated in layers of pure ice that splits the ground. The reason for the water migration is a suction which can be measured when the water migration is impeded.

The fact that the fundamental processes may change the thawed soil properties makes the prediction of the expected frost heaves and their potential minimization even more substantial.

In the past, many experiments were conducted to investigate different influences on the formation of ice lenses (Konrad and Morgenstern 1980, 1982). Until now, the assessment of the frost susceptibility of a soil was based on the particle size distribution and the plastic soil properties but did not take into account the influences of the mineralogy or the ion concentration of the pore water. Nor had the analysis of the suction as cause of the water migration to the ice lens been paid particular attention. However, in recent research the influence of overburden pressure has been investigated (Kellner 2008) with its influence on pore water development due to freezing.

Nevertheless, the underlying mechanisms of suction and their influencing factors are not yet finally resolved. For this reason freezing tests are run at our institute to investigate the development of ice lenses and determine the suction. Our institute has developed a model of osmotic pressure (Zou and Boley 2008) to describe the mechanisms. Based on these tests, the model can be verified and improved. The freezing tests are presented in the following chapters.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the test apparatus to run freezing tests investigating the development of ice lenses as well as determining the suction.

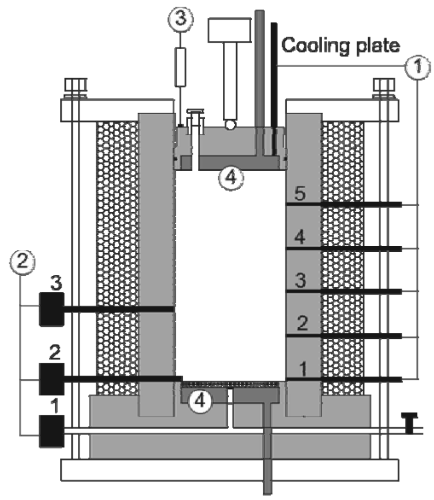


Figure 1. Schematic of freezing cell: (1) temperature sensors 1-5 and temperature sensor at upper cooling plate, (2) pore water pressure transducer, (3) displacement transducer, (4) cooling plate

Test program investigates the influence of the applied surcharge, material type and the ion concentration of the pore water on the suction and development of ice lenses. The test apparatus essentially consists of an acrylic glass cylinder with an inner diameter of 80 mm. The two cooling plates (4) allow setting up a defined temperature gradient in the specimen. The upper sealing and loading is realized through a piston. The ice lens experiments are conducted in open-system freezing, meaning that the specimen is connected to a storage vessel and hence it has free access to water. To investigate the suction, the water access is disabled so the system changes into a closed-system freezing test. The temperature sensors (1) are distributed over the height and record the time depending temperature development. To determine the suction in the closed-system, pore water pressure transducers (2) are used. The frost heave is measured with a displacement transducer (3).

In advance, the test material is mixed with deionized water so that the swelling and ion exchange processes have taken place prior to commencement of the experiments. Subsequently, the ion composition of the water is determined. The material is filled into the cylinder in pasty condition and is consolidated in the test apparatus by applying a defined surcharge. For the closed-system freezing tests, the valve for the water supply is shut. The step-freezing method is used to freeze the specimen. Therefore, the temperature of the upper cooling plate is lowered to a defined value meanwhile the temperature of the lower cooling plate is still held constant. Thus, the frost migrates top down, starting fast and slowing down over time until thermal steady state is reached. The cylinder is lubricated with a high vacuum silicon grease to reduce the friction between the specimen and the acrylic glass. At the end of the test, the specimen is pushed out of the cylinder to saw them into slices. This allows determining the distribution of the water content over the specimen height.

3 MATERIALS TESTED AND TESTING PROGRAMM

The development of ice lenses and suction during freezing strongly depend on the respective material. Different materials are chosen to investigate the influence of grain-size distribution and the mineralogy: kaolin (K), bentonite (TS), silt (S), limestone powder (KK) and quartz powder (Q) were chosen as fine grained materials. Also, tests with fine sand (Fs) were conducted. Figure 2 shows the grain size distribution and further soil properties are given in Table 1.

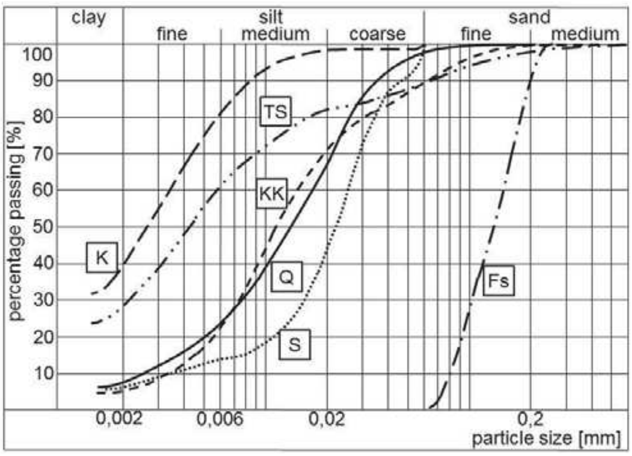


Figure 2. Grain-size distribution curve of the tested materials

Within the scope of the test program, different dependencies shall be analyzed. Primarily, the influence of material on the development of ice lenses as well as on the suction is analyzed. Influences of the applied surcharge will be investigated by applying loads of 20, 50, 100, 300 and 600 kN/m². Besides the normal consolidated specimens with the loads as stated, overconsolidated specimens were tested as well. Further, the tests are conducted with 2 different temperature gradients between the cooling plates. The influences of the ion concentration in the pore water on the suction and the development of ice lenses are analyzed by comparing the results of tests with natural ion concentration in the pore water and those with particularly enriched ion concentration in the water. The natural ion concentration results from the exchange between dried material and the deionized water.

Table 1. Soil properties of the tested materials

	K	*TS*	*S*	*KK*	*Q*	*Fs*
Liquid limit w_L [%]	55,6	134,7	22,7	-	-	-
Plastic limit w_P [%]	24,6	37,1	21,5	-	-	-
Hydraulic conductivity k [m/s] (surcharge 100 kN/m²)	$1{,}5\cdot 10^{-9}$	$1{,}6\cdot 10^{-10}$	$1{,}1\cdot 10^{-8}$	$4{,}0\cdot 10^{-8}$	$2{,}9\cdot 10^{-8}$	$1{,}5\cdot 10^{-6}$
Grain density ρ_s [g/cm³]	2,63	2,73	2,70	2,73	2,66	2,65
Cation exchange capacity Γ [meq/100g]	4,7	88,9	6,1	2,4	0,9	0,3
Specific surface area A_s [m²/g]	10,1	44,4	6,3	2,5	1,1	0,02

4 TEST RESULTS

In the following, the results of the experiments with varying materials in combination with different surcharges will be presented. The specimens have a natural ion concentration in the pore water and are frosted with a temperature gradient of 1.9 °C/cm.

4.1 *Frost penetration*

Figure 3 shows the temperature distribution over the specimen at different times exemplarily for one test.

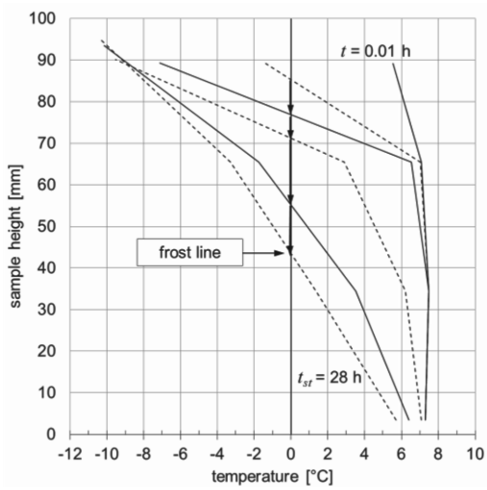
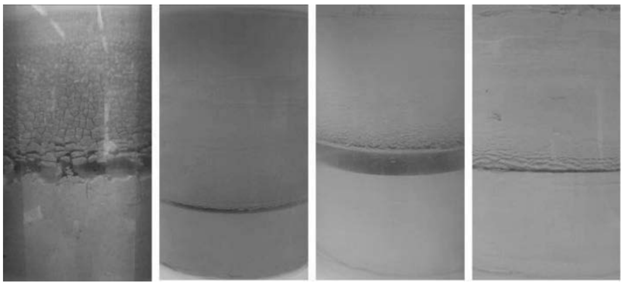


Figure 3. Temperature profile within the specimen (kaolin) at different times, from right to left: 0.01 h, 0.07 h, 0.15 h, 0.83 h, 4.17 h, 28 h

The temperature of the upper cooling plate drops rapidly to the set temperature meanwhile the temperature of the lower cooling plate is kept constant. The temperatures at the other sensors are decreasing time delayed until the thermal steady state is established after the time t_{st}. Based on the diagram the position of the frost line and their temporal shift can be identified. The frost line is the transition between the frozen upper sections and the unfrozen part. The position stays constant by reaching the time t_{st}. The fast frost penetration at the beginning is linked to a sharp temperature gradient. Only within the steady state the requested temperature gradient appears.

4.2 *Ice lens formation in open-system freezing*

Figure 4 shows the different ice lens formation in open system freezing for selected materials. The biggest ice lenses develop in the transition zone between frozen and unfrozen areas in the thermal steady state.



a) b) c) d)

Figure 4. Specimens at the end of open system freezing tests: a) TS (100 kN/m²), b) S (20 kN/m²), c) K (20 kN/m²), d) K (100 kN/m²)

Under the chosen test conditions, the greatest changes can be observed for the bentonite (a) due to its intense capacity to draw water to the frost line and also due to the initially high water content. Water migrates from the storage vessel into the specimen as a result of frost penetration. Furthermore, the existing water in the specimen is reallocated initially resulting in fine distributed ice lenses (dark areas) and with a slowing frost penetration in a development of bigger ice lenses. In contrast, the Kaolin (c) tests show only little structural changes. In the upper part only little water enrichment is noticeable and it is smoother distributed throughout the height. Comparing the results for silt (b) and kaolin (c) with a surcharge of 20 kN/m² it is apparent that the final ice lens can grow thicker for kaolin than for silt. The comparison of ice lens formation in kaolin with a surcharge of 20 kN/m² (c) and 100 kN/m² (d) clearly shows that a higher surcharge is restricting the formation. In tests with quartz powder and fine sand no water migration into the specimen was observed. Tests with limestone powder have shown little water intake and reallocation but it is too less to be visible on the picture.

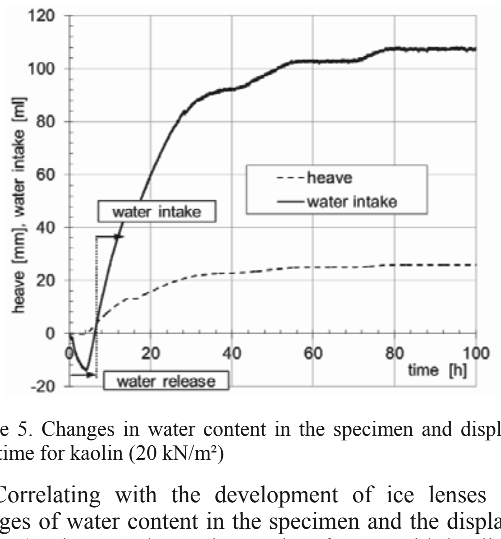


Figure 5. Changes in water content in the specimen and displacement with time for kaolin (20 kN/m²)

Correlating with the development of ice lenses are the changes of water content in the specimen and the displacement (heaves). Figure 5 shows the results of a test with kaolin with a surcharge of 20 kN/m². Initially, water is expelled until it is water drawn in the specimen and a noticeable heave builds up. This effect was also observed in investigations of Konrad and Morgenstern (Konrad and Morgenstern 1982). In the course of the experiment, the kaolin specimen absorbed approximately 122 ml of water. In contrast, the water content for a limestone powder specimen under the same test conditions is at the end lower than at the beginning of the test. This is due to the fact that the absorbed amount of water is not compensating for the water that was initially expelled.

4.3 *Processes in open-system freezing*

The test series aims at investigating the suction as principle for the water flow and the development of ice lenses. For a test with kaolin, Figure 6 shows the development of suction and heave in the course of frost penetration. Simultaneously with the beginning of the freezing process and movement of the frost line into the specimen suction, builds up. Its maximum of 0.88 bar is already reached after approximately 8.5 hrs. The thermal steady state is reached after 16 hrs. The course of the heave follows the temperatures. The initially fast frost penetration is reflected in a strong increase of heave. With the slowing of frost penetration the heave curve flattens. After the thermal steady state has been reached the further increase of the heave is only marginal.

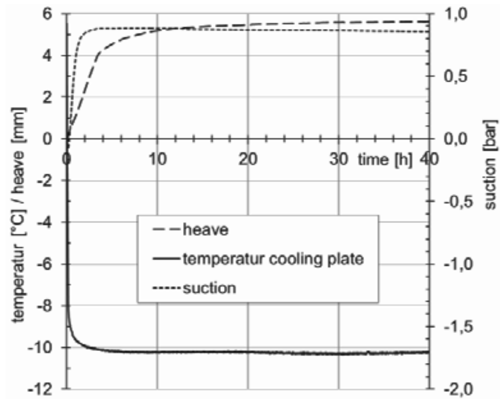


Figure 6. Development of suction and heave for kaolin due to drop of temperature of the cooling plate (surcharge 20 kN/m², overconsolidated, closed system)

Even in closed-system freezing reallocation processes emerge within the specimen due to the suction that develops at the frost line. Under the assumption that water is incompressible and no air is in the system, the water can technically not flow towards the frost front. If the adjacent unfrozen soil could be consolidated further under the influence of suction, it is possible that water can be drawn to the frost line from these unfrozen areas. The amount of water transported in this way is limited by the predefined water content of the specimen and therefore not necessarily visible. However, sawing the specimen allows determination of the water content distribution over the specimen.

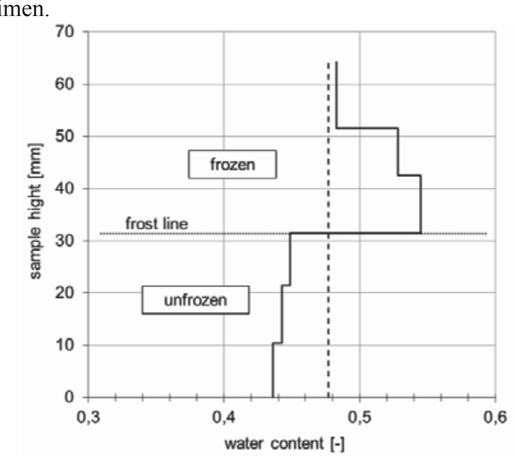


Figure 7. Water content distribution for a test with kaolin with an applied surcharge of 300 kN/m² (closed system)

Figure 7 shows the water distribution for a test with kaolin (300 kN/m²). Shown as the dashed vertical line is the initial water content. The horizontal line describes the border between the frozen and unfrozen areas at the final state of the test. With the onset of freezing the suction increases and the water is drawn into the area of the frost line. The slower the frost penetrates, the more water can reach the frost line. This leads to an increasing water content from the top down and small ice lenses become visible. In the closed system, the consolidating of the unfrozen area leads to a reduction of the initial water content. This water redistribution is also the reason for the slight heave increase after reaching the steady state.

Analyzing suction in a closed system is limited by laws of physics. If the water pressure falls below the atmospheric pressure or increases the suction, the boiling temperature decreases and the water changes its physical state from liquid to vapor even at lower temperatures. This can occur in free pore water as well as in the water of the pressure transducers. Since gas is able to expand in vacuum, the pore water pressure will change if a gas bubble builds up in the system. In order to delay this process, the water used for the tests is conditioned in a vacuum to release dissolved gases in advance. Nevertheless, suctions greater than 0.9 bar are difficult to reach. After reaching the maximum suction and the potential development of gas bubbles the measured suction drops. The water reallocation that occurs in closed systems is supported by the gas forming, because additional water can flow to the frost front when the gas expands.

The magnitude of the measured suction in closed-system freezing varies significantly between the different materials. In tests with fine sand, no suction could be measured. Accordingly no water intake was observed in tests with an open system. The results for quartz powder only show a low suction. Therefore, the consistency of the results will be verified in further tests. In general the highest suction values were measured for kaolin with absolute values around 0.9 bar and bentonite with 0.8 to 0.9 bar. Also silt reached high suction values of 0.4 to 0.9 bar. Lower values were measured in the tests with limestone powder in the range of 0.2 to 0.6 bar.

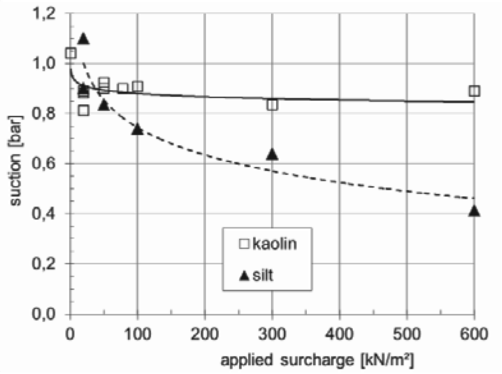


Figure 8. Dependency of the maximum suction on the applied surcharge

Figure 8 shows a comparison of the suction values for kaolin and silt with the same surcharge. A clear correlation between the maximum suction and the surcharge can be deduced from the results of silk. Hence, the higher surcharge is not only hindering the intake of water into the specimen in the open system, but also influencing the suction as principle of the water flow. Constantly high ultimate suction values greater than 0.8 bar were measured in the tests with kaolin under different surcharges. Compared to the results of silk, kaolin shows a stronger suction for surcharges greater than 50 kN/m². This also explains the less intense water reallocation of silk in a closed system and as well as the lower amount of water intake in the open system compared to the same tests done with kaolin. For kaolin under the same test conditions, the ultimate suction values show no correlation with the surcharge. The extremely high suction values suggest that the greatest possible suction could not be reached in these experiments due to the changing aggregate state of the water that is finally limiting the measurement. Consequently, the theoretical possible suction for kaolin is greater than 1 bar, as long as the water has not passed from liquid into a gaseous state.

5 CONCLUSIONS

An experimental apparatus was presented to run tests determining the suction in closed systems and analyzing ice lenses development in open systems. It was demonstrated, that in materials allowing a development of ice lenses as well as an intake of water into the specimen in open-system freezing, a corresponding suction could be measured in the closed system. The test data is used to verify and extend the theoretical model. Besides the dependency of suction on the applied surcharge also the correlation between suction and ion concentration in the pore water and in particular, the material specific properties such as the specific surface area and the surface charge shall be taken into account. Accordingly, further soil properties need to be determined as well as the ion concentration in the free pore water. In the main the magnitude of the cation exchange capacity corresponds to the magnitude of the measured suction. Transferring the results from closed system to open system and to ice lenses development the determining factor for the water migration is suction. However, the hydraulic permeability is crucial for the amount of water that is moved. Bentonite shows a pronounced suction but in comparison to kaolin or silt under the same surcharges only little water can be moved in a certain time due to the lower coefficient of hydraulic conductivity.

6 ACKNOWLEDGEMENTS

The authors would like to thank the Deutsche Forschungsgemeinschaft for supporting this research project.

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