

Ice lens formation in frozen soils: a review on experiments and theory

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ABSTRACT: Ice lens formation is a phenomenon commonly observed in areas with water-saturated, partially frozen fine grained to sandy soils. These can be found, for example, in permafrost regions or underground constructions where frozen soil is used as ground improvement during the excavation process termed as artificial ground freezing (AGF). Currently, models that combine the key processes responsible for ice lens formation are not established in practical engineering due to the lack of validation and computational effort. Therefore, as a first step new research has been initiated aiming for the design and building of an experimental device capable of performing measurements at high spatial resolution needed to validate existing models so far applied in fundamental research. For the conceptual works and consequently for designing the novel experimental device an extensive literature review on the investigations of ice lens formation in partially frozen soil has been carried out. In this study firstly, a detailed description of the search strategy used to identify the reviewed literature is presented. The study covered the fields of geotechnical engineering and nature science reaching for both fundamental and applied research. As a result, factors influencing ice lens formation based on the theories developed and confirmed since 1930 are presented. A major focus on the review was the categorization and discussion on commonly used as well for specific investigations individually designed experimental devices. The principal categorization led to two classes of experimental devices: those collecting data a) from global observations hence measurements at the sample boundaries on the macro-pore scale (e.g. total frost heave) and those b) from isolated observations on the meso-/micro-pore scale (e.g. showing water migration due to a thermal gradient). Based on the discussion of the various concepts of existing experiments in scope of the proposed model validation, the major characteristics of the novel experimental device are drawn. In addition to the works highlighting the specifications of the novel experimental device conclusions are drawn proposing new supplementing investigations (e.g., determination of the soil freezing curve, SFC), necessary to establish the datasets for comprehensive model validation.

KEYWORDS: Ice lens formation, Permafrost, Artificial ground freezing (AGF), Frozen soil, Frost heave, Literature review, experimental device.

1 INTRODUCTION

Artificial ground freezing (AGF) is an environmentally friendly construction technique used to temporarily increase the stiffness and strength of the subsoil and provide water tightness. It can be implemented effectively in urban conditions where the risk of using other subsoil improvement and water tightening techniques can be high due to complex or partially unknown boundary conditions and the consequences of damage (Orth 2018).

A major risk of AGF concerns the change of the pore volume and the associated soil deformations that can be induced by pore water freezing and thawing. From a physical point of view, the volume changes during ground freezing have two different sources: 1) increase of volume of the frozen in comparison to the unfrozen water, and 2) the formation of ice lenses during freezing.

Owing to the negative thermal expansion property of water, the density of water is 9 % larger than that of ice and equally, the volume of ice is greater than that of water. Thus, the freezing and thawing processes during AGF result in volume increase (heave) and decrease (settlements). The volume changes due to the negative thermal expansion property of water can be satisfactorily predicted with existing models (e.g. Zhou & Meschke 2013).

The second source of pore volume changes, i.e., the formation and propagation of ice lenses, is largely attributed to the tendency of ice to actively expel embedded soil particles in the presence of a thermal gradient (i.e., thermal regelation). This leads to the separation of ice and soil in the form of a series of discrete bands of pure ice interspersed by frozen soil layers. The physics of ice lens formation is much more complex than negative thermal expansion. Despite the considerable efforts of the research community, its controlling mechanisms are not yet completely understood (Peppin & Style 2013). Semi-analytical and semi-empirical prediction methods of frost heave, originally developed four decades ago, are still commonly used

to estimate ice lens formation as well as frost heave in AGF, due to the lack of physically based mathematical models and sophisticated numerical solutions (Zhou, et al., 2021). Recently comprehensive models formed by objective equations for the coupled multi-physic phenomena of ice lense formation were published (Ji, et al. 2019; Sweidan, et al. 2022; Amiri, et al. 2021). Despite their generalized formulation these models still lack of broad validation and are yet not commonly applied in engineering practice.

At the authors' laboratory, motivated by underground constructions in Munich, studies from Kellner (2007), Fillibeck, et al. (2005) and Kellner, et al. (2019) investigate the behavior of water saturated over-consolidated clay and silt as well as dense fine sand during freezing and thawing. These soils are comparably prone to ice lens formation hence the works lead to recommendations for the application of AGF for tunneling projects in areas of sensitive urban buildings. For several current underground constructions expanding the public transport of Munich AGF is a key construction method. It proofed to be highly efficient for the building of crosscuts linking tunnels excavated by tunnel boring machines or for connecting emergency exits. Here the authors' laboratory until now focused on the experimental investigation and modeling of the time dependent strength of frozen soils (Schindler, et al. 2023, 2024, 2025).

Beside the importance of modeling the strength of frozen soils for design the risk of ice lens formation is evident and documented for various tunneling projects, like in Kobe (Konrad 2002), Munich (Fillibeck, et al. 2005), Rome (Pingue 2019) and Berlin (Brenner, et al. 2019; Vogelsang, et al. 2021). It remains the ultimate goal to apply an extensively validated model able to predict ice lense formation for the design of AGF. Such model should not only calculate the volume expansion hence heave as well as the increasing stiffness and strength during freezing but the volume reduction loss of stiffness and strength during thawing. In a first phase of a new fundamental research solely experiments will be carried out.

This paper is intended to provide a basic information on the planning of a novel experimental device to be constructed in course of the fundamental research. To this end, a comprehensive structured literature review has been conducted to describe and assess the state of research on experimental investigations of ice lens formation. The review will provide details of the literature review that will be integrated into the novel experimental device. With this device not only, a database on experimental results for the purpose of model validation will be created but moreover it will improve the fundamental understanding of the processes involved in ice lens formation. Challenges in integration ambitious measuring and control techniques will be critically examined.

2 LITERATURE RESEARCH

2.1 Structure and System

The literature discussed by this publication was collected and analyzed in preparation for the current research proposal on the experimental investigation of ice lens formation. This paper includes the presentation of the methodology for the literature review and the prepared structure for the data collection specifically focusing on the state of research on experimental investigations of ice lens formation. The literature research uses methods of Wolfswinkel, et al. (2013) and Bäcker (2024) and is divided into two iterations. In the first iteration, the topic is divided according to individual fields and categories respectively, which are then searched for in databases using search vectors. The first iteration thus serves to find most prominent hence key literature that provides information to further literature. The key literature is used further in the second iteration. Here, the databases are searched for literature that is citing the key literature. The literature research is carried out in the Scopus (Elsevier B.V.) and Web of Science (Clarivate Plc) databases.

Following the example of Wolfswinkel, et al. (2013) the search vectors are divided into three search areas:

1. Geotechnical engineering
2. Natural sciences / permafrost
3. Thermodynamics / physics / basic research

Each of the areas is searched with the combined sub areas “Ice lens formation”, “Frost heave” and “Frozen soils”. The distribution of found papers from the research are collected in figure 1.

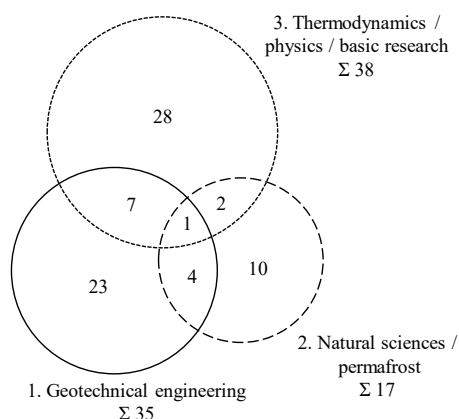


Figure 1. Distribution of publications for a certain search area

2.2 Results

When evaluating the literature research, it was noticeable that the experimental setups found can be divided into subcategories, starting in the meso/ micro pore scale, where different scanning methods are used for the investigation of the

pore space. Furthermore, there are concepts for experiments that enable observations at the scale of macro pores and can in turn be divided into subcategories. Examples here are tests with temperature boundary conditions resulting in a one-dimensional (1D) temperature field, tests representing a 3D temperature field (Zhao, et al. 2021) and tensile tests on frozen soils (e.g. Azmatch, et al. 2011). It is also noticeable that few attempts have been made to combine the observations in the range of macro pores and the meso/ micro pore range. This is of interest because one major aim of the current research project is to observe the pore space as well as temperature and strain fields at high spatial resolution and therefore the experimental setup needs to be planned in order to enable insights into both the change of macro pores and pores at the meso and micro scale.

As a matter of the available literature found by the research presented in this paper, the focus lies on macroscopic observations primarily carried out in experiments for which an 1D temperature field is assumed. Regarding the research on literature studying the mesoscopic/microscopic observations, the focus lies on experiments that observe the soil freezing curve (SFC).

2.2.1 Tests in field of meso- / micropore-scale

Concepts for the investigation of ice lens formation observing the changes inside of pores at the micro- / mesoscale vary widely throughout the last roughly 60 years leading to various experimental setups, depending on the related scope of each research (Everett 1961; Biermans, et al. 1978; Wilen & Dash 1995; Gao, et al. 2024b). Generally, the major object of these freezing tests lies on the isolated investigation of an individual (mostly thermo-hydro) mechanism that induces and governs ice lens formation such as the unfrozen water content, hydraulic conductivity, change of cryostatic suction, etc. (Chai, et al. 2018; Kong, et al. 2020; Tian, et al. 2019; Zhang, et al. 2015; Jang & Cha 2021).

In the following firstly research focusing on the determination of the unfrozen pore water content as a function of the temperature in relation to the specifically examined material is studied. Two of the methods are described.

The investigations here were made to support the understanding of the hydraulic behavior of frozen soil. In this case the tests were used to investigate the permeability of soils for fluids that remain in the pore space despite sub-freezing temperatures. They show that depending on the boundary conditions significant transport of gasses and fluids can take place in frozen soils (see, e.g. Gao, et al. 2024a)

Gao, et al. (2024b) use CT scans to investigate the freezing water in the pore space of sand with grain sizes ranging from 0.6 mm to 1.2 mm. The water within the sample contains a potassium iodide solution, which increases the visibility of the frozen and unfrozen pore water in images from CT scans through the compared to pure water more pronounced difference in density of the frozen and unfrozen water. Depending on the required resolution of the 3D images, it is noted that the scan duration ranges from 20 minutes to 12 hours. The evaluation of the amount and distribution of unfrozen water relates the detected density to the concentration of potassium iodide. By knowing the freezing curves of water with different concentrations of potassium iodide and the temperature within the sample the authors were able to determine the respective unfrozen water content at a comparably high spatial resolution both for the micro- and macroscale.

Applying a different technique, the nuclear magnetic resonance (NMR) method, Chen, et al. (2021) determine the unfrozen pore water content in a test specimen as a function of the temperature. They distinguish between water in large pores

(bulk water), capillary bound water within fine pores (capillary water), and at the minerals chemically bound pore water (bound water) based on the different measured T_2 relaxation times and derive the SFC for three different samples consisting of silty clay from the Yarlung Zangbo River Basin.

In both research of Chen, et al. (2021) and Gao, et al. (2024b), the samples are tested under constant temperature conditions. After each NMR measurement and CT scan respectively, the temperature of the sample was altered including waiting times before carrying out the subsequent measurement and scan respectively for assuring constant temperature within the sample. For the tests specifically adopted sample containers were designed. These containers are described in such a way that the sample sits in a pipe and is surrounded by a cooling liquid until it reaches a certain temperature. When this temperature is reached no ice lens formation, or localized changes of the pore space, is caused in the sample due to the homogeneous temperature distribution hence no temperature gradient induced migration of porewater and ice lens formation in the sample is initiated (see Wilen & Dash, 1995). Therefore, the entire sample is assumed as homogeneous. An advantage of this test setup is that there are hardly any dynamic effects unfavorably affecting the test interpretation, as there is no temperature gradient during the NMR measurements and CT scans respectively.

For the currently planned experiments the idea is to use the described developed testing devices in addition to the newly developed device for 1D freezing tests in the following way: an NMR measurement is carried out in advance on the sample material to be examined by the 1D freezing test and the SFC is determined, the temperature distribution in the sample examined using the 1D freezing test could be used to infer the unfrozen pore water distribution. Hence a connection between the macroscopic and microscopic tests is achieved. The CT scans are not further used in the current research due to the fact that NMR scans can resolve the properties of much finer pore spaces compared to the CT Scan (see Fu, et al., 2015), which is essential for the investigation of clay.

2.2.2 Tests in field of macropore-scale

The evaluation of the literature study shows that many experimental setups follow a comparably similar concept, which is illustrated by figure 2.

These testing devices are used to investigate ice lens formation as an occurring phenomenon without looking too deep into the detailed mechanism happening in the pore space as it is done in literature summarized by chapter 2.2.1. The results of tests in the field of macro pore scale get compared with numerical models which calculate the total frost heave considering the different external boundary conditions applied during the tests (e.g. Sweidan, et al. 2022; Niggemann, et al. 2024, Ji, et al. 2019).

The reviewed experiments basically consist of a cylindrical sample that is either inserted into a thick-walled tubular plastic container (e.g. Zhang, et al. 2023), or alternatively, the container consists of stacked rings that separate apart in axial direction under deformation from frost heave to reduce friction (e.g. Niggemann, et al. 2024). The temperature gradient acting within the sample is controlled by a cooling plate and a heating plate, which are located at the base bottom and top surface of the cylindrical sample respectively. The temperatures at the curved surface of the cylindrical sample are not actively controlled, nor are the compression and shear stresses. The heat transfer and hence the temperature at the curved surface of the sample are not described further in the reviewed papers. The longitudinal temperature distribution in the sample is measured using temperature sensors inserted into the sample at discrete

positions. A comprehensive evaluation of the temperature field within the sample is not considered in detail but moreover by a simplified consideration a linear 1D temperature field is assumed from linearly interpolated measurement values recorded at the temperature sensors (e.g. Liu, et al. 2022; Hu, et al. 2023).

Some experiments investigate the influence of an axially acting total stress. In this case usually the loading by a constant stress is studied and the axial deformation as a result of the test is measured by conventional displacement transducers on the upper side of the specimen (e.g. Dagli, 2017). Some researchers investigate the effect of different loading paths (e.g. Huang, et al. 2020), on the behavior of the freezing sample and observe the corresponding axial deformation. The field of axial deformation throughout the height of the sample is mainly recorded using cameras and the application of the digital image correlation (e.g. Xue, et al. 2021; Arenson, et al. 2005). This experimental observation is limited to the deformations visible from the outside of the sample.

Finally, some researches study the drainage conditions on the freezing process. Therefore, the test rig is equipped with a water supply connected to the sample at the warm base, which can be on top or at the bottom of the sample. Valves allow to open and close the flow of water. The in- and possibly outflow of the migrating water is recorded by gauges (e.g. Liu, et al. 2022). At closed water supply the water pressure at the base of the specimen can be recorded to measure the possibly evolving cryogenic suction like Herzog & Boley (2013) did.

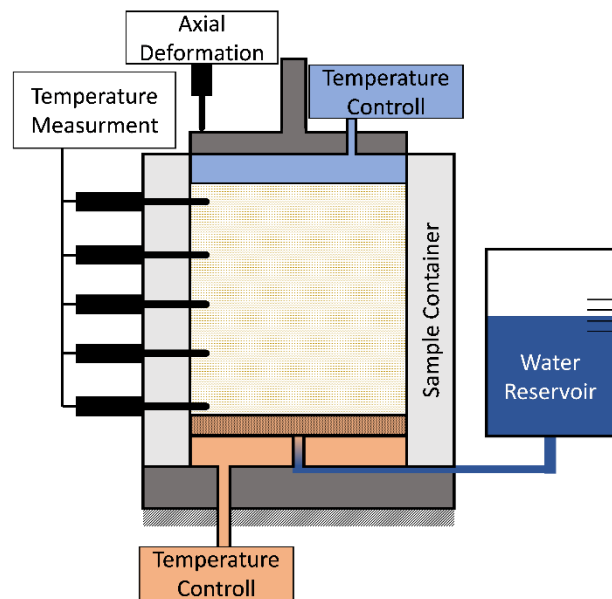


Figure 2. Common concept of an experimental device for investigation the frost heave

3 DISCUSSION IN SCOPE OF THE DEVELOPMENT OF A NOVEL EXPERIMENTAL DEVICE FOR 1D FREEZING TESTS

In the following, some details of the methodology and experimental concepts as well as specific techniques used in certain test setups described above will be taken up and discussed in relation to the development of a novel experimental device for 1D freezing tests. These aspects considering improvements to minimize the unfavorable effects from known limitations are: a) the measurement of the axial temperature distribution, b) the influence of the radial temperature boundary condition, c) the control of the axial temperature boundary conditions (top and bottom), d) the

control of the radial mechanical boundary conditions (stresses and strains), and e) the applicable technologies for stress and strain measurements.

As already described, the common design of the experimental devices for 1D freezing tests aims for the control and measurement of the 1D temperature field. Here, the axial temperature distribution in the sample has so far been measured using temperature sensors placed at selective points within the sample at its top and base which refer to the cold and warm surface of the sample respectively. However, the literature does not discuss what distance should be maintained between the temperature sensors in order to keep the loss of information between the measuring points to an acceptable minimum. This seems as an essential aspect for discussion since the formation of ice lens links to spatially changing temperature gradients that derive from the assumption calculated from homogeneous thermal properties of the sample. Indeed, strongly changing pore space through the ice lens formation leads to changing thermal conductivity as well as changing heat transfer through the mechanism of convection by water flow. Especially in the area of the “warm front” of the ice lens and in the eventually adjacently present frozen fringe area, it seems to be important to utilize temperature measurements at a considerable high spatial resolution as this would reduce the dependency on the interpolation between discrete measuring points. In regard to this challenge e.g. Xue, et al. (2021) verify and draw conclusions about the proportion of the frozen pore water using the information from SFC measured independently from the actual 1D freezing test. This concept shows the advantage that the distribution of the unfrozen water can be determined without performing NMR measurements on the 1D freezing test which certainly requires a comparably large working space for the NMR scanner. Moreover, the NMR measurements for investigating the SFC can be carried out because of the possibly small sample size rather fast and independently from the time-consuming 1D freezing test.

To improve the determination of the temperature field the application of optical fibers for distributed temperature measurement is being discussed for the novel experimental device. This measurement technology achieves high spatial resolution that may capture locally changing temperature gradients in the sample, especially in the frozen fringe. The optical fibers guide a laser beam. By analyzing the back-scatter from “natural” impurities of the fiber an almost continuous (up to 0.6 mm intervals) evaluation of temperatures over the fiber length with an accuracy of ± 0.6 C can be achieved (LUNA 2022). The use of such temperature sensing fibers presents a number of challenges that need to be overcome. One major technical obstacle is briefly described in the following:

A fundamental task will be to mechanically decouple the fiber from the sample minimizing friction and adhesion. This is necessary because the fibers change their back-scatter needed for the temperature measurement from both mechanically and thermally induced strain. At the same time, the fiber itself and the required mechanical decoupling should not alter the temperature field within the sample and should therefore exhibit a thermal behavior similar to the sample material. To achieve this, a as thin as possible but still as robust as necessary capillary may be placed through the sample body in which the measuring fiber is placed. Hence, for the design of the temperature sensing fiber including the capillary for protecting from mechanical strain a conflict exists: On the one hand a) robustness even in the case of high strain gradients within the zone of ice lens formation has to be guaranteed leading to the use of an as thick as possible capillary of high strength material and on the other hand b) the capillary is needed to be constructed as marginally as possible to achieve minimum

disturbance of the temperature field. Commercially available measuring cables for fiber optical temperature sensors are considered to show comparably high robustness and therefore are assumed to influence at least locally the temperature field strongly. Beside trial tests that already started future numerical simulations will be carried out to support the design of the temperature measuring fiber optical cables.

For establishing datasets on the characteristics of ice lens formation aiming for the validation of comprehensive numerical models the selection of specific sometimes exclusive boundary conditions tailored for testing the model performance is of great importance. When considering temperature boundary conditions, it is noticeable that these conditions at the bottom and top surfaces of the cylindrical test specimen examined by a 1D freezing test are well described in terms of the temperature profile over time, assuming that the heating and cooling plates have a homogeneous temperature distribution (e.g. Zheng, et al. 2020). However, this is not the case for the radial condition controlling the temperature at the curved surface of the cylindrical specimen. At this surface of the sample the temperature should follow the assumption of the 1D temperature field which leads to the design of isolating parts preventing excessive heat flow in radial direction. The literature review revealed that no information about the radial temperature distribution in the sample or the influence of the insulation on the radial temperature distribution is provided. Furthermore, the insulating properties of the sample container are not discussed in this context, which means that no conclusions can be drawn for the development of the novel experimental device.

With the aim of creating boundary conditions leading to an as precisely as possible 1D temperature field within the sample, the experimental concept is being further adopted. Instead of creating insulation using a rigid sample mold, thermal insulation will now be assured using gas implying low heat capacity (e.g. CO₂) in a pressure chamber holding the cylindrical specimen only laterally supported by a thin rubber membrane. The gas will be pressurized to apply a certain lateral stress on the sample and be cooled to the freezing temperature of water in order to minimize disruption to the freezing process at the zone of ice lens formation and in the frozen fringe area. Since the gas circulates in the pressure chamber, a constant temperature is created at the curved surface of the cylindrical sample. The heat transfer through conduction and convection is low compared to any solid material because of the marginal thermal capacity of gas. One major challenge in using gases for lateral support is to prevent permeation of gas through the membrane of rubber leading to desaturation of the sample (Lade, 2016). Instead of the widely applied latex membranes of butyl rubber are proven to reduce gas permeation significantly.

The reviewed experimental setups for 1D freezing tests all use thick-walled tubes or rigid containers formed by individual rings for radial support of the specimen. However, no publication goes into detail about the, during the test especially considering the freezing hence volume expansion evolving, radial pressure and radial deformation at the interface between the container and the specimen. Also, the concept of 1D freezing tests assume zero radial displacement in respect to the rigid container neither pressure nor the actual displacement are measured. As some of the reviewed experimental setups utilize a container of stacked rings wall friction between the sample and the container is minimized according to the possibility of gap formation between the rings. Despite this, when gaps related to the sample heave open the influence of the changing dimension of the gaps between the rings on the radial deformations and stresses is not discussed, even though these represent repeated discontinuities in the radial boundary

conditions and most likely sample material will penetrate into the gap.

As for ensuring a more homogeneous 1D temperature field through improving isolation, the use of a pressure chamber is conceivable for the clear application of a radial pressure and measurement of radial deformation. The radial pressure acting on the sample is corresponding to the gas pressure which can be controlled by conventional pressure regulators. The radial deformation can be recorded using digital image correlation technology (DIC). The use of gas as the medium in the pressure chamber facilitates the mounting of cameras and hence improve the quality of images for DIC without putting effort for providing water tightness. When using liquids as the medium in the pressure chamber, the evaluation of the sample deformations poses a challenge, as the refraction of light caused by the phase transition from air to glass to the fluid distorts the recorded deformation. Therefore, it is questionable whether the recorded deformations from outside the cell can be used for quantitative evaluation without complex shape corrections. Here, a more sensible option is to mount the cameras for DIC inside the pressure chamber, whereby it only must be able to withstand the corresponding pressures. The concept of the pressure cell including the installation of fiber optic temperature measurement is shown in Figure 3.

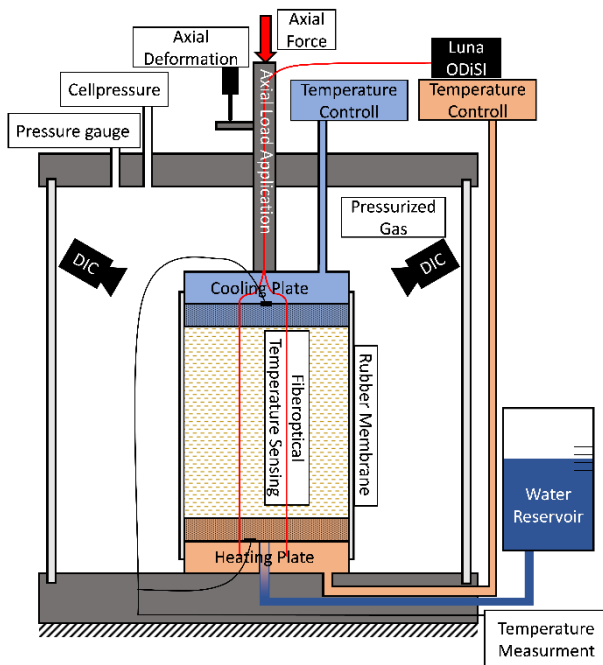


Figure 3. Concept of a new testing device for 1D freezing tests

The for the novel experimental device proposed time-dependent temperature boundary conditions applied to the top and bottom surfaces of the sample are divided into three categories (excluding freeze-thaw cycles): a) constant temperature (e.g. Dagli 2017), b) linear temperature profile (e.g. Penner, 1986) and c) cyclic temperature change (e.g. Zhou, et al. 2009). The test setup should allow these conditions to be carried out at high control quality, which requires loading plates that can not only maintain but change temperatures quickly. The designs of the temperature control plates by Arenson, et al. (2005) and Dagli (2017) will be used as a guide for the new device. They run loops or a spiral shaped channel through the temperature control plates, through which the cooling or heating fluid is conducted. Finite Element Analyses (FEA) carried out by COMSOL simulations are currently being carried out to ensure optimal guidance of the geometry for providing homogeneous temperature control of the surface.

4 CONCLUSION

In preparation of a fundamental research aiming for high quality experiments on studying the formation of ice lenses in saturated soil a comprehensive literature review was carried out. Related to experimental investigations research both from natural sciences motivated by understanding perma-frost soil and civil engineering working on the topic of AGF as well as the design of infrastructure in arctic regions was evaluated. Two major concepts of experimental investigations are prominent. On the one hand experiments are designed in a way that the sample is considered as a homogeneous element in respect to the states of non-soil inherent parameters relevant for the freezing process (e.g. the pore space, stress and temperature). These test focus on investigations understanding the influence of the soil and its pores at the micro- and mesoscale. The size of the specimen in principle is irrelevant for this kind of experiment. Scanning by the methods of NMR and CT is applied for a high-resolution imaging and data evaluation. One major outcome of these tests is the state-dependent SFC and the proportion as well as distribution dependent on the scale of the pores of unfrozen water within the frozen sample. For the currently ongoing fundamental research, the second major concept of investigation is applied. Here in correspondence to the literature review a 1D freezing tests is planned. For the development of the novel experimental setup in extension to the devices found in the literature different measuring technologies are currently tested that not only captures changes at the macroscale in previous experiments mostly recorded at the boundaries of the sample. The proposed experiments moreover aim for spatially highly resolving data at the meso- and microscale. Here in combination with NMR measurements for determining SFC following the concept of element tests according to the result of the literature review the temperature and deformation field will be studied by the application of distributed fiber optical sensing and digital image correlation. To this end, a new test rig is to be developed in order to provide clear boundary conditions that are controlled by measurements. This includes clearly defined temperature and stress fields throughout the sample. A precise and continuous recording of the axial temperature profile correlates the frozen and unfrozen pore water content from the SFC to the sample examined by the 1D freezing test at high spatial resolution important for the analyses of the processes close to the freezing front and zone of ice lens formation respectively. The findings from the literature lead to the conclusion that beside established methods of reducing friction in longitudinal direction between the sample and the container during volume expansion the radial stress remains unknown despite this test result seems important for the validation of comprehensive models. Here the application of a sample wrapped inside a rubber membrane resting inside a pressure chamber in analogy to a triaxial test is proposed. The recording of the radial deformations then supplements the radial stresses. In addition to a clearer application of the mechanical boundary conditions at the radial curved surface of the cylindrical sample leading to a homogeneous stress field, while the inhomogeneous deformation can be recorded by established techniques like the DIC, the thermal isolation by the laterally supporting pressurized gas can be in comparison, by the until now commonly used rigid containers, assumed to result in a more uniform 1D temperature field. As well this assumption will be validated by a corresponding numerical model for FEA and highly resolving extensive redundant measurements.

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