Evaluation of frost heave and moisture/chemical migration mechanisms in highway subsoil using a laboratory simulation method

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ABSTRACT: Seasonal processes in cold countries significantly affect the engineering characteristics of highway subsoil over time. Cyclical freeze-thaw leads to changes in thermal and moisture conditions. As a result, road bearing capacity can progressively change from the initial design. In this work, a modified laboratory method was developed, with cyclical freeze-thaw of soil samples and simultaneous supply of deionised water and a de-icing agent (sodium chloride) to the base. The benefits of the test procedure included slow freezing, simulating the conditions that can be experienced by highway soils in cold environments, extended soil column heights and a larger number of identical soil samples, which allowed experimental variability to be assessed. The method included the monitoring of moisture and chemical mass transfer in the soils. Samples supplied with deionised water experienced ice segregation in their upper parts, and significant heave. While soils supplied with NaCl solution behaved in a similar fashion during their first freeze-thaw cycle, the second cycle saw a reduction in the rate of migration of the freezing front within the soils and also less ice segregation and less heave due to increased salinity. Salt was preferentially transferred upwards in the soil columns as a result of the thermal gradient, including negative pressure associated with cryosuction, and osmotic

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pressure. The new method provides a more realistic laboratory approach to assessing potential freeze thaw impacts, and the effects of de-icing agents on soils beneath roads, and in different settings.

Keywords: Freeze-thaw, highway subsoil, de-icing chemicals, laboratory test, sandy clay.

1. Introduction

Highway subsoils are subject to significant variability in terms of their moisture-temperature regime, especially in countries with a severe cold climate. As highway pavements have higher densities and thermal conductivities, the near surface layers freeze before, and at a faster rate than roadside soils (Vasilenko, 2011; Vasilenko, 2011; Han Chunpeng *et al.*, 2010; Simonsen, Janoo and Isacsson, 1997). The temperature gradient in the highway sub layers may also induce a significant upwards and lateral migration of moisture supplied from the ground water table (Konrad and Samson, 2000).

In a highways context, this groundwater may be modified by deicing agents, with a resultant depression of the freezing point easily down to -25 and with more difficulty up to -41 ºC, depends on the chemical content (Wan, Lai and Wang, 2015). Wan et al. present a modified methodology to examine this depression and the degree to which it enhances migration of soil moisture towards the freezing front under the pavement structure. It also explores whether the de-icing chemical migration responds to the thermal gradient in the highway subsoils. When the temperature of a soil falls sufficiently, the interstitial water starts to segregate into ice crystals. The remaining, unfrozen, water becomes progressively enriched with dissolved salts and has a depressed eutectic temperature (Bing and He, 2011; Torrance and Schellekens, 2006).

Previous studies have provided contradictory evidence for the movement of de-icing agents within soil: Vidyapin and Cheverev, (2008) report de-icing chemicals moving towards the freezing surface, while Brouchkov, (2000) detected no obvious salt migration during the freezing period. As a result, little certainty can be derived from the published literature about the potential nature of frost heave in highway subsoils.

The nature of change in mechanical characteristics during the spring thaw is also unclear. Thawing occurs both from the pavement and base of the frozen soils. However, some parts of the saturated sub soils can remain frozen for some time and block the drainage of moisture downwards. Localised ice lenses and associated deformation of subsoils may lead the significant strains in the pavement structures due to the rapid oversaturation and the weakening of sub base soils (Miller, 1972). A thorough review based on the frost heave thermodynamics has been prepared by Henry (2000).

Numerous studies have attempted to explain the soil properties during the freeze and thaw period since early 1900s (Miller, 1972; Hoekstra, 1969; Hoekstra, 1966; Taber, 1930). Most of the studies have taken place under laboratory conditions to provide experimental control and improved accuracy in the results (Nagare *et al.*, 2012; Bronfenbrener and Bronfenbrener, 2010).

Progressive approaches have been performed in a triaxial cell within a negative temperature (Cui and Zhang, 2015; Zhang *et al.*, 2013; Hazirbaba, Zhang and Leroy Hulsey, 2011; Sinitsyn and Løset, 2011; Ishikawa *et al.*, 2010; Qi, Vermeer and Cheng, 2006; Brouchkov, 2002). Triaxial cell tests enable contemporaneous mechanical loading but only one sample can normally be tested at a time. The size of the tested sample is also restricted by the size of the test cell.

There are several standard methods which are used for freeze-thaw cycles of soils in different countries: BS 812-124:2009, ASTM D 5918-06, GOST 28622-2012 and BS EN 1997-2:2007, section 5, 5.5.10. These typically involve testing 15 cm high soil samples over a limited and controlled temperature range, usually +3 and -3 °C. The number of simultaneously tested samples is normally limited to four. The standard methods provide uniformity and predictability of the obtained results and are suitable for classification tests. However, the sample height and limited range of variables do not allow for a detailed examination of the role of thermal gradient, including a descending freezing front, migration of pore water, or the effects of changing soil water chemistry to be examined. Therefore, in order to better understand the complex processes in the highway sub soils, a laboratory method for freeze-thaw cycles with simultaneous supply of water at the base of the sample was developed.

2. Materials and methods

A new laboratory method with freeze-thaw cycles has been developed from the ASTM D 5918-06 Standard. This allows a more realistic simulation of freeze-thaw with depth.

The height of the soil column was increased up to 1.00 m, including 5 cm of saturated soil at the base. Water was supplied to the base through a 5 cm fine sand filter (Fig. 1). The samples were made from non-saline soil. This enabled the observation of salt mass transfer from a solution supplied at the base of each soil column. Application of the non-saline soils and feeding the base 5 cm layer with sodium chloride solution in the new method facilitates the observation of the chemical mass transfer and its possible secondary salinization in consequence of the freeze-thaw of the soil mass.

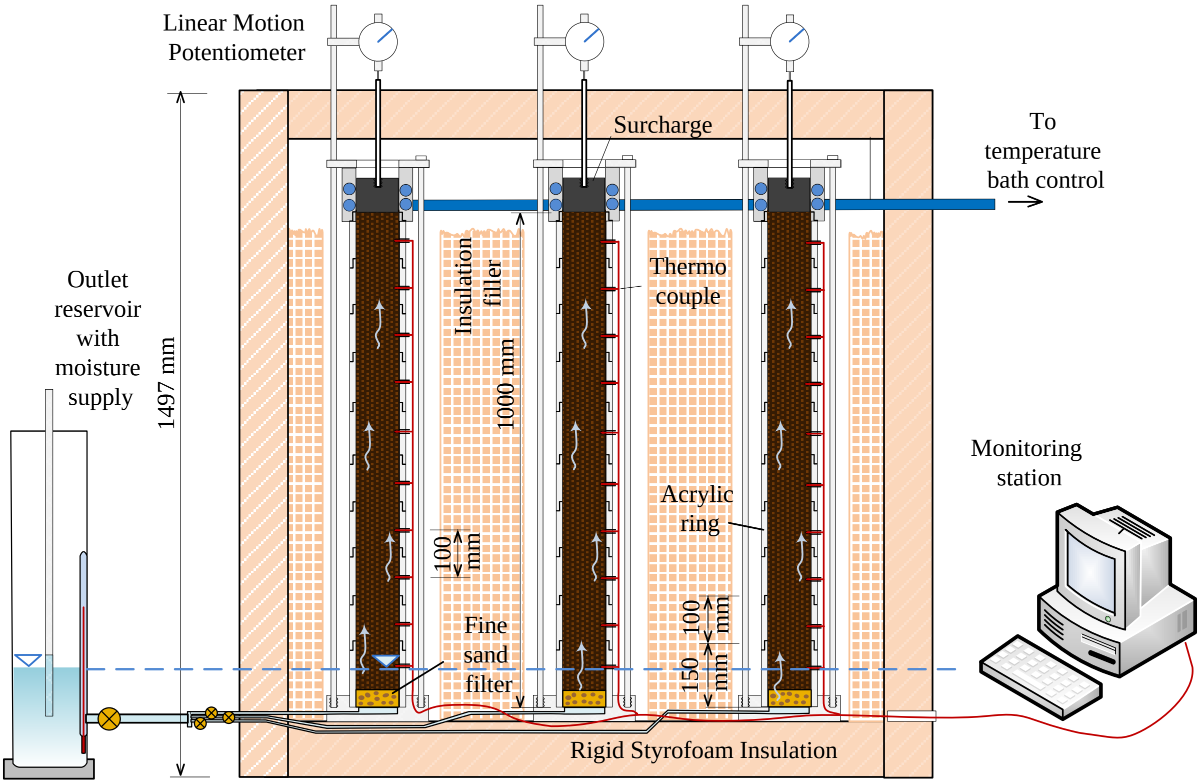


Fig. 1. Environmental chamber for freeze-thaw cycles with 9 soil samples capacity

2.1 Experimental soil characteristics

The soils used in this experiment were remolded on geotechnical data from Astana, Kazakhstan (Karaganda GIIZ, personal communication), where the winter air temperature can drop to below -35 °C. Kazakh Steppe soils typically consist of ancient sedimentary rocks that have been transformed by chemical and physical weathering to residual layers, together with alluvial soils of irregular thickness according to KazGIIZ geological report. To ensure comparability in laboratory tests a remolded sandy clay, reflecting frequently occurring soils 1 metre below the surface, was manufactured from 50% sand with angular shape of the grains (cross-sectional dimension less than 2 mm) and 50% kaolinite clay. A particle size distribution of the sand part in the soil sample is presented in Fig. 2. Average plastic and liquid limits were 23.77 % and 37.05%, respectively. Initial classification properties of the remolded soils are presented in the Table 1.

Table 1 – Initial soil characteristics of soils. Soil tests followed the procedures in BS1377-1:1990. * Note Angle of internal friction is high as a result of the drained, consolidated shear test used on the soil

Characteristic	Symbol	Unit	Value	Annotation
Initial moisture content	W	%	17.2	See Fig. 5 – according to 95% max. dry density – moisture content relationship
Angle of internal friction	φ	°	24.1°*	CD direct shear test, moisture content W=17.2%
Cohesion	C	kN/m^2	10	
Particle density of sandy clay	ρ_s	g/cm^3	2.615	Soil mixture by mass: 50% of sand and 50% of kaolinite
Average dry density before freezing cycle	ρ_{dry}	g/cm^3	1.814 ± 0.012	BS Light compaction test operating with 2.5 kg rammer. The mechanical energy applied to soil is 596 kJ/m^3
Initially bulk density at the beginning of the test	P	g/cm^3	2.128 ± 0.015	
Uniformity coefficient	Cu	-	2.4	Uniformly-graded sand
Coefficient of curvature	Cc	-	3.65	
Activity of Clays	A	-	0.25	Inactive clays
Liquid limit	w_L	%	37.05	CI – Medium plasticity Cone penetrometer test used
Plastic Limit	w_P	%	23.77	Fraction of soil sample passed 0.425 mm sieve
Average linear shrinkage	L_S	%	4.8	
Plasticity Index	PI	%	13	

Table 2 - CBR results and corresponding dry density values for the manufactured soils with different moisture contents

W, %	CBR, %	Dry density, Mg/m^3
4.00	100.41	1.587
15.06	48.83	1.543
16.50	17.19	1.495
17.65	10.69	1.469
19.50	5.50	1.443
20.61	3.90	1.406
22.24	2.75	1.370

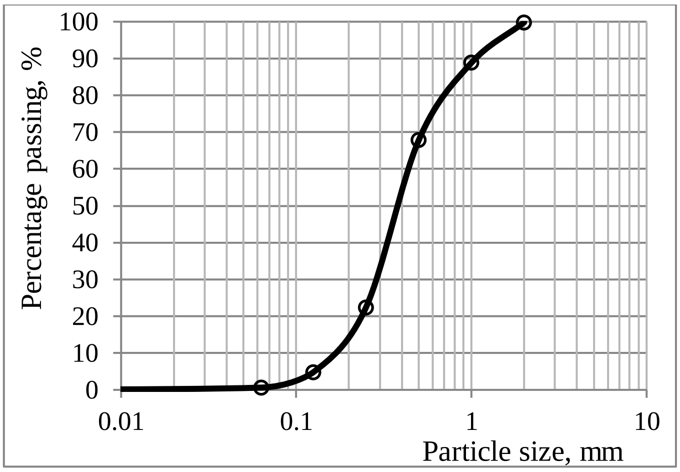


Fig. 2. Particle size analysis of the sand part in the remolded soils, determined by dry sieving. The graph presents only the sand part of the soil which is 50 %, the rest 50 % is a kaolinite clay.

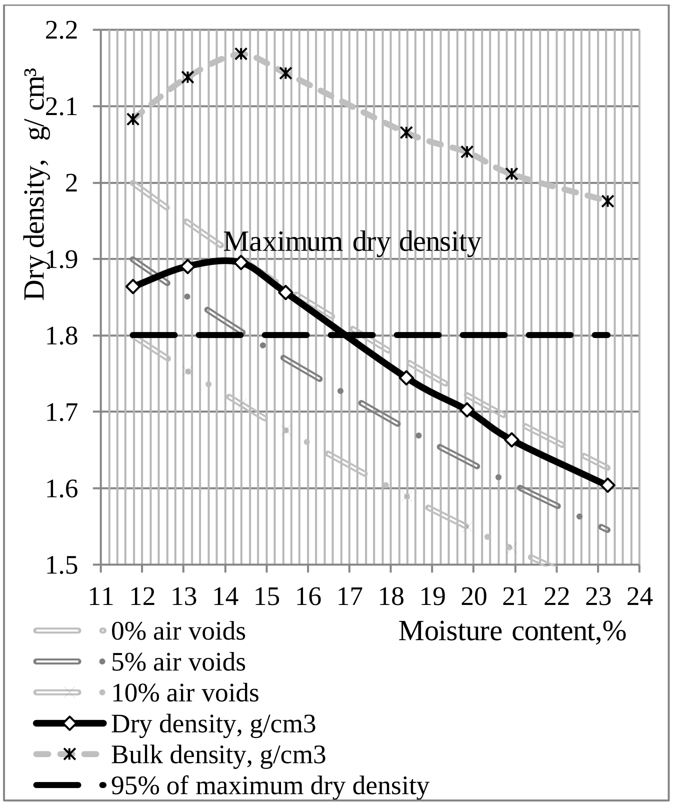


Fig. 3. Dry density – moisture content curves for the remolded sandy clay. Compaction was achieved using a 2.5 kg hammer, following BS 1377-4:1990.

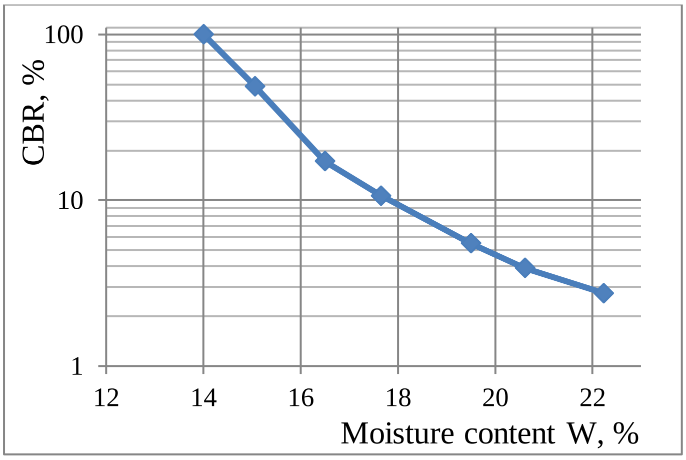


Fig. 4. California Bearing Ratio results for the remolded sandy clay.

The variability in dry bulk density with moisture content of the remolded soil is shown in Fig. 3. The 95% value of maximum dry density is 1.8 Mg/m^3, which corresponds to the w=17.2% moisture content, with the compacted soil being almost completely saturated.

California bearing ratio was derived according to BS 1377-4:1990. The percentage of standard forces for penetrations of 2.5 and 5 mm were calculated. A sequence of CBR tests was conducted for a range of moisture content values (Fig. 4). The corresponding dry density and CBR values at different moisture contents are given in Table 2.

2.2 Sample preparation

The dry soil mass was mixed with 17.2% of deionised water by mass and stored for 24 hours to let the moisture distribute uniformly. Previous studies have used salinized soil from the start (e.g. Nguyen *et al.*, 2010; Arenson *et al.*, 2005). The moistened manufactured soil was then compacted within heavy duty plastic 10 cm x 10 cm cylinders using a 2.5 kg hammer to produce a dry bulk density of 1.8 Mg/m^3. This was done by alternately adding 5 cm of soil and then compacting using 31-32 hammer blows, to provide the same compactive effort as in BS1377-4:1990. After filling and compaction, each stack weighed 16.784 ± 0.1 kg. The cylinder at the bottom included a basal, 5 cm thick layer of fine sand to act as a filter layer. Water was supplied to the base via a pipe to produce saturated conditions in the bottom 5 cm of the manufactured soil. Air taps were left open for 24 hours to allow void excess air pressure to dissipate before the experiment began.

The friction between the soil sample and the mold was managed with the polished coating inside the plastic tubes. Such mode couldn’t exclude the friction completely, however avoided the mechanical disruption during the consisted compaction of the 1 meter height soil samples and chemical interference during the freeze-thaw cycles. To provide the moisture insulation the plastic collars connections were covered with silica gel and rubber sleeves, and the whole soil columns were wrapped with clean film thoroughly (Fig. 5). Nine soil columns were prepared for each of the two tests reported here.

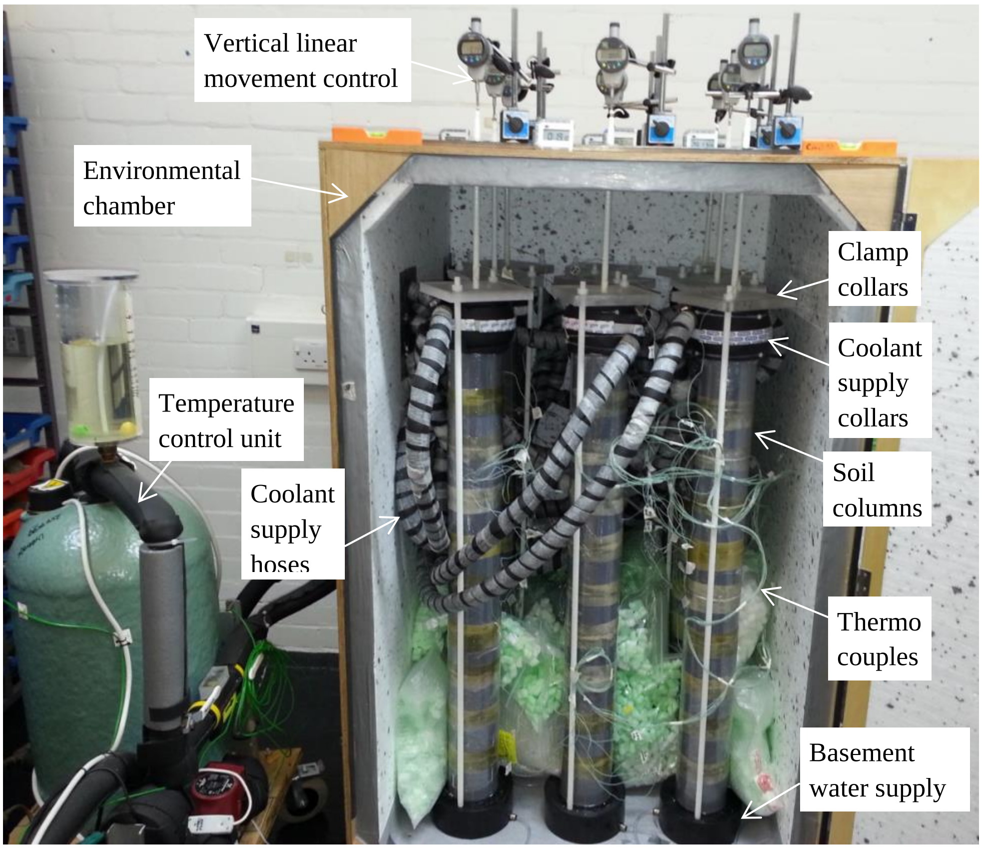


Fig. 5. Environmental chamber for freeze-thaw cycles with a capacity of nine soil columns

During the first test, the soil columns were supplied with deionised water throughout the freeze-thaw cycles. In the second test, the soils were supplied with a sodium chloride solution, where the salt content made up 11 g of NaCl per litre, based on the previous studies of salt distribution in the roadside area (Lundmark and Olofsson, 2007; Pedersen, Randrup and Ingerslev, 2000). Samples for both tests ran with the same freezing regime and equal initial soil properties.

2.3 Environmental chamber design

An insulated environmental chamber with a capacity of nine 1 metre soil columns was designed for the freeze-thaw tests (Fig. 5). The top ring of the columns was supplied with refrigerant liquid circulated to a thermos controlled bath. Circular metal surcharges of 3.5 kPa were placed on the top of the soil samples to provide a load similar to that imposed by pavement layers (Fig. 6). These metal surcharges also acted to equally distribute the temperature reduction created by the cooling collars. To prevent the formation of condensation inside the chilling collars they were covered with clean film.

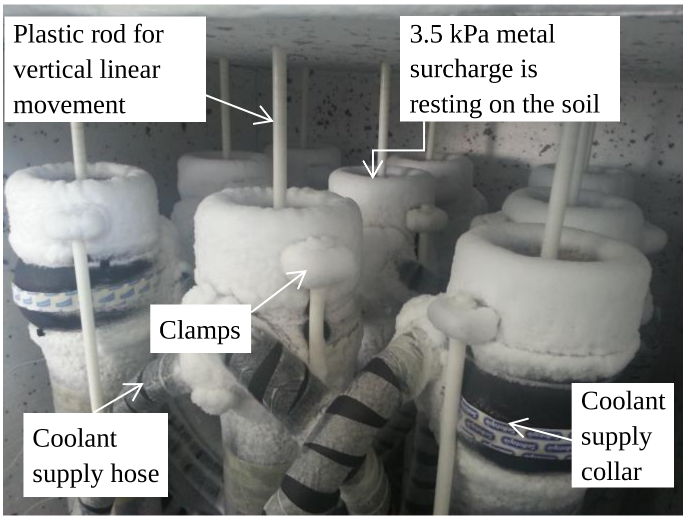


Fig. 6. The surcharges inside the cooling collars evenly cool the soil surface and facilitate the vertical linear movement control.

The base of the soil columns was supplied from a Mariotte bottle with deionised water or 11000 mg/litre sodium chloride solution located in a separate refrigerator.

2.4 Freeze-thaw regime

The freezing rate was 2 °C per day, simulating the natural conditions of roadside soils. The temperature timeline for the freeze-thaw cycles is presented in Fig. 7. The temperature distribution in the top layers depended on the moisture accumulation and the heat capacity of the soils. Daily fluctuation of the environmental temperature also brought the test close to the natural conditions.

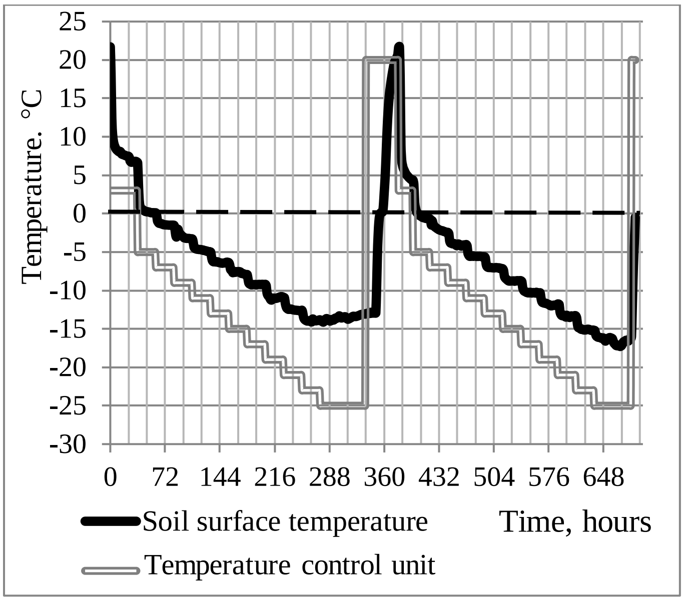


Fig. 7. Relationship between the set for the temperature control unit and the actual temperature of the soil surface.

In the first test the soil columns were supplied from the base with deionised water. The first three columns were removed from the chamber immediately after the first freezing cycle and processed for data analysis. Three other were removed after the first thawing period. The last three columns were removed at the end of the second freezing cycle.

In the second test, the soil columns were fed with 11000 mg/litre sodium chloride solution and all nine columns were kept in the same conditions until the end of the test.

2.5 Temperature monitoring

The temperature in each 10 cm section of the entire 1 m soil column was recorded with K type thermocouples and PicaLog technology LTD logger at hourly intervals throughout the test. Supplementary thermocouples were measuring the temperature of air in the environmental chamber, supplied water or solution and the chilling collar temperature at the top of the sample.

2.6 Monitoring of frost heave and consolidation rates

Vertical linear movements were recorded every 12 hours from the digital gauges mounted outside the environmental chamber. These were connected through the chamber's top to the metal surcharges via low thermal conductivity plastic rods. This allowed observation from outside the chamber and so minimised heat loss.

2.7 Post freeze-thaw sampling and testing

After removal from the environmental chamber, each column was weighed and placed in a horizontal position. The soil in the columns was sliced at 10 cm sections along the joins of the mould rings. Each section was weighed once more and sampled from the top and bottom side of each section for the moisture and chemical content determination.

2.7.1 Determining the moisture content

At the end of the freeze-thaw cycles the soil columns were immediately sliced without waiting for the thaw and sampled to determine the total moisture content, including ice and unfrozen water content. The total moisture mass was defined with the weight difference after drying at 105 °C for 24 hours. The moisture content of the top 10 cm section was determined at a 1 cm interval, while the lower sections were sampled every 10 cm.

2.7.2 Obtaining the sodium chloride content

A multi-range conductivity meter HI 9033 was used to determine the chemical mass content in the soils after the freeze-thaw test. To produce a calibration standard chart for electrical conductivity, a 50 g of oven dried sample of the unused soil was mixed in 500 ml of deionized water and measured for the electrical conductivity. This established a relative “zero” sodium chloride content at the beginning of the test. A calibration standard was then established by progressively adding known amounts of sodium chloride to this sample and mixing thoroughly. At the end of the test run with a sodium chloride solution supply, the soil samples were taken from the columns, labelled and oven dried, and then mixed in deionised water in the same proportion to obtain the chemical content of the solution. The determined salt content was considered in mg per dried soil mass in grams or mg/litre respectively to the moisture content of the sample after the test.

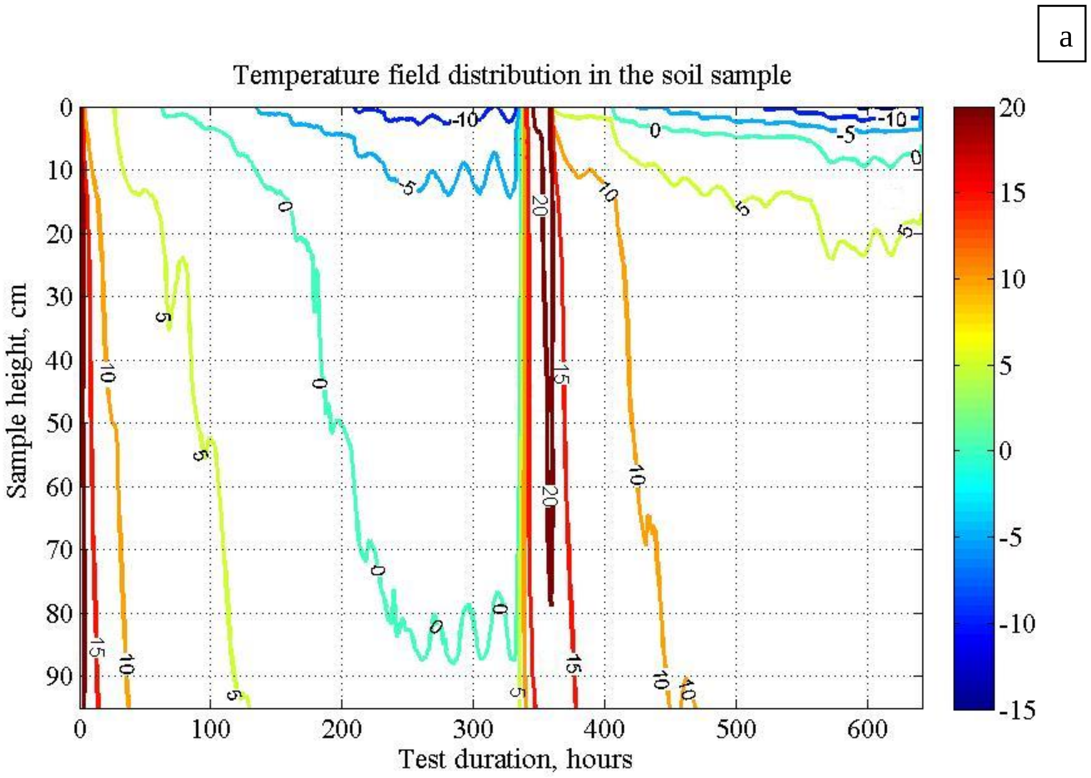
2.7.3 Further tests

The remaining undisturbed soil was also tested with ultrasound for elasticity modulus value using a Pundit Plus ultrasonic equipment (Model PC1006), direct shear test, oedometer consolidation and CBR.

3. Results

3.1 Temperature field distribution

The evolution of temperature fields in the columns developed in a similar way in each test. Some variations within the time line are due to minor variations in the structure of the soil particles and some variation in the thermal conductivities.



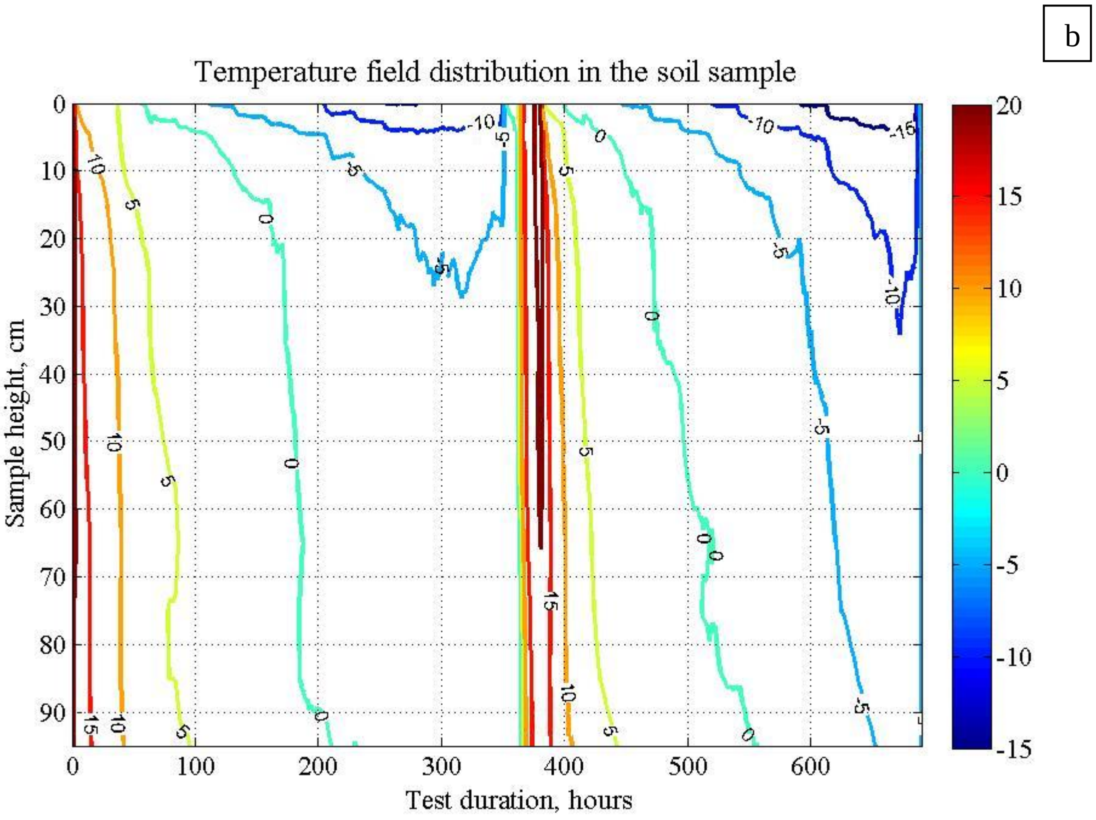


Fig. 8. Example of temperature development in column #2 during the freeze-thaw test, cm: a - supplied from the basement with deionised water; b - supplied from the basement with 11000 mg/litre sodium chloride solution

As shown in Fig. 8 a and b, the first cycle of both tests followed a similar temperature range, while the second cycle differed significantly. The heat capacity of soils supplied by the clean water increased because of greater moisture collection at the top of the soil columns. In the second freezing cycle the heat conductivity and the temperature gradient between sections decreased because of extensive moisture collection. Thus the enlarged heat capacity of the moistened soils required intensified heat loss to chill down in the second freezing cycle (Fig. 8a).

In Fig. 8b, the soil was steadily salinized by chemical solution from the base supply. However, along with increased ion content, it provided better heat conductivity and accelerated the soil cooling. This explains the divergence in the second freezing cycle. The temperature range in the second cycle significantly decreased, in contradiction to the soils supplied with deionised water.

The change in temperature by the height of the soil column is not uniform. In the soil column illustrated in Fig. 9 the temperature gradients varied from 0.22-0.30 °C/cm in the upper frozen section, 0.02-0.05 °C/cm in the middle section and 0.08-0.10 °C/cm in the lowest section.

The significant drop in temperature was associated with the crystallization of the pore water, which is explained by the enthalpy in transition zones. As the cooling process was implemented gradually for a metre depth, the temperature jumps were recorded in depth sequentially in time.

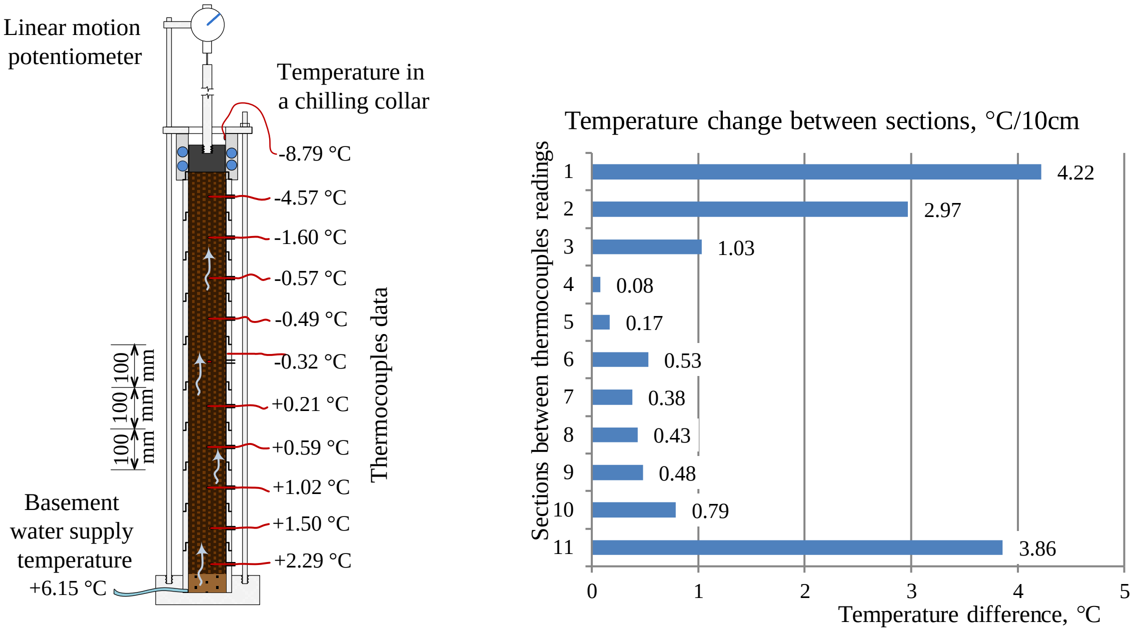


Fig. 9. The temperature field distribution on example of column #2 during the 201st hour of the freeze-thaw test.

3.2 Change in moisture distribution

Moisture content raise in the top soils was up to 82.5% in the deionised water supplied test. The heterogeneous dispersion of moisture in the top 10 cm of soil mass is explained by the growth of segregated ice lens formation that produced a layered fabric (Fig. 10; cf. van Everdingen 2005, Fig. 8c).

The migration of moisture toward the freezing front led to desiccation in the middle height zone from 15 cm to 55 cm, with a moisture content decrease of around 2% (Fig. 11). Negative pressure in top zone forced further feeding from the base water and composed 17.4% in the base zone. Each column had absorbed 170 g on average from base deionised water supply by the end of the test.

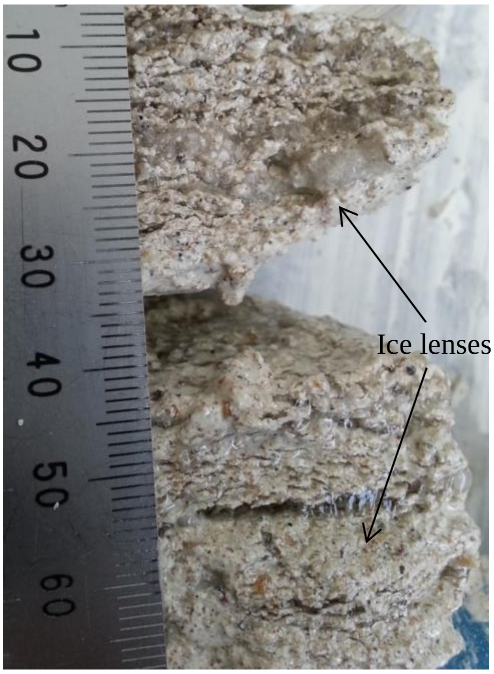


Fig. 10. Horizontal ice lenses present in the top soil with thickness up to 2 mm at the end of the freeze-thaw test, supplied with deionised water.

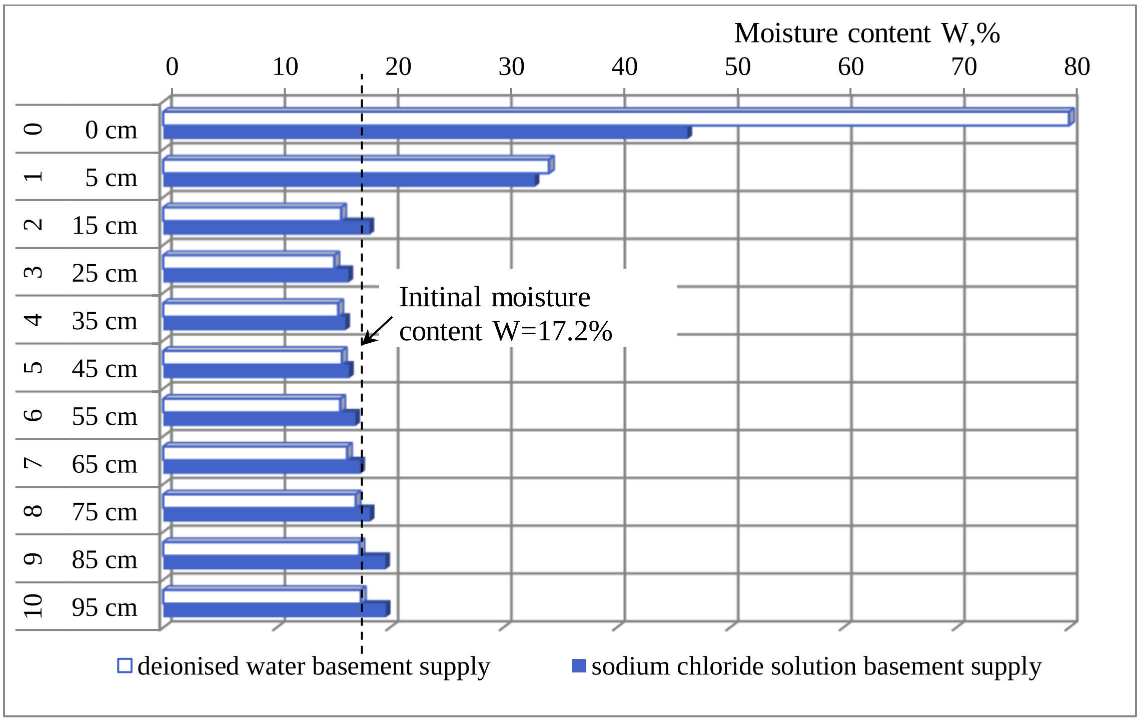


Fig. 11. Average moisture content distribution after 2 freeze-thaw cycles.

In comparison with the distilled water test, the solution supplied test resulted in a smoother moisture redistribution and less hydraulic conductivity. The top soils increased by 46.2% of moisture content at the end of two freeze-thaw cycles. Moisture content in the middle zone was insignificantly desiccated to 16.3% during the test and base soils were moisten by 19.6% of salt-water solution. The average solution intake during the test drew up 130 g per column.

3.3 Frost heave during the freeze-thaw cycles

Frost heave obtained in the deionised water supply test between 13-14 mm on average at the end of the first cycle, which is around 1.4 % from the initial height (Fig. 12a). The frost heave extension during the first 3 days of the first freezing cycle, 46-122 hours, was within the range of 2.6-5.2 cm/day. The freezing speed by the sample length at that period was 2.0 cm/day. While the next day (122-146 hours in Fig. 12) the frost heave extension decreased to 1.0-1.3 cm/day, while the freezing speed increased to 5.5 cm/day. During the next six days (146 to 290 hours) the frost heave extension was 0.1-0.5 cm/day. The freezing speed rose dramatically at the 15 -75 cm depth of the sample achieving the freezing rate of 20.0-35.0 cm per day. At the end of the first freezing cycle the freezing rate had slow down to 5.2 cm/day. In the second freezing cycle the similar heave level was achieved in shorter period. Some individual columns had up to 19 mm of frost heave. The frost heave extension in the first three days of the second freezing cycle (410-482 hours by the timeline), was in a range of 1.4-3.2 cm/day. The further 7 days period, 482-626 hours, the heave extension varied between 0.2-2.0 cm/day. However the freezing speed was only 0.63 cm/day and by the end of the test just the top 5 cm was frozen.

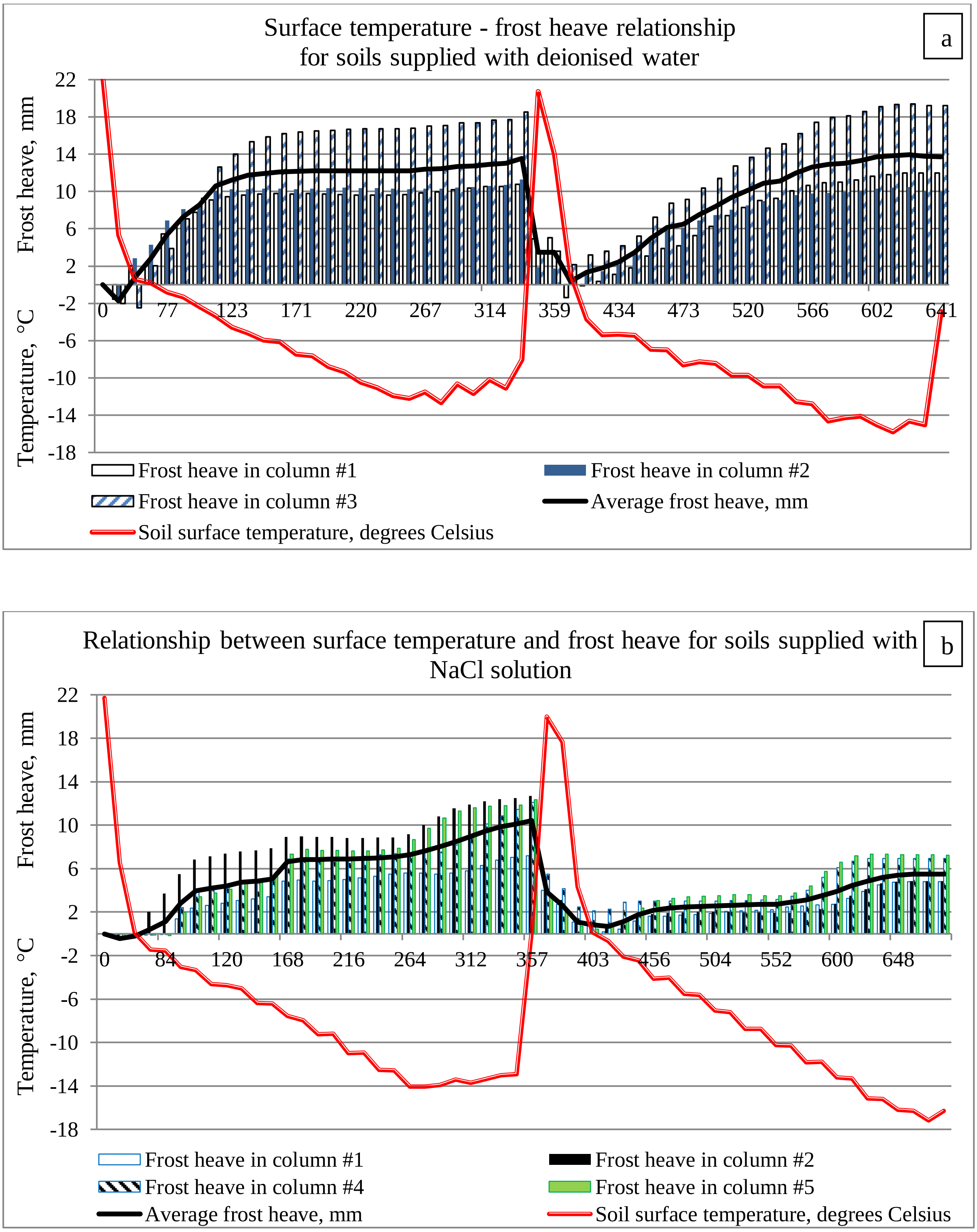


Fig. 12. Relationship between surface temperature and frost heave with time, h: a - deionised water supplied test; b - soils supplied from the base with 11 g/litre sodium chloride solution.

In the test supplied by chemical solution, the final frost heave had decreased to 10 mm on average (Fig. 12b). The freezing speed in the first cycle had a similar pattern to the test with deionised water. The frost extension during the first freezing cycle varied between 0.1-3.4 cm/day, with less heave extension at the surface temperature below -7 ºC. During the second freezing cycle, the vertical linear heave extension of soils did not exceed 1.1 cm/day and by the end of the test was less than 6 mm. This might be explained by chemical mass migration towards the cooling zone and a consequent reduction of the freezing point. The segregation of ice crystals requires its separation from the solution part, which leads the remained salt solution to become even more concentrated. Therefore, the salinization of ground water leads to the reduction in frost heave. The freezing speed in the second freezing cycle was 2.85 cm/day in the 403-447 hours' time interval, and 9.6 cm/day and more afterwards.

3.4 Chemical Conductivity

The measurement of sodium chloride content after freeze-thaw cycles was performed over the entire height of the soils columns with basement chemical solution supply (Table 3).

The average mass transfer of the sodium chloride and moisture content distribution at the end of freeze-thaw cycles is plotted in Fig. 13. Here the relatively zero value represents the initial chemical content measured for the soil sample before the test. In the range of about 20,000-30,000 mg/litre sodium chloride concentration in pore water was obtained after the test, throughout the soils in the middle height zone between 0.1-0.9 m depths. This corresponds to the chemical mass transfer of 0.10-0.14% to the dry soil's weight. Such dimensions basically exceeded the fresh water concentration limits and drastically changed the freezing point of soil samples.

Table 3 – Calculation of sodium chloride content after freeze-thaw cycles with basement solution supply of the soil columns.

Soil sample depth, cm	Electrical conductivity average for 9 columns, μS	NaCl, obtained by electrical conductivity g/250ml	Moisture content average for 9 columns, %	Mass of water dried out from the sample, g	Mass of NaCl per litre of pore water, g	Ratio of the weight of NaCl to the weight of dried soil, %
1	0.27	0.0250	46.3	11.563	8.65	0.100
11	0.26	0.0235	18.9	4.728	19.88	0.094
19	0.27	0.0250	16.9	4.225	23.67	0.100
29	0.29	0.0266	16.3	4.075	26.11	0.106
39	0.29	0.0266	16.3	4.075	26.11	0.106
49	0.29	0.0266	16.7	4.175	25.49	0.106
59	0.30	0.0280	17.2	4.300	26.05	0.112
69	0.30	0.0280	17.8	4.450	25.17	0.112
79	0.24	0.0208	18.9	4.725	17.61	0.083
89	0.35	0.0344	19.6	4.900	28.08	0.138
91	0.45	0.0460	19.6	4.900	37.55	0.184
92	0.78	0.0855	19.6	4.900	69.80	0.342
93	0.78	0.0855	19.6	4.900	69.80	0.342
94	0.77	0.0845	19.6	4.900	68.98	0.338
95	0.81	0.090	19.6	4.900	73.47	0.360
96	0.89	0.098	19.6	4.900	80.00	0.392
97	0.98	0.109	19.6	4.900	88.98	0.436
98	1.01	0.113	19.4	4.850	93.20	0.452
99	0.98	0.109	19.1	4.775	91.31	0.436
100	1.14	0.128	18.9	4.725	108.36	0.512

The electrical conductivity results after freeze-thaw cycles with de-icing chemical solution basement supply have confirmed that sodium chloride did migrate along with moisture toward the freezing top through the soils.

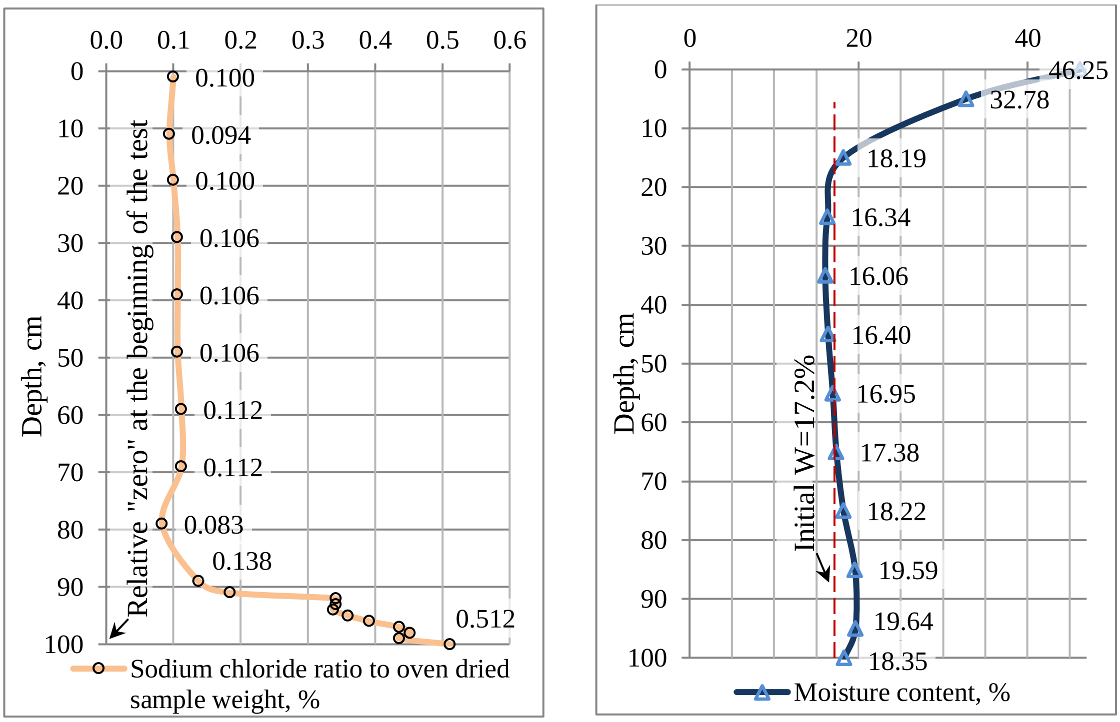


Fig. 13. The chemical mass transfer and corresponding moisture distribution with the column height after two freeze-thaw cycles.

4. Discussion

The applied method allowed clear differences in the results from distilled water and the sodium chloride solution supply to be observed.

The temperature distribution in the samples with the deionised water supply test registered the obvious change in the second freezing cycle, which was explained by severe moisture redistribution of moisture within the soil sample during the slow rate freezing.

On the contrary in the samples supplied with 11000 mg/litre sodium chloride solution the lower temperature was achieved throughout the columns height and less frost heave noted. A similar reduction in the frost heave rate in saline soil samples was observed by Wan, Lai and Wang, (2015). The vertical linear movement gauges displayed the increased soil volume after the first freeze-thaw cycle (Fig. 12), while above zero degree temperatures confirmed the thawing of the entire column length (Fig. 8). This can be explained with the moisture uptake to the soil samples which were at the maximum dry density achievable during sample preparation, and close to zero void content.

The inverse relationship of the frost heave extension and the freezing speed by the soil sample length was admitted. The maximum frost heave extension was observed at the beginning stage of the first freezing cycle when the rate of freezing through the sample was 2.0 cm/day. Iushkov and Sergeev (2015) also found that the maximum frost heave in clay soils is obtained at the slow freezing rate in a range 2-3 cm/day. The second freezing cycle showed the reduced freezing speed in the deionised water supply test and slightly accelerated freezing rate in the solution supplied one.

The results from the sodium chloride content measurements support the version of chemical mass transfer induced by the gradient in temperature. The presence of sodium chloride in the ground water influenced the significant cooling in the second freezing cycle and led to less moisture collection in the top 20 cm of the soil columns, with higher moisture content in the soils below this depth. The supply of sodium chloride solution also reduced the frost heave in the second freeze cycle despite the increase of moisture in the cooling zone. Furthermore, there was a clear migration of NaCl upwards to the freezing zone, which was more than expected given the observed water mass transfer.

The phenomenon of chemical mass transfer during the freeze-thaw cycles was induced by the diffusion of NaCl along a vertical concentration gradient, in excess of the redistribution that would be expected by the cryosuction-induced migration of the pore water.

Similar previous studies on freezing have produced somewhat contradictory results. Significant salt redistribution in a downward freezing test was observed by Baker and Osterkamp (1989), where the chemical mass was rejected from the frozen zone to produce an enriched brine in the unfrozen part of the soil sample. However no salt movement was observed in the upward freezing. Significantly, no additional moisture supply was provided in the Baker and Osterkamp (1989) test.

In contrast, Brouchkov (2000) reported no significant salt migration in a horizontally positioned sample experiencing a long term temperature gradient.

Bing's experiments with red clay samples showed an accumulation of chemical ions in the lower unfrozen zone and no change in the content in the upper frozen part of the sample (Bing and He, 2008). Here the samples were supplied with 5% sodium sulphate solute from the base. The amount of chemical mass transfer was sensitive to the temperature drop, enhancing the ion accumulation in the unfrozen part as temperature decreased.

It is worth noting that these previous studies for chemical mass transfer during freeze-thaw cycles were performed with soils that were already saline.

It is important to note that further work on chemical mass transfer is required as the degree of salt rejection during freezing, and the associated transfer of salt to the remaining soil water solution, is likely to be affected by freezing rate (Iushkov and Sergeev, 2015).

The current experimental design does not include monitoring of pore water pressure. The method also does not allow direct observation of water migration or ice segregation. Clearly, while the method is a more realistic representation of road subsoils than existing standards, it does not directly simulate the more complex soil conditions likely to be encountered on site.

5. Conclusions

From the experimental results using the new method, the following observations can be made:

1. The negative temperature distribution in the salt solution-fed soils was faster and more intense than for the deionised water supplied soils, particularly in the second freeze cycle of the test.
2. Moisture input from the base water table was 30% greater in the deionised water test than with 11000mg/litre sodium chloride solution supply.
3. The frost heave value in the deionised water test was greater than during the sodium chloride solution test, especially in the second freeze cycle. There is an inverse relationship between the frost heave extension rate and the freezing speed in the clay soils. The maximum frost heave rate was obtained when the freezing speed was 2 cm/day.
4. The chemical migration that occurred over the entire height of the columns confirmed the salt migration together with water redistribution towards the freezing top of soils. The chemical mass transfer obtained at the end of two freeze-thaw cycles was within 0.10-0.14%, using the ratio of sodium chloride mass to the dry soil mass. This corresponds to a 20,000-30,000 mg/litre concentration of sodium chloride in pore water.
5. The phenomenon of chemical mass transfer during the freeze-thaw cycles appears to be induced by both the thermal gradient and osmotic pressure caused by equilibration of the chemical potential throughout the soil column.
6. The migration of de-icing chemicals through the subsoil under a pavement area is likely to progressively change the chemical content in the ground water of soils and hence freezing regime under the road over time. Therefore the potential effect of de-icing chemicals and subsequent change of engineering properties of highway subsoils need to be considered at the design period.

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