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A. Sarsembayeva*[1], A. Zhusshupbekov[1,2,3], Ph.E.F. Collins[4]

[1]L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan
[2]Saint-Petersburg State University of Architecture and Civil Engineering,
Saint –Petersburg, Russia
[3]KGS, LTD, Nur-Sultan, Kazakhstan
[4]Brunel University London, London, United Kingdom
Corresponding author: assel_enu@mail.ru

Evaluation of frost heave in clay soils

Abstract. Frost heaving in clayey soils with a low coefficient of permeability raises a lot of questions regarding the cryosuction, surface tension forces, and accompanying phase transfer of water. The freeze-thaw laboratory test results were considered in this work in terms of temperature and volumetric parameters change, dry density, and water mass transfer. The article presents a model for calculating the mass transfer of water (vapour) in the gas state under the influence of cryogenic forces. Findings include the improved understanding of the heat and mass transfer phenomenon during the unidirectional freezing of soils in an open system. Most of the tests for engineering properties registered a slight reduction in relation to strength, cohesion, and angle of internal friction. However, there was a significant increase in the coefficient of permeability after the freeze-thaw cycles with initially dense compacted soil samples, which was due to loosening and moistening of the soil samples during the heave at sub-zero temperatures. The conceptual model for frost heave in soils was developed based on the vapour mass transfer. There was presented algorithm of vapour flow calculation in unsaturated soils using fundamental thermodynamic equations.

Keywords: frost heave, temperature monitoring, moisture transfer, clayey soils, laboratory testing, vapour transfer.

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Introduction

Clayey soils are well-known as frost susceptible soils, despite they have very low permeability and high surface tension. The surface tension in the ground water is around $63 - 64\ 10^{-7} J\ cm^2$ [1]. The soil structure in the freezing fringe includes the moisture in three phases: the solid part - ice lenses; the liquid phase – hydroscopic and capillary water; and the gas phase – saturated and unsaturated vapour. It should be noted that ground soils are subject to unidirectional freezing, which is usually derived from the top downwards. Ice lenses nucleation starts in the pores and channels with gravimetric water, where the pore water pressure is close to atmospheric level. Withdrawal of the thermal energy during soil freezing induces the following phase transformations: the segregation of water in the liquid phase to ice, accompanied by thermal energy release and condensation of the gas phase to liquid, according to the phase equilibrium. A sharp reduction of the water and gas phases in the freezing pores has been ascribed to the analogy of drying by Henry [2].

Arenson *et al.* [3] has also noted that vertical veins do not grow in thickness as the horizontal lenses do over time. However, Arenson *et al.* did not identify a phase in which moisture is transported. They mentioned some concerns about the suction required to drive the hydraulic conductivity at atmospheric pressure, by determining that the negative pressure should be not less than 900 kPa to draw up the water.

Among all structures, the most vulnerable to frost heaving are highways. Due to the high density and increased thermal conductivity of the pavement and sub–base materials the temperature field in highway subsoils differs only slightly when compared to soils in a natural state [4]. Dynamic traffic load increases the pressure and melts some parts of the ice for a short period of time in highway subsoils [5]. The mechanism of short-term load application to the frozen subsoils can be explained by a regelation theory, when that part of the ice located closest to the soil particles starts to melt under the pressure. The liquefied water migrates upwards to the cold side as soon as the dynamic load is removed and refreezes in the new place. The dynamic loading here acts as a piston pump.

The study focuses on moisture mass transfer in unsaturated soils, as this is the most likely state of soils under highways in the winter period. The article considers determination of moisture mass transfer implemented with vapour flow.

Research methods

Frost susceptible soils were conducted for 2 freezing-thawing cycles in open system laboratory tests, so the samples were supplied from the base by deionized water (Figure 1). In test 1 nine soil samples of 1 meter length sandy clay soil were compacted artificially to the maximum dry density and placed to the environmental chamber and simultaneously frozen from the top. In test 2 the length of the samples was reduced twice to 50 cm, while column 1 was compacted with the least dry density, increasing in every other column, and reaching the maximum density in column 9. The characteristics of the freeze-thaw cycles are presented in Table 1. The initial parameters of the soil samples are presented in Table 2.

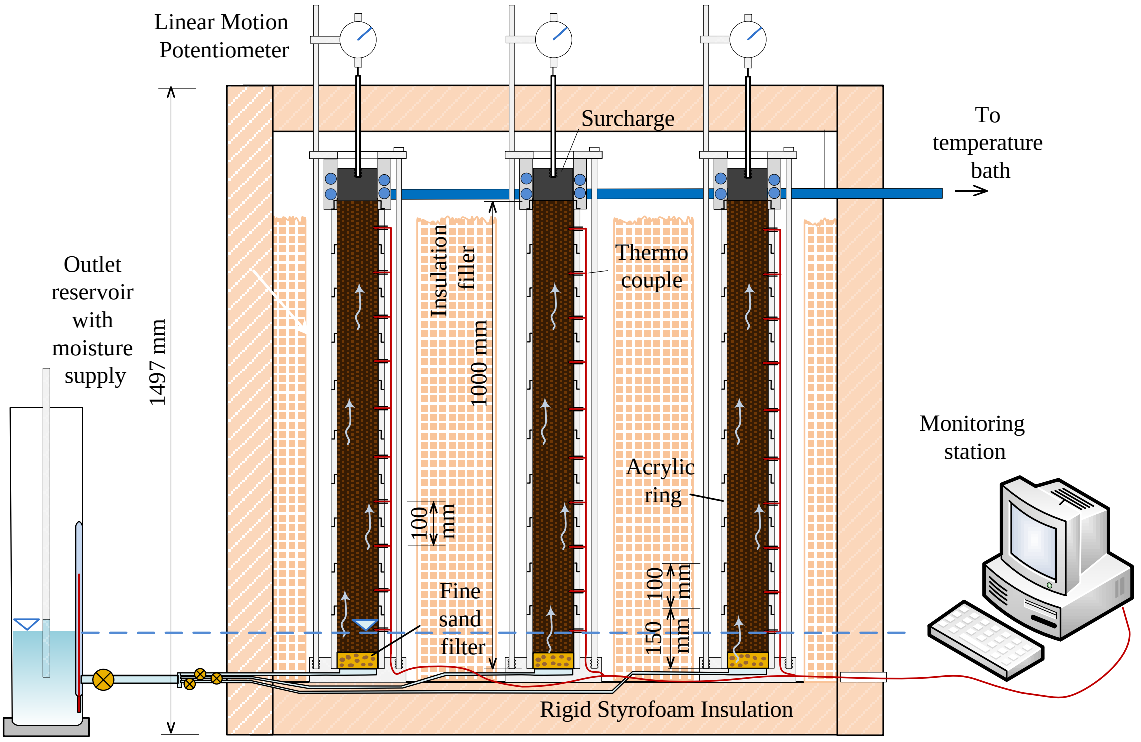


Figure 1. Environmental chamber for freeze-thaw cycles with a capacity of nine 1m length soil columns

Table 1

Freeze-thaw test characteristics

Test no.	Sample length	Base water supply	Dry density of the sample	Sample testing technique
1	100cm	Deionised water	All samples compacted with max dry density: 1.80 Mg/m^3	Three columns removed after the first freeze cycle, three columns after the first thaw and the remained three after the second freeze cycle
2	50cm	Deionised water	Samples compacted with varied dry density: 1.18-1.80 Mg/m^3	Nine columns kept until the end of the second freeze cycle

Table 2

Initial soil samples characteristics

Characteristic	Symbol	Unit	Value	Annotation
Initial moisture content	W	%	17.2	See Figure 3.1 – 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	Mg/m^3	2.615	Soil mixture by mass: 50% sand and 50% kaolinite
Average dry density before freezing cycle	ρ_d	Mg/m^3	1.814 ± 0.012	BS Light compaction test operating with 2.5 kg rammer. The mechanical energy applied to the soil is 596 kJ/m^3
Initially bulk density at the beginning of the test	ρ	Mg/m^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	%	37.18	CI – Medium plasticity cone penetrometer test used
Plastic Limit	w_P	%	23.77	Fraction of soil sample passed through 0.425 mm sieve
Average linear shrinkage	L_S	%	5	
Plasticity Index	PI	%	13	

A slow unidirectional freezing technique was used during the freezing to provide enough time for the cryosuction processes [6, 7]. The temperature drop was set by 2 ^{0}C every 24 hours for 12 days and reduced down to -23 °C at the temperature control unit. Temperature sensors were inserted in the center of each sample by every 10 cm of the length. 96 thermocouples continuously recorded the temperature via Pica loggers while frost heave was monitored by vertical linear gauges. The base of the soil samples were kept unfrozen during the entire experiment. By the end of the freeze-thaw cycles the moisture redistribution over the sample length was determined according to standard BS 1377-4:1990 by weight difference of the wet and oven dried sample at 105 °C for 24 hours.

The heat change Q in a mold section over the time t was found as the sum of the cooling heat and the latent heat during the phase transfer:

$$Q \cdot t = Q_1 + Q_2 \tag{1}$$

where, Q_1 – heat energy is used for cooling the vapour mass to the temperature ΔT (equation 5.5); and $\mathrm{Q}_2 -$ heat energy used for the phase transfer (eq. 5.7).

$$Q_1 = m_{vapour,,}\, t_i \cdot C \cdot \Delta T \tag{2}$$

where, $m_{vapour}, t_{1,}$ - mass of vapour at the starting time t_1,g;C – specific heat of vapour passing through the cumulative air voids cross section, *J/kg·ºC*; ΔT – temperature change, ºC; and t – time interval, h.

Density of the vapour is calculated for each period of time, corresponding to the temperature and saturated vapour pressure:

$$\rho_{vapour,t_i} = \frac{m_{vapour,t_i}}{V_{air,t_i}} \tag{3}$$

where, ρ_{vapour,t_i}- vapour density for period of time, g/cm³.

Heat energy for the phase transfer includes the latent heat for the condensation and solidification of the vapour mass difference at the beginning t_1 and end time t_2 of the calculation period.

$$Q_2 = (m_{vapour,1} - m_{vapour,2}) \cdot L \tag{4}$$

where, $m_{vapour,2}$ – mass of the vapour at the end period t_2; L – is a total latent heat $L = L_1 + L_2$, where L_1 - specific latent heat for condensation ($L_1 = 2.3 \cdot 10^6\, J/kg$) and L_2 - specific latent heat for solidification ($L_2 = 0.335 \cdot \frac{10^6\, J}{kg}$ of 1 kg of water).

The volume of vapour V_{vapour} is equal to the speed of vapour passing through the air voids' cross section A over the time t:

$$V_{vapour} = v \cdot t \cdot A_{air\ voids} \tag{5}$$

where, v – average speed of vapour, cm/h; and $A_{air\ voids}$ – cumulative section cross of the air voids' $A_{air\ voids} = \frac{\pi \cdot {d_a}^2}{4}$, cm², corresponding to the porosity coefficient and moisture content (Figure 2).

Substituting the V_{vapour} in equation (2) the vapour speed was found at the starting time and at the end:

$$v_{vapour} = \frac{Q}{C \cdot \rho \cdot A_{air} \cdot \Delta T \cdot t} \tag{6}$$

The mass of ice built from the vapour passing through the air voids channels in a 10 cm length mould section with correspondent cumulative cross section A_{air} and speed v over time t is calculated:

$$m_{ice} = \rho_{vapour} \cdot V_{air\ voids} = \rho_{vapour} \cdot v \cdot t \cdot A_{air} \tag{7}$$

where, m_{ice} - mass of built ice in grams; ρ_{vapour} – is taken as an average density value of the vapour densities at the start and end time point, g/cm³ .

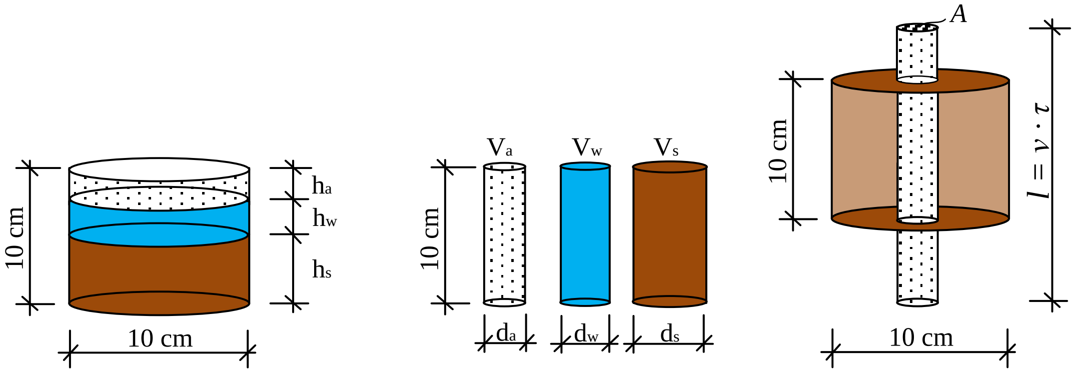
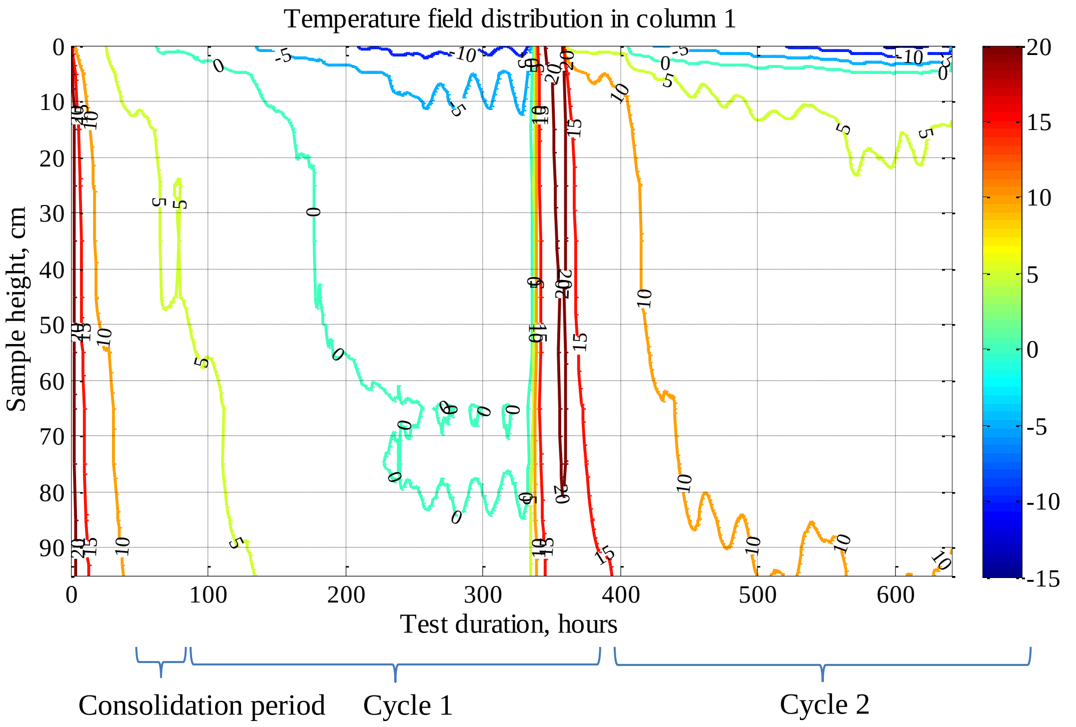


Figure 2. Calculation of the vapour rate passing through the cumulative air voids channel in the mould section over time t

Results and discussion

In Test 1, the temperature drop was less pronounced due to the formation of ice lenses at the top of the soil columns and the resulting latent heat released for the increased amount of water. The top 5 cm of soil in Figure 3a dropped down sub-zero temperatures, while the temperature distribution over the length of the samples stayed in a range of +5 - +10 °C. Ice lens formation was observed at the top of the sample, which appears to act as a heat insulator and prevented the further freezing of the soil. In Test 2 the temperature distribution changed with a range of soil density, although did not obtain a steady pattern of freezing rate in terms of ınıtıal density. This is possible because the freezing rate of 2 °C per day provided sufficient time for temperature distribution across the entire length. Notably, a deceleration of the freezing rate was observed in the second freezing cycle. The temperature field distribution with time in Test 2 was similar to Test 1, where the temperature contours in the second freezing cycle were higher compared to Test 1.

a)



b)

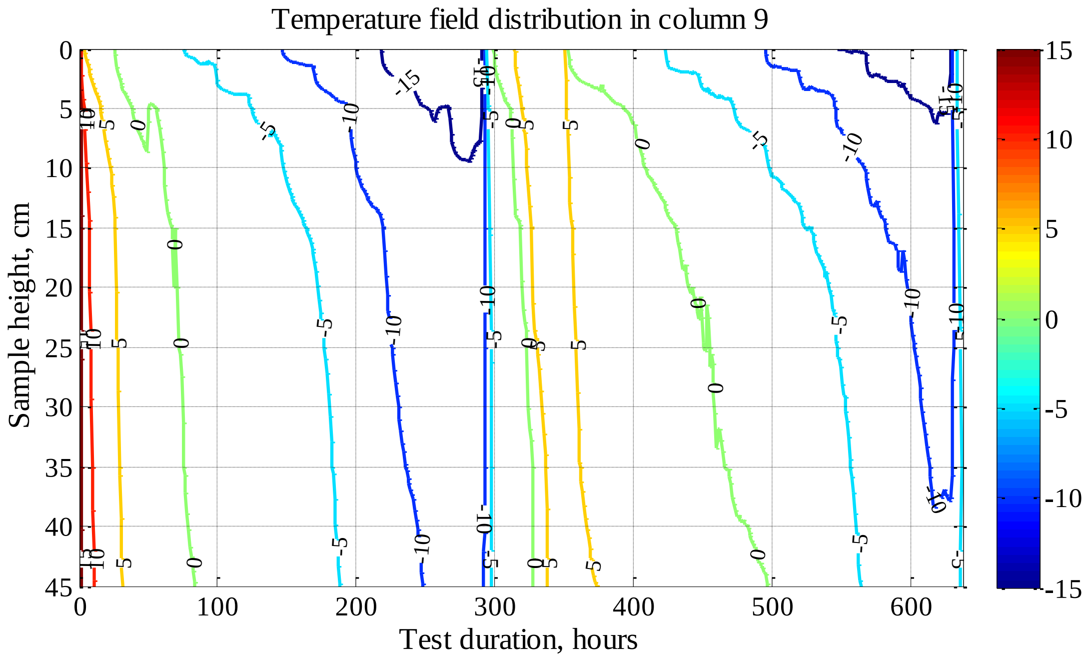


Figure 3. Temperature contours in column 1 in Test 1 and 2, supplied with deionized water from the column base wıth (a) max and (b) variable soil densities.

The average duration of testing comprised over 600 h. The relationship between the surface temperature and frost heave value over time for the soil samples compacted with maximum dry density is presented in Figure 3. In both tests, the greatest variety of volumetric deformation in the vertical axis was registered by the end of the second freezing cycle. The frost heaving value for test 1 twice exceeds the frost heaving in test 2 correspondently to the length of the sample. In Test 3 with a deionized water supply, the maximum rates of frost heave were achieved in columns 7 and 8, where the dry density was close to the maximum value 1.65-1.79 Mg/m^3, while the loose soil samples, with a dry density 1.18-1.47 Mg/m^3, registered very weak heaving in the first cycle and consolidation or compression in the second cycle compared to the initial volume.

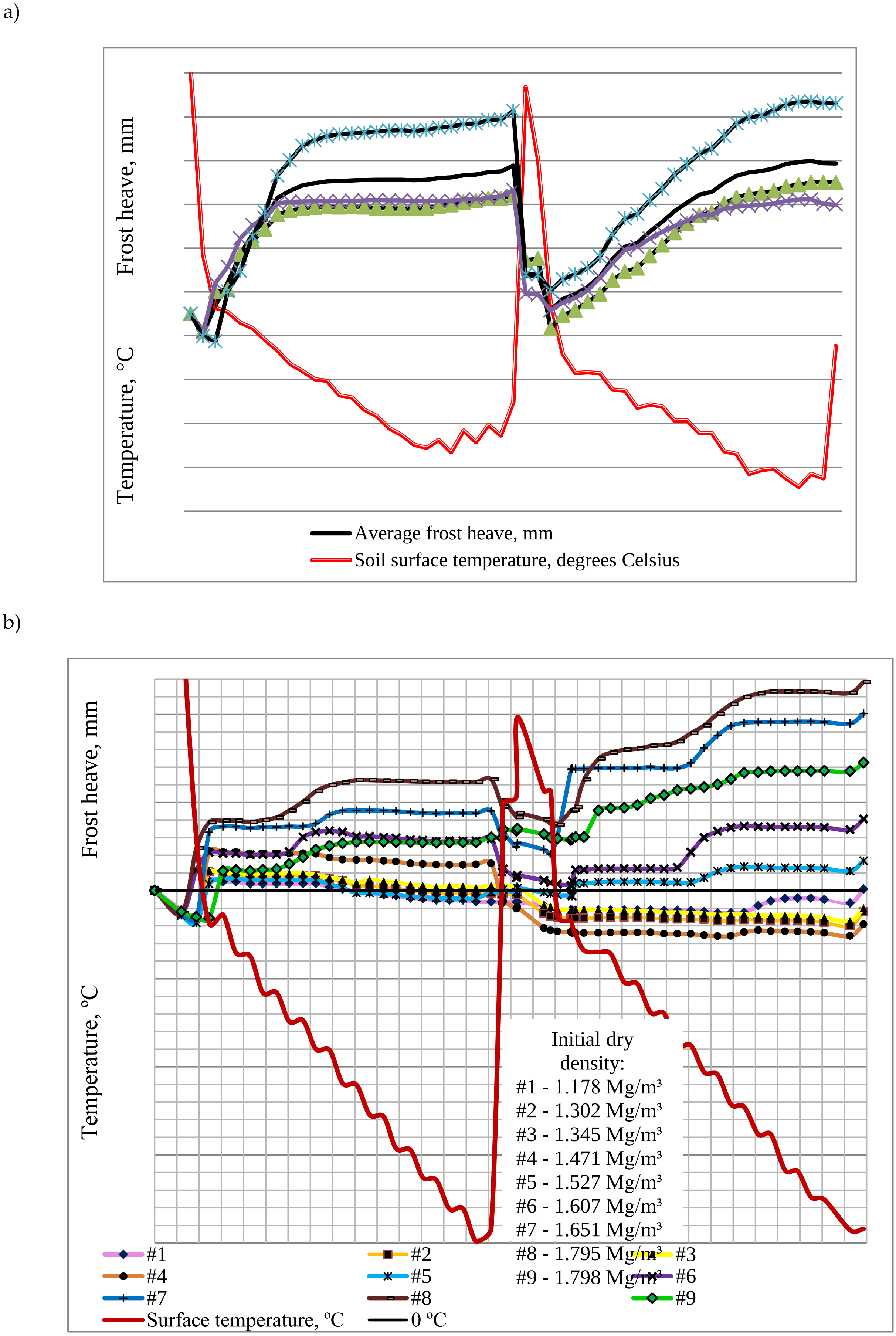


Figure 4. Relationship between surface temperature and frost heave: a - Test 1 b -Test 3

Regarding the moisture intake, there was a significant increase in moisture, reaching 40% in the top 10 cm layer of the soil samples in Test 1, which were draining and moistening the 20 cm under this layer during the thawing period. Although the water was drawn upwards again as the second freezing cycle started. According to the results in Test 2, the moisture content represents advanced water intake in the loose soil, with a dry density range between 1.18-1.65Mg/m^3, comparing to dense soils with dry density 1.8 Mg/m^3. Except for sample 4, in all the columns the moisture content reached 24.5% or above by the end of the test. The reason for low moisture intakes in sample 4 could have been due to occasional violation of the water supply during the freeze-thaw test.

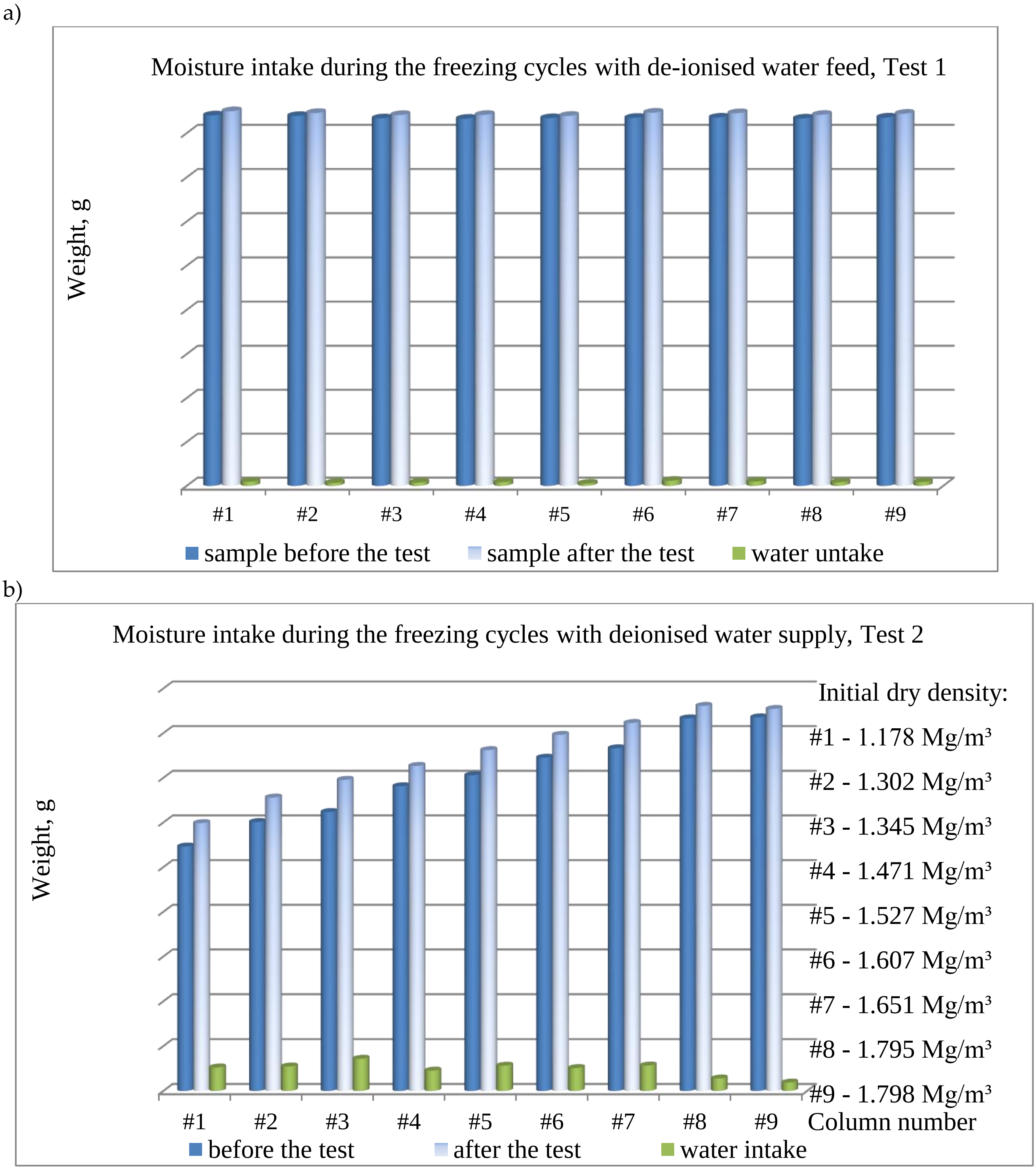


Figure 5. Moisture intake during Test 1 (a) and Test 2 (b) with maximum dry density and 1 m soil sample height

Ice lens formation in the top 10 cm layer caused a highly irregular distribution of moisture, which was confirmed by the centimeter sampling in Figure and also in the soil structure. The moisture intake in Test 2, with a shallow 45 cm depth groundwater supply table was higher than for Test 1, where the water supply was located at 95 cm depth and the soil samples were made with maximum dry density. For this reason, the moisture content between 15 and 45 cm from the soil surface was relatively stable and depended just on the density of the soil samplesa)

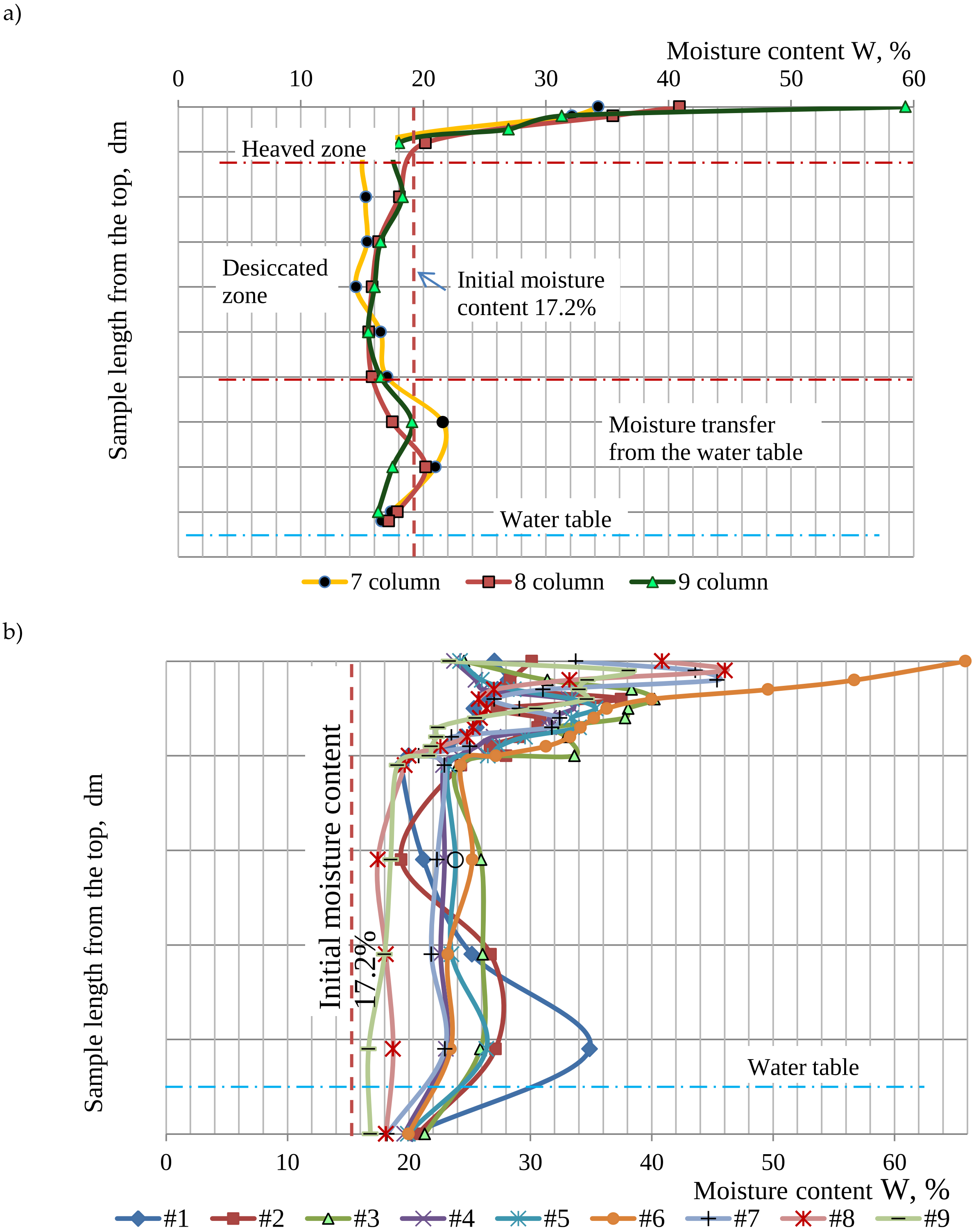


Figure 6. Moisture redistribution by the sample length after two freeze-thaw cycles with a deionized water supply: a –Test 1, b –Test 2

The coefficient of permeability of soil columns in Test 1 varied in the range of *2.9-8.8x10-9* m/s. Here, the moisture transfer was induced by cryosuction forces. The amount of transported moisture is related to the cooling rate and thus to the amount of energy lost, which is distributed to the phase transfer energy and cooling of each soil component, according to its heat conductivity.

Calculations of the vapor mass transfer are presented in Tables 3 and 4 on the example of column 1 in Test 2. The length of the soils sample in Test 3 was 50 cm, which was composed of five assembled mould sections, each 10 cm in length.

Table 3

Initial density characteristic in Column 1, Test 2

Sample section	Volume of solids, cm³	Volume of voids, cm³	Voids ratio e= $\rho_s/\rho_{dry}-1$	Volume of air , cm ³	Temperature at 590 h	Saturated vapour pressure over ice, P_{si}, Pa	Mass of vapour at 590, g	Density of the saturated vapour at 590h, Mg/m³
#11	**370.62**	**448.46**	**1.21**	**180.55**	**-10.99**	**237.93**	**$3.55\cdot10^{-4}$**	**$1.97\cdot10^{-6}$**
#12	352.97	432.43	1.23	228.13	-10.30	253.24	$4.76\cdot10^{-4}$	$2.09\cdot10^{-6}$
#13	352.97	432.43	1.23	198.83	-9.49	272.16	$4.45\cdot10^{-4}$	$2.24\cdot10^{-6}$
#14	352.97	432.43	1.23	129.85	-8.36	300.63	$3.19\cdot10^{-4}$	$2.46\cdot10^{-6}$
#15	352.97	432.43	1.23	154.52	-6.46	354.77	$4.45\cdot10^{-4}$	$2.88\cdot10^{-6}$

Table 4

Calculation of the moisture mass transfer in freezing soils on the example of Test 2, column 1

Sample section	Temperature at 614 h, °C	Saturated vapour pressure over ice, P_{si}, Pa	Mass of vapour at 614 h, g	The heat realised in 24 hours $Q\cdot t=m\cdot C\cdot\Delta T$, J	Vapour rate $v=4\cdot N/(C\cdot\rho\cdot\pi\cdot d^2\cdot\Delta T)$, cm per 24 h	Vapour rate, cm/h	Build-up of ice mass between the period 590/614 h, g/hour
#11	**-13.30**	**193.26**	**$2.91\cdot10^{-4}$**	**0.1702**	**9.008**	**0.375**	**$2.67\cdot10^{-6}$**
#12	-12.60	205.98	$3.91\cdot10^{-4}$	0.2269	9.014	0.376	$3.56\cdot10^{-6}$
#13	-11.68	223.81	$3.69\cdot10^{-4}$	0.2016	9.067	0.378	$3.16\cdot10^{-6}$
#14	-10.43	250.35	$2.68\cdot10^{-4}$	0.1363	9.126	0.380	$2.14\cdot10^{-6}$
#15	-8.96	284.98	$3.61\cdot10^{-4}$	0.2237	8.956	0.373	$3.51\cdot10^{-6}$

The average vapour rate was around 0.4 cm/h. The build-up of ice mass between the period in 24-hour period varied in a range of 2.14·10-6 -3.56·10-6 g, depending on the void ratio and temperature change. Here, it is assumed that the porosity coefficient of the sample remains constant during the calculation period. Consequently, the volume of the air voids and the cumulative cross-section of the air voids also remained constant. It should be noted that only heat consumed for the gas phase energy exchange was considered in this problem. The solid and liquid parts have also been cooled down with the heat withdrawn by the cooling machine. However, they are not counted, because all the necessary energy exchange has been done by an automatic set of temperature controls.

Conclusion

There was considered positioning of the soil structure, based on the experimental data of the measured temperature, vertical linear volumetric change registered by testing time, and the obtained moisture-density relation.

Further outcomes have been concluded from the presented material:

1. The obtained results have improved understanding of the heat and mass transfer phenomenon during the unidirectional freezing of soils in an open system.
2. Most of the tests for engineering properties registered a slight reduction in strength, cohesion, and angle of internal friction. However, there was a significant increase in the coefficient of permeability after the freeze-thaw cycles with initially dense compacted soil samples, which was due to loosening and moistening of the soil samples during the heave at sub-zero temperatures.
3. The conceptual model for frost heave in soils was developed based on the vapour mass transfer. The algorithm of vapour flow calculation in unsaturated soils was presented using fundamental thermodynamic equations.
4. The model is suitable for numerical solutions, like finite element analysis or a model like a coupled heat-water transfer, in terms of considering the vapour flow and considering the cryosuction forces. The latent heat for the phase transitions and the dynamic change of the coefficient of porosity and air void volume needs also to be considered.

References

1. Tschapek M., Scoppa C.O. and Wasowski C. The surface tension of soil water / Journal of Soil Science. -1978. -vol. 29, no. 1. -pp. 17-21.

2. Henry K.S. A review of the thermodynamics of frost heave / Henry, K.S. -Hannover, New Hampshire: US Army Corps of Engineers, -2000.

3. Arenson, L.U., Azmatch, T.F. and Sego, D.C. ‘A new hypothesis of ice lens formation in frost-susceptible soils’// Ninth International Conference of Permafrost, Fairbanks, Alaska, -2008. -pp. 59-65.

4. Chunpeng H., Yanmin J., Peifeng Ch., Guibo R. and Dongpo H. 'Automatic Measurement of Highway Subgrade Temperature Fields in Cold Areas' / Chunpeng, H. - Intelligent System Design and Engineering Application (ISDEA), 2010 International Conference, -2010. -pp. 409-412.

5. Sarsembayeva A.S., Zhussupbekov A.Zh. Experimental study of deicing chemical redistribution and moisture mass transfer in highway subsoils during the unidirectional freezing // Transportation geotechnics. -2021. -26.

6. Sarsembayeva A, Collins P. A modified freeze-thaw laboratory test for pavement sub soils affected by de-icing chemicals. / Engineering Geology for Society and Territory. Applied Geology for Major Engineering Projects 6. Switzerland: Springer International Publishing. -2015. - p.243.

7. Sarsembayeva A, Collins P. Evaluation of frost Sarsembayeva A, Collins P. Evaluation of frost heave and moisture/chemical migration mechanisms in highway subsoil using a laboratory simulation method // Cold Reg Sci Technology. -2017. -Vol. 133. -Pp. 26-35.

А.С. Сарсембаева[1], А.Ж. Жусупбеков[1,2,3], Ф.Э.Ф. Коллинз[4]
[1]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Нұр-Сұлтан, Қазақстан
[2]Санкт-Петербург мемлекеттік сәулет-құрылыс университеті, Санкт-Петербург, Ресей
[3]KGS, ЖШС, Нұр-Сұлтан, Қазақстан
[4]Лондондағы Брюнель Университеті, Лондон, Ұлыбритания

Сазды топырақтардың аяздан қатуын анықтау

Аңдатпа. Өткізгіштік коэффициенті төмен сазды топырақта өтетін аяздың қатуы криосакцияға, беттік керілу күштеріне және судың фазалық ауысуына қатысты көптеген сұрақтар туғызады. Бұл жұмыста мұздату-еріту зертханалық зерттеулерінің нәтижелері бойынша температура мен көлемдік параметрлердің өзгеруі, құрғақ топырақтың тығыздығы және су массасының тасымалдануы қарастырылды. Криогендік күштердің әсерінен газ күйіндегі судың (будың) тасымалдануын есептеу моделі келтірілген. Зерттеу нәтижелері ашық жүйедегі топырақты бір бағытты мұздату кезіндегі жылу және масса алмасу құбылысы туралы түсінікті жақсартуды қамтиды. Инженерлік қасиеттерге арналған сынақтардың көпшілігінде үйкеліс күші, беріктігі және ішкі үйкеліс бұрышының шамалы төмендеуі тіркелді. Алайда, бастапқыда тығыздалған топырақ сынамаларымен мұздату-еріту циклдарынан кейін өткізгіштік коэффициентінің едәуір өсуі байқалды. Бұл нөлдік температурада үйінді кезінде топырақ үлгілерінің қопсытуына және ылғалдануына байланысты болды. Буланған массаның тасымалдануына негізделген топырақта аяздан ісінудің тұжырымдамалық моделі жасалған. Сумен қанықпаған топырақтағы бу шығынын есептеу алгоритмі іргелі термодинамикалық теңдеулер көмегімен ұсынылды.

Түйін сөздер: аязды көтеру, температураны бақылау, ылғалдың берілуі, сазды топырақтар, зертханалық сынақ, будың берілуі.

А.С. Сарсембаева[1], А.Ж. Жусупбеков[1,2,3], Ф.Э.Ф. Коллинз[4]
[1]Евразийский национальный университет им.Л.Н.Гумилева, Нур-Султан, Казахстан
[2]Санкт-Петербургский государственный архитектурно-строительный университет, Санкт-Петербург, Россия
[3]KGS, ТОО, Нур-Султан, Казахстан
[4]Брюнель Университет Лондона, Лондон, Великобритания

Оценка морозного пучения глинистых грунтов

Аннотация. Морозное пучение в глинистых грунтах с низким коэффициентом проницаемости вызывает множество вопросов, касающихся криогенных сил, поверхностного натяжения и сопутствующего фазового перехода воды. В работе рассмотрены результаты лабораторных испытаний замораживания-оттаивания с точки зрения изменения температурных и объемных параметров, плотности в сухом состоянии и массопереноса воды. Представлена модель для расчета массопереноса воды (пара) в газовом состоянии под действием криогенных сил. Результаты исследований включают улучшенное понимание явления тепломассопереноса при однонаправленном промерзании почв в открытой системе. В большинстве испытаний инженерных свойств было зарегистрировано небольшое снижение соотношения прочности, сцепления и угла внутреннего трения. Однако наблюдалось значительное увеличение коэффициента проницаемости после циклов замораживания-оттаивания с изначально плотными уплотненными образцами грунта, что было связано с разрыхлением и увлажнением образцов грунта во время вспучивания при отрицательных температурах. На основе паромассопереноса разработана концептуальная модель морозного пучения грунтов. Алгоритм расчета парового потока в ненасыщенных грунтах представлен с использованием фундаментальных уравнений термодинамики.

Ключевые слова: морозное пучение, мониторинг температуры, влагоперенос, глинистые почвы, лабораторные испытания, парообмен.

References

1. Tschapek M., Scoppa C.O. and Wasowski C. The surface tension of soil water. Journal of Soil Science. 29(1), 17-21 (1978).
2. Henry K.S. A review of the thermodynamics of frost heave. Henry, K.S. US Army Corps of Engineers, Hannover, New Hampshire, 2000.
3. Arenson L.U., Azmatch T.F. and Sego D.C. ‘A new hypothesis of ice lens formation in frost-susceptible soils’. Ninth International Conference of Permafrost, Fairbanks, Alaska, 2008. pp. 59-65.
4. Chunpeng H., Yanmin J., Peifeng Ch., Guibo R. and Dongpo H. 'Automatic Measurement of Highway Subgrade Temperature Fields in Cold Areas'. Chunpeng, H. - Intelligent System Design and Engineering Application (ISDEA), 2010 International Conference, 2010. 409-412.
5. Sarsembayeva A.S., Zhussupbekov A.Zh. Experimental study of deicing chemical redistribution and moisture mass transfer in highway subsoils during the unidirectional freezing. Transportation geotechnics. 26, (2021).
6. Sarsembayeva A, Collins P. A modified freeze-thaw laboratory test for pavement sub soils affected by de-icing chemicals. Engineering Geology for Society and Territory. Applied Geology for Major Engineering Projects 6. (Springer International Publishing, Switzerland, 2015. p. 243).
7. Sarsembayeva A, Collins P. Evaluation of frost Sarsembayeva A, Collins P. Evaluation of frost heave and moisture/chemical migration mechanisms in highway subsoil using a laboratory simulation method. Cold Reg Sci Technology. 133, 26-35 (2017).

Information about authors:

Assel Sarsembayeva - Civil Engineering, Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan.

Askar Zhussupbekov - Civil Engineering, Department of Geotechnics, Saint-Petersburg State University of Architecture and Civil Engineering, Saint–Petersburg, Russia.

Philip E. F. Collins - Civil Engineering, Department of Civil and Environmental Engineering, Brunel University London, London, United Kingdom.

Асель Сарсембаева - Л.Н. Гумилев атындағы Еуразия ұлттық университетінің құрылыс бөлімі, Нұр-Сұлтан, Қазақстан.

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Филипп Ф. Коллинз - Брунель университетінің Азаматтық инженерия, Азаматтық және қоршаған орта факультеті, Лондон, Ұлыбритания.