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EFFECT OF SILT AND CLAY FRACTION CONTENT ON FROST HEAVE OF FINE-GRAINED SOILS

Kinga WITEK-ZIELONKA [a*], Krzysztof PARYLAK [b], Wojciech KILIAN [c], Łukasz ZIELONKA [d]

[a] PhD Eng.; Zespół Szkół Budowlanych, ul. Pestalozziego 18, Bydgoszcz, 85-095, Poland;
*Corresponding author. E-mail address: *kinga.witek88@interia.pl*

[b] PhD DSc; The Faculty of Environmental Engineering and Geodesy, Wrocław University of Environmental and Life Sciences, Grunwaldzka 55 Street, Wrocław, 50-357, Poland

[c] PhD Eng.; The Faculty of Environmental Engineering and Geodesy, Wrocław University of Environmental and Life Sciences, Grunwaldzka 55 Street, Wrocław, 50-357, Poland

[d] PhD; Institute of Mathematics and Physics, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, Bydgoszcz, 85-789, Poland

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Abstract
Frost heave in soils is a significant problem of geotechnical engineering. Despite the introduction of numerous simplified frost susceptibility criteria, there is still no clear relationship between the particle size distribution and their frost heaving susceptibility. Therefore, an experimental attempt was made to link the graining features of the four soils with the mechanisms of the formation of frost heave. The main aim of the study is to determine the influence of the content of silt and clay fractions on the height of the frost heave. The tested soils were characterized by a varied content of the silt fraction, which, together with smaller ones, amounted to 30%, 40%, 50% and 70%, and a variable content of the clay fraction amounting to 0%, 0%, 21% and 5% in individual soils, respectively. For the purposes of the experiment, a test stand was constructed that allows for testing 6 identical samples at a time. The tests were carried out in an open-system test, i.e. with the possibility of water flowing into the freezing zone. The total freezing process was carried out at -10°C and lasted 160 hours. On the basis of the obtained results of the increase in the height of the samples, it was shown that the silt with the highest total content of silt and clay fractions of 70% shows the highest frost heave and the smallest increase in the height of the samples in the freezing process is shown by sandy silt with the lowest sum of both these fractions. On the basis of the analysis of the results of the tested soils, it was found that the height of the frost heave was influenced by the presence of the clay fraction, but in connection with the presence of the silt fraction. In the frost heave soils, the content of the silt fraction influences the amount of the frost heave to the extent of more than two times smaller than the content of the clay fraction.

Keywords: **Frost heave of soils; Ice lenses; Frost susceptibility criteria; Fine-grained soils; Silt and clay fraction.**

1. INTRODUCTION

In the freezing process of soils, ice lenses are formed, which grow as a consequence of water being attracted into the freezing zone. This causes an increase in the volume of soil and, at the same time, a decrease in the dry density. This phenomenon has a direct impact on the change of soil structure and texture, causing changes in physical and mechanical properties.

Frost heave processes are particularly important from the point of view of negative effects affecting the functioning of engineering structures. As documented by numerous studies, these phenomena are generally the causes of various types of construction failures, including mainly road surface deformations [1, 2], highway embankments [3] slope landslides, disasters of damming structures [4, 5], or railway subgrade deformations [6]. They can also cause the failure of water pipes [7, 8], and in the construction of buildings, they can cause scratches on walls. That is why it is valuable to observe the process of crystallization and growth of ice lenses in real-time. Wang et al. proposed [9] a new method of monitoring the process of ice content build-up in the soil during the freezing process.

The year 1854 is considered to be the beginning of Volger's research on the frost heave of soils. However, the basis of the first frost heave hypothesis was the Taber [10, 11] assumptions concerning the migration of water to the freezing zone. This theory, called a capillary theory, describes the occurrence of increasing suction pressure during the formation of ice lenses. Penner [12] and Gold [13] observed that the size of this pressure is determined by the geometry of the porous soil matrix, in which ice lenses are formed. These observations led to the work of Everett [14] who spread the capillary theory.

Due to the inability to apply the capillary theory in predicting the formation of successive ice lenses, Miller [15] introduced the rigid ice model, which was modified by O'Neill and Miller [16]. In this model, the division of freezing soil into individual zones was introduced. Of significant importance is the area which is known as the frozen fringe, in which both ice and water are transported to the frozen zone [17]. The thickness of the frozen fringe depends on the temperature. Reducing the temperature gradient reduces the thickness of the frozen fringe that limits the flow of water to the expanding ice lenses. In the frozen fringe, the dependence of water and ice pressure on temperature is described by the generalized Clapeyron equation. Obviously, the main factor of water movement is hydraulic conductivity and water content in the non-frozen zone [18, 19]. Peppin showed that the growth rate and stability of the ice lens depend on the degree of soil salinity [20].

An important factor influencing the size of the frost heave is the initial degree of saturation of the sample, which affects the process of water migration in the soil. The water content migration process occurs mainly in the liquid phase, however, with incomplete water saturation of the soil and with temperature and pressure differences, the movement also occurs in the form of steam [19, 21]. Frozen samples in a closed system exhibit frost shrinkage when the initial soil saturation (S_r) is low, however, frost heave and frost cracking occur when the initial soil saturation is high [22, 23].

Another explanation for the formation of frost heave is the theory based on the adsorption force developed by Takagi [24]. This theory describes the formation of frost heave through the so-called solid-like stress in non-frozen water films between the surface of ice and soil.

Due to the complexity of assessing the degree of frost heave of soils, many researchers have attempted to link the basic physical properties of soils with the phenomenon of frost heave formation. Therefore, for practical purposes, the so-called frost susceptibility criteria were established.

Over the years, many frost susceptibility criteria have been developed, in which the main factor in assessing the frost susceptibility of soils is their granulation of soil [25, 26, 19, 27, 28]. In light of the literature, there is no clear division of soils in terms of their frost heave. Most of the criteria are based on the percentage of particles smaller than 0.02 mm as a factor determining the amount of frost heave. The results of the work research do not coincide with this assessment.

2. MATERIALS AND METHOD

The main research goal was to determine to what extent the variability of the grain size influences the amount of frost heave. For this purpose, four different soils were selected for the research, which in the area of the Casagrande criterion are classified as frost susceptible or slightly frost susceptible (Fig. 1). At the same time, different contents of the silt and clay fractions were taken into account, the role of which in the susceptibility of the soil to frost heave is large and completely unexplained. The grain size distribution was determined by the method of sieving and hydrometer according to PN-EN 1997-2: 2009 [29], and the soil nomenclature was determined according to PN-EN ISO 14688-2:2018-05 [30].

When selecting materials in soils with a clay fraction, the criterion of the content of particles smaller than 0.02 mm, raised in the literature [19, 28, 31, 32], was also eliminated, because their percentage was the same.

To perform a one-factor analysis, the same initial void ratio was determined for all investigated soils. The initial properties of the soils are summarized in Table 1.

The aim of this paper is an experimental study on the influence of the clay and silt fraction on the frost heave of soils. In the case of other random or natural void ratios, the effect of frost heave would not be a function of the graining characteristics, but would also be dependent on the porosity variable, which determines the capillary rise, which is very important in the process of frost heave.

Due to the different particle size distribution of the examined soils, it was not possible to prepare samples

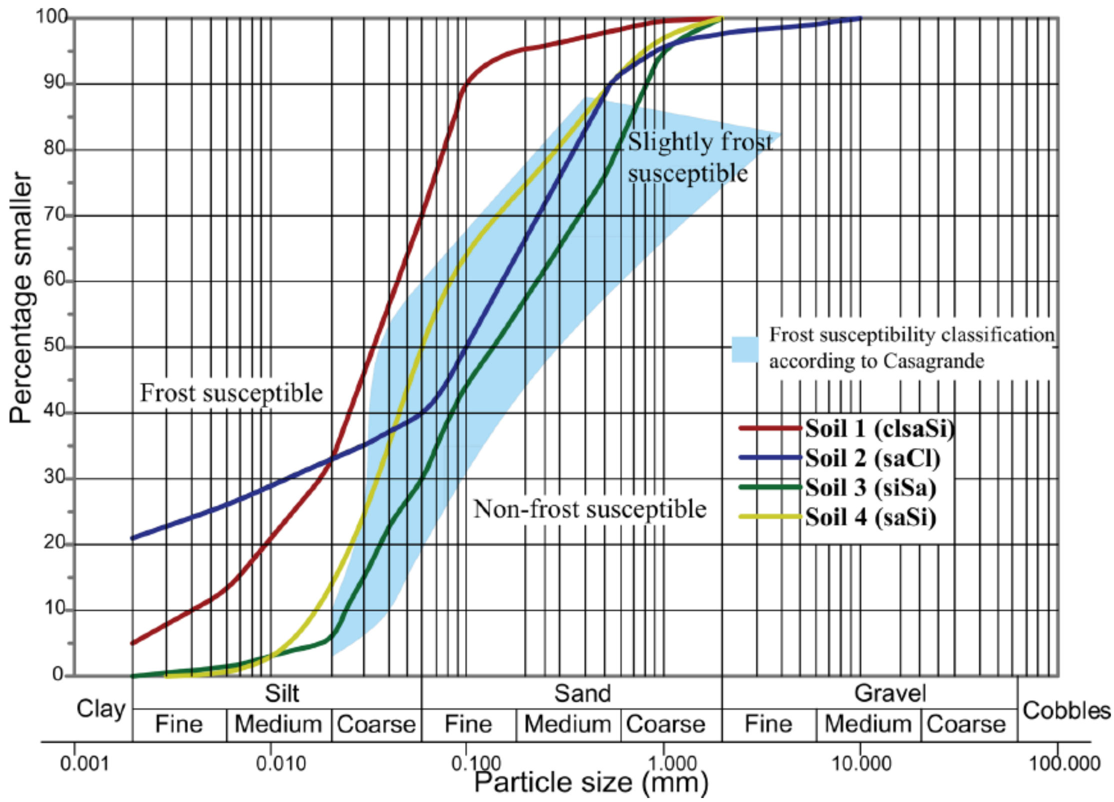

Figure 1.
Grain size distribution of soils

with the same void ratio and saturation ratio at the same time. The reason was to reflect the conditions of saturation which for a given soil with a given porosity may occur in nature, where the soils in the freezing zone are in contact with groundwater. For this reason, frost heave tests were carried out in an open-system test, i.e. with free water infiltration into the freezing zone. During the freezing process, the water level was stabilized by a gradual lowering of the temperature in the climatic chamber and capillary water transport, which affected the change of the initial moisture content of the sample before the process of water crystallization in the soil. The water supply system for the samples is based on the British Standard [BS 812-124:1989], where the water level was regulated and controlled by an overflow pipe. The water supply to the lower tank during the freezing process was supplied by running water.

For each variant, six identical freezing tests were performed which were formed into a cylindrical shape 100 mm in diameter and 110 mm in height. The soils to be tested were mixed with enough water to obtain the appropriate degree of water content and were left sealed for a period of 24 hours. From such prepared

Table 1.
Parameters of soils

Type of material	Dry density ρ_d	Particle density ρ_s	Porosity n	Void ratio e	Saturation ratio S_r
	$[g \cdot cm^{-3}]$	$[g \cdot cm^{-3}]$	[-]	[-]	[-]
Soil 1 (clsaSi)	1.800	2.668	0.325	**0.482**	0.454
Soil 2 (saCl)	1.809	2.679	0.325	**0.481**	0.501
Soil 3 (siSa)	1.789	2.650	0.325	**0.481**	0.704
Soil 4 (saSi)	1.797	2.661	0.325	**0.481**	0.811

soils, samples were formed, using a Proctor rammer in a three-compartment cylinder, obtaining adequate density with assumed comparable porosity indicators and water content degrees. After shaping, the cylinder was removed and the samples were then covered with stretch film to isolate them from the backfill material and to preserve the unidirectional nature of water migration. The practice of laboratory testing is to conduct soil freezing experiments using standardized or custom equipment. On the other hand, none of the methods described in the literature [11, 26, 33, 34, 35, 36, 37, 38, 39, 40] contains a method of solving

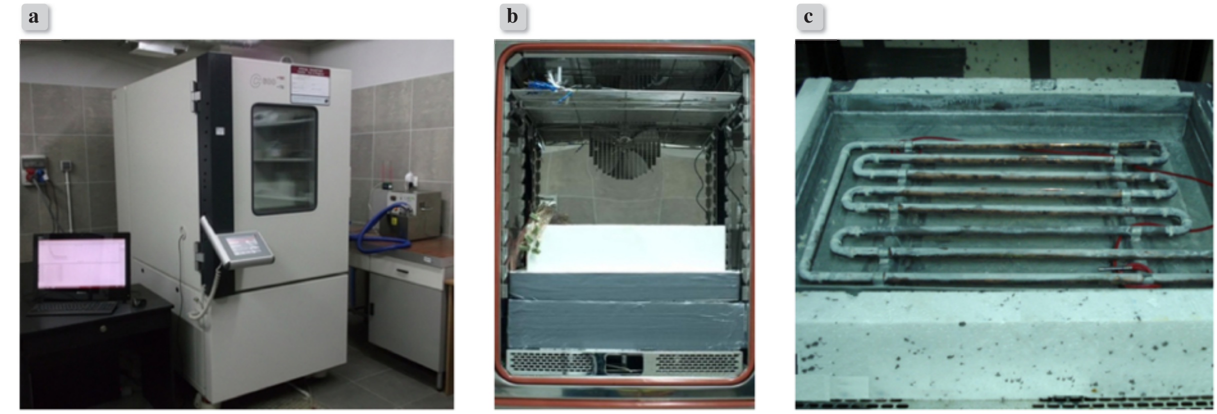

Figure 2.
Test stand: a) general view, b) interior of the climate chamber, c) lower part of the container; 1 – climatic chamber, 2 – computer to record temperature measurements, 3 – refrigerated bath circulator, 4 – upper part of the container with samples, 5 – lower part of the container with water, 6 – coil of thermostatic circuit, 7 – temperature sensors

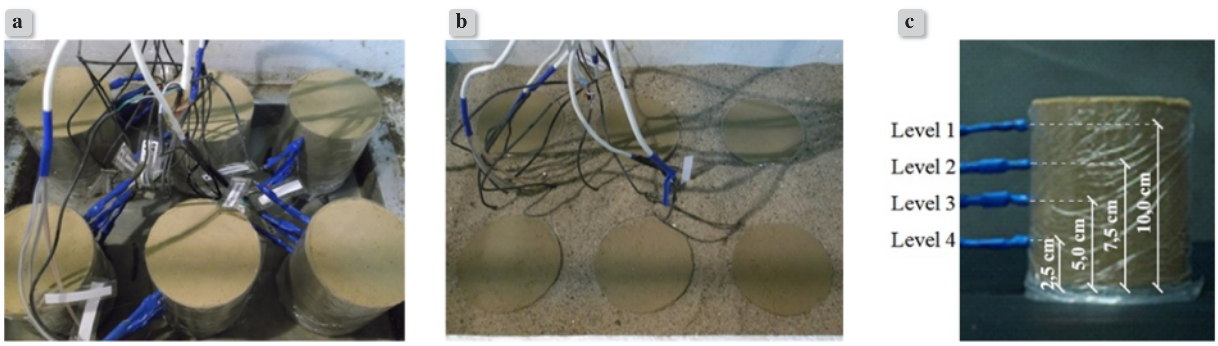

Figure 3.
Measuring stand: a) soil samples without forms, b) soil samples with sand fill, c) soil sample with temperature sensors

soil height tests without the use of rigid side guards.

The basic element of the test stand was the Weiss C600 climatic chamber (Fig. 2a). The interior of the chamber was equipped with a container designed for this purpose, in which the samples subjected to the freezing process were placed (Fig. 2b). This stand was adapted to the so-called open ground-water system, i.e. with the possibility of free water infiltration. Therefore, an automatic and controlled water replenishment system was made which kept the tank at a constant level: 1cm above the lower end of the sample. Additionally, a thermostatic circuit was used, which maintained a positive water temperature during the test, which was controlled and monitored by temperature sensors (Fig 2c).

The paper presents the methodology of laboratory research on soil frost heave with the possibility of not using casing cylinders to enable free sample growth in the freezing process (Fig. 3a). On the basis of Taber's research [11] and the standardized procedure for examining frost heave in the British Standard [33], the space between the samples was filled with dry sand as an insulating material reaching to the upper surface of the sample. The formation of a clear frost line in the soil samples indicates proper insulation and a vertical cooling front of the samples from the top (Fig. 3b).

The temperature measurement system used in the tests was based on DS18B20-type semiconductor integrated temperature sensors operating in a 1-Wire bus system (Fig. 3c). The measurement system and data acquisition were conducted using the freeware LogTemp program. Temperatures were continuously measured throughout the entire test duration.

The temperature sensing unit was constructed using a heat-conducting copper wire with a diameter of 2 mm. One end of the wire was immersed in the tested soil sample at a depth of approximately 3 cm. The other end was bent twice at a 180° angle to create a surface for mounting the DS1820 sensor. Thermal paste was applied to the flat surface of the sensor, and the final attachment of the wire and sensor was secured using a thermally shrinkable plastic pipe. During the freezing process, increases in the volume of the lenses occurred, resulting in an increase in the volume of the tested soils. It was observed that the changes in the volume of the samples took place mainly in the vertical direction, due to the prevention of lateral expansion by the backfill soil. The measurement of the change in height of the samples was performed manually with a caliper, determining the value of the displacement of a metal rod placed on the upper surface of the sample. The rods were moved out above the outer shell of the container with the initial position level marked. On the basis of conditions being commonly used and described in the literature [34, 35, 33, 19, 38] and own experience, the process of freezing soil samples lasted 160 hours at −10°C.

3. RESULTS AND DISCUSSION

3.1. Temperature

The rate of heat transfer in the soil medium depends in particular on the type of soil, thermal conductivity, the initial water content of the soil, and the freezing temperature. The heat transfer rate for all soils is shown in Figure 4. The temperature inside the samples was measured at four levels (Fig. 3c) at five-minute intervals over a 160-hour freezing period. The water transformed into ice releases latent heat, which has the effect on delaying the freezing process of water in the soil, as heat must be transferred from the water to the ice. That is why the freezing point of water in the soil is lowered and a saturated soil medium subjected to negative temperatures contains a certain amount of unfrozen water. The water crystallization in the soil occurs at various temperatures below 0°C. This is determined by the varying granulometric composition of the soil and its initial water content.

The obtained results confirm that the temperature distribution changed depending on the content of the silt and clay fractions. In the first stage of the research, the slowest heat exchange was demonstrated by the soil with the highest content of both fractions and the lowest initial saturation ratio (soil 1). However, this tendency changed in the final stage (for 160 hours), where soil 1 reached lower temperatures than soils 2 and 4 due to greater migration of water into the freezing zone. The soils deprived of the clay fraction (soils 3 and 4) in the first stage of the freezing process showed lower temperature values, which was caused by faster heat exchange in these soils. In the further freezing process, the obtained measurements indicate that soil 4 reached temperatures similar to the soil with the content of clay fraction.

The water absorption below the frost line was not measured during the test. After the test, the degree of moisture was determined for the frozen and unfrozen zones.

The degree of saturation was determined using the standard weighing-drying method by measuring the water content of the soil using the previously defined particle density. Before the test, three samples were taken from the prepared test material. After the freezing process, the water content was determined for all six tested samples (each soil) separately for the frozen and unfrozen zones by taking the whole part of each zone.

The results show (see Table 2) that in soils 3 and 4, the increase in saturation ratios in the frozen zone after the freezing process is much smaller than in the case of soils 1 and 2. This results in a small accumulation of water in the freezing zone and a small increase in ice lenses. In all soils the degree of moisture in the unfrozen zone is lower than in the frozen zone, this is due to the transport and holding of water in the freezing soils, the main role of which is played by capillary forces. In the freezing zone, the formed ice lenses increase their volume by attracting water from below from their immediate surroundings. This increases the average moisture content of the freezing soil, while at the same time reducing the moisture content directly below the freezing zone.

The highest increase in water content in the freezing zone was recorded for soil 1 (silt) with the lowest initial saturation, reaching a water content of 1.12 after the freezing process. However, the lowest increase in saturation ratio was recorded for soil (soil 3) with the lowest silt fraction (30%). Based on the obtained results, it was concluded that the samples with a lower water content showed a higher frost heave. The difference was due to the suction force, which increases sharply as the water content decreases. The suction value of the water in the non-frozen zone is also determined by the magnitude of the temperature below zero. The volume of water suction increases with the decreasing freezing temperature [27].

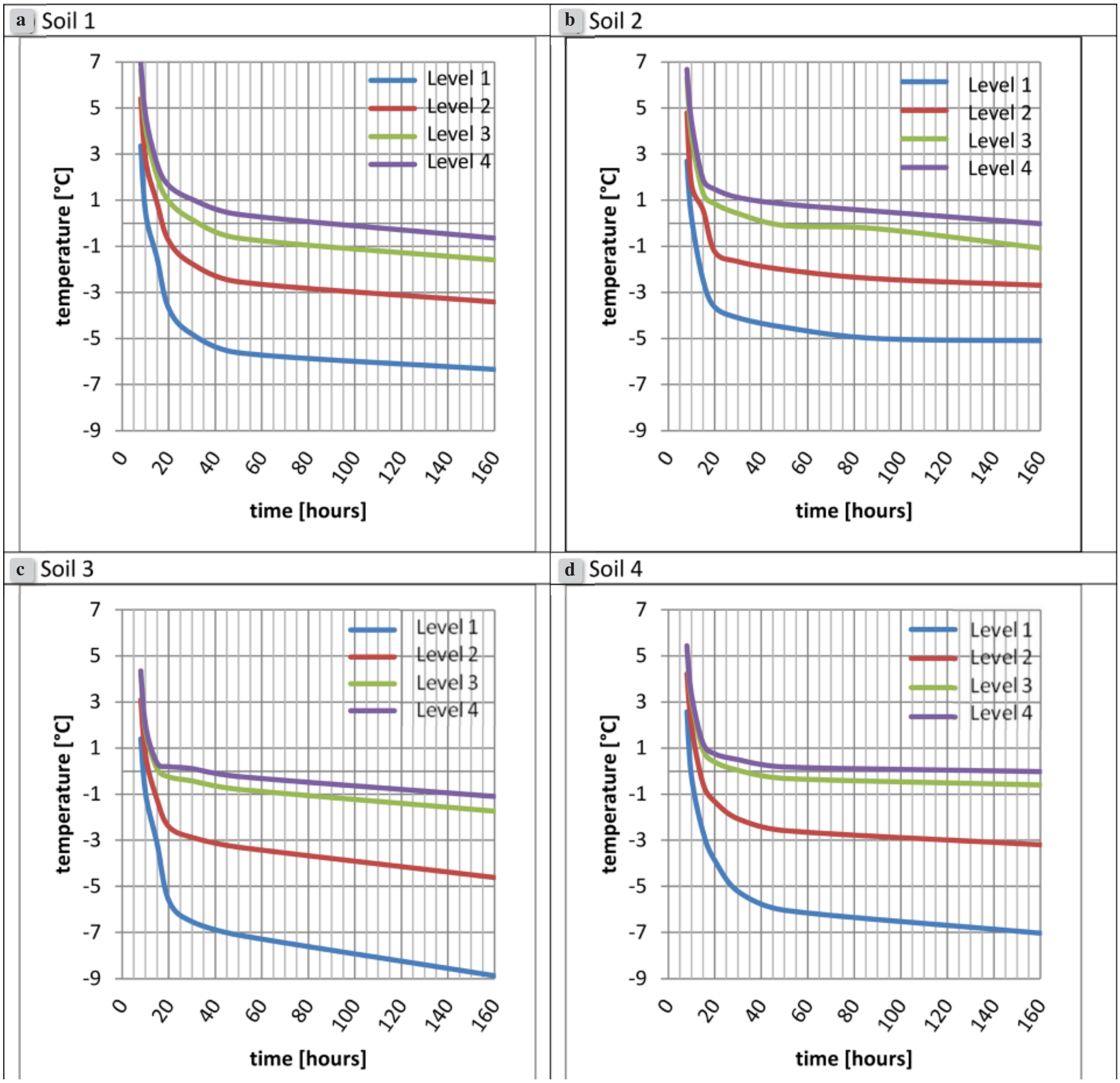

Figure 4.
Distribution of temperature on various levels, a) Soil 1 (clsaSi), b) Soil 2 (saCl), c) Soil 3 (siSa), d) Soil 4 (saSi)

Table 2.
Saturation ratios after the test

Type of material	Saturation ratios S_r		
	before the test	after the test	
		frozen soil	unfrozen soil
Soil 1	0.454	1.121	0.663
Soil 2	0.501	0.853	0.676
Soil 3	0.704	0.711	0.559
Soil 4	0.811	0.936	0.667

3.2. Ice lenses

In the freezing process, changes in the volume of samples were observed, mainly in the vertical direction, due to the fact that lateral expansion was prevented by the use of side insulation. Measurements and observations carried out on samples of all four soils, with different grain size distributions, showed differences in the intensity of ice formation. The structure of the formed ice lenses and their distribution in the tested samples are mainly determined by the content of individual fractions. Fragments of soil samples after the test with ice lenses are shown in Figure 5.

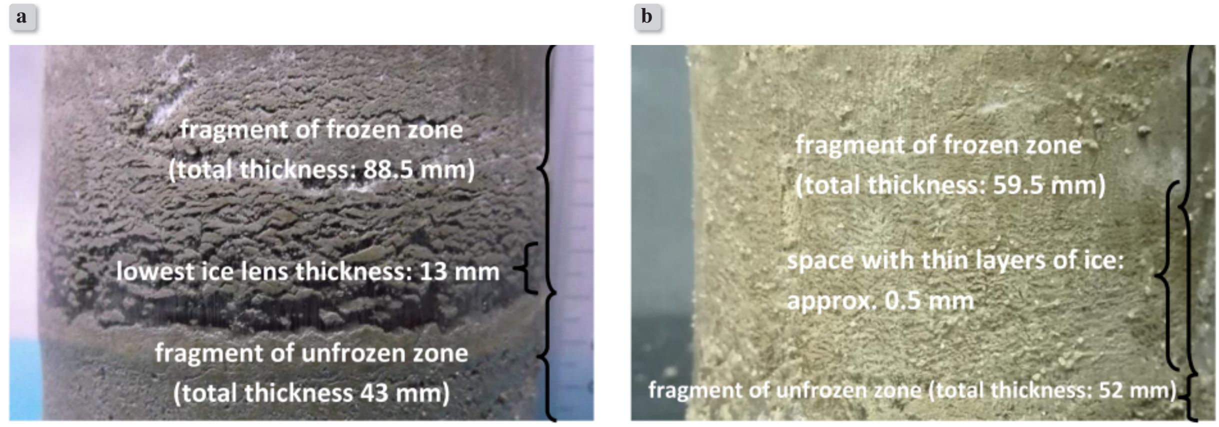

Figure 5.
Distribution of ice lenses in soil samples after freezing, a) soil 2 (saCl), b) soil 3 (siSa)

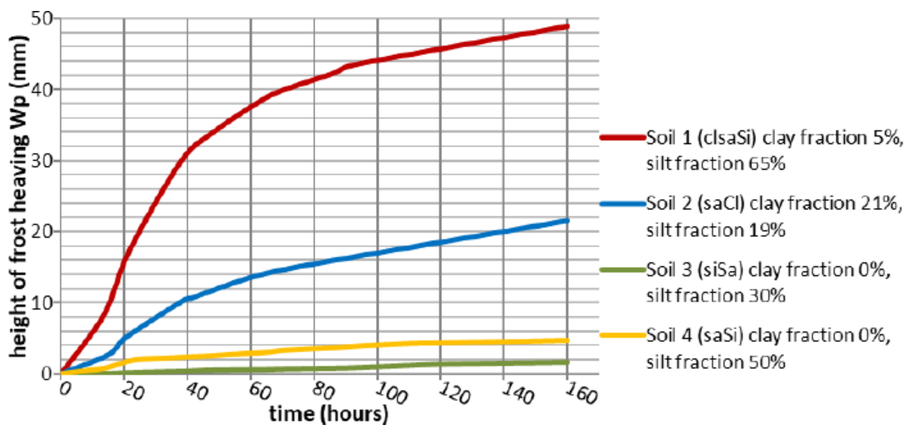

Figure 6.
Increase in the amount of frost heaving with time

In soils with a clay fraction, the increase in the height of the samples was initially caused by the formation of ice crystals, which consequently expanded to form ice lenses. In these soils, thick and continuous layers of pure ice developed (Fig. 5a), the primary source of which was flowing water into the freezing zone. In soils devoid of the clay fraction, thin layers of ice were developed in the frozen zone (Fig. 5b), which filled the pore space and had little effect on the height increase of the samples.

3.3. Amount of frost heaving

The main research objective was to determine the extent to which the variability of the graining characteristics (in the range of fractions determining the susceptibility of soil to frost heave) affects the amount of the frost heave. Average increases in the amount of frost heaving of the samples after the test are shown in Figure 6.

The highest increase in height was obtained for samples from the primary soil (clsaSi) containing only 5% of the clay fraction and the highest, i.e. as much as 65% of the silt fraction, for which the average growth of samples after the freezing process was about 50 mm. The second soil (saCl) with the highest, 21% clay fraction content, and 19% silt fraction content, showed a height increase by half as much as that of soil 1. The value of the height increase in the process of freezing the soils deprived of the clay fraction did not exceed 5 mm.

In soils not containing a clay fraction, the increase in frost heave was not significant. The ice lenses formed in these soils (3 and 4) filled the pore space without significantly affecting the volume increase of the samples. However, the ice formed in soils containing a clay fraction did not have much opportunity to penetrate the pore space. In the process of increasing the volume of the ice, a repulsion of the ice from the soil particles took place, influencing the increase in soil volume.

An important factor in the growth of ice lenses in the soil is capillary rise. This is an issue that is particularly relevant to the formation of frost heave volumes in an open ground-water system, as the height of the capillary rise causes an increase in water migration, which can to some extent supply the frost zone. The size of the capillary rise is determined primarily by the grain size of the soil, which defines the size of the capillaries. The more fine-grained the soil, the smaller the capillary diameter, which results in a higher capillary rise.

In the process of water freezing in the soil, a number of physico-chemical phenomena occur. The magnitude of these phenomena is determined by the mineral composition of the grains and particles and the content of the individual fractions, which influences the size of the specific surface area. The finer the particles of a given soil, the greater the specific surface area and the greater the physico-chemical activity. In the initial freezing process, ice is formed from free water. In the second stage, further attraction of water molecules occurs due to adsorption forces on the surface of the ice lenses. Subsequently, the growing ice crystal begins to attract bound water molecules located even closer to the soil particle, reaching all the way down to the film water layers (however, water molecules more bound to the surface of the soil particle are not subject to the attraction forces of the ice crystals). As the ice crystals enlarge, the thickness of the envelopes of bound water in close proximity decreases, leading to a violation of the water balance in the film. In this way, a forced movement of loosely bound water is created seeking to balance the tensions on the film surfaces and to equalize the thickness of the bound water. Therefore, the waters in the pores of the soil and in the thicker films in the lower soil layers gradually replenish the water deficiency caused by the attraction of water by the ice crystals. This influences the migration of water into the colder area, as bound water molecules are linked together in the entire soil. This movement proceeds very slowly, much slower than the filtration movement in the soil.

On the basis of the obtained height increments of the samples, the relationship between the frost heave and the content of the silt fraction and the total content of the silt and clay fractions was determined. For this purpose, the Pearson correlation coefficient *r*, presented in Table 3, was used.

The obtained correlation coefficient *r* in both analyzed cases is different. This parameter for the dependence of the frost heave of the silt fraction was *r* =0.54, which proves a low relationship, i.e. the lack

Table 3.
The Pearson correlation coefficient *r*

Type of material	Content of fractions		Height of frost heaving W_p	Pearson correlation coefficient *r*
		[%]	[mm]	[-]
Soil 2 (saCl)	Silt fraction	19	21.5	0.54
Soil 3 (siSa)		30	1.6	
Soil 4 (saSi)		50	4.7	
Soil 1 (clsaSi)		65	48.8	
Soil 3 (siSa)	Silt and clay fraction	30	1.6	0.83
Soil 2 (saCl)		40	21.5	
Soil 4 (saSi)		50	4.7	
Soil 1 (clsaSi)		70	48.8	

of an unequivocal influence of the content of this fraction on the amount of the frost heave. On the other hand, the assessed total share of the silt and clay fractions in relation to the amount of the frost heave shows a fairly strong correlation. On this basis, it can be concluded that the amount of the frost heave is determined by the content of both fractions (silt and clay), but the content of each of these fractions may have a different effect on the amount of the frost heave. On the basis of the above analysis an attempt was made to assess the impact of the content of both discussed fractions on the amount of the frost heave. For this purpose, the weighted arithmetic mean (κ_w) was used to be able to determine the impact of the content of both fractions, i.e.

$$\kappa_w = \frac{\omega_s \cdot f_s + \omega_c \cdot f_c}{\omega_s + \omega_c}$$

where

f_s – percentage of the silt fraction in the soil,"

f_c – percentage of the clay fraction in the soil,

ω_s – weight of the influence of the silt fraction content in the soil on the frost heave,

ω_c – weight of the influence of the clay fraction content in the soil " on the frost heave.

Fig. 7 presents an estimation of the linear relationship between the amount of frost heave and the mean κ_w for the weights ω_s and ω_c satisfying the relationship $\omega_c = 1.76 \cdot \omega_s$. It can be assumed that $\omega_s = 1$ and $\omega_c = 1.76$. Based on the results of the weighted arithmetic means, the Pearson correlation coefficient r was determined, which in this case was the highest, i.e. 0.91, proving a strong linear relationship.

A stronger linear dependence was obtained when comparing the weighted arithmetic mean content of individual fractions (κ_w) and the natural logarithm from the amount of the frost heave $logW_p$. Under the condition $\omega_c \approx 2.32 \cdot \omega_s$ (e.g. $\omega_s = 1$ and $\omega_c = 2.32$) the correlation coefficient r is the largest and has the value $r = 0.99$. The estimation of the linear relationship between the natural logarithm from the amount of the frost heave and the weighted arithmetic mean of the content of individual fractions is shown in Figure 8. Using the linear regression equation, the following was obtained:

$$logW_p = 0.2466\ \kappa_w - 1.8876. \tag{1}$$

By equation (1), the formula describing the increase in the height of the frost heave of the examined soils was determined:

$$W_p = 0.1514 \cdot e^{0.2446\kappa_w} \tag{2}$$

Note that the function $W_p(\kappa_w)$ is monotonically increasing and convex. This means that for a fixed f_s, the value of W_p increases with an increasing of f_c. However, we believe that for a fixed f_s there is a value f_c* such that for any f_c>f_c* either the value of W_p decreases or the rate of growth of W_p decreases. For this reason we propose the formula (2) to estimate of the amount of the frost heave just for the soils with content on the clay fraction not greater than 21% (it is the greatest content on the clay in examined soils). Estimated values of the amount of the frost heave for some (not examined) values of content on the clay and silt fractions are presented in Table 4.

On the basis of the obtained results, it can be concluded that the height of the frost heave of the examined soils depends exponentially on the weighted arithmetic mean content of the clay and silt fractions (Fig. 9):

$$\kappa_w = \frac{f_s + 2.32 \cdot f_c}{3.32}.$$

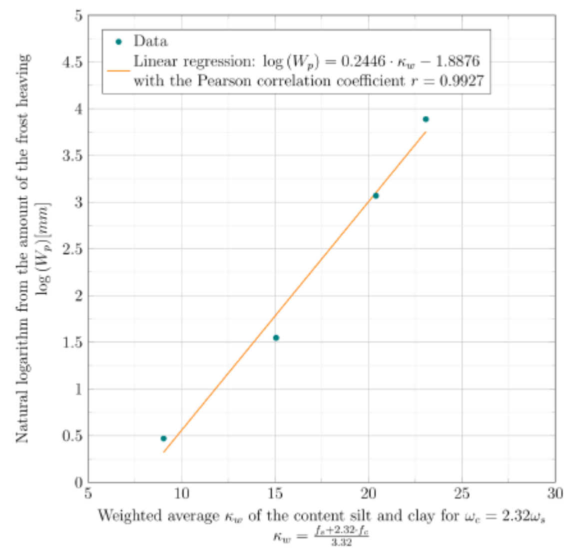

Figure 8.
Estimation of the linear relationship between the natural logarithm from the amount of the frost heave on the weighted arithmetic mean content of the clay and silt fractions

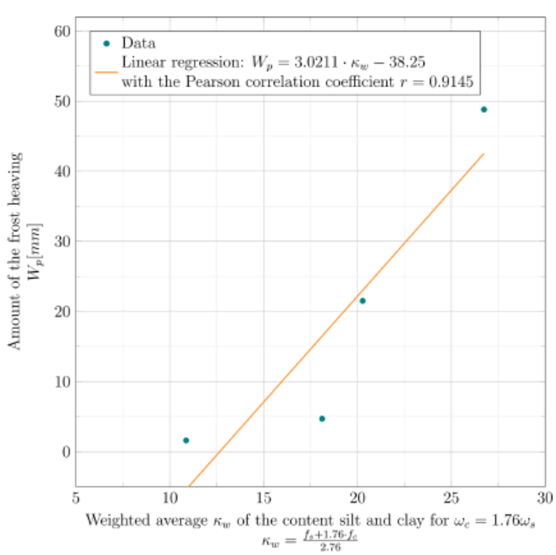

Figure 7.
Estimation of the linear relationship between the amount of the frost heave and the weighted arithmetic mean content of the silt and clay fractions, when ω_c=1.76·ω_s

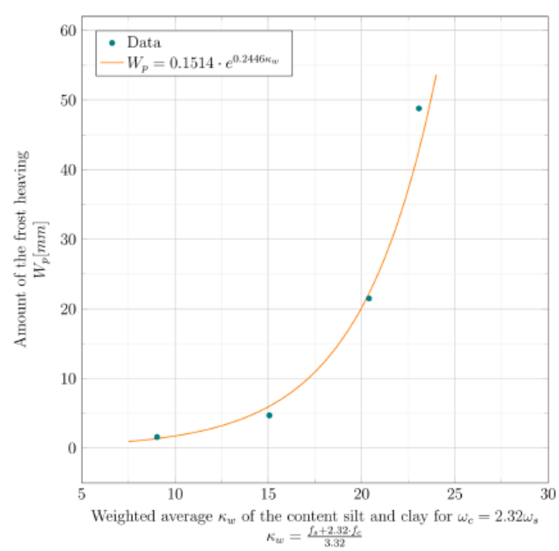

Figure 9.
The dependence of the exponential height of the frost heave on the weighted arithmetic mean content on the clay and silt fractions

Table 4.
Estimation of the amount of the frost heave Wp[mm] for some values of content on the clay and silt fractions

f_s+f_c [%]	f_c [%]					
	0	4	8	12	16	20
25	0.96	1.41	2.08	3.07	4.53	6.68
30	1.38	2.04	3.01	4.43	6.54	9.65
35	2.00	2.94	4.34	6.41	9.46	13.95
40	2.88	4.26	6.28	9.26	13.67	20.17
45	4.17	6.15	9.08	13.39	19.76	29.15
50	6.02	8.89	13.12	19.35	28.56	42.14
55	8.71	12.85	18.96	27.97	41.28	60.90
60	12.59	18.57	27.40	40.43	59.66	88.03
65	18.19	26.84	39.61	58.44	86.23	127.24
70	26.30	38.80	57.25	84.47	124.64	183.90

4. Conclusions

On the basis of the results of the research on the frost heave of four soils, an experimental attempt was made to determine the impact of the content of individual fractions on the soil freezing processes. This allowed to formulate conclusions.

- Clear ice lenses developed in the soils containing the clay fraction, which increased in volume throughout the freezing process. Their primary source of water supply was flowing water from the non-frozen zone. On the other hand, in the soils devoid of the clay fraction, small ice layers developed in the frozen zone, which filled the porous space and had a small effect on the height increase of the samples.
- As demonstrated, the impact of the content of the silt fraction itself on the frost heave processes is small. This is evidenced by the results of studies on soils devoid of the clay fraction (soil 3 and 4), in which the frost heave of samples was low (1-5 mm). This can be explained by the assumptions of the capillary theory developed by Everett, in which it was assumed that the ice lenses formed in the non-cohesive soil fill the space between the particles, having a minor effect on the sample volume increase.
- Based on the analysis of the results, it can be concluded that for the examined soils (in the content range of f_c = 0–21% and f_s = 19–65%), the increase in the height of the samples in the freezing process depends mainly on the content of the clay fraction which has more than twice the impact (2.32) on the frost heave than the content of the silt fraction. For frost susceptible soils, the amount of the frost heave is also influenced by the content of the silt fraction, although more than twice less than the content of the clay fraction.

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