The effect of micro- and nanosilica on the soil permeability coefficient under cyclic freezing and thawing conditions

Zofia Zięba[*], *Kinga* Witek and *Jakub* Mońka

Wrocław University of Environmental and Life Sciences, Wrocław, Poland

Abstract. The paper presents the analysis of the permeability coefficient of frost-susceptible soil with microsilica (MS) and nanosilica (NS) addition. Tests were performed in a triaxial apparatus in three variants: on pure soil samples, on soil samples with a 5% MS and on soil samples with a 5% NS addition. Because of the frost-susceptible properties of analysed soil, the permeability coefficient was determined on unfrozen samples and on samples after 10 cycles of freezing and thawing. The preliminary test results demonstrated that both microsilica and nanosilica have beneficial properties related to subsoil sealing. These properties are considerably stronger for nanosilica. Also, in all cases, the permeability coefficient increased after 10 cycles of freezing and thawing, but the change trend remained the same. Nanosilica shows particularly good sealing properties in frost-susceptible soils. This confirms that it may be applied as a separate additive, which is not commonly used in engineering practice. Nano particles are usually used to extend the scope of micro additives' influence. In order to recognise the beneficial influence of analysed additives on soil permeability, the recognition of the changes in microstructure is necessary.

Keywords: microsilica, nanosilica, permeability coefficient, frost-susceptible soil, cyclic freezing and thawing

1 Introduction

The key factor affecting the suitability of soil for development is its geotechnical parameters. A special group of soils are frost-susceptible soils, whose capacity to increase their volume due to the freezing of the water contained in them is a frequent cause of damage or destruction to buildings, roads and hydrotechnical structures [1, 2].

In order to reduce the susceptibility of soils to freezing processes, various improvement methods are used [3, 4].

The frost heave of soils is closely related to the formation of ice lenses, which increase due to the freezing of migrating water [5, 6]. Water movement through the porous medium is a complex issue that depends on many factors, including its microstructure [7]. For this

---

[*] Corresponding author: zofia.zieba@upwr.edu.pl

reason, the methods of improving the properties of frost-susceptible soils can also include the decrease of their permeability coefficient.

In engineering practice, various stabilising admixtures are used to improve the soils properties [8, 9], including nano additives. Among them, nanosilica is the most commonly used [10, 11], although aluminium oxide [12], polymer compounds [13], organic silica [14], or nanocopper [15] have been also used.

The research on the effects of nanosilica on the formation of soils geotechnical parameters conducted so far has been mainly concerned with the study of basic physical and mechanical properties [10, 16, 17]. There is no research to determine the effects of a given nano additive on the permeability proprieties of frost-susceptible soils.

Research was also conducted on the beneficial changes in the parameters of fine-grained soils stabilised with microsilica [18]. It can therefore be assumed that with the same stabilising additive, but in a nanoscale, the change trend of soil parameters will be similar. However, they should occur to a much greater extent, which results from the properties of nanomaterials [19].

The goal of this work is to recognise the effect of micro- and nanosilica on the permeability process in frost-susceptible soil. The variability of the permeability coefficient, which is the basic parameter describing water movement in porous media, has been analysed in detail. In addition, the use of selected stabilising additives will allow the analysis of changes resulting from their transition from micro- to nanoscale.

2 Materials

The testing was conducted on the soil obtained from the area of Trzebnica Hills in the Lower Silesia province in Poland (Fig. 1), which shows susceptibility to frost heave. Its grain size distribution was determined by a standard hydrometer method according to PN-EN 1997-2:2007 [20]. Based on the resulting grain-size distribution curve, it was established that it is a sandy clayey silt (saclSi) [21].

Fig. 1. Physico-geographical regionalisation of Poland – Trzebnica Hills Mezoregion [22].

Two additives were used for stabilisation, which are often used in the construction industry, but these are not typical additives used in geotechnical engineering.

The first additive was microsilica (MS), also called silica fume. Its grain size distribution was determined by using a laser granulometer (Fig. 2a).

The second stabilising additive was nanosilica (NS) in the form of a colloid. To determine the size distribution of nanoparticles, tests were carried out using the Zetasizer Nano particle characterisation system (Fig. 2b).

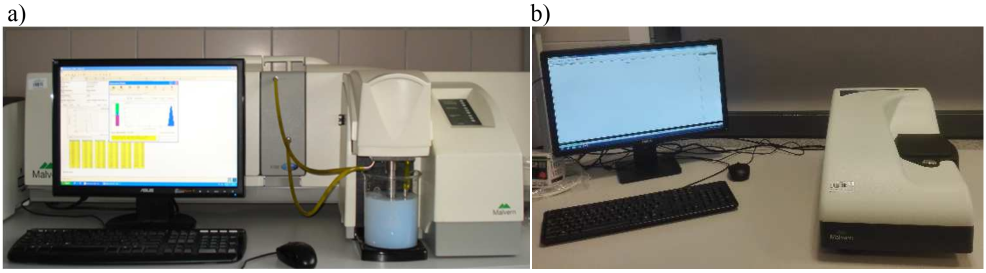

Fig. 2. The grain size distribution analysis of the stabilising additives: a) MS – laser granulometer; b) NS – Zetasizer Nano particle characterisation system.

The differences in grain size distribution of individual additives in relation to the analysed soil are shown in Figure 3.

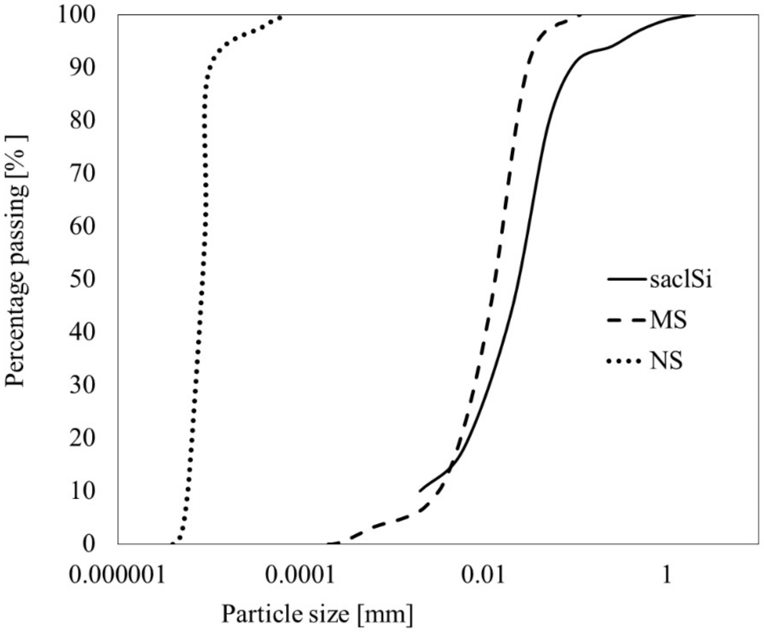

Fig. 3. Grain size distribution of the analysed materials.

3 Methods

Laboratory tests of the permeability coefficient were performed in three variants. The first included pure soil, the second was soil with a 5% admixture of microsilica, and the third was soil with a 5% admixture of nanosilica. For all variants, the tests were performed on 15 samples.

The contents of individual additives and methods for their mixing with soil were determined in the case of microsilica based on Kalkan's test results [18], and in the case of nanosilica based on Seyedi Gelsefidi and Mamaghanian's paper [16], as well as Bahmani and others' [10].

The main assumption of the tests was the analysis of samples at the maximum dry density ρ_{dmax} and the corresponding optimum moisture content m_{opt}. These parameters were determined in the Proctor automatic compactor in accordance with ASTM D698 [23].

Unfrozen samples and samples after 10 cycles of freezing and thawing were tested for permeability. This allowed for the checking of the behaviour of individual soil mixtures in real conditions occurring in winter. This approach also made it possible to determine changes in the permeability coefficient depending on the stabilising additive used, as a result of the effects of cyclic freezing and thawing on the change in the structure of pore space.

Cyclic freezing and thawing were carried out according to PN-88/B-06250 [24] in the Weiss C 600 climate chamber. This device has a temperature range between -70 and +180˚C, as well as two inspection holes to connect the external sensors. Thanks to this, the freezing and thawing temperatures could be monitored during the whole experiment. Additionally, the device is equipped with a panel, which enables the chamber control and automatic data acquisition.

The freezing and thawing process was carried out in a closed system, without any influx of water. This resembles the condition of low groundwater levels or artificially-induced lack of water in the frost zone. Most of all, research in such conditions allowed for the recognition of the fluctuation of the permeability coefficient, which results from the changes in the microstructure caused by the freezing of water in soil of a particular moisture content - in this case of optimum moisture content. Each cycle took place at -20°C/+20°C.

The testing of the permeability coefficient for both unfrozen samples and samples subjected to cyclic freezing and thawing were performed in the triaxial cell apparatus chamber in accordance with BS 1377-6:1990 [25]. Thanks to the apparatus used, the problem of the formation of privileged filtration pathways, which occur in typical permeameters, was eliminated. The tests were carried out on samples of 100 mm in diameter and 110 mm in height, with an effective cell pressure of 50 kPa and a hydraulic gradient of 20 [-].

The stages of preparation of a sample for testing are shown in Figure 4.

Fig. 4. The stages of sample preparation for permeability coefficient testing.

Before the tests, the samples underwent the saturation process to reach the value of the Skempton's coefficient (B-value) at a level of 0.95 [-]. To the permeability tests, the distilled water was used which was additionally deaerated using a vacuum pump. The flow of the water during the tests was upward.

4 Results and discussion

4.1 Compactibility testing

The compactibility testing of soil mixtures showed that the addition of microsilica causes a slight increase in the optimum moisture content and at the same time a decrease in the maximum dry density of soil structure. On the other hand, the soils stabilised with nanosilica show an increase in the maximum dry density of soil structure, while maintaining the optimum moisture content at a comparable level (Table 1).

Table 1. Summary of optimum moisture contents and maximum dry densities for individual soil mixtures

Type of soil mixture	ρ_{max}	m_{opt}
[-]	[g·cm^{-3}]	[%]
saclSi	1.882	11.80
saclSi + 5% MS	1.868	12.30
saclSi + 5% NS	1.912	11.60

4.2 Permeability coefficient testing

Fifteen samples from each variant of soil mixture were tested, both for unfrozen samples and samples subjected to cyclic freezing and thawing.

In order to recognise the arithmetic mean value as representative, a statistical analysis of the obtained results was carried out at a significance level of 0.05 [-]. First, the arithmetic mean value and standard deviation were calculated, and then the dispersion of the results in relation to the mean value based on the coefficient of variation was determined. It is assumed that if its value does not exceed 10%, the variation of a characteristic is statistically insignificant. Otherwise, extreme values must be rejected [26]. The analysis was carried out using the Statistica software. The values of the permeability coefficient averaged after the statistical analysis are shown graphically (Fig. 5).

The addition of 5% microsilica decreased the permeability coefficient of the analysed soil by 43%. This change trend coincides with the results of research by Kalkan and Akbulut [27] and Kalkan [18].

On the other hand, the addition of 5% nanosilica caused a decrease in permeability coefficient by almost 100%. No studies have been carried out so far to determine the effects of nanosilica addition itself on the permeability coefficient. Only mentions of the studies of permeability coefficient of soils stabilised with cement with an addition of nanosilica can be found in the literature [10].

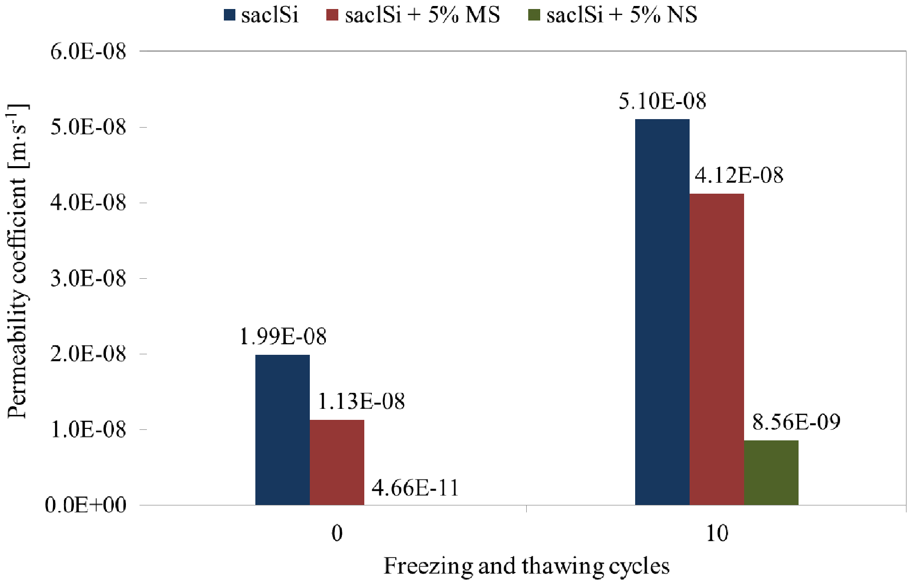

Fig. 5. Variability of the permeability coefficient depending on the stabilising additive before and after 10 cycles of freezing and thawing.

There was an increase in permeability coefficient observed as a result of cyclic freezing and thawing (10 cycles) in all cases. However, the stabilisation with nanosilica shows much lower values of the permeability coefficient (by 64%) than the stabilisation with microsilica. Also, in relation to the pure soil, the stabilisation with nanosilica showed a decrease in permeability coefficient by 83%. Thus, nanosilica has very favourable sealing properties for frost-susceptible soils.

The use of stabilising materials is strictly connected with changes in the structure of the pore space, which heavily influences both, the movement of the water in the soil, and the amount of bound water that is not involved in the flow. Additionally, changes in the microstructure also influence on the heat transfer and distribution of the temperature [28], which is crucial, especially in case of the stabilisation with nanomaterials in the process of freezing and thawing. For this reason, in the further stages of research it is necessary to recognise the changes in the pore space structure of non-frozen and frozen samples in each variant of soil mixtures.

5 Conclusions

The tests carried out allowed for the preliminary recognition of the effect of micro- and nanosilica on the process of water flow in frost-susceptible soils. Based on this, the following conclusions were drawn:

1. Both a 5% addition of microsilica and nanosilica reduced the permeability coefficient of frost-susceptible soil. However, nanosilica shows the capability of sealing frost-susceptible subsoil to a much greater extent.
2. After 10 cycles of freezing and thawing, all samples showed an increase in the permeability coefficient, however, samples stabilised with nanosilica were still characterised by the lowest values.
3. The tests carried out confirm possibilities of using nanosilica as an independent additive, which is not widely used.

4. In order to explain in detail the changes in the permeability coefficient, it is necessary to analyse the microstructure of both, the pure soil and the samples stabilised with individual additives.

References

1. L. Rafalski, J. Wilczek, C. Kraszewski, *Ochrona przeciwmrozowa nawierzchni drogowych na przykładzie wybranych krajów (The case of antifreeze protection of road pavements in selected countries),* Drogownictwo **2**, 39-45 (2014) (in Polish)
2. A.A. Korshunov, S.P. Doroshenko, A.L. Nevzorov, Procedia Engineering, **143**, 682-688 (2016) doi : 10.1016/j.proeng.2016.06.100
3. I. Ickiewicz, *Zjawisko wysadziny zmarzlinowej – metody zapobiegania (The phenomenon of frost heave – methods of prevention)*, Izolacje **2**, 44-45 (2009) (in Polish)
4. K. Augustowski, *Możliwość zapobiegania powstawaniu wysadzin mrozowych (Possibilities of preventing soil movement with conjunction of frost action)*, Drogownictwo **7-8**, 264-268 (2012) (in Polish)
5. I. Ickiewicz, *Analiza zjawiska wysadziny zmarzlinowej dla celów inżynierskich (Analysis of frost heave phenomenon for engineering purposes)*, Tech Trans **5**, 63-70 (2009) (in Polish)
6. R.W. Style, S.S.L. Peppin, A.C.F. Cocks, J.S. Wettlaufer, Phys Rev E **84**, 4, 1-13 (2011) doi: 10.1103/PhysRevE.84.041402
7. Z. Zięba, J Hydrol Hydromech **65**, 1, 80-87 (2017) doi: 10.1515/johh-2016-0054
8. C. Onyelowe Ken, F.O. Okafor, *A comparative review of soil modification methods*, ARPN J Earth Sci **1**, 2, 36-41 (2012)
9. S.Z. Sharifah Zaliha, H. Kamarudin, A.M. Mustafa Al Bakri, M. Binhussain, M.S. Siti Salwa, Aust J Basic Appl Sci **7**, 5, 258-265 (2013) doi: 10.4028/www.scientific.net/KEM.660.298
10. S.H. Bahmani, B.B.K. Huat, A. Asadi, N. Farzadnia, *Stabilization of residual soil using SiO2 nanoparticles and cement*, Constr Build Mater **64**, 350–359 (2014)
11. A. Rezagholilou, H. Nikraz, *The Reasons for Introducing Nano-silica in Cementitious Layer in Pavement*, Electron J Geotech Eng **19**, 1761-1768 (2014)
12. H.L. Luo, D.H. Hsiao, D.F. Lin, C.K. Lin, Int J Transp Sci Technol **1**, 83-100 (2012) doi: 10.1260 2046 -0430.1 60 333
13. W.R. Azzam, Int J GEOMATE **7**, 927-937 (2014) doi: 10.21660/2014.13.29127
14. B.M. Lekha, S. Goutham, A.U. Ravi Shankar, *Laboratory investigation of soil stabilized with nano chemical*, Proc. of the IGC, 22-24, Roorkee (2013)
15. M.R. Taha, O.M.E. Taha, J Nanopart Res **14**, 10, 1-13 (2012) doi: 10.1007/s11051-012-1190-0
16. S.A. Seyedi Gelsefidi, J. Mamaghanian, Proc. of the 5th IYGEC, 134-137 (2013) doi: 10.3233/978-1-61499-297-4-134
17. R. Xiaochuan, H. Kai, Nanosci Nanotech Let **6**, 1010-1013 (2014) doi: 10.1166/nnl.2014.1857
18. E. Kalkan, Cold Reg Sci Technol **58**, 3, 130-135 (2009) doi: 10.1016/j.coldregions.2009.03.011

19. Z.H. Majeed, M.R. Taha, *A review of stabilization of soils by using nanomaterials*, Aust J Basic Appl Sci **7**, 2, 576-581 (2013)
20. PN-EN 1997-2:2007, *Geotechnical design – Part 2: Ground Investigation and testing*
21. PN-EN ISO 14688-2:2006/Ap2, *Geotechnical investigation and testing - Identification and classification of soil - Part 2: Principles for a classification*
22. Website: *https://commons.wikimedia.org/wiki/File:318.44_Wzg%C3%B3rza_Trzebnickie.png*
23. ASTM D698: 2003, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*
24. PN-88/B-06250 *Beton zwykły (Ordinary concrete)* (in Polish)
25. BS 1377-6:1990, *Methods of test for soils for civil engineering purposes. Consolidation and permeability tests in hydraulic cells and with pore pressure measurement*
26. D.J. Sheskin, *Handbook of Parametric and Nonparametric, Statistical Procedures. 3rd ed.*, C&H/CRS, New York (2003)
27. E. Kalkan, S. Akbulut, *Eng* Geol **73**, 145-156 (2004) doi: 10.1016/j.enggeo.2004.01.001
28. J. A. Weaver, and R. Viskanta, *Melting of frozen, porous media contained in a horizontal or a vertical, cylindrical capsule*, Int J Heat Mass Transf, **29**, 1943-1951, (1986)
29. K. Domin, *Wpływ efektu nanouwięzienia na przejścia fazowe w nanoporowatych układach (Effects of Confinement on Phase Transitions in Nanoporous Systems)*, PhD thesis, Uniwersytet Adama Mickiewicza, (2016) (in Polish)