The Influence of Nanosilica on Unconfined Compressive Strength of Frost-Susceptible Soil

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Abstract. In engineering practice there are numerous methods to improve the mechanical properties of subsoil. The paper presents the analysis of changes in the unconfined compressive strength of frost-susceptible soils stabilised with nanosilica (NS). Tests were conducted on samples of fine-grained soil at the maximum dry density (MDD) and optimum moisture content (OMC). Four variants of samples were prepared: soil without additive, soil with 1% NS, soil with 3% NS and soil with 5% NS. Due to the frost-susceptible character of the soil, tests were conducted on non-frozen samples and on samples subjected to ten cycles of freezing and thawing. Cyclic freezing and thawing of soil mixtures allowed for determination of the additive effectiveness in the temperature conditions encountered during the winter season. Based on the research results of unfrozen samples, it was determined that the addition of nanosilica leads to the increase in their unconfined compressive strength. On the other hand, the strength of pure soil samples after ten cycles of freezing and thawing decreased. This is a commonly known trend that results from the soil and soil mixtures freezing. However, in the same conditions, the unconfined compressive strength of samples stabilised with nanosilica demonstrated a significant increase with the increase of the additive content. The highest values were noted for samples stabilised with 5% addition of nanosilica. In order to explain the obtained results, further tests are required. However, the preliminary research has shown the effectiveness of nanosilica as an independent additive stabilising frost-susceptible soils, although it is not commonly used in engineering practice.

1. Introduction
The use of weak soils for development requires an improvement of their geotechnical properties. For this purpose, various methods of subsoil stabilisation are used [1, 2]. Among chemical stabilisation, additives in the nano scale are increasingly applied [3, 4, 5], especially nanosilica [6, 7, 8].

In engineering practice, the frost-susceptible soils cause a special problem. Recent research has shown that nanosilica has also been used within this scope. So far, tests have been carried out into nanosilica's impact on the frost heave process [9, 10] and on changes in the permeability coefficient under cyclic freezing and thawing conditions [11]. Other research has shown the beneficial effect of nanosilica on unconfined compressive strength [10]. However, with frost-susceptible soils, it is necessary to verify the behaviour of an additive in the actual conditions prevailing in winter, where the subsoil is subjected to both above zero and sub-zero temperatures.
The aim of this paper is to analyse the changes in unconfined compressive strength of frost-susceptible soils stabilised with nanosilica under cyclic freezing and thawing conditions. This approach allowed for the determination of additive effectiveness in the real winter conditions.

2. Materials
The tests were conducted on the natural soil obtained from the Trzebnica Hills in the Lower Silesia province in Poland. Based on the laboratory tests of grain size distribution [12], it was determined that it is sandy-clayey silt (saclSi) [13]. Additionally, in order to confirm its frost-susceptible properties, the sand equivalent test was conducted [14]. On the basis of the grain size distribution and the value of sand equivalent (1.09), it was established that it is a highly frost-susceptible soil [15].

Nanosilica (Levasil 200/30) of German production was used for stabilisation. The analysed additive was in the form of a colloid. In order to recognise the properties of NS, the control tests of its grain size distribution, specific surface area and pH were conducted. The grain size distribution was determined using the Zetasizer Nano particle characterisation system. In addition, this device allowed for the determination of the electrokinetic potential ($\zeta$). The same parameters were also determined for the tested soil. The results are presented in table 1.

| Type of material | Average particle size [m] | Specific surface area $[\text{m}^2 \cdot \text{g}^{-1}]$ | pH | $\zeta$ [mV] |
|------------------|---------------------------|---------------------------------|----|--------------|
| saclSi           | $2.50 \cdot 10^{-4}$      | 35.70                           | 8.65 | -13.10       |
| NS               | $9.00 \cdot 10^{-9}$      | 196.49                          | 9.00 | -22.03       |

3. Methods
The unconfined compression tests were conducted on a series of unfrozen samples, as well as on samples subjected to ten cycles of freezing and thawing. Cyclic freezing and thawing was performed in the climate chamber according to the Polish standard [16]. Both unfrozen samples and samples subjected to cyclic freezing and thawing were tested in four variants: pure soil, soil + 1% NS, soil + 3% NS and soil + 5% NS.

The samples for testing were compacted up to maximum dry density (MDD) with optimum moisture content (OMC). These parameters were determined in the Proctor automatic compactor according to the ASTM D698 [17].

The unconfined compression tests were conducted on samples of 38 mm in diameter and 76 mm in height. The tests, both for unfrozen samples and for samples subjected to freeze-thaw cycles, were performed according to the technical specification UNI CEN ISO 17892-7:2004 [18]. The unconfined compressive strength ($q_u$) was assumed as maximum vertical stress ($\sigma_{1\text{max}}$) (equation 1).

$$q_u = \sigma_{1\text{max}} = \frac{P_{\text{max}}(1-\varepsilon_{\text{pmax}})}{A_i}$$

(1)

where:

- $P_{\text{max}}$ – maximum vertical load [kN];
- $\varepsilon_{\text{pmax}}$ – maximum vertical strain [-];
- $A_i$ – initial cross-sectional area of the sample [m$^2$].
4. Results and discussion
The test results for maximum dry density and optimum moisture content for all analysed variants were shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** Maximum dry density (MDD) and optimum moisture content (OMC) of the soil samples stabilised with NS.

The research has shown that the maximum dry density increases with the increase in NS addition, but optimum moisture content change slightly.

In the case of unconfined compression tests, the series of samples were analysed for each variant, both unfrozen and after freeze-thaw cycles. After rejecting the extreme results, the obtained data was averaged and presented in figure 2.

![Figure 2](image2.png)

**Figure 2.** Unconfined compressive strength (q_u) of samples stabilised with NS under cyclic freezing and thawing conditions.

Based on the obtained testing results of unfrozen samples, it was found that the addition of nanosilica causes the increase in their unconfined compressive strength. Figure 2 illustrates that the
strength increases by 3% for soil with 1% NS, by 12% for soil with 3% NS and by 18% for samples with 5% NS. This change trend coincides with the results of other research [10].

On the other hand, the samples of sandy-clayey silt after ten freeze-thaw cycles decreased their strength by 12.5%. It is a typical behaviour for a pure soil as well as for a stabilised soil subjected to cyclic changes in temperature [19]. Interestingly, under the same conditions, the samples stabilised with nanosilica showed a considerable increase in unconfined compressive strength. The strength increased by 19% for soil with 1% NS, by 30% for soil with 3% NS and 41% for samples with 5% NS in comparison with unfrozen stabilised samples. Moreover, compared with pure soil after freeze-thaw cycles, the strength was higher by 41% for soil with 1% NS, by 67% for soil with 3% NS and 91% for samples with 5% NS.

Furthermore, depending on the NS content, the stress-strain behaviour was analysed, both for unfrozen samples and samples after ten cycles of freezing and thawing (figure 3).

![Figure 3. Stress-strain curves: a) unfrozen samples; b) samples after ten freeze-thaw cycles.](image-url)
Unfrozen samples stabilised by NS indicated higher peak stress as well as higher vertical strain than pure soil. These values increase with the NS content. However, this trend changes after cyclic freezing and thawing. With the increase of NS addition, the stress peak increases significantly and the vertical strain decreases. Under the same conditions, samples of pure soil indicated decrease in peak stress but increase in vertical strain.

To describe unusual changes in unconfined compressive strength and stress-strain behaviour of stabilised soils after freeze-thaw cycles, the further detailed tests should be carried out including the analysis of microstructure changes. However, the preliminary tests conducted in the paper have shown that the applied nanosilica has very good stabilising properties for frost-susceptible soils. Not only does it reduce the formation of ice-lenses [9, 10] and improve the permeability properties [11], but it also increases the unconfined compressive strength under freezing and thawing conditions.

5. Conclusions
The following conclusions were drawn from the conducted tests:
1. In the case of unfrozen samples, the addition of nanosilica caused the increase in the unconfined compressive strength of soil mixtures.
2. After ten cycles of freezing and thawing, the pure soil samples reduced their strength.
3. The samples stabilised with nanosilica under cyclic freezing and thawing conditions showed a marked increase in strength as the amount of applied additive increased.
4. In order to describe the changes in unconfined compressive strength and stress-strain behaviour caused by freeze-thaw cycles, the further tests are necessary.
5. The conducted tests have shown the effectiveness of nanosilica as a stabilising additive for frost-susceptible soils.

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