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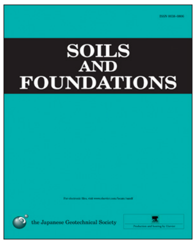

Effect of freeze–thaw cycles on the hydraulic conductivity of a compacted clayey silt and influence of the compaction energy

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Abstract

Compacted clay layers are often used in impervious barrier systems to prevent the migration of water and pollutants. Environmental factors, acting during or after the clay deposition, may affect the layer integrity and induce a variation of hydraulic conductivity over time. The aim of the present research is to assess this variation when induced by freeze–thaw cycles. The paper summarizes some results of tests performed on a series of clayey silt samples, reconstituted at various levels of compaction energy and subjected to cyclic freezing according to a controlled and repeatable procedure, set to reproduce the natural environmental conditions. The hydraulic conductivity is evaluated directly from a flexible wall permeameter and indirectly from oedometric tests. The results show the consequences of cyclic freezing in relation to the compaction level and lead to insights into the development of fracture networks responsible for the increase in hydraulic conductivity.

Keywords: Impervious barriers; Compaction energy; Hydraulic conductivity; Laboratory tests; Freezing

1. Introduction

In civil and environmental engineering, the impervious barriers for the prevention of water and pollutant migration are usually designed as layered systems, each layer serving a specific function, such as resistance to mechanical actions, drainage of collected fluids, and barrier to fluid percolation. The latter function is often provided by compacted clay layers, owing to the low hydraulic conductivity the clay can reach when properly compacted. The standard regulations for environmental protection in waste containment systems usually require a maximum value for the hydraulic conductivity of the upper cover, to limit the water infiltration into the waste body, and of the lower liner, to protect against leakage from the waste body to the foundation soil.

As examples, the European Community recommends a lower barrier with a maximum hydraulic conductivity of 10^{-9} m/s, or 10^{-7} m/s only in the case of inert waste, and an upper barrier that includes an “impermeable mineral layer” whenever the prevention of leachate formation is necessary (Annex 1 in Directive 1999/31/EC). Then, each member state is asked to implement these requirements into a local legislation (e.g., the Italian D. Lgs. N.36/2003). The US Environmental Protection Agency establishes that, in the case of a composite liner with a leachate collection system used at the bottom of a municipal solid waste landfill, the liner must include a layer of compacted soil with a hydraulic conductivity of no more than 10^{-9} m/s (CFR 40, I, 258-D), and that the landfill must be closed with a final system having a lower or equal hydraulic conductivity (CFR 40, I, 258-F).

These requirements must be guaranteed for the long term, to ensure a lifelong proper and environmentally safe performance of the containment system (Rowe, 2005).

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During the layer deposition and over the long term, factors of various origin may induce damage to the materials or to the layered structure, and hence, an increase in hydraulic conductivity (Chapuis, 2002). These factors basically have a mechanical origin, for instance, in the waste body settlement or in the sliding along inclined sides (Dixon et al., 2004; Jessberger and Stone, 1991; Jones and Dixon, 2005), or originate from the interaction with the atmosphere or from a chemical interaction with leachate (Benson, 2000). The soil–atmosphere interaction yields frost, desiccation, and internal or surface erosion of exposed and shallow layers. These actions usually have a cyclic occurrence, being the result of natural atmospheric events.

The physical process of freezing affects the soil micro-structure (Hohmann-Porebska, 2002), and the effects of freeze–thaw cycles on the hydraulic conductivity of compacted clays have been experimentally investigated by several authors (e.g., Benson et al., 1995; Chamberlain and Gow, 1979; Konrad, 1989), who also highlighted the importance of relating the sensitivity to freezing cycles to other factors, such as the physical properties of the clay (micro-structure, plasticity index, water retention, and swelling potential, etc) and the initial compaction conditions.

With reference to the initial conditions, Chamberlain et al. (1990) tested and compared slurry consolidated with compacted samples, to find that freeze–thaw cycles always induce an increase in hydraulic conductivity in consolidated samples, in particular a higher increase when the water content is higher, due to the development of large aggregates and paths of reduced flow resistance. On the contrary, the effect on compacted samples is not always consistent, depending on the water content, the degree of saturation, and the initial compaction.

Konrad (2010) emphasised the role of the changes in void ratio and proposed a framework for saturated consolidated samples to predict the freeze–thaw effects in a void ratio–stress–hydraulic conductivity space, which however could not be readily extended to compacted samples. For these, an experimental procedure was proposed to predict the changes in hydraulic conductivity.

Related to the compaction conditions are the findings by Kim and Daniel (1992), who observed that samples compacted wet of optimum are more susceptible to an increase in hydraulic conductivity than those compacted dry of optimum, although the former shrink while the latter expand. The decrease in void ratio associated with a large increase in hydraulic conductivity, in samples compacted wet of optimum, would confirm that freeze–thaw cycles expand the network of fluid-conducting pores. Moreover, Kim and Daniel (1992) found that an increase in compaction energy, though a variable less significant than the water content, has no consistent effect on the susceptibility to damage, increasing it in samples compacted wet of optimum, but slightly reducing it in samples compacted dry of optimum.

In addition to laboratory small-scale tests, large-scale and on-site investigations were also carried out to verify the effects of long-term freezing (Benson and Othman, 1993; Miller and Lee, 1999).

It is known that a cyclic freezing–thawing process also affects the soil mechanical properties, for instance, in terms of the shear strength response, oedometric compressibility, and particle crushability (e.g, Graham and Au, 1985; Ishikawa and Miura, 2011; Leroueil et al., 1991). Some of these aspects are still under investigation and certain issues are still open for examination, as summarized by Qi et al. (2006).

The comprehensive modelling of the freezing process requires a multi-physics approach and numerical solving procedures, due to the complex coupling of thermo-hydro-mechanical fields in multi-phase porous materials in the presence of liquid-to-solid phase changes (Coussy, 2005; Liu and Yu, 2011; Thomas et al., 2009). All additional insights, from experimental assessments into the factors that influence the soil response to cyclic freezing–thawing actions, may help the refinement of theoretical and numerical approaches and enhance the information database for engineering purposes.

In this framework, some results from a laboratory experimental programme are summarized herein, for the purpose of highlighting the effects of freeze–thaw cycles on the hydraulic conductivity of compacted clayey silt samples and, in particular, the role of the energy level applied in the compaction phase. The compaction energy is considered as a particularly relevant factor of influence, on density and hydraulic conductivity, and it represents a design parameter that could be prescribed in practise rules and controlled at the construction site, in order to achieve the best long-term performance of the barrier. In the investigation, all issues related to the influence on the soil mechanical properties were disregarded; they will be addressed in further experimental programmes.

The hydraulic conductivities were evaluated by oedometric and flexible wall permeameter tests, following the guidelines of ASTM D 6035 (2002). A comparison between the results also allows for recognizing the effect of freezing on the development of fracture networks at the small-scale.

2. Material and sample preparation

The soil used in the laboratory tests is classified as clayey silt, with inorganic medium plasticity clay, characterized by specific gravity $G_s = 2.74$, liquid limit $w_L = 32\%$, plasticity index $I_p = 14$, and the grain size distribution shown in Fig. 1 (Cervi, 2005). Three different compaction curves have been obtained by applying different values of compaction effort (Fig. 2): (A) the standard value, according to ASTM D 698 (2000) and corresponding to 593 kJ/m^3 (25 blows by the standard rammer), (B) a reduced value of 356 kJ/m^3 (15 blows), and (C) a reduced value of 237 kJ/m^3 (10 blows). This choice stems from the fact that the compaction procedure for clay barriers, such as landfill covers, may produce compaction efforts different from point to point, if not properly controlled, and that the standard effort reasonably represents a medium value. The areas of the clay barrier less accessible to heavy equipment or laid on inclined sides may be subjected to reduced compaction energy (Daniel and Benson, 1990).

The sample preparation and the testing conditions are the major factors affecting the experimental outcome. On the basis

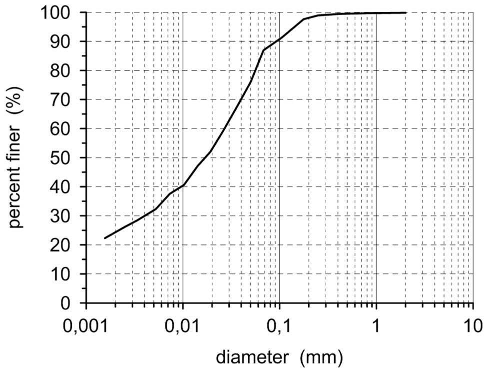

Fig. 1. Grain size distribution of the soil used in the tests.

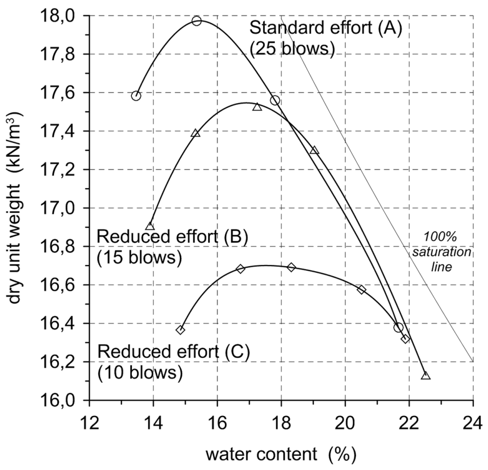

Fig. 2. Soil compaction curves obtained with standard (A) or reduced (B, C) compaction efforts.

of previous experiences (Kim and Daniel, 1992; Konrad and Samson, 2000; Othman et al., 1994) and of standard ASTM D 6035, a testing procedure was defined and the same conditions were kept to ensure the repeatability of the tests and the consistency of the results.

All the samples were reconstituted at a water content that corresponds to the optimal value for the standard compaction ($w_{\text{opt}} = 15.5\%$), assuming this as a target value during construction, since it induces the highest density and most likely the minimum value of hydraulic conductivity. The samples reconstituted with reduced compaction efforts are therefore at the dry side (Fig. 2). This condition is commonly considered not to be as critical as the case of compaction at the wet side, in terms of the freeze–thaw effects on the hydraulic conductivity. The degrees of saturation range from 68% (low compaction samples) to 86% (high compaction), while the void ratios range from 0.49 (high compaction) to 0.62 (low compaction).

A sample was prepared for each planned hydraulic conductivity measurement, and samples prepared to be exposed to freeze–thaw were not considered for a measurement prior to exposure to avoid a variation in their original water content (Test Method A in ASTM D 6035).

From the standard compactor mould, the cylindrical samples, 70 mm in diameter and 124 mm in height, were cored with their axes parallel to the direction of compaction. Later on, after the freezing–thawing process, they will be cut to a height of 30 mm for the oedometric tests and 40 mm for the flexible wall permeameter, while maintaining a diameter of 70 mm, because the saturation process preliminary to the hydraulic conductivity measurement was more effective on reduced height samples.

It is worth noting that the stress–strain boundary conditions applied during the freeze–thaw cycles influence the development of ice lenses and the consequent orientation and spacing of the freezing fractures (e.g., Konrad and Morgenstern, 1982; Othman and Benson, 1993).

In the laboratory tests, the samples were subjected to the freezing–thawing process in their unsaturated condition and before extracting them from the corer, so as to obtain a one-dimensional (oedometric) macroscopic deformation as a consequence of the variation in pore pressure and the increase in fluid volume induced by the liquid-to-solid phase change. This provision reproduces the zero lateral deformation constraint that most likely occurs in the clay barrier on site.

In addition, axial deformation develops in an axial stress-free condition, since there is no confinement to the sample bases during freezing. This condition may be met on-site during construction, before the deposition of additional strata over the barrier. Since a surcharge load during freezing limits the development of fractures, the axial stress-free condition represents the worst expected condition in terms of freezing-induced damage.

Despite the one-dimensional oedometric deformation, at the microstructure scale, the process remains three-dimensional, since there is no thermal insulation at the lateral surface of the sample. However, in their tests, Othman and Benson (1993) observed that the fracture networks induced by 1-D and 3-D cyclic freezing–thawing processes have similar geometries and result in similar hydraulic conductivities.

The thermal gradient is considered a factor of influence on the development of freezing fractures. In these tests, a complete cycle comprises the freezing phase, in a freezing room at −18 °C for 24 h, and the thawing phase, at a room temperature of about 22 °C for the next 24 h. Preliminary tests were conducted on instrumented samples to prove that these temperatures and time intervals would be sufficient to completely freeze and thaw the samples (Chiorazzo, 2011). Sealed plastic bags limited the variation in water content to values less than 0.5%, thus realizing a closed system (i.e., no access to free water during the process). The number of cycles was limited to 4, although ASTM D 6035 prescribes a minimum of 10 cycles, due to the observed trends in the hydraulic conductivity values. Some care must be taken when extracting the samples from the corer and cutting them to the required height, to avoid any disturbance to the possible fracture network.

3. Effects of freezing on hydraulic conductivity

In general, the freezing process induces a fracture network characterized by horizontal fractures, due to the formation of ice lenses, and vertical desiccation cracks, due to the water migration from the unfrozen to the frozen soil under the soil suction generated ahead of the frozen fringe (e.g., Othman and Benson, 1993).

The visual observation on the tested samples after freeze–thaw cycles showed the evidence of permanent fractures, whose spacing and aperture were found to depend on the compaction effort and on the number of cycles. In all the tested cases, the samples contained a sufficient amount of fractures, over the height and the section, to consider their volume as representative for the observation of the specific freezing phenomenon.

The hydraulic conductivity was evaluated with both a direct method, using a flexible wall permeameter (ASTM D 5084, 2003), and an indirect method, from oedometric test results (ASTM D 2435-2435M, 2011).

In the case of the flexible wall permeameter (FWP in the following), the degree of saturation was increased by means of back-pressure, stepwise increased till 300 kPa. With a final cell pressure of 335 kPa, an effective confinement pressure was maintained equal to 35 kPa to reproduce the condition of a shallow overburden on the landfill upper cover. Then, an excess pore water pressure of 4 kPa was applied at the sample base to induce an upward seepage under a constant average hydraulic gradient of about 9. The hydraulic conductivity was calculated after the seepage reached a steady state condition.

A series of preliminary tests was performed to calibrate the procedure. The results reported in Table 1 and in the following figures were assessed from individual tests and recognized as being representative within the testing programme.

The flexible wall permeameter detects, for all the samples with different initial compaction, increases in the hydraulic conductivity with the number of cycles, due to the growing of the fracture network. With reference to a standard value of approximately 10^{-9} m/s, mentioned in the introduction, all the samples would fail to meet this requirement after one or few freezing cycles.

The factors k_4/k_0 (Table 1) confirm that the increase is about one order of magnitude, as from previous results on fine soil samples compacted dry of optimum and tested under similar conditions (Kim and Daniels, 1992).

In addition, a non negligible sensitivity to compaction energy is highlighted. The greater compaction provided by the standard effort (A) leads to the lowest initial value of hydraulic conductivity in undisturbed samples (0 cycles), as expected, but then the damaging effect of cyclic freezing tends to be higher, as a percentage, than for the lesser compacted samples (Fig. 3).

The greater sensitivity of highly compacted samples can be explained considering the effects of freezing on the void ratio and the degree of saturation. In a process occurring at a constant water content, the product of the degree of saturation and the void ratio remains constant (Fig. 4). For a given water content ($w = 15.5\%$), high, medium, and low compaction samples in undisturbed conditions are characterized by positions A, B, and C, respectively. When freezing occurs in a closed system, without access to free water, the increase in volume induced by the water phase change leads the void ratio

Table 1
Values of hydraulic conductivity, as a function of the compaction effort and of the number of cycles, assessed from flexible wall permeameter tests

		Standard effort (A)	Reduced effort (B)	Reduced effort (C)
Undisturbed	k_0 (m/s)	$0.24 \cdot 10^{-9}$	$0.7 \cdot 10^{-9}$	$4.2 \cdot 10^{-9}$
1 cycle	k_1 (m/s)	$1.5 \cdot 10^{-9}$	$3.5 \cdot 10^{-9}$	$11 \cdot 10^{-9}$
	k_1/k_0	6.2	5.0	2.6
2 cycles	k_2 (m/s)	$2.4 \cdot 10^{-9}$	$2.6 \cdot 10^{-9}$	$15 \cdot 10^{-9}$
	k_2/k_0	10.0	3.7	3.6
4 cycles	k_4 (m/s)	$4.5 \cdot 10^{-9}$	$16 \cdot 10^{-9}$	$21 \cdot 10^{-9}$
	k_4/k_0	18.7	22.8	5.0

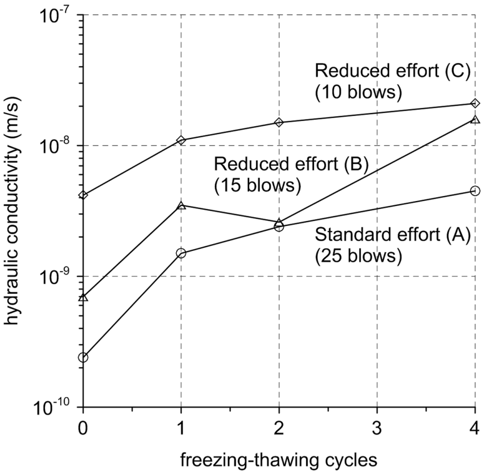

Fig. 3. Variation in hydraulic conductivity with the number of freezing cycles from flexible wall permeameter tests.

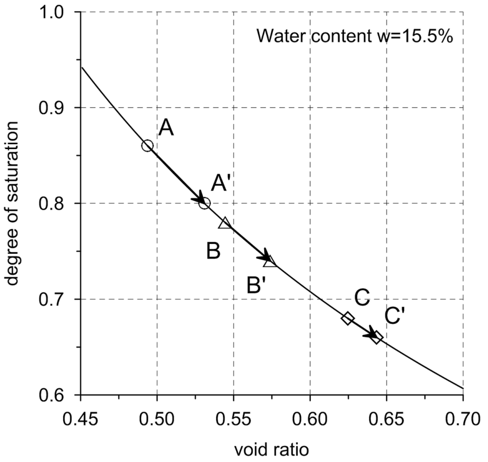

Fig. 4. Relationship between void ratio and degree of saturation, and freezing-induced variations for a constant water content.

to increase and the degree of saturation to decrease, so that the state is modified following the paths shown in Fig. 4.

Moreover, the increase in volume is expected to be large in samples where the water fills a large fraction of the voids, i.e., samples having a high degree of saturation. Therefore, the paths have lengths that depend on the initial compaction: from a long path in the case of high compaction (A–A′) to a short path in the opposite case (C–C′). It turns out that the greatest sensitivity to the freezing effects, in terms of an increase in void ratio, and therefore, in hydraulic conductivity, is exhibited by samples which are initially highly compacted.

The dependence of hydraulic conductivity on the initial compaction tends to decrease with the number of cycles, so the heavily damaged samples (4 cycles) exhibit values within a more restricted range (Fig. 5). Figs. 3 and 5 also show that a large part of the damage occurs starting at the very first freezing cycle, an effect that is not confirmed by the oedometric measurements.

In the case of the oedometric tests (OED data in the following), the samples were initially subjected to a flow of water along with vertical stress, a provision able to increase the degree of saturation (Konrad, 2010). The hydraulic conductivity is then assessed interpreting the test results, for incremental loading limited between 25 and 3200 kPa, with the theory of one-dimensional consolidation, that relates the hydraulic conductivity to the consolidation coefficient and the compressibility. Theoretically, this approach would require a condition of saturation, most likely not fully reached in these samples. For this reason, although the values for hydraulic conductivity turn out to be consistent with those obtained by the flexible wall permeameter method, and therefore, appear reliable, they should nevertheless be considered in comparative terms, to obtain insights into the influence of a post-exposure additional pressure.

It is worth stressing that the freeze–thaw cycles were applied in an axial stress-free condition, as it could occur in the short-term after the clay barrier deposition. Medium to high confinement pressures in the oedometric tests may represent the long-term stress conditions of the lateral and lower liners of the landfill.

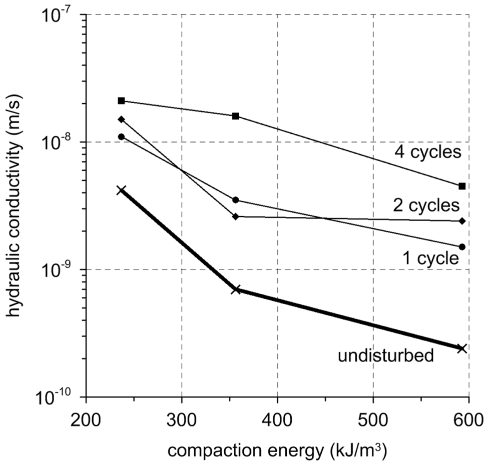

Fig. 5. Variation in hydraulic conductivity with sample initial compaction energy from flexible wall permeameter tests.

The values for hydraulic conductivity, assessed at various vertical stress levels for samples subjected to a given number of cycles, are shown in Fig. 6 (OED data), where the results

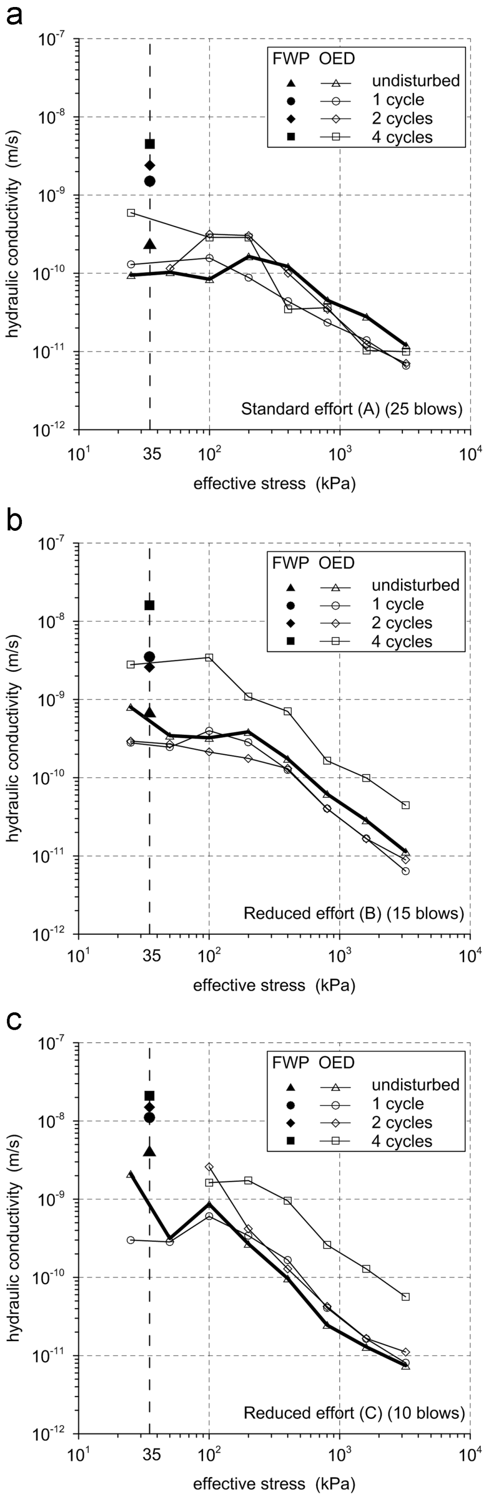

Fig. 6. Variation in hydraulic conductivity with applied stress from oedometric tests (OED), on standard (A) and reduced (B) and (C) compaction energy samples, in comparison with results from flexible wall permeameter tests (FWP) at a confining cell pressure of 35 kPa.

from the flexible wall permeameter (FWP data) are also reported, as values aligned on the effective stress equal to 35 kPa. The lack of some OED data is due to uncertainties in the interpretation of the consolidation settlements in the range of low stress levels.

In general, the hydraulic conductivity is lower when assessed with OED tests, even on undisturbed samples and at applied stress levels comparable to those obtained with the cell pressure in the FWP tests (Fig. 6). This might be due to the lower degree of saturation.

As expected, oedometric tests lead to values that, beyond the stress threshold, gradually decrease with an increasing applied stress. The threshold depends on the sample compaction. For the undisturbed samples of low, medium, and high compaction, it can be identified as approximately 100, 200, and 400 kPa, respectively. The samples subjected to freezing cycles undergo a loss of compaction and, accordingly, show a lower threshold of stress.

Moreover, it is worth noting that, contrarily to FWP findings, OED values reflect the freezing effect as relevant only at the fourth cycle and basically only on samples of medium and low compaction (Fig. 6B and C). For these, the effect also holds at high levels of applied stress, while on highly compacted samples, the fourth cycle induces damage that is remarkable only at low levels of applied stress and is overcome when the high vertical stress increases the density and heals the cracks (Fig. 6A). In the cases of medium to low compaction, the damage appears to be permanent, because for a given applied stress, the hydraulic conductivity remains greater than the value assessed on the undisturbed sample, although it is in any case reduced to values that would be acceptable in terms of the standards for clay barriers (Fig. 6B and C).

The OED response proves that the freezing damage is progressive and that few cycles can develop isolated horizontal ice lenses too small to create a diffuse fracture network and easily closed by the applied stress. Only after additional cycles, the growth of vertical desiccation fractures and the full development of a fracture network, most likely occurring at a late stage of damage (fourth cycle), allow the OED tests to detect the effects of freezing.

The difference between the FWP and OED results stems from the different conditions of stress confinement provided by the two devices: the applied vertical stress in OED tests tends to close the horizontal fractures at early stages of the process and inhibits the water flow, a condition not forced by the isotropic confinement of FWP.

For a given water content, highly compacted samples have a degree of saturation higher than lesser compacted samples, the former having the same water content, but in a denser structure. Consequently, under higher compaction conditions, the vertical desiccation cracks could be more limited, and the fracture network less developed, even at the fourth cycle, so that the freezing effects on the hydraulic conductivity are detected only at low levels of confining stress (Fig. 6A).

4. Conclusions and further developments

Some results from a laboratory experimental programme have been summarized to gain insight into the effects of freeze–thaw cycles and possible post-exposure consolidation on the hydraulic conductivity of clayey silt samples, reconstituted with different compaction energies at a given water content. The aim was to enhance the information database on this subject for engineering modelling purposes.

From the observed behaviour, the following conclusions can be drawn:

(1) Although from the visual observation of the tested samples, it can be inferred that the volume considered here is representative and suitable for an investigation of the freezing effects, the size effects on the laboratory samples could nevertheless be relevant and require further investigation, as well as the axial stress-free condition maintained during the freezing process.

(2) The freezing cycles lead to the progressive and permanent damage of the compacted soil structure. A comparison between OED and FWP test results allows for the recognition of the progressive growth of fractures into a network, consisting of horizontal lenses and vertical desiccation cracks. These fractures form preferential flow paths that eventually lead to an increase in hydraulic conductivity, in some cases up to one order of magnitude.

(3) When the applied stress is low, the sensitivity of clayey silt to the phenomenon is higher for samples initially compacted with higher energy. When the applied stress is medium to high, the effects of freezing tend to vanish in samples compacted with high energy, whereas they remain relevant in samples compacted with low to medium energy. Since the latter are compacted at the dry side in a closed system, the vertical desiccation cracks induced by freezing are more developed.

Since the freezing process affects only exposed and shallow layers, deep barriers, such as the landfill bottom liner, could suffer freezing-induced damage only during construction. During waste deposition, however, the liner can benefit from the increasing overburden stress that reduces the hydraulic conductivity, partially healing the crack network. Therefore, these experimental results are relevant especially for covers and shallow barriers, where the overburden is limited and the induced stress is low. In addition, shallow barriers are also exposed to possible frost action during their working life.

According to these results, the highest energy in barrier compaction is therefore always advisable. In areas where energy compaction is decreased, an initial water content close to the optimal value, characterizing that energy compaction, is advisable.

Finally, it was observed that the nature of clay affects the formation of ice lenses and the fracture network. Moreover, it is recognized that the porous microstructure plays a role in determining the sensitivity to environmental actions, such as freezing or desiccation. Preliminary tests on structured clays prove that the freezing action induces not only the formation of a fracture network, but also the breaking of clay particle substructures. In turn, this effect could result in a major change in the physical and mechanical properties of the material. Research is currently being focused on these aspects, with the extension of the experimental investigation to scaly clays.

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