



Hydraulic conductivity changes in compacted clayey barriers due to temperature variations in landfill top covers

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Abstract

In landfills, due to their low hydraulic conductivity, compacted clays (CC) are commonly used in multilayered structures as base liners and cover systems. Nevertheless, the hydraulic performances of the CC layer can be affected by temperature alterations. The CC barrier of cover systems is exposed to heating caused by waste degradation processes as well as by the air temperature fluctuations, including freezing and thawing and high temperatures. Exposition occurs especially during transitory configurations when the final cap is not completed with the protective soil layers. In the present work, four clayey soils of varying plasticity all suitable for landfill barriers according to the international standard requirements are tested with respect to their sensitivity to thermal stresses in terms of hydraulic conductivity changes. For each material, experimental tests are performed on compacted specimens comparing the values obtained soon after compaction with the ones obtained after exposition to freezing–thawing or drying processes, the latter caused by heating up to 60 °C. The results show that freezing–thawing is more detrimental than heating, since the first can increase the hydraulic conductivity by up to about 20 times, while the second by less than 10 times. The soils of medium plasticity are the most affected, while the ones with high plasticity show the ability to partially withstand the effects of the investigated thermal alterations. This behavior seems related to the water absorption capacity of the material. The results suggest that the optimum water content acquired from the Proctor Standard curve seems to be a suitable indicator of this partial recovery potential.

Keywords Compacted clay · Hydraulic conductivity · Plasticity index · Optimum water content · Heating · Freeze–thaw cycles

Introduction

In landfills, specific containing barriers are engineered in order to isolate the contaminants from the surrounding environment and minimize the release of leachate and gases. The barriers used for the prevention of water and pollutant migration are usually designed as layered systems (composite liners). Each layer serves a specific purpose, such as resistance

to mechanical actions, drainage and collection of liquids and gases, and barrier to fluid percolation and rain infiltration. Compacted clay (CC) layers, owing to the very low permeability obtainable when clays are properly compacted, usually provide the latter function.

The international and national regulations set a threshold value for the required hydraulic conductivity of the cover and bottom/lateral barriers, depending on the type of waste collected in the controlled landfill. For the top cover, the European Community (European Commission 1999 Council Directive 99/31/EC) recommends a thickness of at least 0.5 m for hazardous and non-hazardous wastes. These requirements have been implemented into local legislation by each member state; for instance, Italy requires a maximum hydraulic conductivity of 10^{-8} m/s combined with a thickness of at least 0.5 m for the geological barrier of the top cover of landfills for hazardous/non-hazardous wastes (D. Lgs 36/2003). Similarly, the US regulation requires that, in the case of municipal solid waste landfills with a leachate collection system, the landfill must be closed with a final top cover having a maximum

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hydraulic conductivity of 10^{-9} m/s (CFR 40, I, 258-F) (US Environmental Protection Agency (1996).

These performances must be guaranteed over the long term, to ensure a long-lasting proper performance of the barrier system (Rowe 2005; Benson et al. 2011). However, during their entire lifetime, the barriers are subjected to many processes that could change their properties. Among the most important processes are heat production related to waste decomposition, which increases the inner temperature of the waste mass in relation to time, waste composition, age and water content (Yeşiller et al. 2005; Hanson et al. 2009), and the external local climate variations characterized by seasonal and daily temperature and humidity fluctuations. These factors could induce heating and desiccation processes and/or freeze–thaw cycles in the mineral barrier, therefore affecting the soil microstructure and its hydraulic performance (Chamberlain and Gow 1979; Konrad 1989; Grechishchev et al. 1992; Othman and Benson 1993; Benson and Othman 1993; Benson et al. 2011; Dalla Santa et al. 2019). Several authors already analyzed the effects of temperature variations on the hydraulic performances of the CC bottom barrier of landfills. Aldaeef and Rayhani (2014) studied the effects of heating (up to 55 °C) combined with leachate exposures, while Albrecht and Benson (2001) studied the effects of wet–dry cycles on swelling and hydraulic conductivity of CC. Finally, Othman et al. (1994), Benson et al. (1995), and Sterpi (2015) studied the hydraulic conductivity variation caused by freeze–thaw cycles. An extensive experimental investigation on the changes in engineering properties affecting the cover soils in field was performed by Benson et al. (2011). Benson et al. (1996) and, more recently, Chegenizadeh et al. (2018) investigated how thermal and hydraulic performances of protective layers or of CC barriers can be improved by adding mixtures of recycled tire chips or other materials.

Regulations usually require the geological barrier in a landfill top cover to be completed with an additional drainage layer made of gravel, plus an organic soil layer of about 1 m. The purpose of the final layer is to protect the CC barrier from the thermal variations and to permit vegetation growth. It is well-known that waste degradation leads to differential compaction in the waste mass causing differential settlements of the cover. This causes problems such as surface ponding and deformations of the cover barrier. Numerous models have been developed in order to simulate the movement of solid waste and predict the rate and magnitude of landfill top cover deformations (Morris and Woods 1990; El-Fadel and Houry 2000). Sometimes, for various possible delays (Moo-Young and Zimmie 1996), financial constraints (Chiemchaisri et al. 2010), or improper practices (Kim and Daniel 1992; Albrecht and Benson 2001), the last soil protection layers may be laid not soon after the CC barrier deposition, but after some days or even after the occurrence of the first waste degradation phase. Hence, the application of the protective top

layers of the definitive cover is postponed and the CC layer could remain exposed to external agents for a certain time, only covered with a geosynthetic sheet.

While regulations set the hydraulic performances required by the impermeable barriers, the guidelines indicate which plasticity index (PI) and granulometry the sediment must have in order to satisfy the law's requirements about the hydraulic conductivity and to have, at the same time, an adequate workability. The PI should be between 7–10 and 40%, while the granulometric composition must present a gravel content < 40%, a fraction passing through the n.200 ASTM sieve \geq 25% and a maximum grain size in the range 25–50 mm (Daniel and Benson 1990; Rowe 2005).

In the research here presented, four different materials suitable for the CC barrier and characterized by different PI have been tested in order to compare their vulnerability in term of hydraulic conductivity to temperature variations. For this purpose, after the definition of the optimum water content (w_{opt}) in accord with the Proctor Standard procedure, a series of hydraulic conductivity tests have been performed on specimens of soil compacted at a water content slightly higher than optimum. Particularly, three soil conditions have been examined: (I) soon after the compaction at room temperature, (II) after exposure to 10 freezing–thawing cycles, and (III) after exposure to heating process up to 60 °C. The hydraulic conductivity tests were performed using the falling head method in the oedometer device (BS EN ISO 17892-11 2019), soon after the exposition of the specimens inside the oedometer to the testing temperature variations by means of an expressly made experimental device. This way, the vertical deformations were also measured continuously. Comparison of the results permits a correlation of the soil sensitivity to temperature alterations, in terms of hydraulic conductivity, with its PI and w_{opt} .

Therefore, the novelty of the present study is that both high temperatures and freezing are imposed on the same materials in order to investigate the whole range of temperatures to which the CC top cover of a landfill could be exposed in temperate regions. In addition, the experimental findings suggest the suitability of the w_{opt} as indicator of the vulnerability to hydraulic conductivity changes caused by temperature variations in clayey soils.

Effects of freezing–thawing and wet–dry cycles on CC

CC layers can suffer damage both from freezing–thawing and wet–dry cycles due to seasonal variations of temperature, solar irradiation, and evapotranspiration. These processes cause phase changes of the pore water and/or pore water content variations. These, in turn, can affect the cohesive properties of the soil by altering their internal structure and, as a consequence, their mechanical and hydraulic properties (Farouki 1981; Konrad 1989; Qi et al. 2008; Albrecht and Benson

2001; Aldaeef and Rayhani 2015; Chamberlain and Gow 1979; Dalla Santa et al. 2019; Othman and Benson 1993).

Firstly, Campanella and Mitchell (1968) conducted a series of triaxial compression tests on clays at different temperatures and observed that, in undrained conditions, a rise in temperature (up to about 60 °C) results in a pore pressure increase. They described the pore pressure change as being directly proportional to the expansion of the pore water due to the effect of temperature. Burghignoli et al. (2000) performed a series of tests under drained conditions by varying the temperature between 15 and 60 °C. Their results showed that, under drained conditions, temperature variations in clay produce irreversible changes in volume combined with a change in void ratio; the higher the amplitude of the temperature cycle the higher the magnitude of the volume changes. The magnitude of the deformation was also recognized as affected by the earlier temperature cycles and the duration of the temperature increase. Several authors consider the temperature dependency of the mechanical behavior of saturated fine-grained soils as controlled by the physical chemical forces between the clay particles. These forces, in turn, are significantly affected by changes in pore fluid features such as valence, concentration, or temperature (Mitchell 1993). Therefore, changes in the pore fluid characteristics alter the effective stresses and induce volumetric strain, depending on the imposed temperature, plasticity, and stress history (Towhata et al. 1993; Romero et al. 2005; Abuel-Naga et al. 2009).

Exposure to drying can reduce the water content of the CC layer by causing volume shrinkage, microstructure changes, and the formation of cracks, which may result in a considerable increase in hydraulic conductivity (Albrecht and Benson 2001; Aldaeef and Rayhani 2014; Romero 2013; Yeşiller et al. 2008). The shrinkage behavior of a CC is influenced mainly by clay content and its mineralogical composition. Albrecht and Benson (2001) performed a series of tests on compacted clayey soils subjected to desiccation in order to determine how factors such as soil mineralogy, compaction conditions, and a number of drying cycles affect volumetric shrinkage, formation of fissures, and subsequent augmentation in hydraulic conductivity. They tested eight soils with PI ranging from 11 to 46, and WL from 18 to 67. The specimens were subjected to 10 wet–dry cycles; in the wetting part of the cycle, they were permeated until the hydraulic conductivity was steady while during drying they were allowed to slowly dry at room temperature (around 20 °C). The authors found that the volumetric shrinkage is a direct function of the water content of the compacted soil; thus, soils with higher clay fraction and PI are usually more prone to large volumetric shrinkage. The macroscale pore structure introduced by the cracking that occurs during drying controls the subsequent hydraulic conductivity. After only one drying cycle, the hydraulic

conductivity increases by one or two orders of magnitude, while at the end of all the wet–dry cycles the hydraulic conductivity increments by 8 to 500 times.

Aldaeef and Rayhani (2014) compared the effects of daily thermal variations on four compacted soils with different PI (ranging from 9.5 to 37.2). They concluded that, after more than 30 thermal cycles imposed with a temperature ranging from 22 to 55 °C, all the compacted soils suffer an increase in hydraulic conductivity. The one with higher plasticity (PI = 37.2) displays the more constrained increase with a final hydraulic conductivity equal to 2 times the prior value; on the contrary, soils with low plasticity showed an increase in hydraulic conductivity equal to almost one order of magnitude. The authors ascribed this effect to the expandable clay fraction that is able to provide a partial recovery of previous structure by filling fissures and gaps (Aldaeef and Rayhani 2014; Parastar et al. 2017). This swelling capacity of clays under hydration was observed since the early studies by Foster (1954) as caused by the increase of the inter-particle distances due to the insertion of water molecules (see for example, Seed and Lundgren (1962), Saiyouri et al. (2004), Mishra et al. (2008)). The swelling behavior of CC is generally recognized as influenced by several factors, some depending upon the nature of soil particles such as clay mineralogy, and others depending upon the physical condition and environment of soil, as the dry density and the water content at compaction. Mishra et al. (2008) highlighted that the clay mineralogy dominates over compaction conditions in influencing swell behavior.

Nevertheless, the recovery potential in terms of hydraulic conductivity related to soil plasticity is not uniformly recognized in literature. Albrecht and Benson (2001) performed a long-term permeation of 350 days on two high plasticity clayey soils (IP = 32 and 46) after the exposition to 4 wet–dry cycles (slowly dried at 20 °C); in this case, only a limited recovery of the hydraulic conductivity was measured as clay rehydrates and no relation to PI was reported.

The differences in the experimental findings could either be caused by different experimental conditions in temperature and velocity of the wetting–drying procedure or could be related to the cation exchange. Lin and Benson (2000) observed that the swelling capacity of a bentonite during rehydration can be significantly reduced by cation exchange. The higher the salt concentrations in the pore water, the lower the swelling capacity.

Regarding subzero temperatures, several authors have studied the effects of freezing and thawing cycles on clayey soils (Benson and Othman 1993; Chamberlain and Gow 1979; Kim and Daniel 1992; Othman and Benson 1993; Othman et al. 1994; Coussy 2005; Konrad 1989; Sterpi 2015). The past studies highlighted the importance of relating the vulnerability to freezing cycles to the physical properties of the soil (plasticity index, water retention, and swelling potential) and

to the initial conditions of water content and compaction (Chamberlain et al. 1990). The authors indicate that freeze–thaw (FT) cycles typically lead to irreversible but limited deformations (Othman et al. 1994; Dalla Santa et al. 2016a) and increase the hydraulic conductivity of clays by one or two orders of magnitude (Chamberlain et al. 1990; Dalla Santa et al. 2019; Kim and Daniel 1992).

As in case of drying, the permeability increase is largest the first time the soil experiences FT and terminates after 5–7 FT cycles. This means that just only one FT cycle can affect the hydraulic conductivity of a CC considerably. The increase in hydraulic conductivity is usually larger for clays with lower initial hydraulic conductivity (Othman and Benson 1993).

Despite the dense aggregated structure provided by compaction, the freezing process causes an irreversible change in the internal microstructure; the formation of ice lenses and their subsequent accretion enlarge the macropores, resulting in the development of paths with reduced flow resistance during the thawing phase. A very clear description of the processes that occur during soil freezing, causing the formation of ice lenses and consequent microstructural changes, can be found in previous papers (Benson and Othman 1993; Konrad 1989; Dalla Santa et al. 2019).

With reference to the CC initial conditions, Chamberlain et al. (1990) compared the behavior of specimens obtained by consolidation or by compaction of a slurry. They underlined that FT cycles always induce an increase in hydraulic conductivity in consolidated specimens, higher with a higher water content. The effects on compacted specimens are not always consistent, depending on the initial state of compaction, the water content and the degree of saturation with respect to the soil plastic limit. In order to minimize the damage due to frost action, they indicated that the density achieved after compaction must be characterized by a saturation water content below their plastic limit.

Othman and Benson (1993) and Othman et al. (1994) studied the effects of the stress boundary conditions on the development of ice lenses and fractures, and the consequent hydraulic conductivity variation, caused by FT processes on CC with different PI (PI = 16–60%) and subjected to different stresses. A load applied during the FT process inhibits the formation and the growth of ice lenses, as it lowers the freezing temperature, reduces the suction forces, and limits the movement of water molecules throughout the soil. Moreover, the voids enlarged during the expansion of the ice lenses are compressed and highly reduced during the thawing stage.

In landfills, the effects due to FT can be partially limited in the bottom CC barrier systems if, after temporary exposure, they are covered with wastes (Sterpi 2015). Conversely, the effect provided by the applied load is trivial for the top cover because, once the top soil layers have been laid, the CC barrier is subjected to the weight of the 1-m protective layer only.

Kim and Daniel (1992) arrived at the same conclusion and highlighted that FT cycles can cause a large increase in the hydraulic conductivity of CC under relatively low overburden stresses.

Recently, Sterpi (2015) described the FT effects on permeability of a compacted silty clay treated with different compaction energies (Standard Proctor with 25 blows or compaction with 15 or 10 blows only), but all prepared with the same water content, i.e., the w_{opt} obtained for the standard compaction test. The obtained results are consistent with the previous study (Kim and Daniel 1992) and indicate that, when the applied stress is low as in the top covers, the sensitivity to FT of clayey silts compacted in dry range is higher for specimens initially compacted with higher energy. Therefore, increasing the compaction energy does not contrast the effects induced by the frost action.

In order to facilitate comparison among previous studies dealing with the thermal effects on hydraulic conductivity of CC, Table 1 summarizes the main results of these studies and indicates the tested soils, the experimental conditions, the investigated indicators, and the main findings. It has to be noted that, so far, research has focused either on the effects of FT or on those of drying; conversely, in the present study, the same soils are tested in the whole range of temperatures, therefore allowing the comparison of the effects of FT cycles and those of drying at high temperatures.

Materials and methods

The tested materials

The experimental tests presented here compared the performances of four sediments of varying plasticity, all suitable to be employed in CC liners according to international guidelines. Their physical features and mineralogical composition are listed in Table 2. The grain size distributions and the Atterberg limits are depicted in Fig. 1, while the mineralogical composition, evaluated by X-ray diffraction and validated by comparison to X-ray fluorescence chemical analysis, are represented in Fig. 2.

Samples A, B, and D were collected at different depths in the same borehole, while sample C was collected from a different site and added to the set of tested materials in order to complete the range from low to high plasticity materials. Sample A is poorly graded inorganic silt with slight plasticity while B is a well-graded inorganic silty clay with medium plasticity. Sample C is a micaceous clay of medium/high plasticity; it contains 48% phyllosilicates consisting in mica, chlorite, kaolinite, serpentine, and a consistent amount of expandable clay minerals with mixed layers (illite–smectite), in addition to a small fraction of gypsum and pyrite, minerals which indicate a significant organic content (5%). Sample D is a

Table 1 Summary of the results found in literature about variations of hydraulic conductivity induced in CC by temperature variations

| Reference | Tested soils | Investigated indicator | Measurement conducted | Experimental conditions | Main results |
|----------------------------|---|--|---|--|---|
| Chamberlain et al. (1990) | 5 Compacted and consolidated clays (PI = 10, 15, 22, 24, and 37%) | - Ratio between $W_{\text{Compaction}}$ and PL | - k with falling head method in rigid wall permeameter (consolidometer) - ε_v | - FTCs, 1-dimensional freezing - 2 FTCs per day - low σ_n | 1. Greater increases of k after FTCs as the $W_{\text{Compaction}}$ just below the LL, small increases with $W_{\text{Compaction}} \approx \text{PL}$ 2. To minimize the frost damage protective clay barriers must be compacted to densities at which their saturated $W \approx \text{PL}$ |
| Othman and Benson (1993) | 3 CC (PI = 16, 19 and 60%), known as Wisconsin A, Wisconsin B, Wisconsin C | - PI overburden pressure (σ_n) during or after FTC - Different σ_n during k tests | - k in flexible wall permeameter with $\sigma_m = 20$ kPa - ε_{vol} | - $W_{\text{Compaction}} = W_{\text{opt}} + 2\%$ - 1, 3, and 5 FTCs (T: $-5 \div 22$ °C) - Comparison of effects induced by 1D and 3D FTCs | 1. k increases about 1 o.o.m. after 1 FTC, then increases with the number of FTCs and becomes constant after ≈ 3 FTCs. 2. Higher increases of k in clays with lower initial k_0 3. σ_n applied DURING FT inhibits the increase of k more than the overburden pressure applied after the FT cycles. 4. 1D and 3D FTCs have comparable effects |
| Kim and Daniel (1992) | 1 Compacted glacially derived clay (gravel 3%, sand 9%, fine 88%; LL = 36%, PI = 19%) | - 3 values of compaction energy - Wide range of $W_{\text{Compaction}}$ | - k in flexible wall permeameter with $\sigma_m = 35$ kPa - ε_{vol} | - Constant $W_{\text{Compaction}}$ - 5 FTCs (T = $-17.8 \div \text{room temp}$) - 3D FTCs | 1. $W_{\text{Compaction}}$ appears the most important factor 2. Larger k increases (of about 2 o.o.m.) due to FTC measured for specimens with $W_{\text{Compaction}} > W_{\text{opt}}$; for specimens with $W_{\text{Compaction}} < W_{\text{opt}}$ k increases of $2 \div 6$ times 3. FTCs cause an ε_{vol} up to 4% |
| Albrecht and Benson (2001) | 4 compacted clays (PI = 46, 32, 26, 19, 16, 15, and 11%) | - Soil composition - Compaction condition - Number of drying cycles | - Volumetric shrinkage strain and cracking formation - k in flexible wall permeameter | - Wetting into the permeameter and slowly drying at room temperature for 10 days | 1. Soils with higher clay content and higher plasticity index are more prone to volumetric shrinkage during drying 2. Specimens compacted near w_{opt} with higher compactive effort have lower volumetric shrinkage strains 3. k increases as much as 500 times due to drying cracks 4. The largest increase of k is recorded after the first drying cycle 5. Regardless long-term permeation, a very limited healing of damage is observed |
| Aldaeef and Rayhani (2014) | 4 CC (Halton clay, Leda clay, and mixtures with bentonite) PI = 9.5, 18.7, 25.0, and 37.2%) | - PI | - k with falling head method in rigid wall permeameter - ε_{vol} due to shrinkage by means of a digital caliper | - Heating ($22 \div 55$ °C) every 12 h - Measurements before and after heating (15, 30, 45, 60 days) | 1. Remarkable k increase with wet-dry cycles for low plasticity soils (PI = 9.5%) 2. Soils with medium to high plasticity indexes ($25\% < \text{PI} < 37\%$) show almost constant hydraulic performance; the increase of hydraulic conductivity after 15 days of heating cycles is equal to 2 times |
| Sterpi (2015) | 1 Compacted clayey silt LL = 32%, PI = 14% | - 3 values of compaction energy - several σ_n applied during k test | - Comparison between k obtained with falling head method in rigid wall permeameter and in oedometer | - $W_{\text{Compaction}} = 15.5\% = W_{\text{opt}}$ constant for all tests - 1, 2, 4 FTCs (T: $-18 \div 22$ °C for 24 h) - 3-dimensional FTC | 1. k increases with FTCs (about 1 o.o.m. after 4 FTCs) 2. Higher compaction energy leads to lower initial k , but the increase due to FT cycles appears to be wider 3. When the applied stress (σ_n) is low (as in landfill top cover) larger k increases die to FTC are observed in case the initial compaction was achieved with higher energy |

k , permeability; LL , liquid limit; PL , plastic limit; PI , plastic index; W , water content; $W_{\text{Compaction}}$, water content during compaction; W_{opt} , optimum water content according to Standard Proctor tests; ε_v , vertical deformation; ε_{vol} , volumetric deformation; CC , compacted clay; σ_m or σ_n , vertical stress applied during the test; FTC , freezing–thawing cycle, $1D$, test in one dimension; $3D$, test in three dimensions; $o.o.m.$, order of magnitude

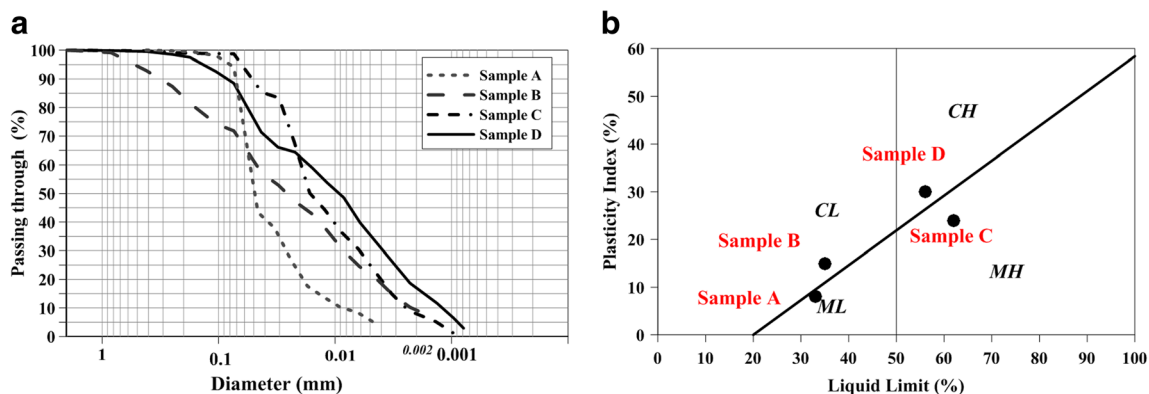
Table 2 Physical properties, mineralogical composition and results obtained from the Standard Proctor test of the tested soils

| Characteristics | Sample A | Sample B | Sample C | Sample D |
|---------------------------------------|-----------------------------|-----------------------------|--------------------------------------|-----------------------------------|
| Sampling location | Molinella (Italy, Po plain) | Molinella (Italy, Po plain) | Padova (North East Italy) | Molinella (Italy, Po plain) |
| Sampling depth (m) | 5.00–5.70 | 27.70–27.90 | 93.10–93.80 | 7.00–9.80 |
| Liquid limit, WL (%) | 33 | 35 | 62 | 56 |
| Plastic limit, WP (%) | 25 | 20 | 38 | 26 |
| Plasticity index, PI (%) | 8 | 15 | 24 | 30 |
| Organic content, OC (%) | 2 | 1 | 5 | 2 |
| Specific gravity, G_s | 2.74 | 2.70 | 2.69 | 2.71 |
| Clay content (%) | - | 8 | 10 | 16 |
| Activity index | - | 1.88 | 2.4 | 1.88 |
| Soil type (USCS) | ML | CL | MH/OH | CH |
| Mineralogical composition | | | | |
| Phyllosilicates | 32 | 39 | 48 | 62 |
| Expandable fraction | - | - | Significant amount (illite–smectite) | Very few expandable clay minerals |
| Quartz | 31 | 30 | 24 | 19 |
| Calcite | 24 | 19 | 3 | 12 |
| Dolomite | 1 | 1 | 13 | 1 |
| Feldspars | 12 | 11 | 7 | 6 |
| Others | - | - | 3% gypsum 2% pyrite | - |
| Standard Proctor test | | | | |
| $\gamma_{d,max}$ (Kn/m ³) | 17.0 | 18.0 | 14.8 | 16.6 |
| W_{opt} (%) | 17.3 | 15.1 | 25.2 | 19.6 |

well-graded inorganic clay of high plasticity; the analysis of its mineralogical components detects the highest percentage of phyllosilicates (62%) with very few expandable clay minerals, and no minerals related to high organic content.

The wide gradation that characterizes the granulometric size distribution of samples B and D must be noted (Fig. 1a), contrary to A and D that display a more homogenous granulometric composition. In addition, the Casagrande Plasticity chart (Fig. 2b) evidences the different plasticity features (WL, PI) of samples; A and C are below the A-line, while B and D are above the A-line.

The compaction curves of soils (Fig. 3) are obtained according to the Standard Proctor test (ASTM Standard D698-2000), in order to evaluate the Optimum Water content. The red crosses represent the optimum values, also reported in Table 1. The combined effects of the samples' mineralogical composition, plasticity features, and granulometric gradation result in the relative position of the compaction curves. The values of $\gamma_{d,max}$ and w_{opt} displayed by samples B and D comply with the relationship proposed by Blotz et al. (1998), while A and C show a different behavior, due to poor granulometric

**Fig. 1** a Particle size distribution of the tested materials; b samples represented in the Casagrande Plasticity Chart

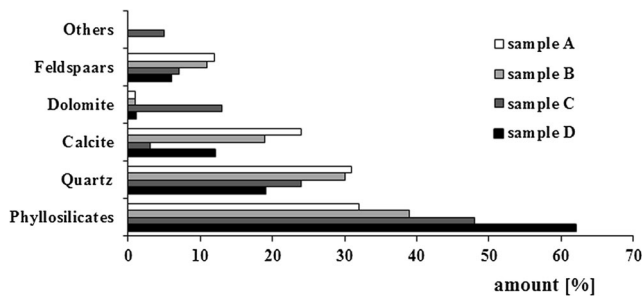


Fig. 2 Mineralogical compositions of tested soils

gradation (see Fig. 1a) and different plasticity (see Fig. 1b). Even if sample C is not the most plastic of the tested soils, it exhibits the highest w_{opt} , probably owing to its higher content of expandable clayey minerals and organic materials.

Specimens’ preparation

Each soil was firstly compacted at a water content equal to its w_{opt} inside the Proctor mold. From the core of each compacted sample, three 7-cm large and 2-cm high specimens were formed by means of a die cut and were fit inside three standard oedometer rings. The hydraulic conductivity tests were conducted by adopting the falling head method in the oedometer cell (BS EN ISO 17892-11), as described in Par. 2.4.

- (I) The first specimen was tested directly after the compaction procedure, in order to represent the initial condition of the CC barrier and provide the reference value.
- (II) The second, after being inserted into the thermally controlled oedometer (described in detail in paragraph 2.3), was subjected to 5 freezing–thawing cycles with a

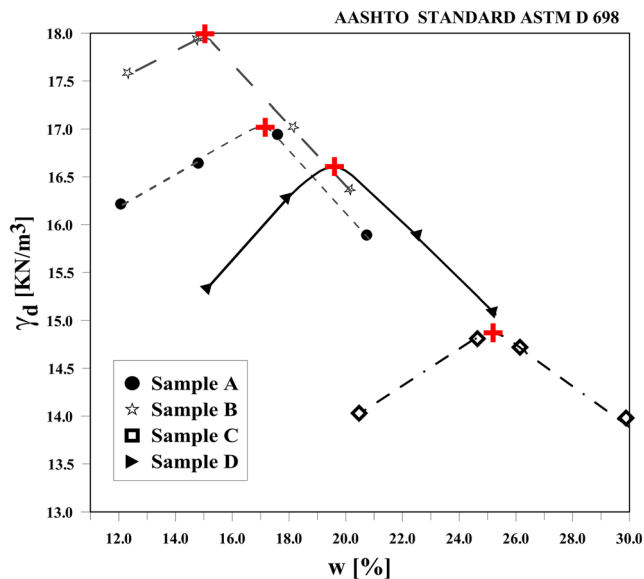


Fig. 3 Compaction curves obtained for the four tested soils with the Standard Proctor test (ASTM D698-2000). The obtained w_{opt} are depicted in the graph by the crosses

temperature ranging between -5 and $+5$ °C, in order to reproduce the possible daily temperature fluctuation in winter conditions. The temperature changes were imposed every 12 h in a closed system, thus with no possibility for water uptake. Since previous studies demonstrated that the changes in the CC microstructure occur in the first cycles (Konrad 1989), it is possible to suppose that 5 FT cycles are enough to reach a stable modified structure. The vertical deformations were recorded by the oedometer device, hence obtaining the specimen’s thickness at the end of the induced FT cycles.

- (III) In the same way, the last specimen inside the oedometer ring was subjected to a 3D heating for 24 h at $T = 60$ °C. This testing temperature was chosen in order to reproduce the heat of summer solar radiation on the upper layer of the CC barrier covered by a dark geomembrane (Thiel et al. 2006; Aldaeef and Rayhani 2015). After heating exposure, a reduction in volume was observed; in addition to the thickness variation, also the diameter reduction was recorded by means of a digital caliper (reported in Table 4). Before the hydraulic conductivity test, the inner surface of the oedometer ring was coated with a layer of vaseline-based grease for sealing gaskets at high pressures to avoid water leakage along the internal sides of the cell, as suggested by BS EN ISO 17892-11 (2019) and Engineers Manual 1110-2-1901 (1986). The test setup was examined for signs of sidewall leakage, but no evidence of a short circuit was found. Afterwards, when the specimen was rehydrated during the first phase of the permeability test, some volume variations were observed and registered at the end of the hydraulic conductivity test. The values are reported in Table 4.

The thermally controlled oedometer

In order to impose the temperature variations (freezing–thawing cycles and heating up to 60 °C) to the specimens, an expressly conceived experimental device was used. It had been previously developed at the Department of Geosciences of the University of Padua in collaboration with CNR —IGG (National Research Council, Institute of Geosciences and Georesources). This consists in a thermostatically controlled box made of insulating material where the oedometer can be inserted. A system of 12 Peltier cells located in the lateral walls of the box permits an accurate temperature regulation by means of an electronic control unit. The box is filled with an anti-freeze liquid, in order to transmit the heat from the lateral walls to the oedometer and the specimen inside homogeneously. The temperature inside the oedometer is continuously measured by a PT100 probe positioned under the specimen, within the porous stone. Externally, the Peltier cell’s temperature is stabilized by means of a continuous water

circulation system completed with a degasser and several safety devices. This experimental device permits controlled temperature conditions, and also continuously measures the vertical deformations of the specimens. Figure 4 shows a schematic representation of the thermally controlled oedometer, already applied in previous studies and described in detail in (Dalla Santa et al. 2016a; Dalla Santa, 2016b).

Hydraulic conductivity tests

The hydraulic conductivity tests were performed using the falling head method in the oedometer device (BS EN ISO 17892-11 2019) just extracted from the testing device that imposed the temperature variations. Hence, all the hydraulic conductivity tests were conducted at room temperature. The laboratory is a thermally controlled room where the temperature is maintained at a constant 20 °C.

Saturation was conducted by permeating the specimens with an upward flow of water using a hydraulic gradient of 10 and a load of 5 kPa. The specimens were permeated with deaerated tap water to prevent entrapment of air until the hydraulic conductivity measured in this phase was steady. This provision has been demonstrated to increase the degree of saturation, finally resulting in nearly saturated specimens reflecting a likely field condition as previously reported in Albrecht and Benson (2001), Konrad (2010), and Sterpi (2015). This procedure took from 10 to 35 days depending on the plasticity of the sample.

After the first phase of permeation, the tests were performed by using low confining stress and low initial hydraulic gradients, in order to better represent the real load conditions applied to a landfill cover. The specimen was subjected to a vertical stress equal to 5 kPa and the initial upper head in the graduated burette was fixed at 30 cm. The water level was then allowed to drop in the falling head tube, and the head

measurements were recorded two times a day. The test was repeated three times. The hydraulic conductivity acquired from each test was steady over time.

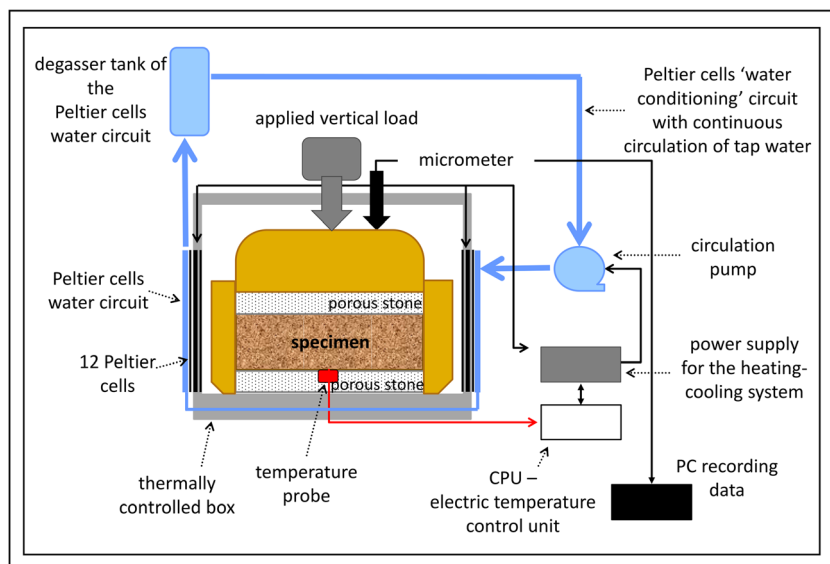
Despite the fact that flexible wall testing is often used to determine the hydraulic conductivity of fine-grained soils, in this case the oedometer was chosen in order to compare the results before and after the thermal treatments, that are imposed by means of the thermally controlled box already described, specifically made for specimens contained within the oedometer ring in order to register the development of vertical strains. The device applies a 3D freezing/heating process; however, Othman and Benson (1993) from their studies concluded that the fracture networks induced by 1D and 3D cyclic freezing–thawing processes have similar geometries and result in similar hydraulic conductivities. In addition, the permeability values obtained by Konrad (2010) and Sterpi (2015) with the oedometer device are consistent with those obtained using the flexible wall permeameter method in similar conditions.

Results

Figure 5 reports and compares the hydraulic conductivity obtained for all the tested samples.

The obtained results highlight, as expected from the literature review, that temperature variations affect the hydraulic conductivity of the compacted specimens; the FT cycles produce greater effects than the heating process does. This means that the exposure to FT processes appears to be more detrimental than high temperatures on the hydraulic performances of a landfill cover barrier. As in previous works, the hydraulic conductivity ratio K is defined as the ratio between the modified hydraulic conductivity and the value of the reference specimens; K_{FT} is the ratio

Fig. 4 Experimental setup for the oedometer tests in thermally controlled conditions



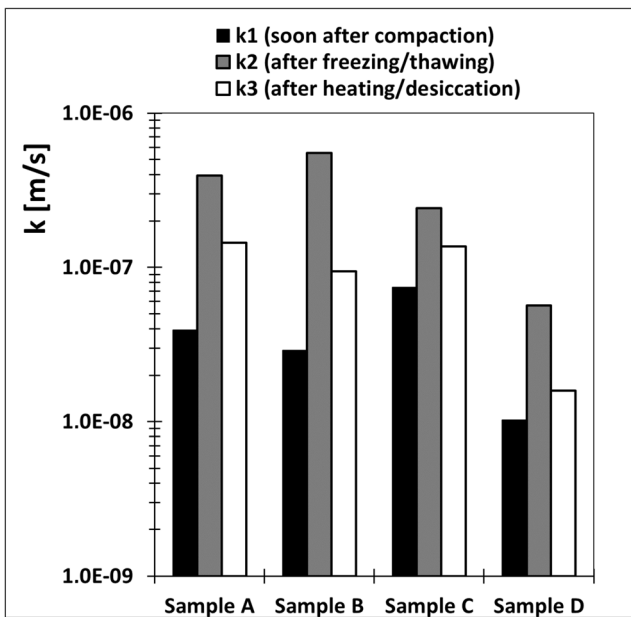


Fig. 5 Mean hydraulic conductivities of the four soils obtained soon after the compaction (k_1), the cyclic freezing–thawing (k_2), and the heating procedure (k_3).

between the hydraulic conductivity of frozen-thawed specimens and the reference, while K_H is the ratio between the values displayed by the heated specimens and the reference. The observed values confirm that no significant side-wall leakage is occurring; in this case, higher hydraulic conductivity values would be observed. The values of K_{FT} and K_H are reported in Table 3; Fig. 6 depicts their variations in accordance with the soil PI or with the w_{opt} determined in the Standard Proctor tests. It is important to note that these values of K could be underestimated with respect to the hydraulic conductivity in a CC barrier in field, given that previous studies have demonstrated that the hydraulic conductivity measured in field on exhumed clay liners from landfill final covers is typically one or more orders of magnitude higher than the small-scale laboratory hydraulic conductivity obtained from 75-mm specimens (Benson et al. 1994; Benson et al. 2011). Hence, the experimental results here presented should be considered primarily in comparative terms.

Table 3 Mean hydraulic conductivities and standard deviations in various test conditions and corresponding mean hydraulic conductivity ratios K_{FT} and K_H

| Soil | Compacted | | After freeze–thaw | | $K_{FT} = k_2/k_1$ | After heating/desiccation | | $K_H = k_3/k_1$ |
|----------|-----------------------|-----------------------|-----------------------|-----------------------|--------------------|---------------------------|-----------------------|-----------------|
| | k_1 (m/s) | St dev. | k_2 (m/s) | St dev. | | k_3 (m/s) | St dev. | |
| Sample A | 3.95×10^{-8} | 2.35×10^{-9} | 3.92×10^{-7} | 2.69×10^{-8} | 10 | 1.44×10^{-7} | 4.03×10^{-9} | 4 |
| Sample B | 2.90×10^{-8} | 4.40×10^{-9} | 5.50×10^{-7} | 3.64×10^{-8} | 19 | 9.45×10^{-8} | 9.52×10^{-9} | 3 |
| Sample C | 7.42×10^{-8} | 1.89×10^{-9} | 2.42×10^{-7} | 2.00×10^{-8} | 3 | 1.37×10^{-7} | 5.66×10^{-9} | 2 |
| Sample D | 1.03×10^{-8} | 1.56×10^{-9} | 5.64×10^{-8} | 3.60×10^{-9} | 5 | 1.59×10^{-8} | 3.92×10^{-9} | 2 |

The volumetric deformations of the specimens due to the heating treatment were calculated from direct measurements of their heights in the oedometer device and of their diameter by using a digital caliper (see Table 4). The lowest volumetric shrinkage (8.1%) was observed for the soil with the lowest PI and the highest shrinkage (19.8%) for the highest plasticity soil, as observed also by Aldaeef and Rayhani (2014) and Liu et al. (2015). In addition, the values comply with the trends reported in the graphs proposed by Albrecht and Benson (2001): the higher clay content and PI of the soil, the higher the volumetric shrinkage. Despite having a slightly lower PI, sample C registered less volumetric shrinkage than did sample D, due to the presence in sample C of higher expandable fraction and higher organic content. For the same reason, this sample registered a higher swelling capacity due to hydration.

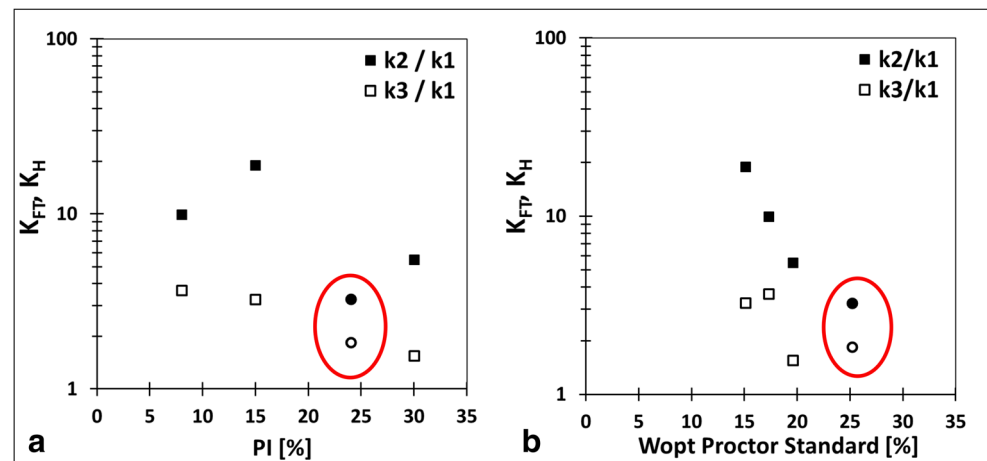
Discussion

The comparison between the results obtained from soils with different plasticity (see Fig. 6) points out the vulnerability of the sediments to thermal variations inducing phase changes (like FT cycles) or change in effective stress due to changes in pore water pressure as the drying induced by heating (up to 60 °C), in terms of hydraulic conductivity. Further analysis of the induced structural modifications exceeds the scope of this paper.

For all the samples, the experimental results show that the hydraulic conductivity is higher for the specimens that have been exposed to thermal stresses than for the reference; the freezing–thawing cycles appear to be more detrimental than the heating/drying process.

The hydraulic conductivity measured after FT increases by at least three times and up to more than one order of magnitude (see Table 3, Fig. 5). The maximum increase of hydraulic conductivity due to FT cycles is observed in the medium plasticity soil (PI = 15%) for which K_{FT} reaches the value of 19, complying with the respective value reported in (Sterpi 2015) for a silty clay with the same plasticity. On the other hand, the minimum values of K_{FT} are displayed by soils with $PI \geq 24\%$ ($K_{FT} = 3–5$), complying with the observations of Othman et al.

Fig. 6 Relationships between K_{FP} or K_H and **a** the sediment plasticity index or **b** optimum water content w_{opt} in the Standard Proctor test. The points in the round circle represent the values obtained for sample C



(1994) who noted that the effects on hydraulic conductivity of high plasticity soils are limited.

After the heating process (and the following hydration during the first part of the hydraulic conductivity test), all the recorded changes in hydraulic conductivity are quite restricted but not negligible. The highest increase measured after the heating procedure is shown by the soil with the lowest plasticity (PI = 8%), for which $K_H = 4$ (see Table 3) and diminishes at increasing plasticity, since the soils with higher PI display a $K_H = 2$. The observed values and the fact that the soils with highest plasticity suffer the lowest damage complies with the findings of Aldaeef and Rayhani (2014), who applied similar temperature and drying rate. Conversely, our data lie in the lowest limit of the results reported by Albrecht and Benson (2001), who observed a very wide range of hydraulic conductivity increases (from 8 to 500 times) and registered only a partial recovery of the hydraulic conductivity as clay rehydrates. This difference could be explained by different experimental conditions, as well as different salinity and cation exchange conditions related to the permeating water (Lin and Benson 2000).

The fact that the hydraulic conductivity of the soils with higher plasticity (PI = 24% and 30%) display the lowest alterations both after FT cycles and after heating/desiccation can be ascribed to their partial recovery potential, provided by both the water-absorbing attitude of the expandable clay fraction of phyllosilicates and by the organic content. A

greater amount of expandable clay fraction leads to higher swelling potential that can help the soil to partially regain its initial volume by filling the enlarged macropores and gaps caused both by the formation of ice lenses during FT and by fissures due to heating/desiccation; both the enlarged macropores and fissures constitute preferential pathways for permeating water. Hence, the water absorption and the swelling capacity accomplished by the expandable clay minerals and the organic fraction bestow the ability to significantly recover cracks and fractures caused by both heating and FR and, therefore, provide a partial recovery of the hydraulic conductivity.

The healing capacity was previously observed by Aldaeef and Rayhani (2014) after drying (up to 55 °C), although it was not observed by Albrecht and Benson (2001) who applied different experimental conditions. In the present study, a partial recovery potential is observed also in case of freezing–thawing. The clay domains and their consequent destruction, resulting from the interaction of diffuse double layers in micropores, have been recognized as the primary cause of decrease in hydraulic conductivity after rehydration. The response of the CC during rehydration is determined by the relative influence of several factors such as water content, suction, aggregate dimensions, pore size distribution, and stresses acting on the clay aggregates (Sivakumar et al. 2006). Hence, the swelling potential of a CC after drying and the capability to partially recover the prior hydraulic

Table 4 Volume variations during the heating testing procedure; in the columns are reported (I) the shrinkage after the heating procedure (negative volume variation); (II) the swelling during the subsequent hydration and hydraulic conductivity measurements and (III) the final water content

| Soil | Volumetric shrinkage due to heating (%) | Swelling due to hydration (%) | Final water content (%) |
|----------|---|-------------------------------|-------------------------|
| Sample A | − 8.6 | 0.8 | 16.7 |
| Sample B | − 13.3 | 0.3 | 14.7 |
| Sample C | − 9.1 | 6.6 | 21.2 |
| Sample D | − 19.8 | 4.6 | 13.9 |

conductivity depends on the mineralogical composition of the clay fraction, on the plasticity, on the permeating fluid's composition, and on the ion exchange capabilities (Foster 1954; Quirk 2001). This may explain why the results reported in literature are not completely in agreement.

The importance of the mineralogical composition in establishing the partial recovery potential and, therefore, the capability to partially withstand the alteration in hydraulic conductivity caused by FT cycles and exposition to heating/drying, is evidenced by the results obtained for sample C compared to the ones obtained for sample D. Despite soil D having higher PI since it is constituted by a higher amount of phyllosilicates (reported in Table 2), the analysis of the volume variations (see Table 4) suggests that soil C has higher water absorption capacity, which stems from the presence of more active clay minerals and higher organic content, as detected by the mineralogical composition analysis. The water absorption capacity is also evidenced by the fact that soil C displays lower loss of water than D (see the final water content and the volume shrinkage) due to the heating procedure, regardless the highest water content that was used in the specimen preparation (w_{opt}). In addition, the comparison between the Proctor curves obtained for the tested soils highlights that sample C exhibits the highest w_{opt} (see Fig. 3).

Figure 6 describes the relationship between K_{FT} and K_H and the w_{opt} determined in the Standard Proctor test; the higher the optimum is, the lower the hydraulic conductivity alteration due to both heating and to FT (see Fig. 6). Therefore, rather than the PI, the w_{opt} detected by the Proctor curve appears to be the most representative indicator of the partial recovery potential of CC exposed to temperature alterations. This value can be easily used as indicator, given that the Standard Proctor curve must already be carried out in the characterization of cohesive soils to be applied in a landfill's CC barrier.

Obviously, the degradations of the hydraulic performances are restricted in the parts of the CC liners actually exposed to sufficient thermal solicitations, mainly depending on the local climate conditions, on the features of the disposed wastes (age, types, moisture content), and, finally, on the thermal behavior (Dalla Santa et al. 2020) of the materials applied in the multilayered top cover and on its thickness (as already observed also by Benson et al. (1995) and by Benson and Othman (1993)). Future works will aim at the assessment of the affected thickness by means of finite element modeling.

Nevertheless, even if the occurrence is restricted to a part of the CC layer, the effectiveness of the whole barrier could be deteriorated because the thickness of the impervious part of the barrier could be reduced. Consequently, depending on the temperature variations suffered in the temporary condition of the top CC barrier, its effectiveness of isolating the disposed wastes could be irreversibly damaged for all the expected lifespan of the landfill.

Conclusions

In the multilayered structures used to constrain landfills, the effectiveness of isolating the waste material is entrusted to impervious layers often made up of properly compacted clayey soils.

The experimental tests performed highlight the following:

1. Even if the soil used in the CC layer satisfies the regulations' requirements in terms of hydraulic conductivity just after the laying, its impervious capacity and therefore the effectiveness of the isolating landfill barrier can be irreversibly deteriorated by temperature solicitations, in case the top cover barrier is maintained for a certain time in the temporary configuration, without the upper protective natural soil layers.
2. In the tested conditions, the hydraulic conductivity appears to be more deteriorated by cyclic freezing–thawing than by the heating/drying processes. In the first case, the hydraulic conductivity shows an increase even equal to one order of magnitude ($K_{FT} = 19$ in case of $PI = 15\%$), while the maximum value assumed by K_H is equal to 4. It is already known from literature that, in cyclic FT, the hydraulic conductivity increase is largest the first time the soil experiences FT and the effects diminish cycle after cycle. This means that just a few, or even only one, FT cycles can affect the hydraulic conductivity of a CC barrier considerably.
3. The soils with the lowest plasticity (sample A with $PI = 8\%$ and sample B with $PI = 15\%$) and lowest w_{opt} suffer the highest degradation in terms of hydraulic conductivity due to cyclic freezing and thawing as well as due to heating/drying. Conversely, the materials with higher plasticity (samples C and D with $PI \geq 24\%$) appear to be able to partially withstand the effects of thermal alterations caused by either freezing–thawing (K_{FT}) or by heating (K_H), since relatively smaller changes are observed in their hydraulic conductivity ($3 < K_{FT} < 5$ and $K_H = 2$).
4. Among the materials with $PI \geq 24\%$, the one that exhibits the highest w_{opt} (sample C), which is provided by the greater expandable clay fraction (phyllosilicates with mixed layers) and by the greater organic content, is the one that suffers the lowest increase in hydraulic conductivity ($K_{FT} = 3$; $K_H = 2$), and therefore seems to exhibit greater partial recovery potential. This could be ascribed to its higher swelling capacity that allows a partial recovery of structure alterations caused by temperature variations.

The relationship between the K_{FT} and K_H and the w_{opt} suggests that the optimum water content identified in the Standard Proctor test is more reliable than the PI as indicator of the

partial recovery potential of a soil and of its capacity to withstand the effects of temperature variations on the CC barrier's hydraulic conductivity. Therefore, in addition to the PI and the granulometry, it could be useful to take into account also the w_{opt} when choosing the soil to be used in the CC barrier of a landfill, without prejudice to the fact that it is more advisable the laying of the top soil protection layers soon after the CC barrier deposition.

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