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Sustainable impermeable landfill barriers: The potential of using geological waste and surplus masses

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ABSTRACT

This study investigated the potential to reuse excavated cement stabilised clay (CSC) and press filter residual (PFR) as impermeable landfill barriers. First, laboratory experiments including particle size distribution, consistency limits, standard Proctor and permeability tests were carried out on reconstituted samples. Subsequently, a full-scale compaction trial was performed for both materials. Nuclear density tests and results from cylinder samples were compared to evaluate the compaction behaviour. The cylinder samples were utilised to quantify the properties of the compacted soil layers. Multi-sensor core logging (MSCL) and X-ray image techniques were adopted to visualise the homogeneity of the field samples. Results showed that both the CSC and PFR are well-graded and fine-grained soils which can be classified as high plastic silts or high plastic clays. For both materials, hydraulic conductivity values, k, less than 1×10^{-9} m/s were obtained when compacted in the laboratory to their maximum dry densities according to standard Proctor. The field compacted samples were, however, more permeable (e.g., $k = 6.1 \times 10^{-8}$ m/s (SD = 9.1×10^{-8}, $n = 3$) for CSC and $k = 1.5 \times 10^{-9}$ m/s (SD = 4.3×10^{-10}, $n = 3$) for PFR at a vertical stress, σ_v, of 40 kPa). Both materials reached the hydraulic conductivity requirements for barriers for inert waste landfills. For the PFR, an average $k < 1 \times 10^{-9}$ m/s was obtained at $\sigma_v = 160$ kPa which suggests that PFR might be reused as a bottom liner for ordinary and hazardous waste. The CSC results showed a considerable variability which can be explained by its innate heterogeneity.

Keywords: landfill liners, reuse, press filter residual, cement stabilised clay, field compaction

1 INTRODUCTION

A key aspect of safe and sustainable landfilling is to ensure resilient barriers (bottom, top and lateral barriers) to prevent long-term unwanted gas and leachate emissions. Traditional landfill closure often involves various layers of primary raw materials to form a reliable barrier between the waste and its surrounding. Typical materials used as impermeable layer in landfill capping are compacted clay, geomembranes or composite barriers (Cossu and Garbo, 2019). Consequently, landfill closures add to the consumption of construction aggregates including clay, sand, gravel and crushed rock and thus contribute to negative environmental, economic and social impact. At the same time, construction projects frequently result in surplus of excavated soils (e.g. clay soils, moraine soils), which are generally landfilled. There is therefore an urgent need to better explore these masses for applications in landfill barriers.

This study set out to explore the performance of two recycled soils, excavated cement stabilised clay (CSC) and a press filter residual (PFR), as impermeable barrier using both laboratory and field investigations. The remaining part of this contribution continues by describing the CSC and PFR and the used laboratory and field methods. It will then go on by presenting and discussing the obtained results with a focus on the obtained hydraulic conductivity values. Finally, vital conclusions obtained from this work are listed and practical implications are pointed out.

2 MATERIALS

2.1 Sample description

Two recycled soils were explored: a so-called excavated cement stabilised clay (CSC) from the excavation pit of a building construction project in Oslo, Norway, and a press filter residual (PFR) from and soil washing plant located in Nes, Norway. Figure 1 shows these materials. The CSC consists of a mixture of a soft clay, which is typical to Norway (e.g., Bjerrum, 1954), and clay stabilised using the dry deep mixing method (e.g., Larsson, 2021). This method adopts dry binders such as lime and cement to improve the mechanical properties of natural clay. 80 kg/m^3 of Multicem (Norcem, 2022) was used for the utilised CSC.

***Figure 1.** Excavated cement stabilised soil at immediate storage area before being used as sealing layer (left). Press filter residual (PFR) in the filter press (right).*

The PFR stems from a soil washing plant, which generally recycles aggregates from contaminated earth materials using a range of mineral processing techniques (e.g., sizing, classification, dewatering). The products from the soil washing plant are, for example, used as bound materials (e.g., concrete aggregates, asphalt) or unbound materials. A filter press is used in the final step of the mineral processing to separate liquids from fine aggregates (predominantly silt, clay fractions). The remaining material of this process, with currently limited reuse options, is the so-called press filter residue, PFR.

The CSC material contains low heavy metal concentrations, depending on the site-specific conditions and background values. However, the material possesses an elevated pH (~10) due to the addition of cement (Kristensen, 2017). The PFR may contain elevated pollutant concentrations because of the treatment method, where the contaminants in soil are removed from coarser particles to both the water phase and adsorbed to fines. The environmental characterization, investigations and assessments of these two materials are investigated separately and results will be reported later in a separate manuscript.

2.2 Geotechnical laboratory testing

Table 1 lists the main geotechnical laboratory tests carried out on samples of the CSC and PFR which were derived before a compaction trial was carried out. The CSC samples were taken from the intermediate storage area, which is shown in Figure 1 (left). By contrast, the PFR samples were obtained directly from the filter press (Figure 1 (right)). The objective of the lab testing programme summarised in Table 1 was to obtain relevant geotechnical properties to conduct an initial evaluation if the sampled materials can be used to construct an impermeable sealing layer. In addition, the compaction properties of the CSC and PFR were quantified to inform the full-scale compaction experiment.

Table 1. *Laboratory tests performed on samples taken before the full-scale compaction experiment.*

Parameter	Laboratory test	Standard
Particle size distribution	Falling drop	NS-EN 17892-4:2016
Water content	Loss on drying	NS-EN ISO 17892-1:2014
Consistency limits	Atterberg limits	NS-EN ISO 17892-12:2018
Compaction	Standard Proctor test	NS-EN 13286-2:2010
Hydraulic conductivity	Permeability test in oedometer cell	NS-EN ISO 17892-11:2019

2.3 Full-scale compaction experiment

A field experiment was carried out in June 2021 to investigate the performance of the CSC and PFR when compacted at full-scale field conditions. Two impermeable geological barriers with a footprint of approximately 40 m^2 and a thickness of approximately 0.60 m were designed. The compaction was carried out in three layers with a designed layer thickness of 0.20 m. For each layer, the sealing layer material was loosely laid out with an excavator until an approximately 0.35 m thick layer was achieved. Each layer was then compacted with a CAT D6 XE (Caterpillar, 2023) bulldozer using 6-8 passes (Figure 2 (left)).

In-situ tests were carried out for each layer. A Troxler nuclear moisture density gauge (Troxler, 2009) was employed to obtain the in-situ water content and density. Additionally, 50 and 72 mm diameter samples were taken (Figure 2 (right)) to conduct further tests. The 50 mm diameter samples were utilised to obtain the water content and density and used to compare with the Troxler nuclear moisture density gauge. Particle size distribution, water content, plasticity, and hydraulic conductivity tests were carried on the 72 mm samples and the laboratory tests as listed in Table 1 were adopted. In addition, the 72 mm samples were studied using a Multi-Sensor Core Logging (MSCL) and X-ray computed tomography imaging (Geotek, 2023).

Figure 2. *Field compaction (left). Field sampling using 72 mm diameter tubes (right).*

3 RESULTS AND DISCUSSION

The following sections present the obtained results for both the CSC and PFR. Throughout this paper, the results of the tests on the samples taken before the full-scale field trial are called "prior", while the remaining specimens were directly derived from the full-scale compaction experiment.

3.1 Particle size distributions

Figure 3 shows the particle size distributions of the two materials. According to the Unified Soil Classification System (USCS), the tested samples are fine-grained soils. From the graph, the CSC is coarser than the PFR. In particular, the CSC sample taken before the compaction test (i.e., CSC prior) was notably coarser (i.e., ~5% clay) and can be classified as a silt. The remaining specimen were finer and are silty clays. The PFR specimen consisted of ~18% clay. By contrast, similar sand content (between 5-10%) were obtained for both materials. Both the CSC and PFR are well-graded soils.

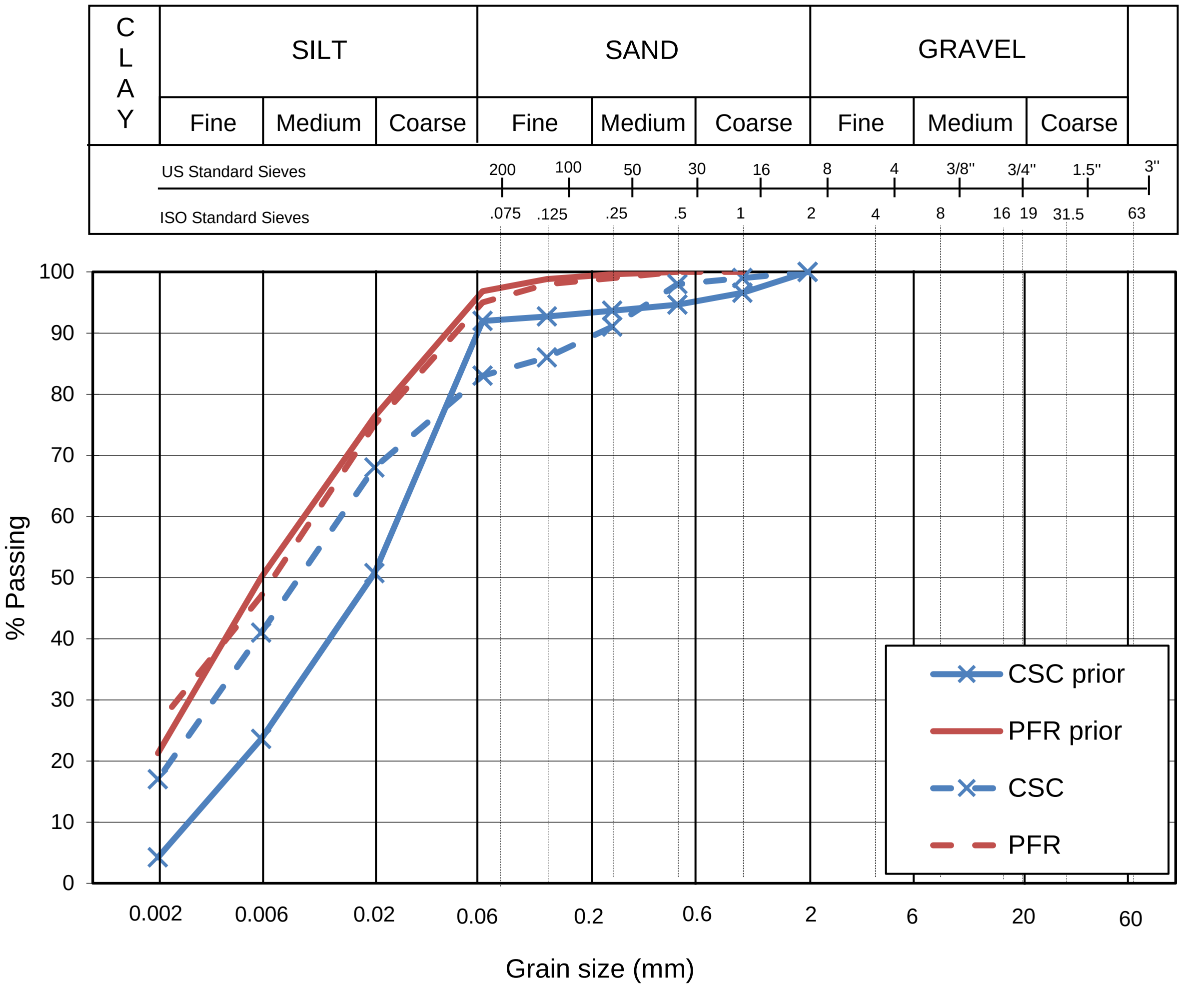

Figure 3. *Particle size distribution of excavated cement stabilised clay (CSC) and press filter residual (PFR) samples obtained before the compaction trial ("prior") and after field compaction.*

The data in Figure 3 further suggests that the grain size distributions of the CSC were more heterogenous in comparison to the PFR samples. More precisely, the clay content of the CSC increased from ~5% to ~20% after compaction. The compaction likely loosened some of the CSC particles, which were initially agglomerated due to the added cement. The grain size distributions of the PFR were not influenced by the compaction.

3.2 Atterberg consistency limits

The Atterberg consistency limits in terms of liquid limit (LL), plastic limit (PL) and plasticity index (PI) are summarised in Table 2 and visualised in Figure 4. Again, results for samples taken prior to the compaction test and for samples derived after the field compaction are presented. From the data, it is evident that both materials are cohesive materials (i.e., LL > 20%). LL values above 50% were measured for all studied materials which indicates that these materials have a high plasticity. PI values greater than 20% were obtained for all samples which is within the recommended range (i.e., PIs between 15 to 30% (Regadío et al. 2020)) to ensure landfill stability. Especially, the mean PI of 25% for the PFR agrees with the suggested good PI of 25% for clays as landfill liner material (Regadío et al. 2020). Overall, the measured consistency limits indicate good workability and that both materials are not prone to dispersion.

Figure 4 shows that the CSC and PFR data points almost align with the empirical boundary between clays and silts ("A" Line). The two materials can, thus, be classified as high plastic silts (MH) or high plastic clays (CH). This implies that the CSC and PFR are not susceptible to dispersion and erosion which typically occurs for clays of low plasticity and to a lower degree also for low plastic silts and sands (Regadío et al., 2022). The PFR sample taken before compaction ("prior") is in good agreement with the field samples. On the contrary, a notable difference between CSC prior and CSC sample was observed which indicates that the CSC is more heterogeneous. In addition, the field compaction likely impacted the properties of the CSC as was already mentioned in the previous section

Table 2. *Atterberg consistency limits of excavated cement stabilised clay (CSC) and press filter residual (PFR) samples obtained before the compaction trial ("prior") and after field compaction.*

Material	***n* ()**	**LL (%)**	**PL (%)**	**PI (%)**
CSC prior	1	65	34	31
PFR prior	1	56	30	26
CSC	4	52 (2.2)	29 (1.3)	23 (1.0)
PFR	3	58 (1.2)	32 (1.5)	25 (2.5)

n = number of samples, LL = liquid limit, PL = plastic limit and PI = plasticity index. The CSC and PFR values after compaction (i.e., field samples) are presented using average values and the values in brackets show the respective standard deviation.

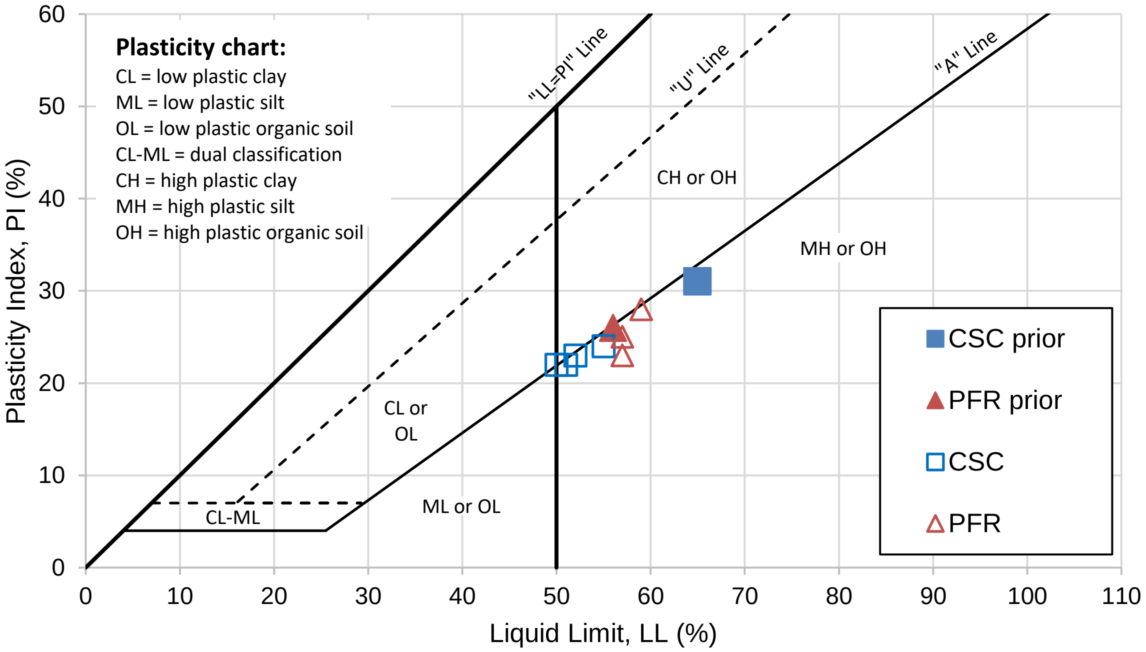

Figure 4. *Plasticity chart for soil classification of excavated cement stabilised clay (CSC) and press filter residual (PFR) samples obtained before the compaction trial ("prior") and after field compaction.*

3.3 Compaction behaviour

The compaction results from the standard Proctor tests, which were carried out on the samples from before the compaction trial, the in-situ tests and the field samples are presented in Figure 5**Error! Reference source not found.**. According to the standard proctor tests, the optimum water contents of the CSC and PFR were 24% and 29%, respectively. The associated maximum dry densities were 1582 kg/m^3 and 1501 kg/m^3.

Figure 5 compares the standard proctor test results to the in-situ results. Overall, both the results from the Troxler nuclear density tests and the more traditional estimates of the water content and dry density using tube samples indicate that the full-scale tests resulted in good compaction. Table 3 compares the dry density (ρ_d) values obtained using the different test procedures. As can be seen from the table, the field compaction resulted in average dry densities smaller than the maximum dry densities obtained from the standard Proctor compaction tests, which were conducted in the laboratory. Interestingly, the measurements from the Troxler nuclear moisture density gauge were considerably lower for the CSC compared to the two other procedures. A possible explanation for this observation might be that the chemically bound hydrogen due to the added cement affects the readings of the Troxler nuclear moisture density gauge (Troxler, 2009). For the PFR, this difference between the adopted test procedures was not observed.

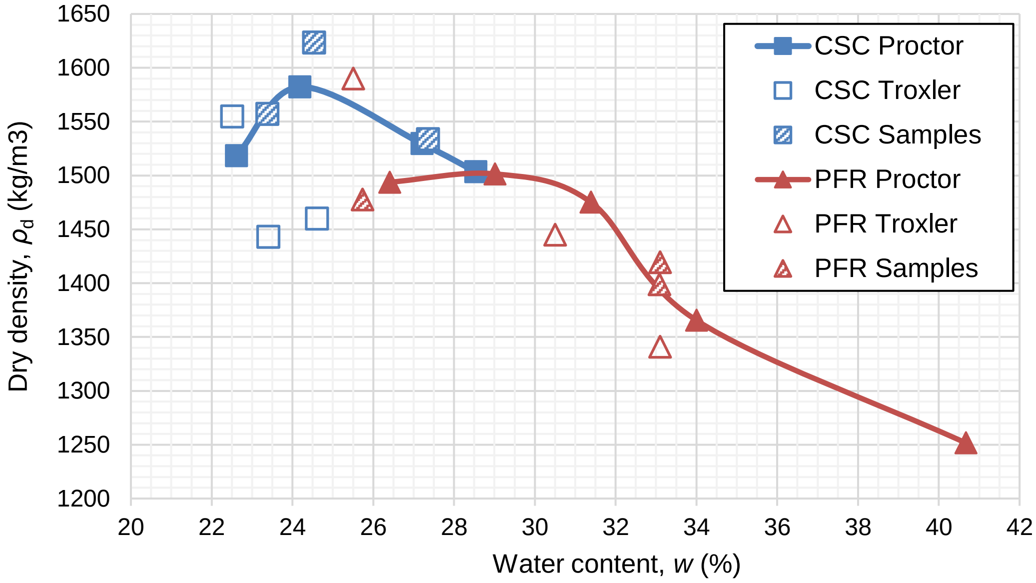

Figure 5. *Compaction curves of excavated cement stabilised soil (CSC) and the press filter residual (PFR) obtained from standard Proctor test. The dry densities and respective water content measured in-situ using the Troxler nuclear* moisture *density gauge and tube samples are shown for comparison.*

Table 3. *Dry densities (ρ_d) and relative compaction (R) of the excavated cement stabilised clay (CSC) and the press filter residual (PFR).*

Material	$\rho_{d,opt}$ (kg/m^3)	$\rho_{d,Tr}$ (kg/m^3)	$\rho_{d,Sa}$ (kg/m^3)	R_{Tr} (%)	R_{Sa} (%)	R_{av} (%)
CSC	1582.1	1486.0 (60.4)	1571.5 (46.7)	93.9	99.3	96.6
PFR	1501.5	1458.7 (125.1)	1432.0 (40.9)	92.2	90.1	91.4

$\rho_{d,opt}$ = maximum dry density from the standard Proctor test, $\rho_{d,Tr}$ = dry density from Troxler nuclear moisture density gauge measurements, $\rho_{d,Sa}$ = dry density derived from 50 mm tube samples, R_{Tr} = relative compaction based on Troxler nuclear moisture density gauge measurements, R_{Sa} = relative compaction using results from 50 mm tube samples and R_{av} = average compaction considering both field procedures. The field ρ_d values are presented using average values based on three measurements and the values in brackets show the respective standard deviation.

The relative compaction, R, which is defined as the ratio between the field measurement to the maximum dry density, $\rho_{d,opt}$, was employed to further quantify the field compaction results. From the data in Table 3, it is apparent that R values greater than 90% were obtained for both the CSC and the PFR. The compaction of the CSC resulted in R_{av} of approximately 97%. A lower R_{av} of approximately 91% was obtained for the PFR. Overall, the obtained data suggest that both materials can be reliably compacted in the field.

3.4 Hydraulic conductivity

The 72 mm tube samples obtained in the field (Figure 2 right) were utilised in a falling head oedometer test to derive the saturated hydraulic conductivity values. Three different consolidation pressures (i.e., 40, 160 and 640 kPa) were explored to account for different applications within a landfill (e.g., bottom liner, top cover). In addition to field samples, reconstituted samples (i.e., lab samples) were prepared at the maximum densities obtained in the standard Proctor tests (Table 3). Figure 6 and Table 4 show the obtained results.

From Figure 6 it is evident that the samples prepared in the laboratory performed better (i.e., lower hydraulic conductivities) than samples derived in the field. This observation can be explained by the lower compaction achieved in the field compared to the laboratory. For both laboratory samples, hydraulic conductivity values below 1.0×10^{-9} m/s were measured at all three vertical stress levels. The hydraulic conductivity values of the PFR samples were generally in better agreement with the laboratory samples compared to the CSC. A large scatter in the data was observed for the CSC. For this reason, two additional field samples were tested.

Table 4. *Mean and standard deviation (SD) of the hydraulic conductivity, k, values obtained from the field samples at different vertical stress levels, σv. Two samples of the press filter residual (PFR) and four samples of the excavated cement stabilised clay (CSC) were tested.*

σ_v (kPa)	$k_{PFR,mean}$ (m/s)	$k_{PFR,SD}$ (m/s)	$k_{CSC,mean}$ (m/s)	$k_{CSC,SD}$ (m/s)
40	$1.5x10^{-9}$	$4.3x10^{-10}$	$6.1x10^{-8}$	$9.1x10^{-8}$
160	$6.8x10^{-10}$	$8.1x10^{-11}$	$4.7x10^{-8}$	$8.5x10^{-9}$
640	$3.9x10^{-10}$	$1.6x10^{-10}$	$1.5x10^{-9}$	$2.0x10^{-9}$

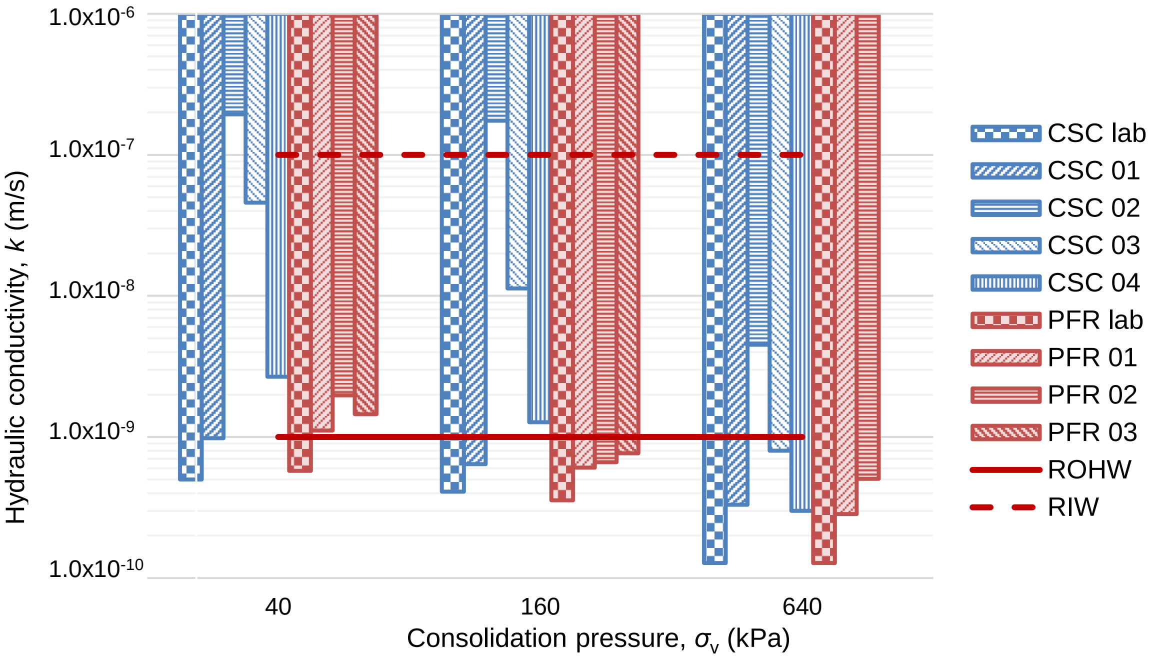

Figure 6. *Hydraulic conductivity, k, for the excavated cement stabilised clay (CSC) and the press filter residual (PFR) at three different vertical stress, σv, levels. The requirements for ordinary and hazardous waste (ROHW) and inert waste (RIW) according to the EU Landfill Directive (1999/31/EC) are shown.*

Table 4 lists the mean and standard deviation values of the field samples. From this table, it is apparent that the hydraulic conductivity values of the PFR are approximately an order of magnitude lower than the CSC ones. In other words, the PFR is less permeable than the CSC. This finding can be related to the coarser grain sizes of the CSC, which is also apparent from Figure 3. The difference between the PFR and CSC field samples was, however, not statistically significant at $P < 0.05$.

The hydraulic conductivity values of both the PFR and the CSC samples decreased with the vertical stress level. This mechanism was expected due to the closer packing of the grains caused by the increase of the vertical stress. At a vertical stress of 40 kPa, which represents a top cover application, the hydraulic conductivity value of the PFR was close to the widely accepted threshold of $1.0x10^{-9}$ m/s. Hydraulic conductivity values below this threshold were achieved for the PFR at 160 kPa while this threshold was not achieved for the CSC. These findings imply that the PFR is likely an effective sealing material for both top cover and bottom liners while the CSC may be adopted as a top cover.

What is striking in the data is the considerable variability in the CSC hydraulic conductivity data compared to the PFR. Notably greater standard deviations were obtained for the CSC field samples, as can be seen from Table 4. X-ray computed tomography (XCT) and results from a Multi-Sensor Core Logger (MSCL) reveal that the sealing layer consisting of CSC was less homogeneous compared to the PFR (Figure 7). For the CSC, a considerably greater variation in the gamma density and fractional porosity was obtained (Figure 7a). This heterogeneity is likely a result of the composition of the CSC which consists of agglomerates of cement stabilised clay and clay. By contrast, the compacted PFR resulted in a homogeneous sealing layer with almost consistent density and porosity (Figure 7b).

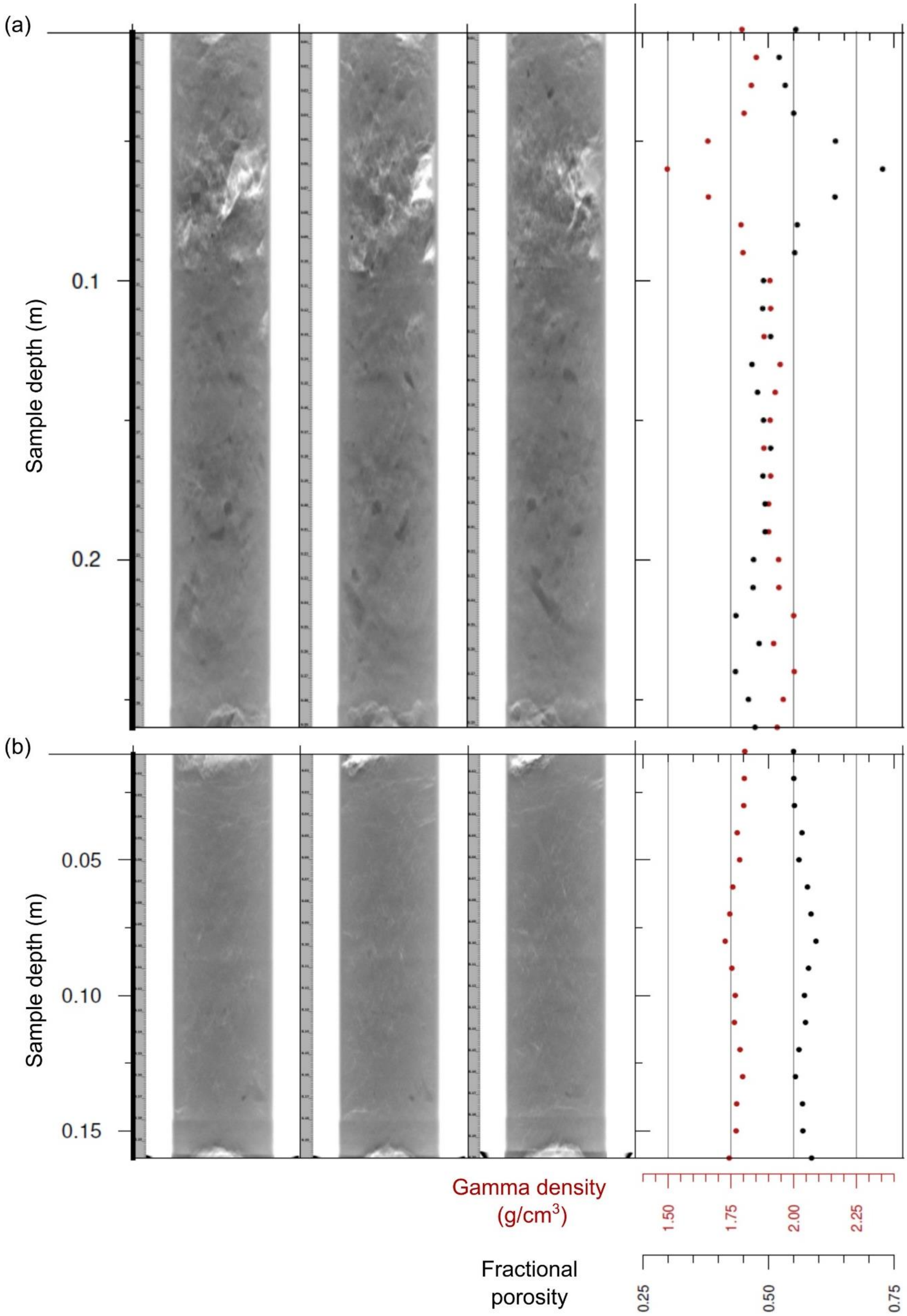

__Figure 7.__ X-ray computed tomography (XCT) images and Multi-Sensor Core Logger results (i.e., gamma density and fractional porosity for (a) CSC 01 and (b) PFR 01. The white regions indicate pore space while the dark regions represent soil particles.

4 CONCLUSIONS

The performance of two reused materials (i.e., cement stabilised clay (CSC) and press filter residual (PFR)) as impermeable landfill barriers was studied using laboratory tests and a full-scale compaction trial. From this study, the following conclusions can be made:

1. The tested CSC and PFR samples were well graded and fine-grained soils. The fine content of the CSC increased after compaction. A possible explanation for this might be that the compaction loosened some of the larger CSC particles, which were agglomerated by the cement addition.
2. Both reused materials can be classified as high plastic silts (MH) or high plastic clays (CH). The obtained consistency limits indicate that these materials are easy to compact, have a low erodibility and ensure landfill liner stability.
3. The field tests revealed that both materials could be compacted to densities greater than 90% of the maximum densities achieved in standard Proctor tests. The CSC field compaction resulted in a 97% relative compaction, while for the PFR a relative compaction of 91% was achieved.
4. Hydraulic conductivity values smaller than $1x10^{-9}$ m/s were obtained for laboratory CSC and PFR samples. The samples derived in the field showed a greater permeability which decreased with the applied vertical stress. At vertical stresses greater than 160 kPa (e.g., an application as a bottom seal), the hydraulic conductivity values of the PFR field samples were lower than $1x10^{-9}$ m/s. This finding implies that the PFR has the potential be reused as a bottom sealing for ordinary and hazardous waste landfills. For both materials, the hydraulic conductivity requirement for geological barriers for inert waste landfills was met at the investigated vertical stress level.
5. The CSC material is more heterogeneous than the PFR which can be explained by the composition of the CSC (i.e., a mixture of agglomerates of cement stabilised clay and clay). Consequently, the CSC results showed a larger variability. In particular, the hydraulic conductivity values of the CSC field samples varied considerably which was also shown by Pedroni et al. (2018) for lime cement stabilised clays. This finding suggests that the construction of a sealing layer with CSC should adopt a specific pre-mixing procedure to better homogenise the CSC. Mixing equipment, such as, bucket- or shovel mixers (Kronsell et al. 2020) should be explored in the future.

This contribution suggests that both CSC and PFR have the potential to be reused as geological landfill barriers for inert waste landfills. Furthermore, the PFR can likely provide an effective material to be utilised as a sealing layer for ordinary and hazardous waste landfills. It is, however, important to bear in mind that the hydraulic conductivity data were obtained for saturated conditions. Further work is required to establish the performance of both the CSC and PFR at partially saturated conditions, which are typically observed in the field and result in lower hydraulic conductivity values. In addition, future studies should focus on characterising the environmental impact of these materials.

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