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The permeability characteristics of compacted recycled materials for landfill barriers in Norway

Les caractéristiques de perméabilité des matériaux recyclés compactés pour les barrières d'étanchéité des décharges de déchets en Norvège

T. Kim*
NGI, Oslo, Norway

E.W. Ånes, G.W. Åsli, Y. Suzuki
NGI, Oslo, Norway

S. Ritter
Oslo Metropolitan University, Norway

**taeheon.kim@ngi.no*

ABSTRACT: Recycling waste materials for barrier system of landfills has more recently been increasingly considered in geotechnical engineering to improve sustainability. Among various geomechanical parameters, hydraulic conductivity is one of the essential factors to be evaluated when designing landfill liners. With such motive, three types of materials were studied in our ongoing research: press filter residue (PFR), cement stabilized clay (CSC) and dry crust clay (DCC). The three recycled materials were compacted in a field pilot project to investigate their applicability as landfill liners. Compacted samples from the pilot project were then cored in tube samplers and transported to the laboratory for hydraulic conductivity measurements. Permeability was measured using oedometer, flexible wall permeameter and triaxial permeability cells. Permeability measurements were made on horizontal and vertical directions to investigate potential permeability anisotropy characteristics at a wide range of consolidation stress levels (15 kPa to 650 kPa). The hydraulic conductivity measured on the samples was in the range of 2×10^{-7} m/s to 10^{-10} m/s. For most of the samples, permeability decreased to below 10^{-9} m/s with increasing stresses, where Norwegian regulations and practice recognises that it is suitable for, liners of landfills containing non-hazardous and hazardous waste. Moreover, the hydraulic conductivity of the materials was anisotropic, and the anisotropy changed with increasing consolidation stresses.

RÉSUMÉ: Le recyclage des déchets pour les systèmes de barrières d'étanchéité des décharges a plus récemment été de plus en plus pris en compte dans l'ingénierie géotechnique pour améliorer la durabilité. Parmi les différents paramètres géomécaniques, le coefficient de perméabilité est l'un des facteurs essentiels à évaluer lors de la conception des barrières d'étanchéité des décharges. C'est pour cette raison que trois types de matériaux ont été étudiés dans nos recherches en cours: les résidus de filtres presses (PFR), les argiles stabilisées au ciment (CSC) et les argiles à croûte sèche (DCC). Les trois matériaux recyclés ont été compactés dans le cadre d'un projet pilote sur le terrain pour étudier leur applicabilité en tant que barrières d'étanchéité des décharges. Les échantillons compactés du projet pilote ont ensuite été carottés dans des tubes d'échantillonnage et transportés au laboratoire pour des mesures de conductivité hydraulique. La perméabilité a été mesurée à l'aide d'un œdomètre, d'un perméamètre à paroi flexible et de cellules de perméabilité triaxiale. Des mesures de perméabilité ont été effectuées dans les directions horizontale et verticale pour étudier les caractéristiques potentielles d'anisotropie de perméabilité dans une large gamme de niveaux de contrainte de consolidation (15 kPa à 650 kPa). Le coefficient de perméabilité mesuré sur les échantillons était compris entre 2×10^{-7} m/s et 10^{-10} m/s. Pour la plupart des échantillons, la perméabilité a diminué jusqu'à moins de 10^{-9} m/s avec des contraintes croissantes, là où la réglementation et la pratique norvégiennes reconnaissent qu'elle convient aux barrières d'étanchéité des décharges contenant des déchets non-dangereux et dangereux. De plus, la conductivité hydraulique des matériaux était anisotrope, et l'anisotropie changeait avec l'augmentation des contraintes de consolidation.

Keywords: Permeability; recycled materials; landfill liners; vertical and horizontal permeability.

1 INTRODUCTION

A research project called earthresQue on reusing waste soils from various origins was laid out by the Norwegian centre for research-based innovation (SFI). The main purpose of earthresQue is to improve the sustainability of treating waste and surplus earth materials from the building and construction industry. One work package investigates recycled earth materials as alternative, more sustainable materials for landfill liners. As part of this, there has been constructed a final cover pilot test at a landfill site in southern Norway, using two such materials: PFR (Press Filter Residue) and CSC (Cement Stabilized Clay). These are compared to a DCC (Dry Crust Clay), a type of raw material that is a common surplus mass from construction projects in parts of Norway and has been used as barrier materials. This paper presents results from permeability tests conducted on undisturbed, compacted samples of these materials. Initial results from the pilot test itself is presented in the other paper of this conference (Ånes et al., 2024).

Norwegian regulations require barrier materials for bottom liners in hazardous and non-hazardous waste landfills to have hydraulic conductivity lower than 10^{-9} m/s(Ministry of Climate and Environment, 2004), which is classified as impermeable according to Casagrande and Fadum (1940). Typically, the environmental authorities also set the same permeability requirement to final cover for these landfills. The materials that match the criteria are usually rich in clay minerals (and clay-sized particles) and have homogenous internal structure.

The work presented in this paper aims to evaluate the suitability of the three materials as landfill liners and to characterize their hydraulic conductivity.

2 EXPERIMENTAL PROGRAMME

2.1 Materials

The press filter residual (PFR) is the clay and silt fractions of excavated, lightly contaminated soils that have been washed and sorted at a soil washing plant. The cement stabilized clay (CSC) is a marine clay that was stabilized with cement and cement-kiln dust before excavation at a construction site in Oslo. The dry crust clay (DCC), being the upper, weathered part of a clay deposit, was excavated from another construction site in Oslo. The soil properties of the tested materials are listed in Table 1. For further description of PFR and CSC, refer to (Ritter et al., 2023). Based on the index properties of the soils, hydraulic conductivity lower than 10^{-9} m/s is expected to be achievable (Benson et al., 1994).

The three materials were compacted in the field at the final cover pilot site. The samples were then cored using a 72 mm diameter Shelby tube sampler. Cored samples were sealed and sent to the laboratory at the Norwegian Geotechnical Institute (NGI) for permeability tests.

Table 1. Soil composition and index properties of three recycled materials.

Sample	**Soil fraction (%)**			**Atterberg limit (%)**			**Particle density (Mg/m^3)**
	Sand	**Silt**	**Clay**	**Plastic limit, w_p**	**Liquid limit, w_l**	**Plasticity index, I_p**	
PFR	4.2	67.3	28.5	28	53	25	2.74
CSC	1.2	63.7	35.1	23	41	18	2.76
DCC	2.5	49.3	48.2	23	43	22	2.80

2.2 Permeability measurements

Three different testing types were used for hydraulic conductivity measurements: oedometer cell, flexible wall permeameter and triaxial cell. Both vertical (normal to the bedding plane) and horizontal (parallel to the bedding plane) permeability measurements were investigated. The specimens for vertical permeability were trimmed as per normal triaxial specimens, while the specimens for horizontal permeability were sub-sampled horizontally of the vertical cores using a horizontal extruder and cradle built in-house.

Constant head method was adopted for all three types of tests (NS-ISO, 2019). Three measurements were made with different hydraulic gradients for each stage of the permeability test. The permeability was measured when the flow rate became linear assuming it reached a steady state. The three values were then averaged to obtain hydraulic conductivity at each stage.

2.2.1 Oedometer

One-dimensional incremental loading oedometer cells were used for the permeability measurements. A nominal initial specimen height of 20 mm and diameter of 67 mm was used. Vertical stress was increased step by step and permeability was measured at designated vertical stresses. Back pressure was not applied for the oedometer test.

For the permeability measurement, a VPC (Volume Pressure Controller) was connected at the bottom reservoir whilst the top reservoir was opened to the atmosphere. A small constant head difference was applied between the bottom and the top of the specimen.

To simulate a range of relevant overburdens (road embankment, final cover to bottom liner), the vertical stress range at which permeability was measured was between 20 kPa and 650 kPa.

2.2.2 Flexible wall permeameter

Flexible wall permeameter was used for measuring the horizontal permeability. Unlike the typical triaxial samples, a height to diameter (H/D) ratio of 1.0 (H = D = 50 mm) was used.

The stress conditions were always isotropic as a deviator load was not applied or measured. The mean effective stress range at which the permeability was measured was between 15 kPa and 650 kPa and the deformation was traced monitoring the pore volume and a Linear Variable Differential Transformer (LVDT) mounted externally on the piston. For the permeability test, two VPCs were connected to the top and bottom reservoirs allowing the control over the pore pressure. The permeability was measured by applying differential pressures at bottom and top reservoirs.

2.2.3 Triaxial cell

Permeability was measured as a part of triaxial testing. Initial triaxial specimens had a H/D ratio of about 2 (either H = 140 mm and D = 72 mm or H = 108 mm and, D = 54 mm). The stress conditions were isotropic, and the deformation was measured using the pore volume change and the LVDT measurements. The stress range at which permeability tests were carried out was between 20 kPa and 640 kPa. The permeability measurements were done the same way as in the flexible wall permeability test.

3 RESULTS

Figure 1 plots the hydraulic conductivity with respect to void ratio, density and vertical effective stress. With increase in effective stress the soil compacts leading to decreased void ratio and increased bulk density and finally a decrease in hydraulic conductivity. Most of the samples reached hydraulic conductivity lower than 10^{-9} m/s when the effective stress exceeded above 150 kPa. Note that the effective stress of oedometer tests is the vertical effective stress and that of the flexible wall permeameter and triaxial test are mean effective stresses.

It can also be seen from the plots that the permeability measurements are widely distributed unlike soils reconstituted in the laboratory under well controlled environments. Table 2 lists the initial

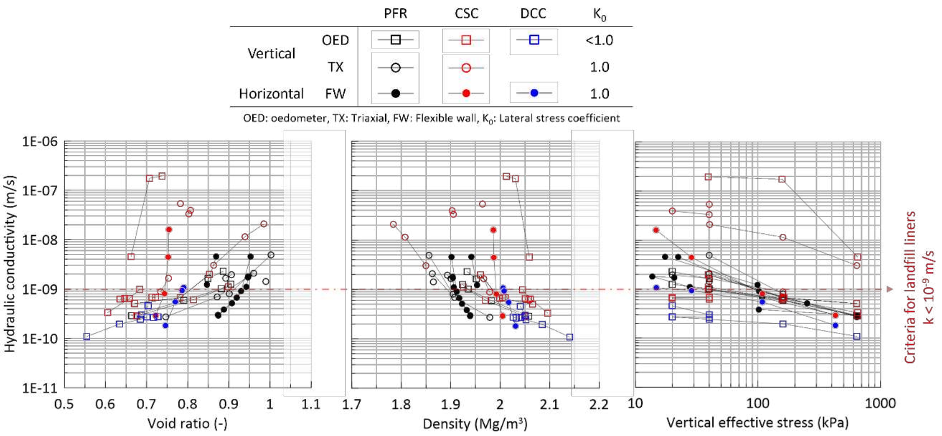

Figure 1. Hydraulic conductivity with respect to void ratio, density and vertical effective stress.

properties of each material compacted in-situ (In Table 2, k_v is the vertical hydraulic conductivity, e is the void ratio and ρ is the density). Large variability was detected for initial vertical hydraulic conductivity, void ratio and bulk density. PFR and CSC results showed large scatter, whereas the DCC results were more constant. Such a distinction seems to be from the origin of the specimens compacted and sampled in the field, noting that DCC were from a single core and PFR and CSC samples were from multiple cores extracted from various locations.

Table 2. Range of initial properties of intact materials.

Material	k_v (m/s)	e (-)	ρ (Mg/m³)
PFR	4.9×10^{-9} – 1.2×10^{-10}	1.00 – 0.67	1.86 – 1.96
CSC	1.9×10^{-7} – 6.4×10^{-10}	0.98 – 0.65	1.78 – 2.05
DCC	2.7×10^{-10} – 4.6×10^{-10}	0.73 – 0.70	2.03 – 2.04

Comparing the vertical and horizontal permeabilities, the horizontal permeability was not necessarily larger than the vertical which is often reported for reconstituted consolidated soils (Adams et al., 2013; Clennell et al., 1999; Zhang et al., 2019).

The evolution of horizontal permeability was more significant than the vertical permeability with the equivalent amount of void ratio decrement (Figure 1 left) and increase in bulk density (Figure 1 centre). This may be due to the anisotropic structure of the compacted soils. Similar to the vertical hydraulic conductivity, the value dropped below 10^{-9} m/s satisfying the Norwegian criteria for landfill liners for non-hazardous and hazardous waste after loading to high stresses.

4 FINAL REMARKS AND DISCUSSION

This paper observed the hydraulic conductivity characteristics of three materials, using three different apparatuses in the laboratory. The following points summarize and discuss the observations made:

- The field compacted PFR and CSC initial properties such as void ratio and bulk density had a wide variability. For the DCC, the initial properties varied less compared to others.
- Most of the recycled samples (PFR and CSC) did not satisfy the criteria for landfill liners ($k \leq 1.0 \times 10^{-9}$ m/s) at the low consolidation stresses (approx. below 100 kPa). Increasing the effective stress led to a large drop in hydraulic conductivity; with effective stresses exceeding 150 kPa the hydraulic conductivity decreased satisfying the criteria. The criteria may be met with sufficient deposition of landfills; however, this does not guarantee the suitability of landfill barriers and may require further improvement to ensure impermeability.
- The evolution of hydraulic conductivity with respect to void ratio change was more significant on the horizontal direction than on the vertical direction. Such behaviour may be attributed to the anisotropic soil structure of the compacted soils. This observation suggests that the horizontal flow should be considered for sidewalls of landfill liners.
- The permeating fluid was deionized water that does not necessarily represent the field conditions as permeating leachates tend to have high salt content. Changes in salt content/species of the permeant has the possibility of changing the permeability in orders of magnitude (Das & Bharat, 2021). Therefore, the effect of salt concentration of permeants on the hydraulic conductivity of these materials should be investigated prior to implementing to the field.

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