Effect of wetting on pore structure of compacted fine-grained soils

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Gowthaman Sinnathamby[1], Debra H. Philllips[1], V. Sivakumar[1], Andras Paksy[2]
[1]*School of Planning, Architecture and Civil Engineering, Queen’s University Belfast, Belfast, Northern Ireland, BT9 5AG, United Kingdom*
[2]*National Nuclear Laboratory, Hilton House, Risley, Cheshire, WA3 6AS, England, United Kingdom*

ABSTRACT
Pore structure of fine-grained soils can be affected by wetting and drying cycles. The flow of water in vertical and lateral directions occurs through the pores in these soils. However, redistribution of these pores due to wetting and drying could affect the hydraulic conductivity of fine-grained soils. The purpose of this study is to investigate the change in soil structure before and after the wetting at the microscopic level. Compacted samples prepared from two natural clay-rich deposits which are widely used as landfill liner material were subjected to wetting. Specimens were taken from these samples before and after wetting for Scanning Electron Microscope (SEM) observations. It was found that wetting influenced the pore structure of both fine-grained soils and this may be attributed to the change in hydraulic conductivity of the landfill barrier layers.

Keywords: Pore structure, Hydraulic conductivity, SEM analysis, Landfill liners

RESUMEN
La estructura porosa de los suelos de grano fino puede verse afectada por ciclos de humedecimiento y secado. El flujo de agua en dirección vertical y lateral se produce a través de los poros en estos suelos. Sin embargo, la redistribución de estos poros, debido al humedecimiento y secado, podría afectar a la conductividad hidráulica de los suelos de grano fino. El propósito de este estudio es investigar el cambio en la estructura del suelo antes y después del humedecimiento a nivel microscópico. Muestras compactadas preparadas a partir de dos depósitos naturales ricos en arcilla, ampliamente utilizada como material de revestimiento de vertederos, fueron sometidas a humedecimiento. Las muestras fueron tomadas antes y después del humedecimiento para las observaciones del Microscopio Electrónico de Barrido (MEB). Se determinó que el humedecimiento influyó en la estructura porosa de ambos suelos de grano fino, y que esto se podría atribuir al cambio en la conductividad hidráulica de los revestimientos del vertedero.

Palabras clave: Estructura porosa, Conductividad hidráulica, Análisis MEB, revestimientos vertedero

1 INTRODUCTION

The importance of understanding the effect of pore size distribution (PSD) and pore structure of unsaturated fine-grained soils on the hydraulic conductivity has become paramount in geotechnical and geoenvironmental applications. Studies have shown that the pore size distribution and the pore structure could be affected by cycles of wetting and drying (Albrecht and Benson, 2001; Bresson and Moran, 2003). There are numerous applications of compacted fine-grained soils such as earthen dams, embankments, pitches for sports facilities, waste disposal facilities and etc. In most of the landfill sites, fine-grained soils have been used as compacted barrier layers both in closure caps and base liners. Depending on the intended long-term performance, it can be used as a sole barrier layer or a member of a composite barrier layer. Either way, the performance of compacted fine-grained soil layer is significant for the long-term integrity of closure caps and base liners (Phillips et al., 2010).

This study was conducted as a part of a major research study which examines the long-term performance of landfill closure caps. The main focus of this study was to investigate the change in soil structure before and after the initial wetting of two different fine-grained soils which are widely used for the construction of landfill liners in the Northern Ireland (UK) and in the Republic of Ireland.

2 BACKGROUND

Because of its changing nature, the soil structure is generally considered as a dynamic property which can be influenced by several factors such as initial water content, compaction effort, material type and etc.

Porosity is one of the properties of soils which can be affected by the changes in soil structure. Most of geotechnical applications deal with unsaturated soils which have an unpredictable complex behavioural nature. Pores in unsaturated soils are generally described as bimodal which has micro and macro structures where micro structure consists of intra-aggregate pores within the aggregates and macro structure consists inter-aggregate pores between the aggregates (Wan et al., 1995; Sivakumar et al., 2011). Micro-pores are generally discontinuous and can have a width of up to few microns. This type of pores often occurs in fine grained soils such as clays where the water retained in micro pores could arguementably contribute to the flow through the soil. Macro pores, on the other hand, can be observed by the naked eye and having a width of several millimetres which is bigger than the micro pores. These pores can be filled by water at low suction values (Sivakumar et al., 2011). Micro pores can be widened due to wetting and drying of soils which create fissures in the soil structure. Grouping of several fissures in a long-term could lead to the formation of cracks which dramatically increase the hydraulic conductivity by creating preferential flow paths within the soil system (Hillel, 1998).

Effects of cycles of wetting-drying and swelling-shrinking on the soil structure and hydraulic properties have been historically reported by many researchers (eg; Sartori et al., 1985; Pagliai et al., 1987; Jessberger and Stone, 1991; Hussein and Adey, 1998; Albrecht and Benson, 2001; Bresson and Moran, 2003; Suter et al., 1993). Several cycles of wetting and drying can cause rearrangement of soil particles, resulting with an altered soil structure and pore system.

There are numerous laboratory and field studies on cyclic wetting and drying of fine-grained soils. Laboratory investigations show that wetting and drying of compacted fine-grained soils caused extensive cracking / formation of macro-pores which resulted from shrinkage after each cycles (Chen, 1965; Chen et al., 1995). Similar results are reported on soils which are allowed to dry partially (allowed drying up to its initial compacted moisture content) and to dry up to their shrinkage limit (full shrinkage). Both showed destruction of its original structure with a continuous rearrangement of soil particles during each wetting and drying cycles. Further more, soils subjected to complete shrinkage exhibit significant increase in the swelling potential with the number of wetting and drying cycle increases (Basma et al., 1996).

A field study conducted by Pagliai (1987) on the effect of cyclic wetting and drying on clay loam that was compacted by wheel traffic examine showed that the elongated pores had undergone significant changes over a 12 month period. Pagliai (1987) concluded that wetting and drying had increased the porosity of the soil significantly. Some findings report that the wetting and drying of non-aggregated soils could lead to the formation of aggregates with a significant change in their structure; however, the nature of aggregation heavily depends on the percentage of fines (Newman and Thomassonm, 1979; Pagliai et al., 1987).

In an attempt to find out the changes in hydraulic conductivity with cycles of wetting and drying, Benson et al. (1993) found that the hydraulic conductivity of Live Oak clay rose by an order of one magnitude after initial two cycles. Compacted fine-grained soils experience heavy structural changes during the first wetting and drying cycle and the structure become more stable during the successive cycles (Ng et al., 2000). Although, several cycles of wetting and drying of fine grained soils have an impact on the soil structure, the initial wetting of compacted unsaturated fine-grained soils is always crucial as the majority of the structural rearrangement take place during this stage (Osipov et al., 1987).

Laboratory tests performed by Sivakumar et al. (2010; 2011) clearly indicate a significant change of pore size distribution of kaolin clay before and after wetting. Isotropically and one dimensionally compressed samples were prepared at different water contents under different compactions and tested for pore size distribution by MIP. Specimens were saturated at zero suction. Upon wetting a lightly compacted sample showed a reduction on pore volume (pore size 10 μm) from 0.075 cm^3/g to 0.025 cm^3/g while a heavily compacted sample showed a reduction from 0.035 cm^3/g to 0.020 cm^3/g. These tests also showed a significant increase in the intra-aggregate pore size due to wetting. On the other hand, some samples showed a significant reduction in the inter-aggregate pore volumes because of the expansion of the aggregates into the inter-aggregate pores.

Changes in the pore structure of clays are important in determining the hydraulic conductivity. As the landfill barrier layers often composed of clayey soils, care should be given to the structural changes that can take place within the barrier layers. In a long-term, barrier layers could experience severe structural changes and the hydraulic conductivity of barrier soils can be increased by several orders of magnitude which is considered as a major threat for the long-term integrity of landfills. This study is looking at any such possible structural changes of two natural clay rich deposits which are widely used as landfill liner material from UK and Ireland that can take place due to wetting by using the SEM technique. Specimens were prepared at different moisture content and subjected to SEM analysis.

3 MATERIALS AND METHODS

Two naturally occurring clay based deposits Belfast Sleech and Glacial Till respectively from Belfast (Northern Ireland, UK) and Co. Kilkenny (Republic of

Ireland) were selected for this study. Each of these soils had been extensively used as barrier layers in landfill covers and base liners in the recent years. Table 1 summarises some basic geotechnical properties of the above clays.

Table 1. Geotechnical properties of Belfast Sleech and Glacial Till (Phillips et al., 2010)

Properties	**Belfast Sleech**	**Glacial Till**
Hydraulic Conductivity (m/s)	3 to 5 E-10	2 to 4 E-10
Plastic Limit	35	16
Liquid Limit	90	35
Clay Minerals	Kaolinite, Illite, Smectite, Chlorite	Kaolinite, Illite, Chlorite

3.1 Sample Preparation

Air dried bulk soil samples were crushed and passed through 5 mm sieve (BS 1377-1: 1990). Crushed and sieved samples were then dried in the oven over night. The soil was wetted and mixed well with tap water to achieve the required moisture content. Plastic bags were used to seal the wetted samples and left for 24 hours to ensure uniform distribution of moisture throughout the soil mix. Cylindrical specimens were prepared after 24 hours of hydration as specified in the BS 1377-4(1990). Samples were approximately 100mm in diameter and 100 mm in length.

Standard compaction test was carried out on both soils using a 2.5 kg standard hand compaction hammer and 1 L mould to find out the optimum moisture content and the maximum dry density according to BS 1377-4 (1990). After determining the optimum moisture content, a total of twelve specimens were prepared by standard compaction method; six specimens from each soil, two at optimum, two at dry of optimum and another two at wet of optimum moisture contents. One specimen from each moisture contents was subjected to hydraulic conductivity tests; and the others were kept for comparisons during image analysis

After compaction, specimens for hydraulic conductivity test were immediately set up in a tri-axial cell for testing. The other three specimens prepared for comparative analysis were wrapped in cling film and sealed in a plastic bag to prevent moisture loss.

3.2 Saturation and Hydraulic Conductivity Testing Procedure

Hydraulic conductivity tests were carried out in a triaxial cell using three automatic pressure controllers (APC) as specified in BS 1377-6:1990. All three APCs were calibrated for both volume and pressure. De-aired water was used as the testing medium/permeant and the test was carried out under a constant temperature at 20°C as per the requirement.

Setting-up a specimen for hydraulic conductivity test involved; flushing of all APCs and pressure lines with freshly de-aerated water, saturation of porous disk with de-aerated water, placing the specimen into a leak free pre soaked filter papers, setting up the sample on the pedestal and placement of top cap at the top of the sample. Pre-soaked filter papers were used at the top and bottom between the specimen and the porous discs to prevent clogging soil particles into the discs. Silicon grease was sprayed on the curved surface of the pedestal and top cap to give a tight contact between the caps and membrane prior to the placement of O-rings. Care was taken to avoid entrapped air during the setting up procedure. De-aerated water used to fill the cell. The cell assembly was immediately attached to the APCs by ensuring that there is no entrapped air in the pressure lines.

The following pressures were selected to apply an average effective pressure of 30 kPa and a hydraulic gradient of 10 kPa across the sample:

- Cell - 500 kPa,
- Bottom PWP - 475 kPa and
- Top PWP - 465 kPa

According to the guidance in BS 1377-6:1990, the hydraulic conductivity tests were conducted in three stages, namely; Saturation, Consolidation and Permeability stages. During the saturation process, change in pore water pressure was monitored by increasing the cell pressure in increments. For each increment, the Skempton's pore water pressure coefficient 'B' was calculated. It was assumed that the sample is not saturated if the B<0.95. In this case, a pore water pressure was applied to the sample so that an inflow of water took place into the sample. To ensure a small effective stress on the sample, pore water pressure was applied 10 kPa below the cell pressure. All the readings were recorded using the data logger. When the volume of water into the sample began to cease, drainage lines were closed and further increment of cell pressure was applied. B was calculated. This procedure was repeated until 'B' reaches 0.95.

For the consolidation of the sample, cell pressure was brought up to 500 kPa. Bottom pore water pressure was applied at 475 kPa and pore water allowed to dissipate to back pore water pressure through both top and bottom using the bypass. When the pore water outflow begins to cease, the sample was ready for the final permeability stage.

In the permeability stage, a pore water pressure of 465 kPa was applied from the top while the drainage was closed. After the pressure became steady, drainage lines at the top and bottom are opened and water is allowed to flow across the sample. Inflow and outflow volumes were monitored and plotted against time. The vertical permeability coefficient K was calculated as per BS 1377-6:1990.

3.3 Sample Preparation for SEM

Once the permeability test finished, the cell pressure was reduced in stages while the drainage lines were closed to ensure minimal disturbance to the soil structure. Freeze-drying technique was employed for the specimen preparation for the SEM (Shi et al., 1999). Freeze-drying comprises two stages; removal of pore fluid by freeze drying and obtaining a flat smooth surface. Thin-sharp edged knife was used to prepare small cylindrical soil specimen with a diameter of 5 to 10 mm and a height of 20mm by cutting along the axis of flow. Specimens were then dipped into liquid nitrogen before cutting them into two parts with a sharp knife to produce an observation surface. Specimens were then transferred to the freeze dryer immediately where the samples were left for approximately 48 hours for drying. Dried specimens were then taken out and stored in tight containers for SEM analysis. Specimens were then gold coated. The same procedure was followed on the other six samples which were not subjected to the hydraulic conductivity test as well.

Table 2. Soil samples at different moisture contents and corresponding hydraulic conductivity values

Sample	**Category**	**Moisture content (%)**	**Bulk density (Mg/m^3)**	**Hydraulic Conductivity (m/s)**
Belfast Sleech	Dry of Optimum	25.0	1.892	3.3 E-09
Belfast Sleech	Optimum	27.5	1.908	4.8 E-10
Belfast Sleech	Wet of Optimum	30.0	1.868	1.1 E-09
Glacial Till	Dry of Optimum	10.0	1.976	9.4 E-09
Glacial Till	Optimum	12.5	2.057	2.4 E-10
Glacial Till	Wet of Optimum	15.0	2.112	1.3 E-09

4 RESULTS

4.1 Compaction

Standard compaction tests were carried out on both soils to determine the optimum moisture contents of each soil. Belfast Sleech has a maximum dry density of 1.485 Mg/m^3 and an optimum moisture content of 27.50%. Glacial Till has a maximum dry density of 1.985 Mg/m^3 at optimum moisture content of 12.50% (Figure 2).

Three different moisture contents were selected for the sample preparation: optimum, dry of optimum and wet of optimum side. Figure 2, shows compaction curve and selected samples at 2.5% either side of optimum. For Sleech, samples were prepared at 25, 27.50 and 30% and for Glacial Till, moisture contents at 10, 12.50 and 15% were considered.

4.2 Hydraulic Conductivity

Table 2 shows the hydraulic conductivity test results for all six samples and Figure 2, shows the relationship between the compaction moisture contents and the hydraulic conductivity values. Both Belfast Sleech and Glacial Till have their lowest hydraulic conductivities at their optimum moisture content. Belfast Sleech showed lowest hydraulic conductivity of 4.8 x 10^{-10} m/s at its optimum moisture content 27.5%, and the Glacial Till has the lowest hydraulic conductivity of 2.4 x 10^{-10} m/s at its optimum moisture content 12.5%.

4.3 Scanning Electron Microscopy (SEM)

Figure 3 & 4 list some of the images obtained from the SEM analysis of Belfast Sleech and Glacial Till at different compaction moisture contents. The images were taken at x1000 magnification to observe the macro pores and soil aggregation clearly.

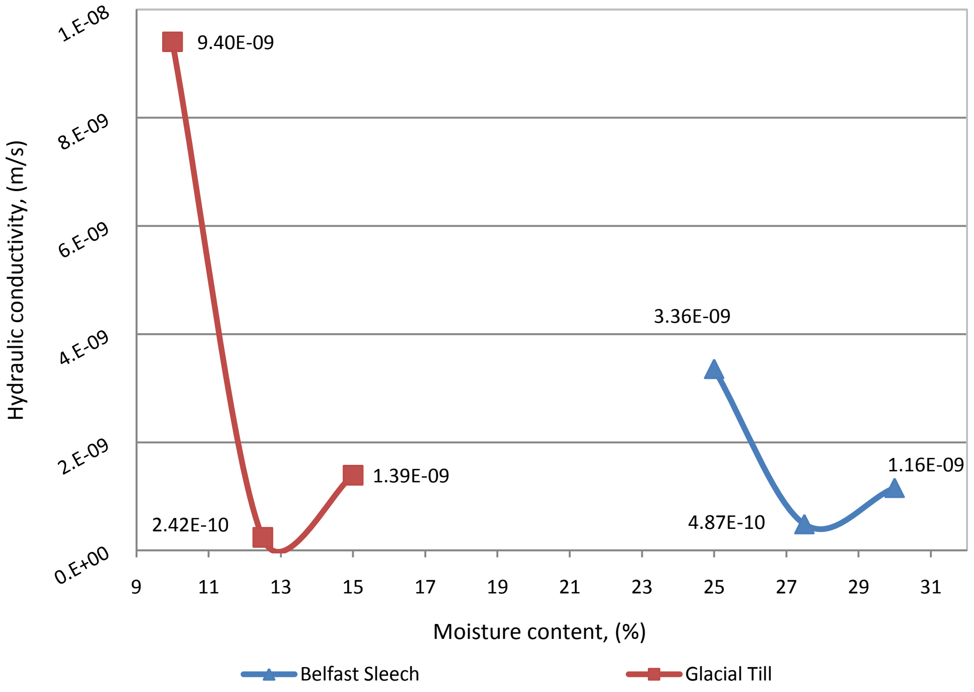

Figure 1. Variation of hydraulic conductivity against moulding moisture content

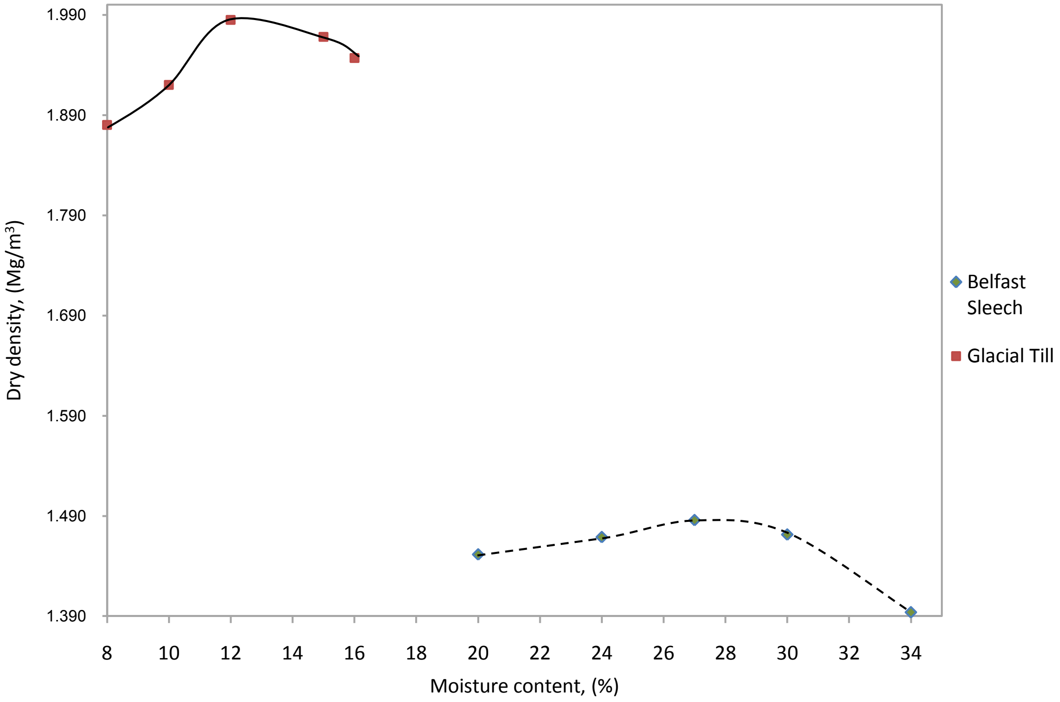

Figure 2. Standard compaction results for Belfast Sleech and Glacial Till

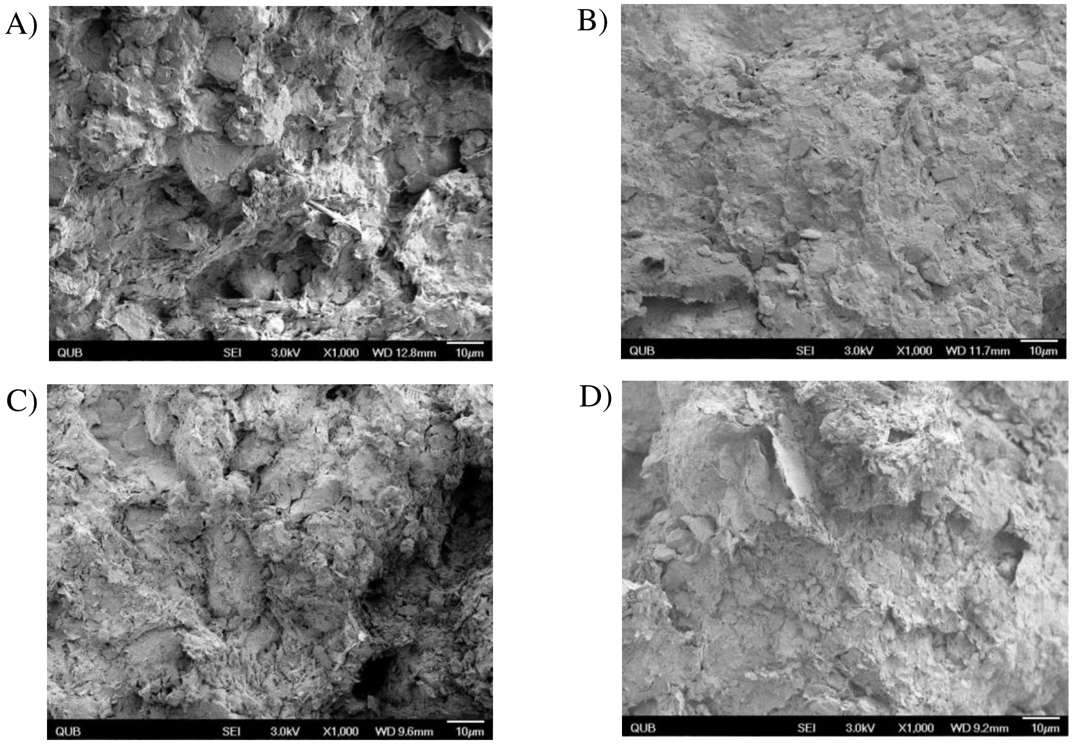

Figure 3. Scanning Electron Microscopy images of Belfast Sleech (A) Compacted at Optimum moisture content/ before wetting (B) Compacted at Optimum moisture content/ after wetting (C) Compacted at Wet of Optimum moisture content/ before wetting, and (D) Compacted at Wet of Optimum moisture content/ after wetting

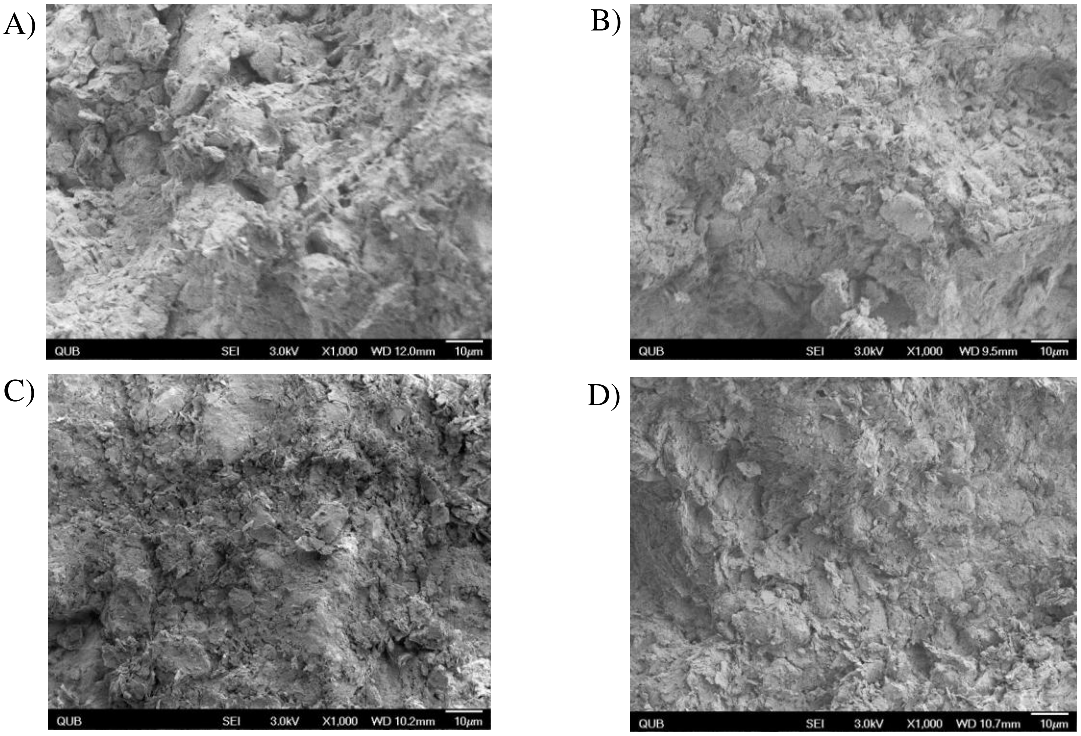

Figure 4. Scanning Electron Microscopy images of Glacial Till (A) Compacted at Dry of Optimum moisture content/ before wetting (B) Compacted at Dry of Optimum moisture content/ after wetting (C) Compacted at Optimum moisture content/ before wetting, and (D) Compacted at Optimum moisture content/ after wetting

5 DISCUSSIONS AND CONCLUSIONS

The SEM images indicate structural changes in all the specimens due to wetting. Significant reduction in the macro pores due to wetting is noticeable in all the samples apart from the Glacial Till specimen which is compacted to the wet of optimum moisture content where there is no evidence of major structural changes. However, this could be due to the random selection of the focus point in the SEM analysis. In unsaturated fine-grained soils, aggregates are held together by high suction resulting macro pores in the soil structure. During wetting aggregates absorb water and swell. Swelling could eventually cause a permanent change in the inter-aggregate orientation.

Figure 1, showed the hydraulic conductivity values against the compaction water content for both soils. The hydraulic conductivity has reduced at the optimum moisture content than that of dry of optimum. This could be due to the reduction in macro inter-aggregate pores at the optimum moisture content. However, as the compaction moisture content increases from optimum to wet of optimum, the hydraulic conductivity has gone up in contrast to the previous case. This could be due to the increased water content resulting in an increase in the breakdown the existing aggregates and eliminating inter-aggregate pores (Mitchell et al, 1965; Benson and Daniel, 1990).

Images obtained from SEM analysis were used to compare the soil pore structures before and after wetting. Effect of the compaction moisture content on the soil structure was clear in both soils and similar to the observations reported by Sivakumar and Wheeler (2000). Samples compacted dry of optimum showed a well defined aggregated structure as the aggregates held together by high suction. However these soils showed clear evidences of loss of aggregated structure upon wetting where the suction brought down to zero. On the other hand, swelling of the aggregates into the macro voids could also cause disappearance of aggregated structure. Swelling of aggregates can take place easily in soils with high specific volume; however it is limited in specimens with low specific volume and hence results in an overall volume change/swelling (Thom et al., 2007; Sivakumar, 2005).

Specimens compacted at optimum and wet of optimum moisture content on both soils showed less evident of well defined aggregated structure. There are no major changes observed upon wetting as both soils were swelled into the macro pores prior to wetting. This could have caused by the high moisture content. (Wiebe et al., 1997).

Even though the SEM images do not represent the entire soil structure due to the random selection of image location, it provided significant information about structural changes. A detailed study has to be done including the soil thin sectioning and Mercury intrusion porosimetry (MIP) for a better understanding of soil pore structure change due to wetting.

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REFERENCES

Albrecht, B. & Benson, C. 2001, "Effect of desiccation on compacted natural clays", *Journal of Geotechnical and Geoenvironmental Engineering,* vol. 127, no. 1, pp. 67-76.

Basma, A.A., Al-Homoud, A.S., Husein Malkawi, A.I. & Al-Bashabsheh, M.A. 1996, "Swelling-shrinkage behavior of natural expansive clays", Applied Clay Science, vol. 11, no. 2–4, pp. 211-227.

Benson, C.H., and D.E Daniel, 1990, "Influence of clods on Hydraulic conductivity of compacted clay", Journal of Geotechnical Engineering ASCE, vol. 116, no. 8, pp. 1231-1248.

Benson, C.H. & Othman, M.A. 1993, "Hydraulic conductivity of compacted clay frozen and thawed in situ", Journal of Geotechnical Engineering, vol. 119, pp. 276-294.

Bresson, L.M. & Moran, C.J. 2003, "Role of compaction versus aggregate disruption on slumping and shrinking of repacked hardsetting seedbeds", Soil Science, vol. 168, pp. 585-594.

BSI (1990). *Methods of test for soils for civil engineering purposes: General requirements and sample preparation, BS 1377: Part 1.* Miltonkeynes: British Standard Institution.

BSI (1990). *Methods of test for soils for civil engineering purposes*: *Compaction-related tests, BS 1377: Part 4.* Miltonkeynes: British Standard Institution.

BSI (1990). *Soils for civil engineering purposes: Consolidation and Permeability tests in hydraulic cells and with pore pressure measurement, BS 1377: Part 6.* Miltonkeynes: British Standard Institution.

Chen, F.H. 1965, "The use of piers to prevent uplifting of lightly loaded structures founded on expansive soils.", *International Research and Engineering Conference on Expansive Clay Soils*Texas A&M Press, , pp. 152.

Chen, X.Q., Lu, Z.W. & He, X.F. 1985, "Moisture movement and deformation of expansive soils", *11th International Conference Soil Mechanics and Foundation Engineering*, pp. 2389.

Hillel, D. 1998, *Environmental soil physics.* Academic Press, San Diego, CA.

Hussein, J. & Adey, M.A. 1998, "Changes in microstructure, voids and b-fabric of surface samples of a Vertisol caused by wet/dry cycles", *Geoderma,* vol. 85, pp. 63-82.

Jessberger, H. & Stone, K. 1991, "Subsidence effects on clay barriers", *Ge´otechnique,* vol. 41, no. 2, pp. 185-194.

Mitchell, J.K., Hooper, D. & Campanella, R. 1965, "Permeability of Compacted Clay", *Journal of Soil Mechanics and Foundation Division,* vol. 91, no. 4, pp. 41-65.

Newman, A.C.D. & Thomasson, A.J. 1979, "Rothamsted studies of soil structure: III. Pore size distributions and shrinkage processes", *Journal of Soil Science,* vol. 30, pp. 415-439.

Ng, C.W.W., Wang, B., Gong, B.W. & Bao, C.G. 2000, "Preliminary study on soil-water characteristics of two expansive soils", *Asian Conference on Unsaturated Soils: From Theory to Practice, Singapore*, eds. H. Rahardjo, D.G. Toll & E.C. Leong, , pp. 347.

Osipov, V.I., Bik, N.N. and Rumjantseva, N.A., 1987. Cyclic swelling of clays. *Applied Clay Science,* **2**(4), pp. 363-374.

Pagliai, M. 1987, "Micromorphometric and micromorphological investigations on the effect of compaction by pressures and deformations resulting from tillage and wheel traffic", *Soil compaction and regeneration*, eds. G. Monnier & M.J. Goss, , pp. 31.

Pagliai, M., La Marca, M. & Lucamante, G. 1987, "Changes in soil porosity in remolded soils treated with poultry manure", *Soil Science,* vol. 144, pp. 128-140.

Sartori, G., Ferrari, G.A. & Pagliai, M. 1985, "Changes in soil porosity and surface shrinkage in a remolded, saline clay soil treated with compost.", *Soil Science,* vol. 139, pp. 523-530.

Shi, B., Wu, Z., Inyang, H., Chen, J. & Wang, B. 1999, "Preparation of soil specimens for SEM analysis using freeze-cut-drying.", *Bulletin of Engineering Geology and the Environment,* vol. 5, no. 8, pp. 1-7.

Sivakumar, V., Sivakumar, R., Murray, E.J., Mackinnon, P. & Boyd, J. 2011, "Mechanical behavior of unsaturated kaolin (with isotropic and anisotropic stress history) Part 1: wetting and compression behaviour.", *Ge´otechnique,* vol. 60, no. 8, pp. 581-594.

Sivakumar, V. & Wheeler, S.J. 2000, "Influence of compaction procedure on the mechanical behaviour of an unsaturated compacted clay, Part 1:", *Wetting and isotropic compression. Ge´otechnique,* vol. 50, no. 4, pp. 359-368.

Suter, G.W., Luxmoore, R.J. & Smith, E.D. 1993, "Compacted soil barriers at abandoned landfill sites are likely to fail in the long term", *Journal of Environmental Quality,* vol. 22, no. 2, pp. 217-226.

Thom, R., Sivakumar, R., Murray, E.J. & Mackinnon, P. 2007, "Pore size distribution of unsaturated compacted kaolin: the initial states and final states following saturation", *Ge´otechnique,* vol. 57, no. 5, pp. 469-474.

Wan, A.W.L., Gray, M.N. & Graham, J. 1995, "On the relations of suction, moisture content and soil structure in compacted clays.", *1st International Conference Unsaturated Soils*, pp. 215.

Wiebe, B., Graham, J., Tang, G.X. & Dixon, D. 1997, "Influence of pressure, saturation, and temperature on the behaviour of unsaturated sand–bentonite", *Canadian Geotechnical Journal,* vol. 35, pp. 194-205.