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EFFECT OF STATE OF COMPACTION ON THE HYDRAULIC CONDUCTIVITY OF SAND-CLAY MIXTURES

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ABSTRACT

Sand-clay mixtures used as liners for waste containment or water barriers are very sensitive to the hydraulic conductivity and need to be designed for different values of effective pressures and different molding conditions and states of compaction. Therefore, the relationship between initial molding condition and the coefficient of hydraulic conductivity of sand-natural expansive clay mixtures were examined in the laboratory. Natural expansive clay used in this study was characterized as highly plastic and highly expansive. The testing program involved determination of hydraulic conductivity values for different percentages of sand-expansive clay mixtures at three initial molding conditions; namely dry of optimum (DOMC), optimum moisture content (OMC) and wet of optimum (WOMC). All hydraulic conductivity tests were conducted using flexible wall constant head permeameter at a hydraulic gradient equal to 30. The specimens were subjected to an average effective confining pressure during testing in the range of 50 to 400 kPa. Experimental test results indicated that the clay content, compacted molding conditions and confining pressure had a significant effect on the hydraulic conductivity of sand-expansive clay mixtures. SEM technique was utilized to view the microfabric structure of the mixtures at DOMC, OMC and WOMC states. Associated features were highlighted. The study concluded that compaction of landfills can be specified within the wet of optimum range of moisture dry density relationship.

Key words: Hydraulic conductivity, water content, sand, clay, mixtures.

1. INTRODUCTION

The hydraulic barriers with low hydraulic conductivity are used as part of waste containment systems in order to prevent groundwater contamination by leachate from the waste. Currently, horizontal or sloping barriers called liners may be artificial (geomembranes) or composed of natural materials such as sand-clay mixtures (Chapuis 1981).

Clay liners are very common and preferred by many designers due to their cost effectiveness and large capacity of attenuation. Traditionally, clay barriers for the containment of landfill leachate are made up of compacted clay liners (Kalkana and Akbulut 2004). In the absence of impermeable natural soils, compacted mixtures of clay and sand have been used to form barriers to fluids (Kenny *et al*. 1992; Daniel 1993).

The coefficient of hydraulic conductivity for sand-clay (or sand-bentonite) mixtures is one of the most important parameters in the design of waste disposal facilities. The hydraulic conductivity property is normally investigated through laboratory tests and assessed quantitatively. The task to produce a liner material which meets the criteria given at the lowest possible cost requires good knowledge of the different factors affecting the final hydraulic conductivity of the mixture. Factors affecting the hydraulic conductivity include initial molding conditions, confining pressures and clay content of the sand-clay mixtures. The general requirement for a barrier material such as compacted clay liner, sand-bentonite or sand-clay mixture whether used for cover system or landfill is that the hydraulic conductivity shall not exceed 1×10^{-7} cm/s (US EPA 1995; Swedish EPA 2000). However, since the waste disposal facilities for radioactive wastes are critical structures and their design requires much more attention, it is advisable to design barrier layers such that they have much lower hydraulic conductivities than specified.

Limited studies focused on the properties of the mixtures consisting of sand-natural expansive clay (Tuller and Or 2006). Studies on the effect of confining pressure on the behavior of hydraulic conductivity of mixtures are also not covered widely. Dafalla *et al.* (2015) considered a comparison between indirect hydraulic conductivity tests and standard flexible wall tests. The results indicated that oedometer tests underestimate the hydraulic conductivity by 2 to 3 orders at variable effective pressures.

Works of Ameta and Abhay (2008), Anderson and Sivakumar (2008) covered the testing methods used to obtain the hydraulic conductivity. The effect of initial moisture content and state of compaction was investigated by Sallfors *et al.* (2002). Tang *et al.* (2014) studied the compaction degree of layers enhanced by bentonite for better barrier performance with regard to migration of contaminants. Several researchers studied the impact of water content on hydraulic conductivity of sand and bentonite mixtures (Haug and Wong 1992; Kaoser *et al*. 2006; Fan *et al.* 2014; Oren *et al.* 2014). Common practices and local codes requirements specify a range of molding water contents between dry of optimum, optimum and wet of optimum conditions for soil liners in order to achieve low hydraulic conductivity. However, little information is available on the relationship between mold-

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ing water content and the hydraulic conductivity for sand-clay mixtures. For this reason this research is aimed at investigating the effect of initial molding water content, confining pressure and clay content on the hydraulic conductivity of sand- natural expansive clay mixtures. The hydraulic conductivity of the compacted material depends greatly on whether the compaction is performed on the wet side or the dry side of optimum (Sallfors *et al*. 2002). This study is aimed at investigating the influence of clay content, compaction molding conditions and confining pressures on the hydraulic conductivity of compacted sand-natural expansive clay (Al-Qatif).

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials Used

The expansive clay samples for this study were brought from the town of Al-Qatif, which is a historic, coastal oasis region located on the western shore of the Arabian Gulf in the Eastern Province of Saudi Arabia (26°56′0″N, 50°1′0″E). Al-Qatif expansive clay is considered highly expansive in nature due to the presence of high montomorillonite and smectite minerals content (Abduljuawad *et al*. 1992; Azam 2003). Soil samples were obtained from test pits at a depth of three meters below ground level. The laboratory testing conducted on extracted samples included routine classification and physical property tests. The geotechnical characterization test results of Al-Qatif clay are listed in Table 1.

The sand used in this study was local sand obtained from within Riyadh city which is typical to that used in construction. The index properties of sand used in the present study are given in Table 2 and the grain size distribution of sand is presented in Fig. 1. The sand was classified as poorly graded sand (SP) according to the unified soil classification system (USCS) and ASTM D 2487.

2.2 Sample Preparation and Compaction Tests

The main objective of this study is to evaluate the effect of initial molding conditions on the hydraulic conductivity behavior of sand-Al Qatif clay mixtures. The soil moisture content and the dry unit weight relationship for different clay contents was investigated. The compaction tests were carried out in accordance with the standard proctor compaction method (ASTM D698-02). The range of clay content prepared for this investigated included 0%, 5%, 10%, 15%, 20%, and 25% by dry weight of sand. All mixtures were prepared at different water contents in the range of 3 to 22%. Distilled water was added to the mixtures to obtain the desired water contents. The mixtures were allowed to hydrate in plastic bags for at least 24 hours prior to compaction. The compactor with a 5.5-lb hammer was used in compacting different mixtures into a 100 mm internal diameter mold and with 112.5 mm in height. Uniform compaction was applied for each layer. Three layers were compacted as specified in the test method. The weights of the compacted mixtures were determined along with their water contents. Figure 2 shows the variation of compaction curves for different clay content of sand-Al Qatif clay mixtures. The compaction curves provided were used to determine the initial molding conditions considered in this study as is described later in the experimental program. Samples were prepared at three different states of compaction and are referred to as optimum moisture content (OMC), dry of optimum (DOMC) or wet of optimum (WOMC). The dry of optimum state was selected at moisture content 4% lower than the optimum value while the wet of optimum was selected at 4% moisture above optimum.

Table 1 Geotechnical characteristics of Al-Qatif clay

Property	Value
Index parameters	
Specific gravity, G_s	2.75
Liquid limit, LL (%)	137
Plastic limit, PL (%)	45
Plasticity index, PI (%)	92
Unified soil classification system	CH[1]
Swelling results	
Swelling pressure (kN/m^2)	550 ~ 600
Swelling potential (%)	20 ~ 24

(1) CH refers to clay with high plasticity.

Table 2 Properties of Sand

Property	Value
Specific gravity, G_s	2.66
Range of particle size (mm)	0.1 ~ 0.6
Coefficient of uniformity (C_u)	1.737
Coefficient of curvature (C_c)	1.078

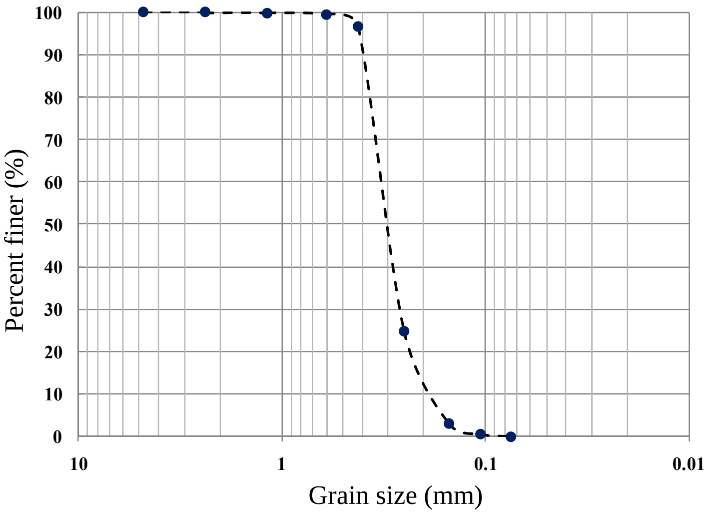


Fig. 1 Grain size distribution of sand

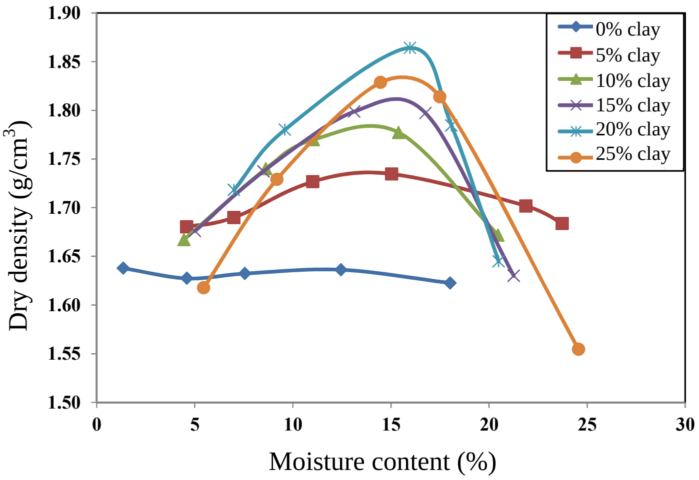


Fig. 2 Compaction curves of mixtures

2.3 Test Procedure

The hydraulic conductivity of sand-clay mixtures was tested using flexible wall constant head permeameter. All tests were performed to evaluate the hydraulic conductivity under different confining pressures (50 ~ 400 kPa) and three molding conditions (DOMC, OMC and WOMC). The samples were prepared using static compaction to the required dry density and water content. Dimensions of the samples were 7 cm in diameter, and 3.4 cm in height.

All tests were performed in accordance with ASTM D-5084 Method A (constant head). This procedure includes the following test stages:

1. Soaking of specimen

This procedure is aimed at reducing the time required for saturation. The specimens were soaked under partial vacuum applied to the top of the specimen.

2. Saturation of the specimen

The back-pressure saturation procedure was adopted. This consists of gradually increasing both the confining and the back pressure to force any air bubbles or voids out of the sample. Saturation was verified by measuring the *B* coefficient (The *B* coefficient is defined for this type of test as the change in pore-water pressure in the porous material divided by the change in confining pressure) as described in Test Method D 4767. The specimens were considered saturated with assurance of *B* values ≥ 0.95.

3. Consolidation

The specimens were consolidated under effective confining pressure. Effective confining pressure in this test is defined as cell pressure minus back pressure.

4. Permeation

The saturated hydraulic conductivity of mixtures were based on Darcy's law; which describes the relation between volume of water which flows through a cross section area of the sample during an elapsed time under constant hydraulic gradient, *i* (in this research *i* was selected to be 30). Hydraulic conductivity, *k*, was calculated using:

$$k = Q \cdot L / (t \cdot A \cdot \Delta h) \quad \text{(cm/s)} \tag{1}$$

where

Q is the average of outflow quantity (cm^3)
L is the specimen height (cm)
t is the time elapsed in permeation stage (s)
A is the cross-section area (cm^2).
Δh is the difference of back pressure of bottom and top of specimen (cm).

2.4 Microfabric Features

As a part of this investigation scanning electron microscope was used in order to observe and view microfabric features associated with different states of compaction. Sand-Al Qatif clay mixture with 20% clay content was selected. The samples were initially prepared following the same technique used for preparing samples for hydraulic conductivity tests as described in the section 2.2, then cut it into small pieces to fit the desired size of the sample. All samples were dried and coated with platinum to form electrical conducive specimens. To minimize fabric disturbance accompanying the drying, saturated samples were dried using the freeze-drying technique.

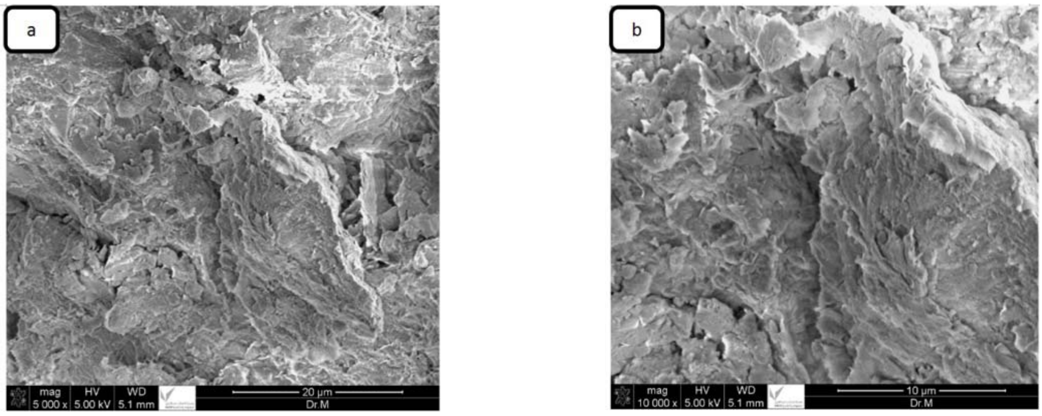
Scanning electron microscope technique (SEM) was preferred used to view the microfabric features at different magnifications. This technology is more advanced than the optical microscope and can provide better visibility. High magnifications were used to view clay alone (× 5,000 and × 10,000). This can be seen in micrographs of Fig. 3.

Tests were performed using Joel apparatus (Model JSM-7600F) with a high resolution of 3.0 nm, and operated at 5kV-10kV. The magnifications 40 × and 80 × were used for the examination of the mixtures fabric. This SEM allows the viewing of relatively large specimens up to 10 mm × 10 mm × 10 mm. SEM can be used to view the material at high magnifications, but the selected micrographs were found appropriate to show in this publication. At this level of magnification it is easier to see more pores and repeated features unlike extra high magnifications.

3. RESULTS AND DISCUSSION

The hydraulic conductivity test results for all sand clay mixtures at OMC, DOMC and WOMC conditions are summarized in Tables 3, 4 and 5 respectively. Figure 4 shows plots of the saturated hydraulic conductivity for all sand clay mixtures at variable effective confining pressures and clay content for the three states of compaction considered in this study. Figure 5 shows a plot of hydraulic conductivity of variations for 25% clay content mixture against confining pressures for three molding conditions.

It's apparent at all molding conditions, the values of hydraulic conductivity were observed to decrease with the increase in the confining pressure (Figs. 4 and 5). The increase in clay content is associated with decrease in the hydraulic conductivity (Fig. 4). This relationship is approximately linear up to certain limit (20% clay) for the dry of optimum and optimum state of compaction and then drops significantly. Similar description can be applied for the wet of optimum state but the gradient is getting steeper for clay content greater than 10%. When adding excessive clay, the fine material will push the sand grains apart, and the mixture will behave as clay with inclusions of impermeable particles.



a: × 5,000 **b: × 10,000**

Fig. 3 SEM of Al-Qatif clay

Table 3 Hydraulic conductivity of sand-clay mixtures at OMC condition

Hydraulic conductivity (k, (cm/s))-OMC				
Confining pressure (kPa) Clay content (%)	50	100	200	400
0	4.6250E-04	4.4742E-04	4.4005E-04	3.5416E-04
5	4.2414E-04	3.2383E-04	2.8098E-04	1.8744E-04
10	1.7961E-04	1.7212E-04	1.6568E-04	1.1407E-04
15	1.3645E-04	1.2060E-04	8.6150E-05	5.9761E-05
20	6.4874E-05	6.2651E-05	4.4994E-05	3.9053E-05
25	3.3888E-06	2.9656E-06	1.8841E-06	6.9813E-07

Table 4 Hydraulic conductivity of sand-clay mixtures at DOMC condition

Hydraulic conductivity (k, (cm/s))-DOMC				
Confining pressure (kPa) Clay content (%)	50	100	200	400
5	5.0227E-04	4.5236E-04	3.3368E-04	3.0880E-04
10	3.7097E-04	3.4497E-04	2.8145E-04	2.4925E-04
15	2.3449E-04	1.9125E-04	8.8320E-05	6.5504E-05
20	1.1465E-04	9.5177E-05	7.2447E-05	4.7406E-05
25	3.0411E-05	2.3796E-05	1.9793E-05	8.4739E-06

Table 5 Hydraulic conductivity of sand-clay mixtures at WOMC condition

Hydraulic conductivity (k, (cm/s))-WOMC				
Confining pressure (kPa) Clay content (%)	50	100	200	400
5	3.7153E-04	2.7444E-04	1.5821E-04	6.0715E-05
10	2.2221E-04	1.3913E-04	9.1318E-05	4.4715E-05
15	3.3413E-05	1.5981E-05	1.5293E-05	8.8771E-06
20	4.0200E-06	2.7858E-06	8.4026E-07	7.6383E-07
25	2.1827E-08	1.8640E-08	1.3031E-08	1.1578E-08

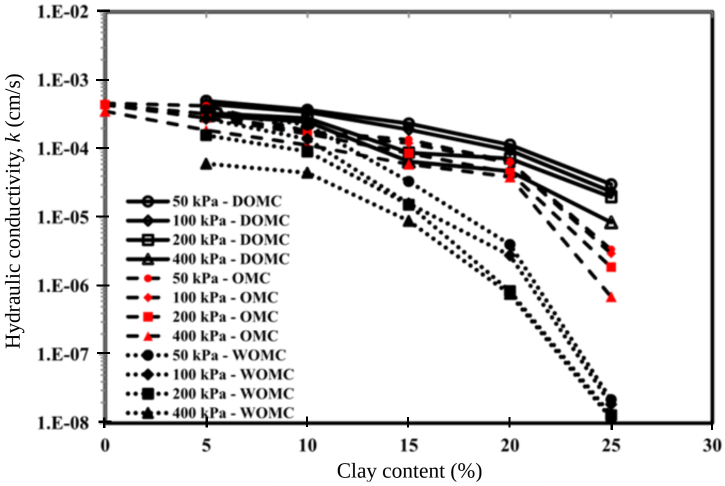


Fig. 4 **Variation of hydraulic conductivity of all mixtures with clay content at DOMC, OMC and WOMC**

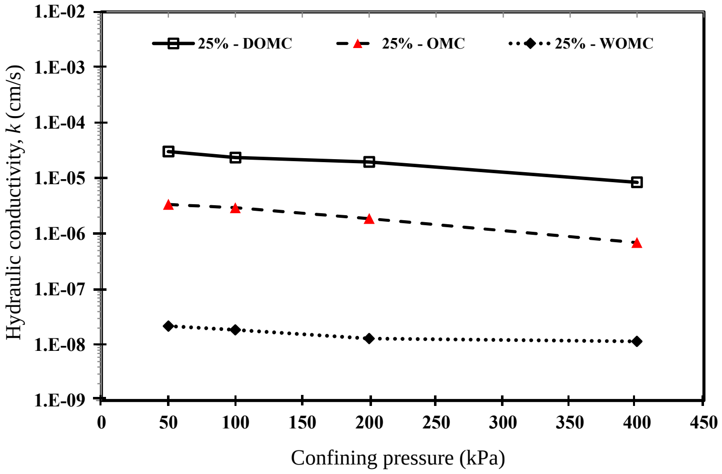


Fig. 5 **Variation of hydraulic conductivity of 25% clay content mixture versus confining pressure at DOMC, OMC and WOMC**

The hydraulic conductivity curves indicate reduction with the increase of the effective confining pressure in general. For all mixtures of the same clay content, it was observed that the effect of confining pressure on the hydraulic conductivity was more pronounced at clay contents greater than 20% for mixtures prepared at DOMC and OMC conditions. Also, for samples at WOMC condition the effect of confining pressures was evident at clay contents greater than 10%.

Assuming the landfill material is subjected to minimum environmental and moisture changes for being at a depth below the vadose level then state of compaction dry of optimum shall be avoided. The difference in hydraulic conductivity between sand-clay mixtures prepared at a dry of optimum state (DOMC) and mixtures prepared wet of optimum is estimated at 2 to 3 orders of magnitude for 15 and 20% clay content respectively. This huge variation will lead to a strict call to consider the wet of optimum state as the most appropriate when compacting landfills. It seems the wetter the sand-clay mixture, the better values of hydraulic conductivity when compared to the requirements of the widely accepted standards for landfills ($k < 10^{-7}$ cm/s). The compaction energy needed for extra wet mixtures may not be practical but ensuring the mixture is wetter than optimum will enhance an important design property to keep the landfills functioning.

25% clay content showed three to four orders of magnitude difference in hydraulic conductivity when comparing dry of optimum to wet of optimum. All test results were combined and presented in one figure in order to help easy comparison. The set of curves for the hydraulic conductivity of sand-Al Qatif clay mixtures; DOMC, OMC and WOMC appear as three bundles with the dry of optimum case on top, optimum in the middle and the wet of optimum to the bottom. The difference in order of magnitude can be clearly seen in Fig. 4.

The range selected for this study is 4% plus or minus the optimum moisture content. It is common in practice and construction codes the required field compaction is recommended between 2% plus or minus the optimum moisture content. The basic findings of this study will call for compacting all landfill at wet of optimum state. The exact range may vary for different clays due to mineralogy and affinity to water.

The flow of water through soils is dependent on the ease of water flow through the formation. Therefore, confinement plays a very important role in hydraulic conductivity of sand-clay mixtures. In addition the compaction state is very important parameter to estimate the hydraulic conductivity of the mixtures. Where the specimens compacted at the wet-of-optimum water content were of lower *k* value as compared to specimens compacted at the dry of optimum moisture content.

The percentage of clay is the prime parameter in the sand-clay mixtures because clay is a material with very low hydraulic conductivity. It is quite obvious that the higher the percentage of clay, the lower the hydraulic conductivity. Therefor the clay content is considered the most crucial parameter to measure the hydraulic conductivity.

Figures 6, 7 and 8 show the SEM micrographs of sand-clay mixture prepared at 20% clay content simulating tested samples; dry of optimum (DOMC), optimum (OMC) and wet of optimum (WOMC) viewed at two magnifications (40× and 80×). At these two magnifications sand grains and clay particles can be easily distinguished. The freeze drying technique helped to have the voids seen and original skeleton and structure remain intact.

Variations in the form of clay and sand placement can be observed clearly from the images, for the 20% clay mixture at the three investigated molding conditions. For the DOMC case sand grains can be grouped together forming passages for water with minimal interruption. Grain to grain contact is enabled in the mixture of an estimated 30% of the viewed section. For the OMC case a nearly even distribution of clay particles reduces grain to grain contact zones. Not all air gaps are filled. For the WOMC sand grains appear as floating within the clay paste. Air gaps are present but hardly interconnected.

The microfabric classification system suggested by Collins and McGown (1974) and Collins (1984) describes many common forms and features that can be viewed in SEM micrographs. It describes elementary particles as different arrangements which may take a parallel or random orientation. They also introduced the connecters which describe bridging or clothed grain to grain connection. Particle assemblages are described as interweaving bunch or matrices. These are common in clay region. Although the system presents many useful forms but this study concentrated on the nature of clay flakes with regard to flattening and orientation and the way they fill up pore spaces.

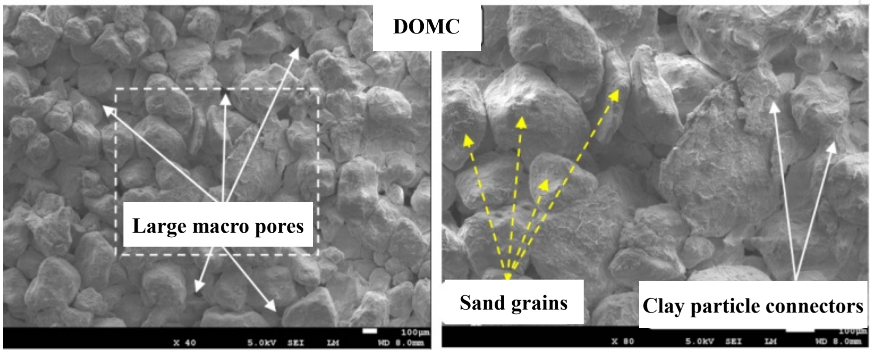


Fig. 6 SEM of mixture at 20% clay content at DOMC condition

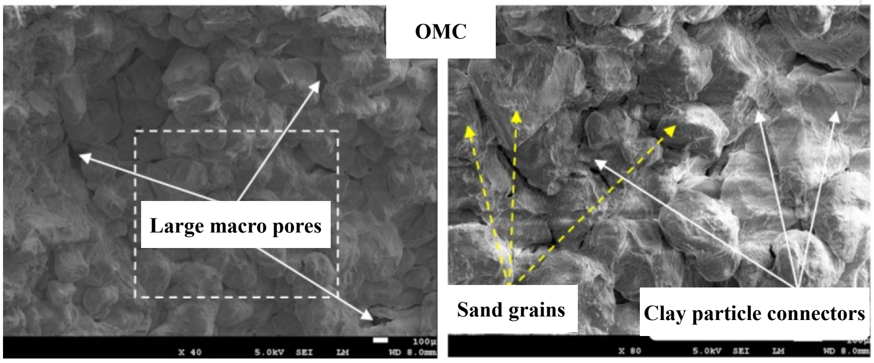


Fig. 7 SEM of mixture at 20% clay content at OMC condition

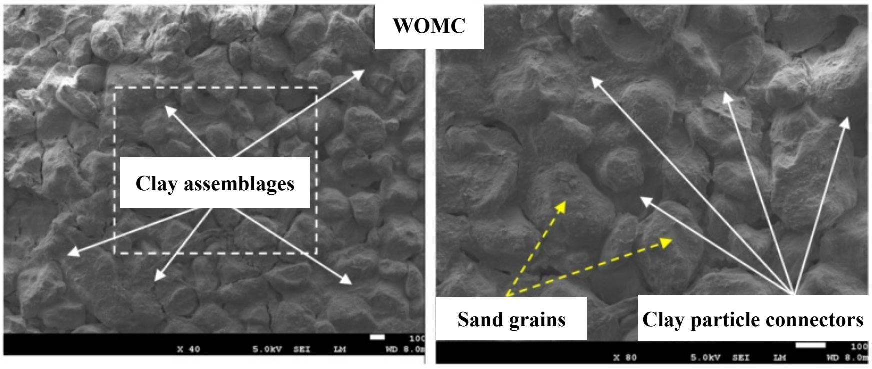


Fig. 8 SEM of mixture at 20% clay content at WOMC condition

SEM for the viewed mixture at WOMC condition showed that the clay particle assemblages occupying the majority of voids between sand grains and develop connectors through sand grains. This leads to a significant reduction in hydraulic conductivity. It can be concluded that mixtures compacted at DOMC and OMC conditions had larger macropores and more variable.

The outcome of this result can be seen different from what may be expected for soils compacted to the dry side, due to the flocculated structure and randomly-orientated particles likely to impede the water flow. For soils compacted to the wet side, the particles are dispersed with a preferred-orientation. The hydraulic conductivity in this study is computed for saturated material when a steady flow is established. The compaction on the wet side is associated with good kneading and a fairly homogeneous distribution of voids within the material.

4. CONCLUSIONS

The state of compaction as applied in the field for waste material landfill is of prime importance to assure a better hydraulic conductivity parameter. Material compacted dry of optimum is expected to give higher permeable media than material compacted at optimum or wet of optimum moisture content. The increases in clay content and effective confining pressure are associated with a decrease in the hydraulic conductivity. The rate of reduction depends on the clay content and the sand gradation sharp changes are expected at certain clay content which is expected to vary according to the mineralogy and proportions of sands and clay. However for the same clay content and confining pressures it was found that material compacted wet of optimum will give lower hydraulic conductivity. The difference in hydraulic conductivity between sand-clay mixtures prepared at a dry of optimum state (DOMC) and mixtures prepared wet of optimum is estimated at 2 to 3 orders of magnitude for 15 and 20% clay content respectively. The scanning electron microscope (SEM) imaging showed that WOMC condition enabled clay particle assemblages occupying majority of voids between sand grains and develop connectors through them. This leads to a significant reduction in hydraulic conductivity. It is strongly recommended to consider specifying compacting landfills at a wet of optimum condition within a moisture content range compactable by heavy vibrating compactors.

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