

Hydraulic Properties of Smectite Clays from Iraq with Special Respect to Landfills of DU-contaminated Waste

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Abstract

Landfills of material contaminated by depleted uranium and other low-level radioactive waste must be isolated from the biosphere for a sufficiently long time. This can be effectively made in desert climate by collecting contaminated waste in suitable areas confined by tight embankments and covering them with very tight clay liners protected from desiccation and erosion by suitably composed filters and coarse rock fill. Examples of design principles and construction are described in the paper. The clay liners are made of air-dry expanding clay that can be found in sufficient quantities in Iraq and that provide very good tightness at low cost. The construction technique is well known from various projects.

Keywords: smectite, depleted uranium, hydraulic conductivity, hazardous waste

1 Introduction

Soil with radioactive contaminants needs to be isolated from groundwater and living species for sufficient time, which is about 300 years for low-level waste from nuclear plants and even longer for waste with long-lived radionuclides [1]. Climatic conditions, that can represent arctic to desert environments, need to be considered in the design and construction phases and short-term extreme conditions, like very heavy rainfall for a day or two every fiftieth year may have to be included in the scenarios taken as basis of the design work. Top covers of waste piles shall therefore contain an erosion-protective drain layer over the engineered barrier that shall minimize infiltration of rain and melt water into and through the waste. The barrier below the erosion-protecting top cover is

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commonly proposed of a low-permeability clay liner of smectitic clay and a similar layer suggested to form the base of the waste pile. If maintenance of the landfill in the form of drainage and treatment of water that has percolated the waste is required, the respective organization or authorities responsible for this must see to that the function of the landfill is acceptable for the long time considered. If, on the other hand, no monitoring, repair or reconstruction are planned the landfill must perform automatically. This latter principle is preferable from economic points of view if a durable barrier system can be made and various attempts for this have been comprehensively described in the literature [2,3]. The aim can be to design the top liner so that infiltrated precipitation is retained until evaporation recycles the water back to the atmosphere hence preventing irreparable desiccation, but it is realized that the whole wetting/drying process is a key issue of great complexity and further complexed by entering electrolytes and freezing/thawing. A fundamental matter is the hydraulic performance of smectitic clay for the special case of complete water saturation with respect to the microstructural constitution and the impact of hydraulic gradients. They are in focus of the present paper.

2 Principle of Design of DU Waste Landfill

2.1 Legislation and Criteria

Waste with very low content of radioactive matter (LLW) shall be isolated from the biosphere for 300 and 500 years according to IAEA and NRC regulations [1,4]. The following criteria are taken as a basis of the design:

- Disposal within a defined area within which there must be no wells for drinking water or irrigation.
- Confinement by construction of stable and tight embankments or dikes.

The ideal function of the disposal site is to design the top liner so that infiltrated precipitation is retained until evaporation recycles the water back to the atmosphere [5]. If this can be achieved there is no need for constructing pipe systems for collecting percolate and clean it and such a solution is aimed at for the DU waste landfill in Iraq. Figure 1 shows a cross section of such an arrangement.

2.2 Function of a Landfill in Desert Area

2.2.1 Principle

The landfill is constructed so that no maintenance will be needed for the required time, at least 300 years, of isolation of the waste. The conditions are that no human activities will take place that can cause deterioration, i.e. excavation for use of engineered barriers and that very significant exogenic impact, like earthquakes of very high magnitude, does not take place.

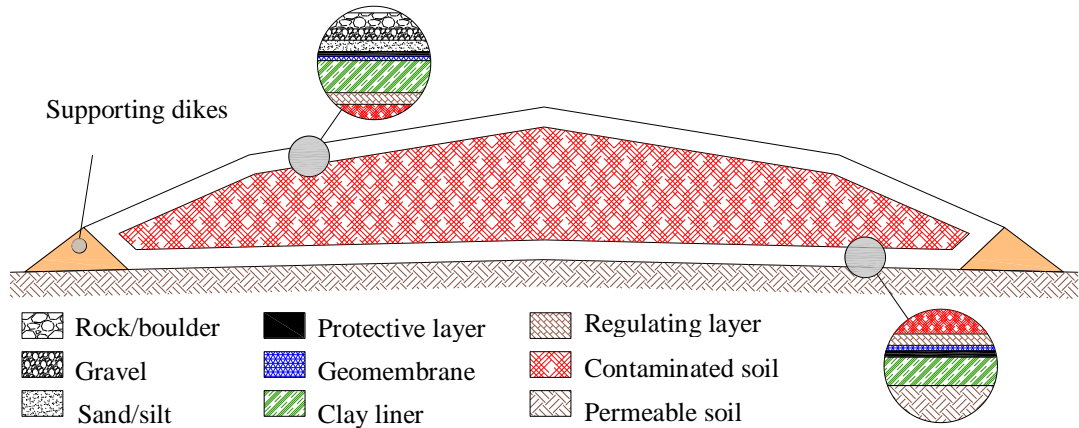


Figure 1: Cross sectional profile of a suggested landfill confining contaminated soil with Depleted Uranium.

2.2.2 Site selection

The construction site should be in an elevated area where precipitation of rain or melt water cannot accumulate and cause flooding, and where wind-driven sand migration is not expected to cause significant erosion or lead to considerable sand drift. Areas with significant seismic or tectonic events are known to take place shall be avoided. The disposal area should be on dense sand, which minimizes settlement and provides effective drainage of occasionally occurring rainfall. Cold conditions causing freezing shall be avoided.

2.2.3 Construction sequence

The construction of a landfill of the type shown in Figure 1 starts by evening the natural ground and placing a base layer of coarser material that is effectively compacted. A filter consisting of silt/sand/gravel is then placed and compacted upon which embankments are constructed for supporting the waste to be filled. A bottom liner of clay material can then be placed over the entire area, reaching up on the sloping embankments but this may not be required depending on the stipulations by the authorities. The next phase is placement of DU-contaminated soil in layers that are compacted by vibrating rollers, the shape of the fill being a ridge with sloping sides. The compacted waste is covered by a top liner of smectitic clay that is suitably in the form of air-dry granulate. The inclination of the sloping waste fill must not exceed the angle of internal friction of the clay layer, which is covered by a filter of silt/sand/gravel, with rock blocks for erosion protection of the clay liner being the uppermost barrier.

2.2.4 Evolution

A normal scenario in desert areas is that the temperature rises to more than 47°C in daytime [6], by which the upper barriers become heated but sufficient height of the erosion protection and filter will keep the temperature of the clay liner at much lower temperature. Three scenarios can appear respecting the clay in the top liner:

- No precipitation keeps the initial water content of the clay constantly at 5-10 percent by weight through days, weeks, months and years,

- Rainfall for a limited period of time causes wetting and homogenization of the clay, which will self-seal and stop migration of infiltrated water. Intermediate dry periods will cause reverse migration of water, ultimately leading to the original state with microstructurally heterogeneous clay with a water content of 5-10 percent by weight through days, weeks, months and years etc.
- Very long, intense rain can create an artificial groundwater table in the filter covering the top liner and create complete water saturation of the clay in the top liner. Taking the lower boundary of the clay to have no water pressure, the hydraulic gradient across the clay will be $i=H/d$, where H is the water pressure on the upper boundary of the liner and d its thickness. For practically selected dimensions i will be in the range of 1-50 m/m, with duration of the highest gradients ranging from days to weeks while the lower will dominate and become negative in periods of draught because of capillary suction.

The most critical conditions with respect to percolation of the top liner will be those prevailing in paragraph 3, with the clay liner being completely water saturated. This is the case that we will examine in the paper.

3 Hydration and Permeation of Clay Liners

3.1 General

The amount of water that is infiltrated into the top liner of a waste pile and that penetrates the waste mass and the bottom clay liner per time unit depends primarily on the water pressure exerted on the liner. The hydration of it is transient since it depends on the varying access to water from the overlying drain layer, the water pressure and relative humidity of the air in the voids of this layer and in the clay layer. Taking the clay to consist of smectitic clay, like bentonite, and assuming that access to water from the overlying drain layer is unlimited, one can assume that hydration of the clay takes place by diffusive migration of water [7]. The time for saturation of the clay liner is very long as illustrated by the fact that a 20 mm thick layer of smectite clay with a dry density of 1300 kg/m^3 is almost 12 days by one-sided wetting if the diffusion coefficient is $3 \times 10^{-10} \text{ m}^2/\text{s}$, which is typical for dense smectite-rich clay. Considering that rain- and snowfall and hence access to water for uptake by the clay are intermittent and that draught will occur in periods, the actual time for complete saturation will be several tens of years and even more for a few decimetre thick smectite clay layer.

After water saturation of the top liner it will be percolated under the hydraulic gradient that is produced when a pressure head develops in the overlying drain layer. Prediction of the percolation rate is trivial, while definition of pressure heads and their persistence requires estimation of the water balance based on statistical precipitation data. As a very conservative case one can assume that the water level in the drain layer on top of the upper clay liner is maintained at a height over the clay liner that corresponds to 100% of the annual precipitation, which is taken here as 1 m. Using Darcy's law the percolation rate is:

$$v=K \times i \tag{1}$$

where: v =flow rate in m/s, K =hydraulic conductivity in m/s and i =hydraulic gradient (m/m)

Taking as an example K as 10^{-11} m/s, which is achievable by using smectitic clay with a density of about 2000 kg/m^3 at water saturation and a thickness of the clay layer of 1 m one has $i=1$ and $v=10^{-11}$ m/s, which means that a flow-transported water molecule moves by about 10 mm in 300 days and that it would take 100 years for it to migrate through a 1 m thick clay layer. Such a clay exerts a swelling pressure which can cause upheaval of the overlying soil layers if it exceeds the effective pressure caused by these layers. For a fully water saturated smectite-rich clay with a dry density of 1590 kg/m^3 , yielding a bulk density of about 2000 kg/m^3 after water saturation, the swelling pressure would be disastrous, i.e. 10 MPa. It is therefore required to use less smectite-rich clay and compact them to lower density. Taking the overburden to have an average density of 2000 kg/m^3 and be 5 m high it will exert a pressure on the upper boundary of the top liner of 100 kPa which is hence the upper limit of the swelling pressure exerted by the liner.

4 Iraqi Candidate Clay for Use in Top Liners

4.1 Location and Identification

Green and Red smectite rich clays were selected from Mosul City located in the northern part of Iraq. The clays belong to the Fatha formation, [8]. This formation is of Lower Miocene age and is composed of alternating beds of limestones, gypsum and green and red clays and siltstones. These beds are very thick toward the upper most part of the formation. The formation in its type locality is few hundred meters thick [9]. The green clay was extracted from a thick layer (at least 2 m) exposed near the ground surface in Qadia district, Figure 2, which appeared as hard light-green coloured pieces (Green clay). The Red clay had the form of brown/red hard pieces sampled from a thick layer (at least 3 m) about 4 km SSE from the place where the Green clay is located.

4.2 Characterization

The two smectite clays were crushed by means of impact before doing laboratory tests. The crushing product was sorted on a 1 mm sieve and further disaggregated by ultrasonic treatment before carrying out consistency limits, grain size analysis and specific gravity tests [10]. All the laboratory work was conducted according to the American Society for Testing and Materials (ASTM) or British Standard (BS).

4.2.1 Granulometry

Both wet sieving and pipette analysis were conducted, the grain size analysis being shown in Figure 3. Table 1 shows some physical properties of the Green and Red clays. Both were classified as CH soils according to the unified soil classification system (USCS). Further, clay activity characterization (Plasticity index/fraction<0.002mm) indicated both clays are active [11].

Table 1: Physical properties of the green and red clays from the Fatha formation

Soil	Liquid limit, w_L (%)	Plasticity index, PI (%)	Fraction <0.002 mm (%)	Activity, a_c	Specific gravity	CEC, meq/100 g
Green clay	148	91	65	1.40	2.76	23.1
Red clay	115	60	48	1.25	2.75	19.7

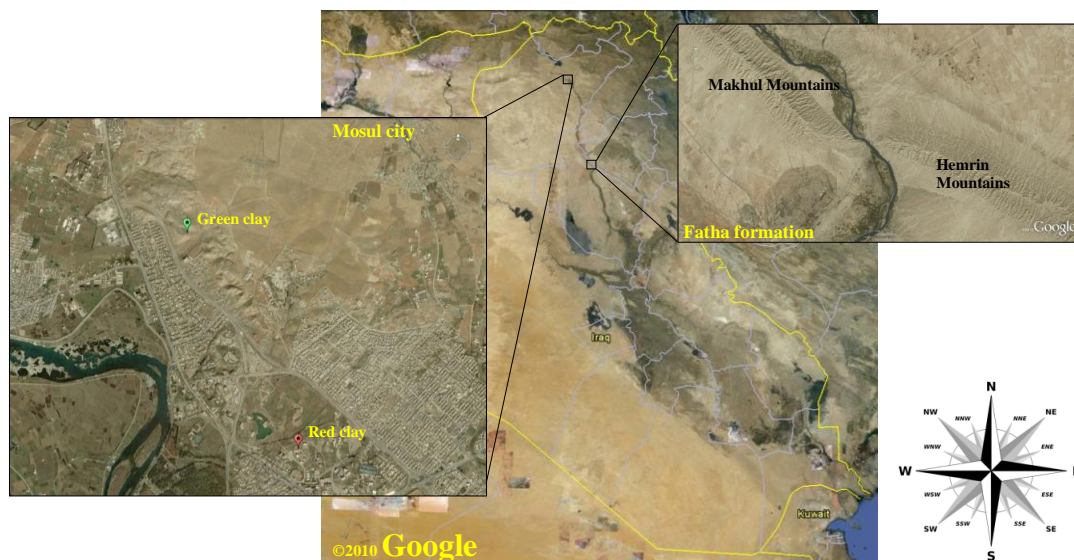


Figure 2: Left, the locations of green and red clays near Qadia district. Right, the Fatha formation within Makhul Mountains.

4.2.2 Methylene Blue test

Methylene Blue testing for approximate evaluation of the smectite content was conducted following the European Standard (spot method) [12]. Both clays were sieved on the 63 μ m sieve then treated with 3% hydrogen peroxide for removing organic substances [13]. The clays were then crushed again after oven-drying and sieved. The Methylene Blue value (MBV) was calculated using Equation 2 [14] and found to be 10/100g and 9.3/100g for the Green and Red clays respectively. These values reflect a high swelling potential according to the relation between MBV and the clay fraction content [15]. The Methylene Blue test could also be utilized to determine the cation exchange capacity (CEC) of the soil by using the formula suggested by Çokca and Birand [16]. The CEC values for the Green and Red clays are shown in Table 1.

$$MBV(g/100g) = \frac{[V_{cc}(mL) \cdot 10(g) \cdot 100(g)]}{[1000(mL) \cdot f'(g)]} \quad (2)$$

where, V_{cc} : Volume of methylene blue solution added, f' : dry weight of the soil used.

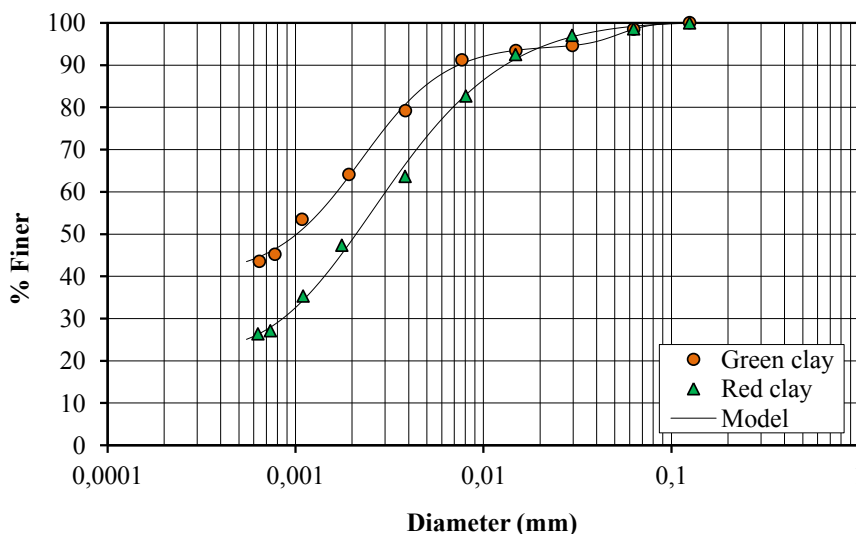


Figure 3: Grain size distribution of the green and red clays.

4.2.3 X-ray diffraction analysis of the Green and Red clays

The clay and non-clay minerals were identified by X-ray diffraction of randomly oriented powder. The Empyrean-PANalytical diffractometer at the division of Sustainable Process Engineering, Luleå University of Technology was utilized for the identification of major clay minerals and for the semi-quantitative analysis. Randomly oriented powder mounts were prepared by loading the soil powder using the back-loading technique via special arrangement. Another set was prepared for ethylene glycol solvation for better detection of expanding clay minerals like montmorillonite. The powder mounts were left inside a desiccator containing about 200 mL of ethylene glycol. The desiccator was stored into 60°C oven for 24 hours for better exposure to ethylene glycol vapor [17]. The diffraction patterns for the air-dry and glycolated samples were determined using CuK α radiation with Ni-filter at 40 mA and 45 kV. The divergence slit was kept in automatic mode (sample length 10 mm, radiation length 10 mm), the diffraction angle (2θ) ranged between 5-90° running at a speed of 0.026°.

4.2.3.1 Clay minerals identification

The X-ray patterns for the Green and Red clays shown in Figure 4 were analyzed using HighScore Plus software. The non-clay minerals calcite and quartz were detected from their strong peaks at 3.04 Å and 3.3 Å respectively in both clays. feldspar, zeolite, anhydrite and ankerite were spotted in the Red clay only. The clay minerals were detected from their $d_{(001)}$ reflections. The smectite was characterized in both clays from the $d_{(001)}$ reflection having about 15 Å for air-dry powder and about 17 Å in the glycolated powder, Figure 5. This indicates that the smectite is montmorillonite with Ca⁺² as a major cation. That is also evidenced from the liquid limit (wL) value of 148 and 115% for the Green and Red clays respectively. Pure Ca-montmorillonite wL usually range between 160-500%, whereas the pure Na-montmorillonite wL is much higher (500-700%) [18]. Further, clay activity values (a_c) also prove that the smectite is in Ca-form. The activity of

pure Ca- and Na-Montmorillonite is about 1.5 and 7.2 respectively. The activity values for the Green and Red clays were calculated to be 1.4 and 1.25 respectively. Illite and chlorite were also pinpointed in the Green and Red clays from the $d_{(001)}$ reflection at 10.1 Å and 14.2 Å respectively, Figure 4. The clay mineral kaolinite was detected in the Red clay only at 7.2 Å. It is believed that both clays also have some traces of palygorskite and sepiolite.

4.2.3.2 Semi-quantitative analysis of clay minerals

After qualifying the minerals existing in the Green and Red clays, a simple quantification procedure was conducted to determine the percentage of each clay mineral from the XRD patterns. The semi-quantification was based on the estimation of the area (intensity \times width) under strong peaks of each mineral. The goal is to precisely calculate the mineral intensity factor (MIF) for each clay mineral with respect to a reference strong peak of a certain clay mineral. The procedure was described by Moore and Reynolds [17]. However, only the major clay minerals were quantified, i.e. smectite, illite, chlorite and kaolinite. The illite (I_{002}) was selected as a reference peak to calculate the MIF for other minerals, Figure 4. Semi-quantification results are shown in Table 2 for the Green and Red clays.

Table 2: Percent of the major quantified clay minerals in Green and Red clays

Quantified clay minerals	Green clay	Red clay
Montmorillonite (%)	64	49
Illite (%)	25	48
Chlorite (%)	11	1
Kaolinite (%)	--	2

The smectite content in the Green clay is higher than the Red clay which also evidenced from wL , a_c and CEC values.

4.2.1 Experimental determination of hydraulic conductivity and swelling pressure

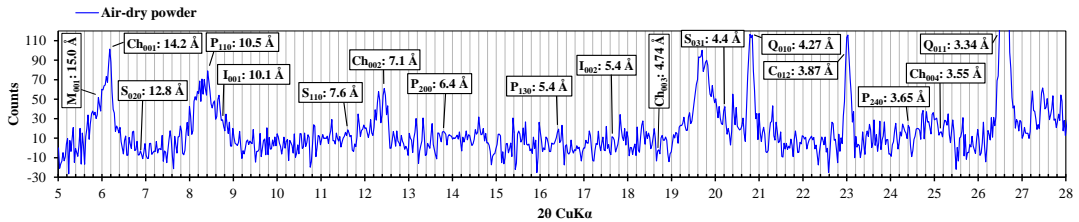
The following paragraphs will discuss the experimental procedures and results of the hydraulic conductivity and swelling pressure for the Green clay only. All the tests were conducted at the GeoLab, Luleå University of Technology. Stainless steel oedometer cells of 30 mm diameter were utilized for hydraulic conductivity determination, Figure 6. Three dry densities were selected to determine the hydraulic conductivity 1000, 1250 and 1500 kg/m³. Air dry samples were prepared by static compaction in four layers (5 mm thick) to meet the specified dry density. The interior of the oedometer cell was coated by a thin layer of very smectite-rich clay (MX-80) paste to eliminate leakage along the clay-wall contacts.

Filters of sintered stainless steel were used at the inflow and outflow ends of the cells. These filters were cleaned (after each run) by ultrasonic treatment in distilled water and de-aired by gentle boiling for 10 minutes prior to use. After compacting the samples, distilled water was supplied from the bottom end of the cells for reaching saturation without applying any back pressure.

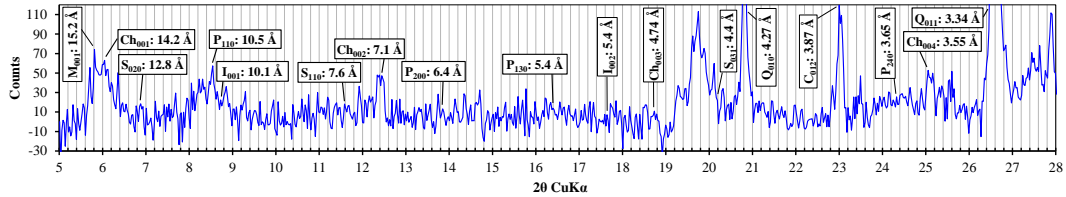
Hydraulic conductivity tests were conducted under different hydraulic gradients ranging between 5 and 95 m/m (meter water head divided by sample height). The hydraulic gradients were applied by use of a vessel connected to the inflow end of the cells and placed so that the intended gradient was maintained with very high accuracy. The testing

was made according to the method proposed by [7,19].

After saturation of the 20 mm thick samples, permeation started under the three specified gradients and the tests continued until stable values were reached [19]. The discharged water was collected in 100 mL glass containers with a rubber cap. A small needle was mounted on the cap for equalizing air pressure in the container without allowing desiccation as verified by a separate test using a free-standing arrangement of the same type. Permeation with distilled water at the lab temperature $20^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ lasted for 1–3 weeks depending on the clay dry density.

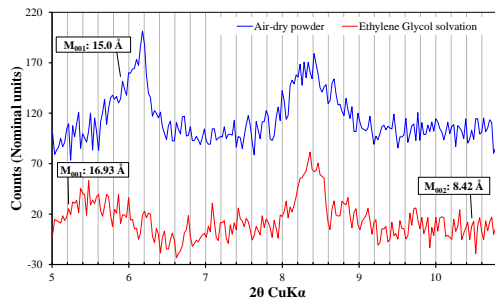


(a)

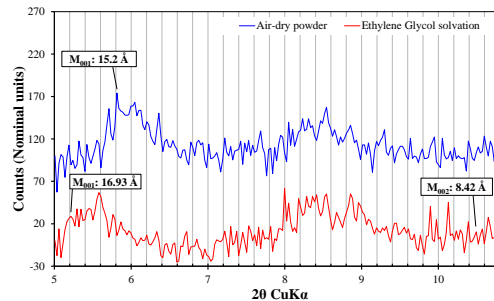


(b)

Figure 4: X-ray diffraction patterns of randomly oriented air-dry powders of (a) Green clay, (b) Red clay. Legend; M: Montmorillonite, Ch: Chlorite, S: Sepiolite, P: Palygorskite, I: Illite, Q: Quartz and C: Calcite. (The numbers indicate the d-spacing and the subscript indicates the reflection order of the mineral).



(a)



(b)

Figure 5: The identification of Montmorillonite of the air-dry and glycolated powders of the (a) Green clay, (b) Red clay.

4.2.2 Impact of hydraulic gradient on the hydraulic conductivity

The hydraulic conductivity increased as the applied hydraulic gradients were raised. This pattern was observed for all three densities and most clearly for the soil with lowest density, Figure 7-a. If K_{35} (K under $i=35$ m/m) is taken as a reference value for each

density, the ratio $K_{65}/K_{35} = 30\%$ and $K_{95}/K_{35} = 212\%$ for $\rho_d = 1000 \text{ kg/m}^3$, Figure 7-b. The difference between the two ratios is 182%. If we apply this to the dry density 1250 and 1500 kg/m^3 we get much smaller change, i.e. 28% and 11% respectively. This means that as the dry density increases, the impact of hydraulic gradients on the hydraulic conductivity decreases. This can be logically attributed to the fact that clay samples prepared at higher densities are more resistant to change in their structure. The clay plates will be closely arranged due to swelling pressure exerted by them [11].

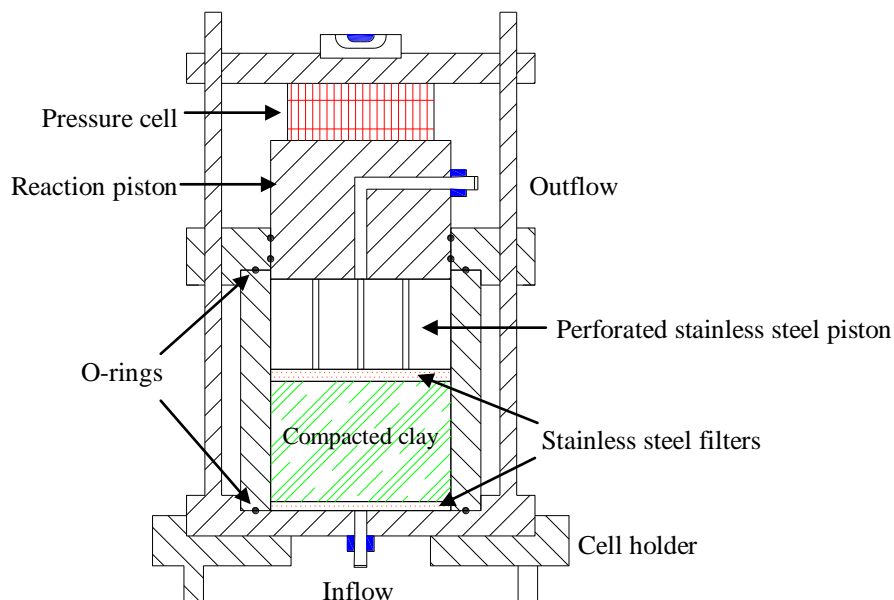


Figure 6: Schematic diagram of testing setup for hydraulic conductivity and swelling pressure.

4.2.3 Evaluation of the hydraulic conductivity under low hydraulic gradients

Table 3 shows the mathematical expressions for evaluating and predicting the hydraulic conductivity at very low gradients. The coefficient of determination (R^2) ranged between 0.91–0.99 which indicates good correlation. The right column shows the expected K values at $i=1 \text{ m/m}$ for different dry densities. This is a very important issue in the permeation of the top liners after fully saturated condition since the hydraulic gradients will be very low.

4.2.4 Experimental determination of the swelling pressure

The same oedometer cells were used for determining the swelling pressure of the green clay. Zero displacement pressure cells with 3–5 kN load capacity were mounted on the oedometers for logging the swelling pressure generated in the saturation phase, Figure 6. Four dry densities 1000, 1250, 1375 and 1500 kg/m^3 were investigated to correlate the swelling pressure with the dry density. The swelling pressure was not stable until after 2–6 weeks according to the criterion that the percentage change is less than 0.5% depending on the clay dry density. Stabilization of the swelling pressure indicates clay saturation [20].

Table 3: Models relating hydraulic conductivity with respect to hydraulic gradient and dry density

ρ_d (kg/m ³)	Models for predicting K , (m/s)	a	b	R^2	Expected K (m/s) under $i=1$ m/m
1000	$K_{(E-07)} = \exp(a + b \cdot \ln i)$ (3)	-1.506	0.094	0.99	2.2×E-08
1250	$K_{(E-10)} = \exp(a + b \cdot \ln i)$ (4)	-0.073	0.432	0.99	1.0×E-10
1500	$K_{(E-11)} = a + b \cdot i^{0.5}$ (5)	-0.024	0.174	0.91	1.5×E-12
1175 [§]	$K_{(E-09)} = \exp(a + b \cdot \ln i)$ (6)	-22.478	0.522	0.99	1.7×E-10

[§] interpolated, see Figure 8.

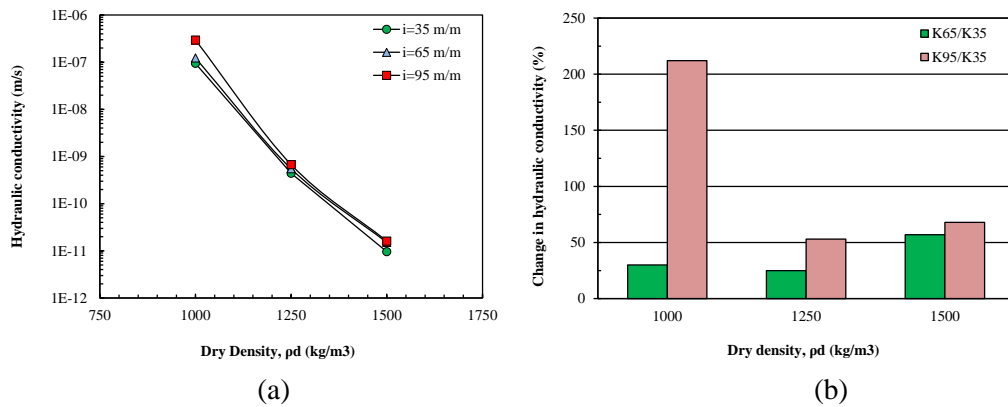


Figure 7: Left: Relation between hydraulic conductivity and dry density under various hydraulic gradients. Right: The impact of dry density on the percentage change in hydraulic conductivity, denser samples are less susceptible to change in hydraulic conductivity under increased gradients (notice the difference between the two columns for a given dry density).

4.2.4.1 Swelling pressure limitations for maintaining top liner stability

As the dry density increases the swelling pressure (S_p) increased as seen from Figure 9 and Equation 3. If the erosion protection layers overlying the top clay liner have an average density of 2000 kg/m³ and are 5 m thick, the generated overburden pressure would be 100 kPa. On that basis, the maximum permissible swelling pressure of the top liner is around 100 kPa. The dry density of the clay liner which is suitable to maintain the equilibrium will be about 1175 kg/m³, Equation 3.

$$S_p = \exp(-2.54142 + 0.000869 \times \rho_d \ln \rho_d) \tag{3}$$

5 Discussion and Conclusions

5.1 Predicted Performance

Landfills can be constructed in desert climate by locating them on elevated areas that will save them from flooding. A landfill designed as in Figure 1 with stable sloping sides and suitably composed overburden covering the clay top liner should guarantee long-term performance without maintenance. Assuming the top liner to be 1 m thick and exposed to a pressure of 1 m water head would be exposed to a hydraulic gradient of 1 m/m. By considering the aforementioned dry density 1175 kg/m^3 to be used for top liner construction, the hydraulic conductivity can be interpolated from Figure 8, giving K $1.5 \times 10^{-10} \text{ m/s}$, (Equation 6 in Table 3). This conductivity value will meet the USEPA and German code regulations, which are 1×10^{-8} and $1 \times 10^{-9} \text{ m/s}$ respectively for the top clay liners [21,22]. The bottom liner could be constructed with much higher dry density. Assuming the total height of materials overlying the bottom liner to be at least 10 m (including the final cover) with an average density of 2000 kg/m^3 , the overburden pressure would be 200 kPa. A height of 20 m would give the pressure 400 kPa. The bottom liner can hence have a dry density of 1375 kg/m^3 for the first mentioned height and still meet the stability requirements concerning swelling pressure. The hydraulic conductivity will be about $1.0 \times 10^{-11} \text{ m/s}$ if the liner is subjected to 1 m/m gradient, Figure 8, and this would also meet the regulations. However, there are other factors that can affect the performance of landfills as discussed below.

5.2 Risks

5.2.1 Physical stability of waste mass and liners

5.2.1.1 Liner desiccation

The upper most part of the top liner will be wetted by infiltrated water and undergo desiccation during drought seasons, causing risk of fracturing. The fractures can be filled with frictional material emerging from the filter material overlying the top liner and hence reduce the “effective” liner thickness as indicated in Figure 10. Such problems can be eliminated or minimized by installing a thick overburden over the top liner that for at least partial evening out temperature and moisture fluctuations. Further, one should also consider the self-healing capacity of smectites subjected to pressures greater than 50 kPa, which will self-heal the cracks generated from shrink–swell cycles [23]. The proposed overburden thickness of 5 m (100 kPa) may in fact prevent formation of desiccation cracks.

5.2.1.2 Internal erosion

High hydraulic gradients may cause internal erosion and migration of small particles in and from the top liner. Extensive laboratory tests [24] indicated the hydraulic gradients between 20–30 m/m are capable of tearing and transporting clay soft gel. Such threats are not applicable for thick clay liners but should be considered when using thin geosynthetic clay liners. These thin synthetic clays have microstructural heterogeneities at which the percolated water under high gradients will easily tear off and transport the soft gel [25].

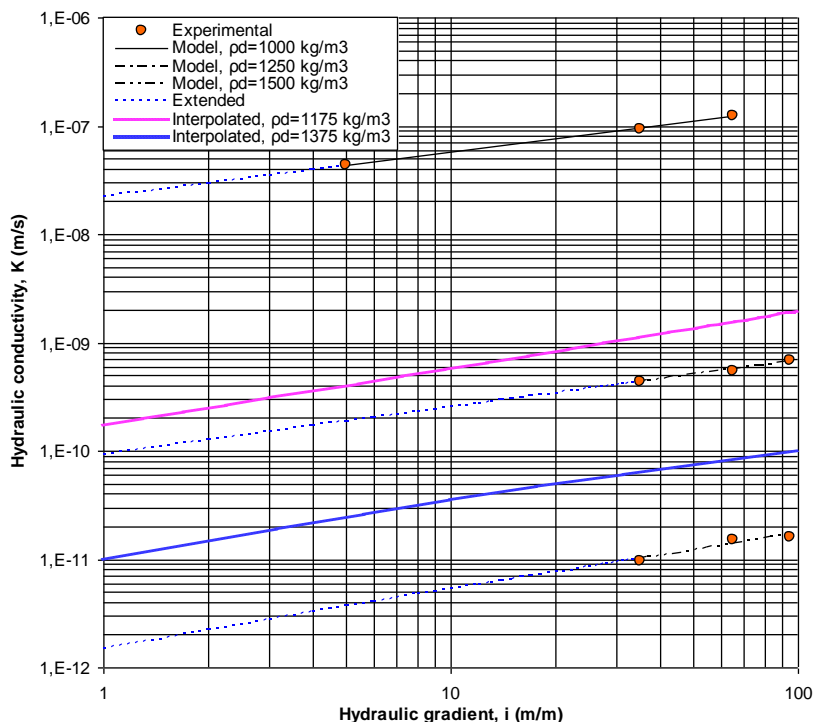


Figure 8: Relation between hydraulic gradient and hydraulic conductivity under different dry densities. The predicted relation of dry density 1175 and 1375 kg/m³ is based on interpolation of experimental data.

5.2.1.3 Gas generation

Top clay liners should be designed for maintaining physical stability in the case of gas generation that can cause upheaval of the entire top cover if the gas conductivity of the top liner is too low. Self-healing of the clay liner implying closing of gas channels depends on the clay expandability upon wetting. From a practical perspective, 40-50% smectite is sufficient to self-heal clay liners after gas penetration [24].

5.2.1.4 Cementation and permanent collapse

Silicification of smectite, i.e. cementation, is the consequence of chemical degradation of smectite to illite, chlorite or kaolinite. The dissolution of non-clay minerals like feldspar or mica due to hydrothermal processes will release H_3SiO_4 and finally the precipitation of silica in colder parts. The hydraulic conductivity will be increased due to the reduction of smectite expandability caused by welding of clay plates by the precipitated silica. The same process can take place in high temperature environments, more than 100°C, in deep geological repositories hosting highly radioactive waste but to a smaller extent in surface landfills [26,27]. A separate matter, related to displacement and malfunctioning of the top liner, is the risk of compression of the waste mass. For eliminating this problem the waste body must be effectively compacted to maintain the required stability and prevent mass body collapse. Stabilization of the waste mass by mixing or injecting low-pH cement is a suitable additional measure to be taken.

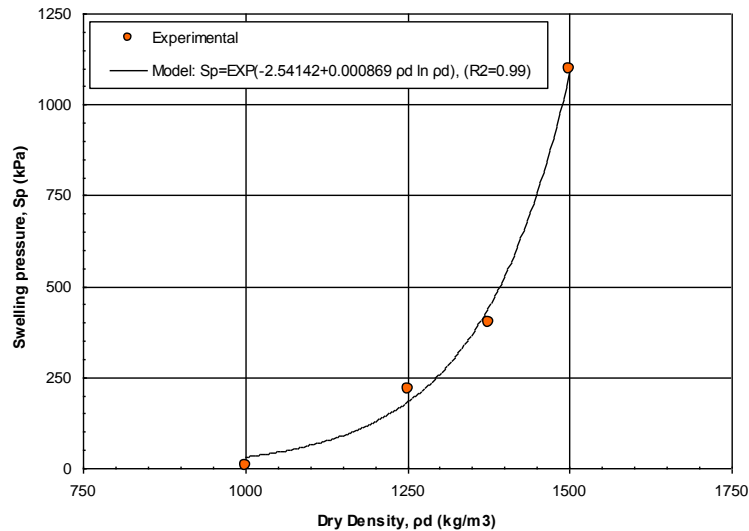


Figure 9: Swelling pressure of the Green Clay under different dry densities and saturation with distilled water.

5.2.2 Chemical stability of liners

Chemical degradation is the most threatening chemical process at which smectite minerals lose their expanding and healing capacity. Illite and Chlorite were considered as the ultimate products of such degradation process [7]. The smectite transformed either to mixed layer smectite/illite or to pure Illite. Suitable environment (pH and temperature) greatly control such process according to Pytte's theory [28]. The saturation process of the top liners normally occurs with low-electrolyte rain water that will not significantly alter the porewater chemistry. One should be aware of the layers overlying the top liner since they may contain sulphide minerals, and consider if the precipitation is in acidic form, since both will significantly lower pH of the porewater. However, a thick overburden layer with some carboniferous content can be capable of maintaining pH value of the percolated water between 6–8. By applying Pytte's model and considering pH value kept between 6–8 and the temperature at 60°C for the top liner, smectite will stay intact for at least ten thousands years [5]. Hazardous wastes generally undergo partial chemical stabilization prior to disposal in landfills, except for those containing radioactive contaminants. The chemical attack by leachate must be kept in mind as it causes serious defects. This issue is of great importance for bottom liners where it is considered as the final defence line. Acids have been reported to dissolve alumina while bases are capable of dissolving silica. Clay minerals contain large quantities of both silica and alumina hence are susceptible to partial dissolution by either acids or bases. Some acids like hydrofluoric and phosphoric acid aggressively dissolve clays. Leachate with $\text{pH} < 3$ and > 11 have the most affecting factor on the clays [5, 29, 30].

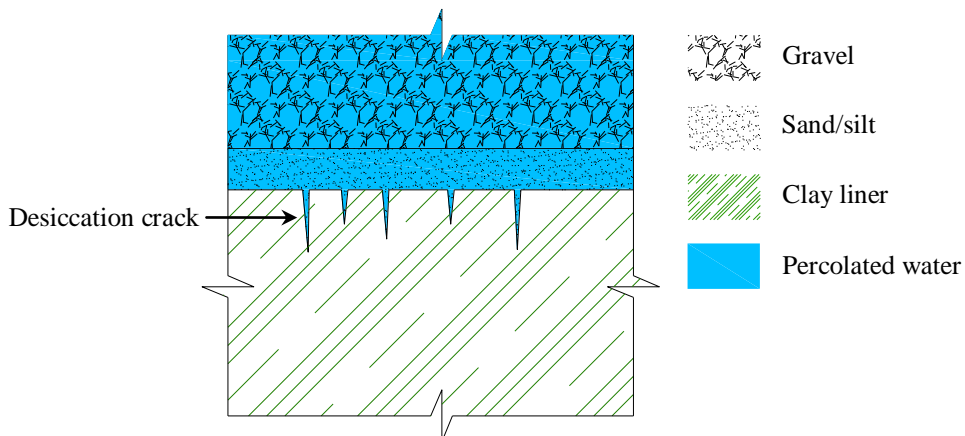


Figure 10: Poorly protected top liner against desiccation. Cohesionless materials overlying the top liner (i.e. sand/silt) may drop down in the cracks upon drying. Expandability of the clay due to the next wetting cycle will not effectively close up these cracks, hence reducing the liner thickness.

5.2.3 Biological activities and clay liners

Microorganisms present in the soil can adversely affect the hydraulic properties of the clays (increasing organic matter). Nutrient availability, temperature, oxygen, moisture and osmotic pressure are factors creating excellent environment for their impact. When a clay minerals gets in contact with certain bacteria, the later will degrade the bonding energy in the crystal lattices of clay minerals, leading to dissolution of them by biotransformation processes. Many waste forms are considered toxic to many microorganisms depending on the contact time and the concentration [26].

5.2.4 Landfill stability

Excessive differential settlement of clay liners can cause shear failure or fracturing under dry conditions. These effects are minimized if the clay layers are thick enough and ductile. A particularly important issue is the stability of sloping liners since failure of slopes will lead to release of pollutants and need for reconstruction. Slope instability can be caused by too low angle of internal friction or by artesian conditions triggered by seismic events. Slope stability must be insured by sufficient liner shear strength and the selection of appropriate slope angles as well as by well-designed supporting dikes. Most modern landfills are designed with side slopes of 3:1 (H:V) ratio, [29,30,31].

5.3 What is most Effective, the Top or the Bottom Clay Liner?

Considering the factors mentioned there are great advances in constructing very tight top liners. Thick protection covers for eliminating erosive degradation and for minimizing temperature variations in the top clay liner, as well as stable slopes of the landfill will create preconditions for acceptable long-term performance. If water percolation occurs through the top liner due to unsuitable design and construction, water will pass through the waste body and be charged with electrolytes released from the waste, thereby affecting the pH and causing cementing by precipitation of products like gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), calcium carbonates (CaCO_3) or iron complexes emanating from

reinforced concrete (Fe^{+2}) etc. The accumulated water in the waste mass will effectively raise the hydraulic gradient over the bottom liner and may cause breakthrough and failure of the bottom clay liner in a few years. Finally, a well-designed “very tight” top liner is believed to create a dry waste tomb for hundreds of years.

5.4 Recommendations for further Studies and Investigations

The landfill should be located on an elevated area for eliminating flooding and erosion. Efforts should be directed on constructing a very tight top liner with sufficiently heavy overburden to balance the swelling pressure caused by water saturation of the top liner. Further, the green and red smectites seems to be good candidates from engineering and economical point of view in Iraq. Both clays can be found in sufficient quantities for liners construction and be suitably processed by crushing via suitable technique. The inclusion of non-smectite constituents fine materials, e.g. silt and sand, makes the expandability suitable, but does not significantly reduce the required tightness. It also serves to give the clays a relatively high angle of internal friction and sufficient shear strength to provide the required slope stability.

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