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PRIMARY RESEARCH

Evaluation of clay soils' permeability: A comparative study between the natural, compacted, and consolidated clay soils

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Abstract— Many cities in Turkey use groundwater in order to meet their need of drinking water. Municipal solid waste landfills in all of the cities are major threat for groundwater. Low permeability clay soils by landfill operators are used as a standard practice. However, it has been shown that certain contaminants change the structure of clay soils, making them highly permeable. A lot of investigators have demonstrated that concentrated organic chemicals can alter compacted clays and cause increase in permeability. In this study, the effects of leachates on permeability and the treatment capabilities of the natural, compacted-consolidated, and compacted clay soil have been investigated. Clay soil samples were obtained from the Sile-Komurcuoda landfill area on the Asian side of Istanbul. In the experimental studies, Standard Proctor compaction tests and consolidation tests were applied to the clay soil obtained from the same area. The clay soil samples have permeability k of between 1.10^{-7} and 1.10^{-9} m/s. In order to determine the removal rate of the natural, compacted-consolidated, and compacted clay soil, Pb, Cr, Mn, and Fe are measured in the influent and effluent of the lab-scale reactor. The effects of leachates on the permeability of the natural, compacted-consolidated, and compacted clay soil samples have been analyzed. Initially, some decrease has been observed in the clay soil permeability associated with the contamination. The suspended solid matters in the leachates have filled the spaces between the particles of the clay soil pores and this caused a decrease in the permeability. After some time, it is shown that leachates may cause increase in the permeability. The treatment capabilities of the natural, compacted-consolidated, and compacted clay soil samples were quite high. The highest removal rates and the lowest permeability are obtained in natural clay, compacted-consolidated clay, and compacted clay, respectively.

I. INTRODUCTION

The infiltration of wastes causes a change in the structure of the leachate later. The composition of leachates is made of rich organic and inorganic pollutants, especially heavy metals [1, 2]. The leachate serves as an indicator in determining the type of waste. Process formation continues with the presence of contaminants such as hazardous chemicals, pesticides, and heavy metals in the leachate. [3, 4, 5, 6]. However, many organic substances are biodegradable and are further reduced by aerobic and anaerobic microorganisms [7].

Sililo [8] claimed that organic contaminants are able to move rapidly through the unsaturated zone [2, 8, 9]. Ground and surface water sources exposed metal ions

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which are often seen in landfills leachates [10, 11]. Removal strategies avoid the migration of these pollutants. Removal of metals is achieved by adsorption with filter materials [11, 12]. It is generally used as clay liners barrier to obstruct leachate transport and water source contamination [11, 13, 14]. The bottom liner can adsorb metal ions [11]. Leachate includes various organic and inorganic compounds. Therefore, storage areas possess a threat to groundwater [6, 15, 16].

Clay soil is a natural material that reduces hydraulic conductivity in landfills. Clay soil and uncompacted clay soil, which are frequently found in the nature, are the key components of the landfills. [17]. Given their high impermeability, clay soil is often used as pollution barrier for waste storage sites [1, 18, 19]. In most cases, the nature of clay soil that seals the site floor is a criterion for selecting the landfill site [1].

Contamination of soil and groundwater from the landfill is prevented by utilizing a system of composite liner including compressed clay soil or geosynthetic clay liner [20]. Compacted clay soil is preferred because it is low-cost and provides leachate treatment with high efficiency [21, 22]. Although the compacted clay soils have many superiorities like low permeability ($< 10^{-9}$ m/s), they have instability problems because of their potential of high shrinkage and expansion [22, 23, 24]. According to the design criteria of Turkish Solid Waste Management Legislation, the liner component is compacted to provide a hydraulic conductivity no greater than 10^{-9} m/s [25].

The composition of leachates changes over time due to the evolution process of waste degradation which is strongly linked to the mechanical-chemical and biological reaction taking place in the landfill [1]. The leachate quality changes corresponding to such factors as the type of waste, climatic factors, area hydrogeology, waste settlement, and type of cover material. The clay soils in the landfills may cause an increase in hydraulic conductivity over time due to water pressure [21]. Sivapullaiah *et al*. [25, 26] determined that the permeability of soils decreases with increasing content of smaller particles.

In the experimental studies, the effects of leachates on permeability and the treatment capability of natural clay, compacted consolidated clay, and compacted clay soil have been investigated. Clay soil samples were obtained from the Sile-Komurcuoda landfill on the Asian side of Istanbul. Standard proctor compaction tests and consolidation tests were applied to the clay soil. The soil samples have a permeability, k, between 1.10^{-7} and 1.10^{-9} m/s. Aiming to determine the removal rate of the natural clay, compacted-consolidated clay, and compacted clay soil, Pb, Cr, Mn, and Fe are measured in the influent and effluent of the lab-scale reactor.

II. MATERIALS AND METHODS

In this study, standard proctor compaction tests and consolidation tests were performed to the clay soil obtained from the Sile-Komurcuoda landfill area. Additionally, natural clay soil was also used without any treatment. Aiming to determine the removal rate of the natural clay, compacted-consolidated clay, and compacted claysoil, Pb, Cr, Mn, and Fe are measured in the influent and effluent of the lab-scale reactor. Chemical, physicochemical, and sieve analyses of clay soil have been taken from previous studies [27]. The aim of this paper has been carried out in two stages:

- In the first stage, clay soil taken from the Sile-Komurcuoda landfill site has been compacted, consolidated, and the permeability of the leachate has been investigated.
- In the second stage, Pb, Cr, Mn, and Fe analyses have been carried out to determine the treatment capacity of the natural clay, compacted-consolidated clay, and compacted clay soil. These analyses have been conducted on the samples taken from the influent and effluent of the reactors.

A. Experimental Setup

Constant-head permeameters experimental methods were used in this study [28]. Reactors, which were made of plexiglass materials (Figure 1), were filled with natural clay, compacted-consolidated clay, and compacted clay soil. Using distilled water as a permeant, permeabilities (k) were determined in 3-4 weeks to ensure proper column behavior. Permeability (k) was found to be: water, 5.284x10^{-9}, leachate, 2.64x10^{-8} m/s. Samples were taken from the soil and transferred to the laboratory and then pressed into the permeability reactor. In order to prevent the swell (expansion) of the clay soil in the apparatus, pieces of gravel were placed upon it. Meanwhile, a perforated plexiglass filter has been placed on and under the soil sample together with the filter papers. The mold reactor tests were performed by flowing the liquid downward through the 100 mm diameter natural clay, compacted-consolidated clay, and compacted clay specimens (Figure 1). Height of the clay soil specimens was 110 mm. Clay soil specimens were saturated under 0.3 bar pressure. Permeability tests were performed with water. After 3-4 weeks, water was replaced by leachate. Figure and photograph of experimental setup are given in Figure 1.

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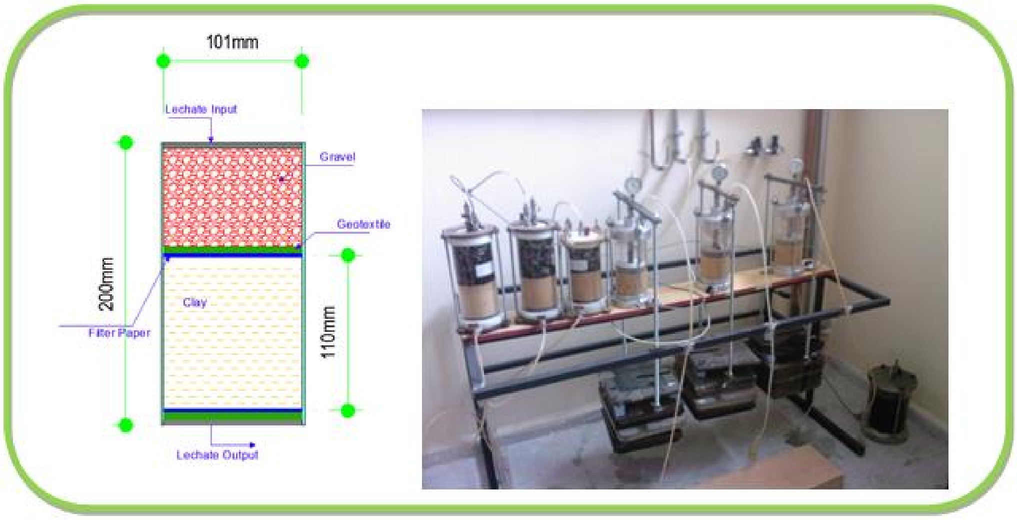

Fig. 1 . Experimental setup

B. Permeability Tests

Constant-head tests have been performed to calculate the permeability of the clay soil using Equation 1:

$$k = \frac{QL}{At(h_1 - h_2)} \tag{1}$$

where k is the permeability coefficient (cm/s), A is the surface area of specimen (cm^2), L is the distance between the manometers (cm), Q is the total discharge (cm^3/s), and t is the elapsed time (s).

C. Standard Proctor Compaction Test

Standard Proctor Compaction Testing is performed using the method ASTM D 698/AASHTO T99 [29] in the laboratory.

D. Consolidation Test

The consolidation test is based on the standard method (ASTM D2435-04) which has been designed to correct for the effects of sampling disturbance [30].

E. Effluent Analysis

Aiming to determine the attenuation capacity of the natural clay, compacted-consolidated clay, and compacted clay soil Pb, Cu, Mn, and Fe have been measured based on Standart APHA Methods in the influent and effluent of the continuous reactor [31].

III. RESULTS AND DISCUSSION

In this research, permeability and the removal rate for the Pb, Cr, Mn, and Fe have been investigated for the leachate taken from the Sile Komurcuoda Organized landfill site and the natural samples and the disturbed samples taken from the same place and natural soil samples, compacted with the standard compaction methods and compacted and consolidated soil samples. The results obtained are presented below. Chemical, physicochemical, and sieve analyses of clay soil have been taken from previous studies [27, 28].

A. Physico-Chemical Properties of the Clay

The clay soil was taken from Komurcuoda landfill site which is located in partially or totally abandoned mine quarry areas with damaged native soil surfaces. The clay is taken from a slightly inclined valley covered with Neogene aged layers of clay soil, sand, gravel, and coal lenses. The clay soil is chemically compatible with the fill area. The thickness of the clay liner underlying domestic solid wastes stored in the Komurcuoda solid waste landfill site is 60 cm and its permeability factor is between $1x10^{-7}$ and $1x10^{-8}$ m/s [27, 32, 33, 34, 35]. Colour of soil samples was brownish-gray. The clay samples that are taken from the site mentioned are made of kaolinite 68-71%, free quartz 6-9%, illite 15-18%, and others 2-5%. The kaolinite and illite are considered to be true clay soil minerals. The soil samples have the permeability k = $1x10^{-8}$ m/s and a discharge loss of 8.5-9%, and water of 0.2-0.4% [27, 28].

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B. Properties of the Leachate

The characteristics of the leachate have been investigated. The results of the characterization studies are presented in Table 1. Leachate has a colour of dark brown and includes very small granules and also large amounts of organic and inorganic contaminants, and a high concentration of metals.

TABLE 1
PROPERTIES OF THE LEACHATE

Parameter/Averages	pH	Pb (mg/L)	Cr (mg/L)	Mn (mg/L)	Fe (mg/L)
Samples	7.9	0.6	1.8	4.8	38.25

B. Results of the Compaction, Consolidation, and Permeability Tests

The compaction in the laboratory determines experimentally the change fullness of dry unit weight with the content of water and indicates the packing degree under certain compaction energy. The compaction experiments were conducted for the clay soil used in filling. Standard and modified compaction tests are the two most commonly used methods of compaction tests. The results of the experiment performed to obtain the correlation between the water content of the soil and compacted dry density are given in Table 2 and Figure 2. Figure 3 shows the stress and strain curves of the samples to which consolidation was applied.

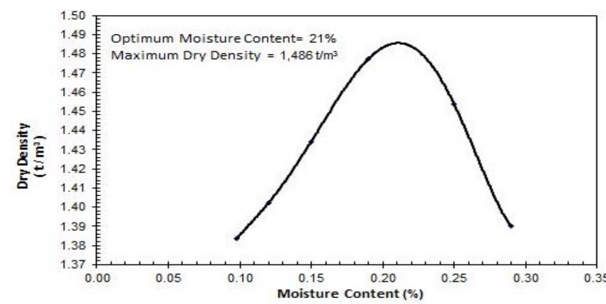

Fig. 2 . Moisture content and dry density relationship

TABLE 2
COMPACTION STUDY RESULTS

Sample place	Volume of container (cm^3)	Diameter (cm)	Height (cm)	Number of layers	Weight of hammer	Height of drop	Number of strike
Komurcuoda	1000 cm^3	10.47 cm	11.56 cm	3	2.5	30.5	25 strikes for every layer

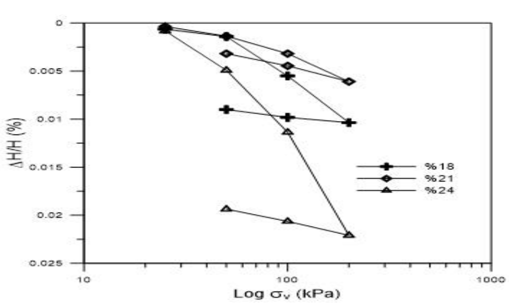

Fig. 3 . Oedometer stress and strain test relation

The experiments were performed in the laboratory to determine the effects of Pb, Cr, Mn, and Fe on permeability of clay soil for about 220 days. Permeabilities are determined by performing the experiments on compacted clay and compacted-consolidated clay samples by different energy applications in the laboratory. Permeability experiments were performed on the samples that were prepared at the optimum water content, over 3% and under 3% of the optimum water content, obtained as a result of the standard compaction application. Then permeability measurements were carried out, where leachate was passed through the samples. The same procedures were repeated on the samples prepared by applying consolidation with the standard compaction and natural clay soil.

As seen in Figure 4 (a, b, c), changes were observed in the permeability of the natural, compacted-consolidated, and compacted clay samples. Initally, the suspended solids, metal ions, and microrganisms within leachate were seen to decrease the permeability by filling the void spaces among

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the particles of the clay soil. The permeability decreased significantly with time (up to 29^{th} day), since the permeating liquid microorganism growth inside the soil pores caused pore clogging and suspended solids, and precipitated some metal ions to fill the void spaces among the particles of the compacted clay soils. However, some deformations occur in the structure of clay soil due to the presence of very high concentration and a variety of pollutants in leachate. These deformations lead to an increase in the permeability of clay soils over time (after the 29^{th} day).

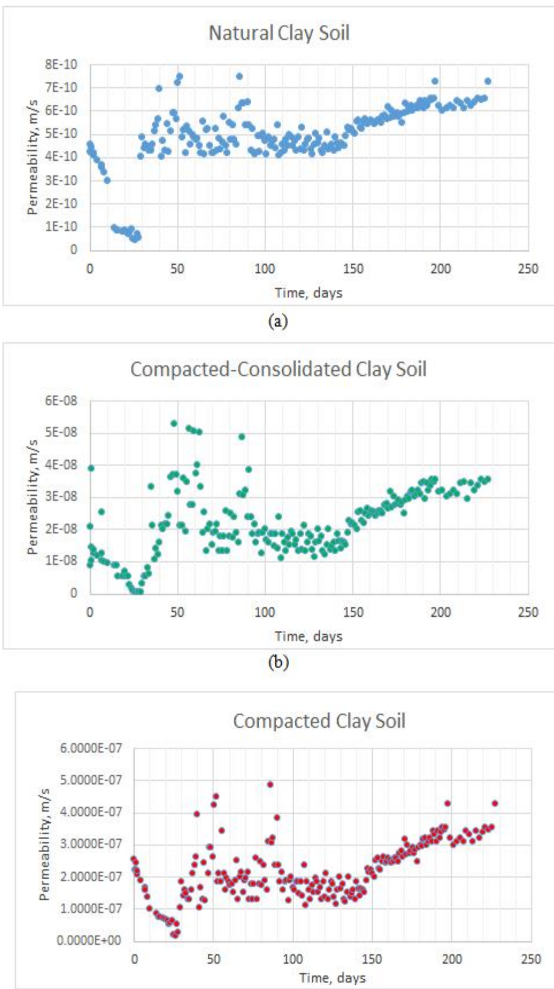

Fig. 4 . Permeability and Time Relation

In addition, it was also observed that leachate passed faster through samples to which standard compaction was applied only and passed with more difficulty through compacted-consolidated samples. Leachate gets through with a slower rate in natural clay soil, while the permeability of compacted samples was seen to be at the level of 10^{-7} m/s, that of compacted-consolidated samples was at the level of 10^{-8} m/s, and the permeability of natural clay soil was found as 10^{-10} m/s.

C. Effluent Analysis Results of the Landfill Leachate in the Clay Soil

Effluent analysis results for Pb(II), Cr(II), Mn(II), and Fe(II) are shown in Figure 5 (a, b, c, d). The initial Pb(II) value of leachate was 0.6 mg/L. The first passage of leachate through natural clay soil was observed on the 40^th day. The time required for compacted and consolidated clay soil is about 35 days and for compacted clay soil, it is about 28 days. Pb(II) effluent value was 0.16 mg/L and removal efficiency was 73% on the 90^{th} day in the reactor filled with natural clay. On the same age-day for the compacted and compacted-consolidated samples, Pb(II) effluent value was 0.23 mg/L and the removal efficiencies of 62% by standard compaction with 21% humidity (optimum humidity rate) can be located. Removal rate efficiencies were monitored for 220 days. The leachate's breakpoint for clay soil occured at the end of the three months. Figure 5a shows that removal rate efficiency increases until the 90^th day; afterwards, it decreases. The reason for this variation can be the adsorption until the turning point, then desorption begins. Pb(II) removal efficiency was observed to be quite high for natural clay.

The influent Cr(II) value of leachate obtained experimentally was 1.8 mg/L. For the natural clay at the end of the third month, removal efficiency and Cr(II) effluent values were 92% and 0.14 mg/L, respectively. For compacted and consolidated clay soil in the same period of time, the removal efficiency was found as 89% and the Cr(II) effluent value as 0.19 mg/L. The efficiency value is 82% and effluent value is 0.32 mg/L for the compacted clay soil on the 90^th day. Removal rate was meassured for 220 days. During the first 90 days, removal rate went up; afterwards, it went down. This can be explained by the same reason as in the part of removal of Pb.

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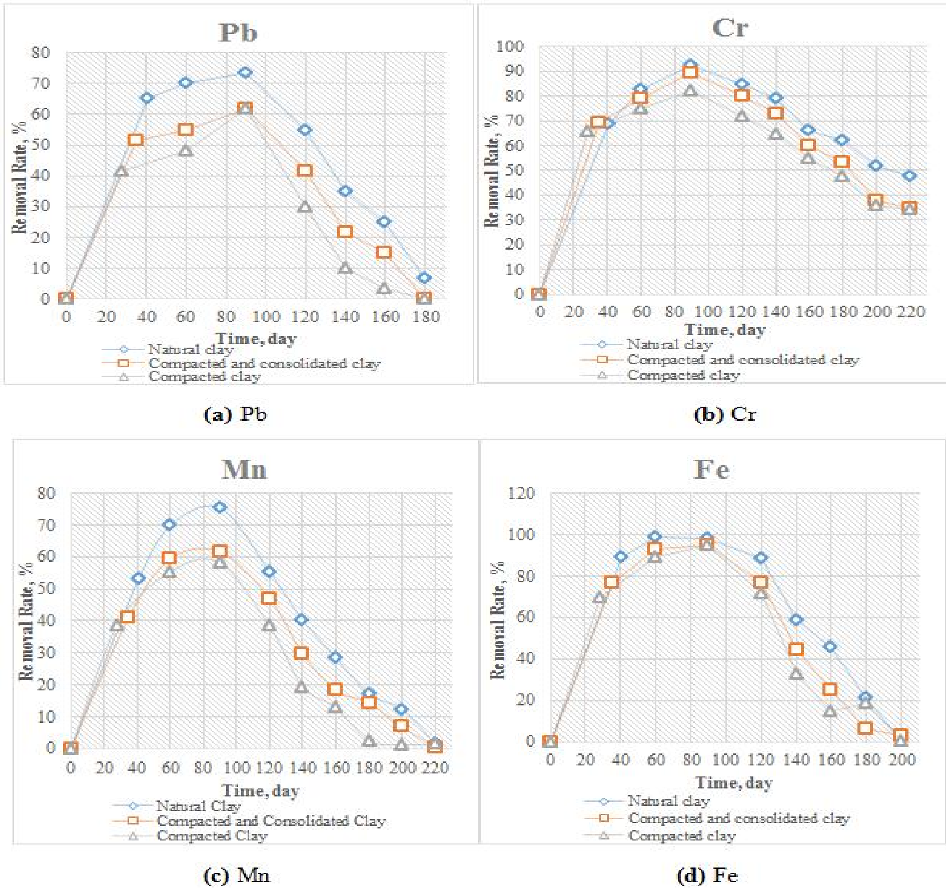

Fig. 5 . The removal rate of Pb (a), Cr (b), Mn (c), and Fe (d)

The experimentally obtained influent Mn(II) value of leachate was 4.8 mg/L. Mn(II) effluent value was obtained as 1.18 mg/L and removal efficiency as 75% on the 90^{th} day in the reactor for natural clay. For compacted-consolidated clay soil samples, the Mn(II) effluent value was meassured as 1.84 mg/L and removal efficiency as 62% on the 90^{th} day. 2.01 mg/L is the determined Mn(II) effluent value and 58% is the removal efficiency on the 90^{th} day in the samples compacted by standard compaction. However, as it can be seen in Figure 5, the removal efficiency of Mn(II) was seen to increase generally until the 90^{th} day and it began to decrease in the following days. This change can be explained so that adsorption turns to desorption after the 90^{th} day. Mn(II) removal efficiency was observed to be quite high for natural clay.

The influent Fe(II) value of leachate is obtained experimentally as 38.25 mg/L. Fe(II) effluent value was 0.54 mg/L and removal efficiency as 99% on the 60^{th} day in the reactor with the natural clay sample. For compacted and consolidated clay soil, 2.05 mg/L is the Fe(II) effluent value and removal efficiency is 95% at the end of the third month. For compacted clay soil, 2.01 mg/L is the Fe(II) effluent value and removal efficiency is 95% on the 90^{th} day in the reactor with clay sample compacted by standard compaction with 21% humidity (optimum humidity rate). Removal was monitored for 200 days. However, as it clearly can be seen in Figure 5, the removal efficiency of Fe(II) was seen to increase generally until the 60^{th} day for natural clay and 90^{th} day for compacted-consolidated and compacted clays and began to decrease in the following days. This change can be explained by adsorption until the 60^{th} and the 90^{th} day followed by desorption. Fe(II) removal efficiency was observed to be quite high in the study examining the removal of natural clay.

IV. CONCLUSION

In this study, high removal efficiencies have been obtained after leachate passes through clay samples and it has been observed that the clay has a natural purification capacity. It has been observed that the suspended matters in the leachate filled the spaces between the clay particles and

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the growth of microorganisms inside the soil pores caused pore clogging which led the permeability to decrease. In the long term, it is expected that this variation would take place in the reverse direction. In other words, the permeability would increase. It is considered that this variation would be the result of the certain chemical and physical deteriorations produced by the contaminative components in the leachate.

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