



# Measuring the engineering properties of landfill leachate-contaminated soil in Egypt

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## Abstract

Industrial activities produce millions of tons of hazardous waste annually, which are eventually disposed of in landfills. In this study, the effect of saline industrial hazardous landfill leachate (SIHLL) on the geotechnical properties of natural and contaminated silty clay soil was investigated via laboratory-based experiments in order to assess the potential application of this soil as a barrier lining in a saline hazardous industrial waste landfill. Contaminated soil specimens were prepared by mixing natural soil with SIHLL at different concentrations (0%, 25%, 50%, 75%, and 100%). The results revealed that the permeability coefficient ( $k$ ) and the total pore volume (TPV) of the SIHLL-contaminated soil decreased from  $8.6 \times 10^{-8}$  to  $5.91 \times 10^{-8}$  cm/s and from  $10.24 \times 10^{-2}$  to  $7.65 \times 10^{-2}$  cm<sup>3</sup>/g, respectively, as the SIHLL concentration was increased from 0 to 50%. These effects were mainly due to the high concentration of salts in the SIHLL. The addition of SIHLL reduced the optimum moisture content (OMC) of the soil from 18% for natural soil to 14% for 100% SIHLL-contaminated soil, and the maximum dry density (MDD) recorded (for 100% SIHLL-contaminated soil) was 17.95 kN/m<sup>3</sup>. The angle of internal friction ( $\varphi$ ) of the soil dropped from 27.8° for 0% SIHLL-contaminated soil to 23.7° for 100% SIHLL-contaminated soil. Also, the cohesion ( $c$ ) decreased as the SIHLL concentration increased. In addition, considerable lowering of the consistency limits was observed for the SIHLL-contaminated soils. Based on these findings, the studied silty clay soil would be suitable for use in the construction of a new hazardous solid-waste landfill liner due to its low permeability and widespread availability in Egypt.

**Keywords** Landfill leachate · Silty clay soil · Permeability · Shear strength · Contamination · Geotechnical properties

## Introduction

Rapid population growth and industrial expansion are the biggest challenges facing many developing countries, as this growth leads to the generation of massive amounts of municipal and industrial solid wastes. Appropriate management of these wastes is urgently required. The disposal of solid waste in traditional ways such as incineration or open dumping poses threats to health and the environment (EQI 2005). Recently, landfilling has become the preferred technology

for the final disposal of solid waste because this technology is more economical and environmentally friendly than other disposal technologies (Meky et al. 2019). Generally, landfills are classified into municipal solid-waste landfills, construction and demolition solid-waste landfills, and industrial solid-waste landfills.

Clay soil plays a crucial role in the barriers that are used to line solid-waste landfills, as its low permeability helps to minimize the migration of hazardous leachate into the environment. Such barriers take the form of slurry walls, landfill liners and covers, and lagoon liners (Moavenian and Yasrobi 2008). The infiltration of hazardous leachate into the soil causes groundwater contamination and changes the geotechnical properties of the soil. Therefore, when the landfill barrier is significantly damaged, toxic leachate can be transported by rainfall into the groundwater, meaning that it can disperse into the areas surrounding the landfill (Ratnaweera and Meegoda 2006).

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The interactions between soil and contaminants from a landfill depend greatly on factors such as the nature and chemical compositions of the soil and the contaminants, the electrolyte concentration, the types and valences of the ions present, and the dielectric constants of the contaminants (Sunil and Shrihari 2004). Saline industrial hazardous landfill leachate (SIHLL) contains numerous cations, anions, and heavy metals that can modify the geotechnical properties of the clay liner of a landfill. The effects of salts on soil compressibility and consistency have been studied for various types of soils (Yukselen-Aksoy et al. 2008; Arasan and Yetimoğlu 2008). Other studies (Gajo and Maines 2007; Wahid et al. 2011; Li et al. 2015) have investigated the effects of chemical contaminants such as inorganic acids and bases, hydrochloric acid, ethylene diamine tetraacetic acid (EDTA), and lead on soil shear strength. Nayak et al. (2007) demonstrated that soil permeability increased and the MDD slightly decreased upon increasing the leachate content from 0 to 20%. The properties of contaminated soil were found to be radically different from those of natural soil in terms of consistency limits, compaction, and compressive strength (Sunil et al. 2006). Burns et al. (2006) reported that contamination with benzyltriethylammonium chloride (BTEA) increased the friction angle of organoclay. Other studies, including those by Sridharan et al. (1981), Foreman and Daniel (1986), Uppot and Stephenson (1989), Gnanaprasam et al. (1995), Kamon et al. (1996), Soule and Burns (2001), Roque and Didier (2006), Sunil et al. (2006), Abollino et al. (2008), Cuevas et al. (2009), Yong et al. (2009), Li et al. (2015), Trzciński et al. (2015), Deng et al. (2017), and Khodary et al. (2020), have also indicated that some soil contaminants (e.g., heavy metals, organic liquids, and landfill leachates) change the properties of their host soils. Li et al. (2013) found that the hydraulic conductivity of compacted clay dropped due to the reduction in effective porosity resulting from landfill leachate infiltration. Hakan and Akar (2017) stated that the hydraulic conductivity of bentonite contaminated with landfill leachate was almost the same as that of bentonite permeated by distilled water. A few studies have focused on the geotechnical behavior of soil contaminated with industrial waste. By way of illustration, Srivastava et al. (1994) studied the impacts of four wastewaters (from a sugar mill, a paper mill, the power generation equipment manufacturing industry, and a fertilizer plant, respectively) on the behavior of low-plasticity clay. In all four cases, elevated consistency limits, permeability, and compression index values as well as decreased shear strength and bearing capacity were observed. Gratchev and Towhata (2016) studied the compressibility of soil contaminated with sulfuric acid. They noted that the compressibility of soil increased due to the dissolution of calcium carbonates and ferric oxides between clay particles. Emmanuel et al. (2020) studied the effect of MSW leachate on Malaysian marine

clay to check the effectiveness of this clay as a liner for the bottom of a landfill. Their findings revealed that the coefficient of permeability of the studied clay soil increased with leachate contamination; however, the value of  $k$  still met the local regulatory requirements. Khodary et al. (2020) examined the behavior of a high-plasticity clay soil contaminated with industrial landfill leachate. They noticed that the plasticity index of the contaminated soil decreased significantly as the leachate content increased.

Therefore, to evaluate the performance of a clay liner that can be used as a barrier in a landfill, its behavior in the presence of real landfill leachate must be investigated. The effects of municipal landfill leachate on the geotechnical properties of soil have been extensively investigated in previous studies, but less attention has been paid to the impact of hazardous industrial landfill leachate on the geotechnical properties of clay soil (Khodary et al. 2018). Hence, the primary objective of this study was to systematically investigate the effects of SIHLL contamination on the geotechnical characteristics of silty clay soil, in particular its permeability, compaction characteristics, Atterberg limits, and shear strength, in order to assess the potential of this clay for use as a barrier material to line a hazardous industrial solid-waste landfill.

## Materials and methods

### Study area

Egypt produces approximately 0.3–0.8 kg MSW/day/person, a figure that is growing by 3.4% annually (Elfeki et al. 2015). 85% of this waste is mainly dumped in the desert and open areas. Likewise, approximately 6.2 million tons of industrial wastes are produced in Egypt annually, including 0.2 million tons of hazardous waste (Elfeki et al. 2015). Alexandria, a densely populated Egyptian city (3.8 million residents in 2017), has a wide range of industries, including roughly 1900 medium/large-sized industries (around 40% of all the industries in Egypt). The El-Nasreya Landfill (Fig. 1) was established in 2004 to dispose of industrial hazardous solid wastes that are generated within and outside Alexandria and to protect the environment and public health from the adverse impacts of improper disposal practices. This facility was the first and is the largest landfill of its type in Egypt. It receives only particular types of industrial waste materials, including dry inorganics, asbestos, ash from heavy fuel oils, contaminated soil, heavy metals, sludge from galvanic processes, insoluble metal salts, inks, dyes, lacquers, paint sludge, resins, polymers, and chemical containers. The landfill is still active; it produces approximately 10 m<sup>3</sup> of leachate per day, which is stored in a pond (Ramadan et al. 2005).



**Fig. 1** Location of the El-Nasreya Landfill (from Google Maps)

The El-Nasreya Landfill has a cell with a capacity of 40,000 m<sup>3</sup> and four solar evaporation ponds covering a total area of 5000 m<sup>2</sup>. They were constructed as a means of drying liquid and sludge wastes in the dry and hot climate of this area (where the mean temperature is 30 °C and 19 °C in summer and winter, respectively). The average rainfall (rain occurs only in the winter) is 200 mm per year. The lining consists of a 300 mm drainage layer made from crushed stone (particle size: 6–32 mm) and a 2 mm high-density polyethylene membrane to prevent leachate leakage (Ramadan et al. 2005).

Double-liner systems are mainly used in hazardous waste landfill linings that include a compacted clay liner. The upper liner is designed to collect leachate, while the lower one serves as a leak detection system. Because bentonite (the clay most commonly used in liner construction) is expensive, there is a pressing need to find a more economical alternative, such as natural soil, which is investigated in this research work.

### Saline industrial hazardous landfill leachate (SIHLL)

The SIHLL used in this study was collected from the landfill site located in the El-Nasreya area, 35 km southwest of Alexandria, Egypt (Fig. 1). The fresh SIHLL was transported to the laboratory in sealed plastic barrels and used directly. The chemical composition of the SIHLL is presented in Table 1. The standard deviations presented in Table 1 were calculated based on analyses of three SIHLL samples. Five distinct concentrations of SIHLL were used in this study: 0% (i.e., distilled water), 25% (i.e., 1:3 SIHLL:distilled water by

volume), 50% (i.e., 1:1 SIHLL:distilled water by volume), 75% (i.e., 3:1 SIHLL:distilled water by volume), and 100% (i.e., raw SIHLL).

### The soil

The natural soil was collected from borrow pits located in Borg Al-Arab City, Alexandria, Egypt (longitude 29°36'42"E, latitude 30°50'56"N) at a depth of 1.5 m. Soil was taken at ten sampling points in a zigzag pattern to ensure that the samples were distributed uniformly across the sampling site. The same amount of soil was taken using shovels from all sampling points. All soil samples were well mixed and then placed in plastic bags that were subsequently tightly sealed and arranged in cardboard boxes before being shipped to the laboratory. After that, the mixed soil samples were thinly spread over plastic trays in order to dry them uniformly in the oven at a temperature of 100 °C for 24 h. The large soil aggregates were carefully crushed to accelerate the drying process with the aid of a pestle and mortar. After grinding, the soil samples were passed through a no. 16 sieve and stored in plastic containers. The grain-size distribution curve of the soil (from ASTM D421, D422) is presented in Fig. 2, while the geotechnical properties of the natural soil are listed in Table 2.

### Methods

The specific gravity of the natural soil was tested according to ASTM D854-92. The standard Proctor test for compaction

**Table 1** Chemical composition and characteristics of SIHLL

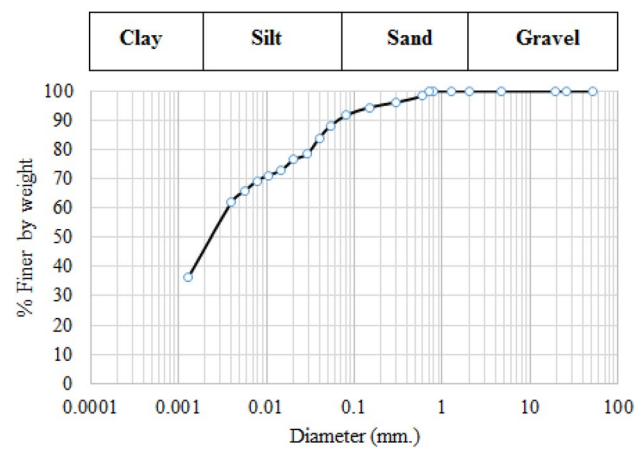
Parameter	Value (mean ± standard deviation) (n=3)
pH at 25 °C	8.8 ± 0.1
Total dissolved solids (TDS; mg/L)	38,990 ± 2321
Electrical conductivity at 25 °C (EC; dS/m)	61 ± 3.8
Total chemical oxygen demand (CODt; mg/L)	3618 ± 234
Soluble chemical oxygen demand (CODs; mg/L)	3492 ± 212
Heavy metals (mg/L)	
Cu <sup>2+</sup>	0.011 ± 0.001
Pb <sup>2+</sup>	0.09 ± 0.02
Cd <sup>2+</sup>	0.3 ± 0.1
Zn <sup>2+</sup>	0.5 ± 0.2
Cr <sup>2+</sup>	1.42 ± 0.31
Fe <sup>3+</sup>	20.97 ± 1.48
Mn <sup>2+</sup>	22.75 ± 1.59
Ni <sup>2+</sup>	38.53 ± 2.73
Ions (mg/L)	
Na <sup>+</sup>	15,159.3 ± 23.8
K <sup>+</sup>	425.1 ± 32.7
Ca <sup>2+</sup>	190 ± 2.8
Mg <sup>2+</sup>	312 ± 29.7
Al <sup>3+</sup>	74.7 ± 10.3
HCO <sub>3</sub> <sup>-</sup>	2013.6 ± 46.2
Cl <sup>-</sup>	23,501 ± 231
SO <sub>4</sub> <sup>2-</sup>	504 ± 23

characteristics was carried out according to ASTM D698 using different dilutions of the SIHLL in lieu of water.

In the permeability test, the SIHLL was used as the permeant to simulate the conditions in situ. Falling head tests were conducted to determine the permeability coefficients using a cylindrical mold (diameter 10.16 cm) according to ASTM D5084 and at room temperature (25 °C). At its maximum dry density, the clay (which contained 18% water) was compacted in a mold into three layers. After extruding the clay from the mold, it was trimmed. All experiments were repeated three times for each concentration. Making the assumption that Darcy’s law was applicable, the *k* value was calculated as follows:

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2}, \tag{1}$$

where *a* is the cross-sectional area of the standpipe (cm<sup>2</sup>), *L* is the length of the soil sample (cm), *A* is the cross-sectional area of the soil sample (cm<sup>2</sup>), *h*<sub>1</sub> is the head loss across the sample at time *t*<sub>1</sub> (cm), *h*<sub>2</sub> is the head loss across the sample at time *t*<sub>2</sub> (cm), and *t* is the time between *h*<sub>1</sub> and *h*<sub>2</sub> (s).



**Fig. 2** Particle-size distribution curve for the natural silty clay soil

The Atterberg limits of the portion that passed through sieve no. 40 were examined according to ASTM D4318. Distilled water was used as the pore liquid for the natural soil, while SIHLL dilutions were used as the pore liquids in lieu of distilled water for the contaminated soils. A series of direct shear tests were performed using a shear box of size 6 × 6 cm and at a shear rate of 0.02 mm/min in accordance with the ASTM D3080 method under normal stresses of 50, 100, and 150 kPa. The samples were remolded samples at MDD and OMC and were presaturated with different concentrations of SIHLL (0%, 25%, 50%, 75%, and 100%) for 24 h inside the box. Each test was conducted thrice.

Each SIHLL-contaminated soil sample was taken out of the permeability mold in order to perform EC tests. This involved cutting the contaminated clay samples and drying

**Table 2** Properties of the natural silty clay soil

Property	Value
Color	Pale yellow
Specific gravity (Gs)	2.65
Grain size (%)	0
Gravel	8
Sand	43
Silt	49
Clay	
Optimum moisture content (%)	18
Maximum dry density (kN/m <sup>3</sup> )	17.52
Permeability coefficient (cm/s)	8.6 × 10 <sup>-8</sup>
Angle of internal friction	27.8°
Cohesion (kPa)	16
Plastic limit	19
Liquid limit	36
Plasticity index	17
Classification	CL

them in an oven at approximately 105 °C before determining their EC values using a method that involved mixing the dried samples with distilled water at a ratio of 1:1 solid:water, shaking this suspension periodically for 1 h, and then measuring the EC of the suspension with a conductivity meter.

A GLP21 pH meter calibrated with a pH standard was used to determine the pH of each SIHLL sample. The total chemical oxygen demand (COD<sub>t</sub>), soluble chemical oxygen demand (COD<sub>s</sub>), and total dissolved solids (TDS) of the SIHLL, as well as its anion and cation concentrations, were determined according to standard methods (APHA 2005). The samples were filtered through a 0.45 µm membrane to measure the soluble COD. The concentration of hydrocarbons in the SIHLL was measured using a gas chromatograph–mass spectrometer system (GC/MS; Shimadzu Qp2010 Ultra). The hydrocarbons in the SIHLL samples were extracted using methyl *tert*-butyl ether as a solvent and injected into GC/MS at a ratio of 1:1. 2-Bromo-1-chloropropane at 20 ppm was used as an internal standard. The injection temperature was set at 200 °C, and helium was used as the carrier gas at a flow rate of 1 mL/min. The oven was initially kept at a temperature of 35 °C for 7 min, and the column temperature was programmed from 35 to 90 °C at a flow rate of 20 mL/min. The concentration of heavy metals was analyzed using an atomic absorption spectrophotometer (AAS; Perkin Elmer AAnalyst 200). Liquid samples were first filtered through a 0.45 µm cellulose acetate membrane filter (Sigma–Aldrich, USA), and then the filtrate was analyzed for residual heavy metals after acidification with nitric acid (pH < 2) to prevent metal precipitation and adsorption onto surfaces.

Morphological studies of natural and contaminated soil were carried out using a scanning electron microscope (SEM; JEOL JSM 6360 LA, with a high-resolution range from 100 to 0.5 nm at 20 kV). The dried samples were coated with a thin layer of gold that was typically between 5 and 50 nm thick. Images were obtained at 1000× and 30,000× magnification for both the natural and 100% SIHLL-contaminated samples.

The X-ray diffraction (XRD) technique was used to identify the chemical compositions of and the mineralogical changes in the soil samples. XRD analysis was carried out on the natural and 100% SIHLL-contaminated samples using a PANalytical X'Pert PRO instrument with a monochromator and Cu radiation ( $\lambda = 1.542 \text{ \AA}$ ) at 45 kV, 35 mA, and a scanning speed of 0.03°/s. The reflection peaks between  $2\theta = 2^\circ$  and  $60^\circ$ , the corresponding spacing ( $d$ , Å), and the relative intensities ( $I/I_0$ ) were obtained. Diffraction charts and relative intensities were derived and compared with International Center for Diffraction Data (ICDD) files. The Brunauer–Emmett–Teller (BET) test was carried out to determine the TPV and surface

area of each soil sample using the BEL Sorb device. The test measurement conditions were as follows: sample weight = 0.2169 g, standard volume = 9.826 cm<sup>3</sup>, dead volume = 16.698 cm<sup>3</sup>, equilibrium time = 0.0 s, apparatus temperature = 0 °C, adsorption temperature = 77.0 K, saturated vapor pressure = 101.64 kPa, and adsorptive cross-section area = 0.162 nm<sup>2</sup>.

## Results and discussion

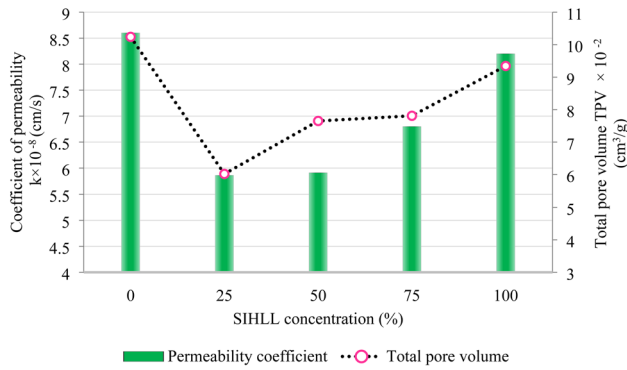
### Results of SIHLL and soil analyses

The SIHLL was found to be an alkaline liquid (pH = 8.8) that was contaminated with relatively high concentrations of Fe<sup>3+</sup>, Mn<sup>2+</sup>, and Ni<sup>2+</sup> as well as low concentrations of Cu<sup>2+</sup>, Pb<sup>2+</sup>, Cd<sup>2+</sup>, Zn<sup>2+</sup>, and Cr<sup>2+</sup>. It also contained high concentrations of cations and anions. Moreover, the following hydrocarbons and sulfur compounds were detected in the leachate: 3-3-oxybis[2-chloro-1-propene]; bicyclo[2.2.2]oct-2-ene; pentafluoropropionic acid decyl ester; cyclohexanol; 4-(1,1-dimethylethyl)-2-methyl-benzenepropanal; hexadecane; oxalic acid; cyclohexylmethyl tridecyl ester; 1,2-benzenedicarboxylic acid, bis(2-methylpropyl) ester; cetene; octadecene; heptadecane; 9-eicosene; nonadecane; phthalic acid; octadecane; dodecane; sulfurous acid; propane; hydrazine; glycidyl isopropyl ether; methanol; and monomethylhydrazine.

Based on grain-size distribution analysis, the soil was classified as a silty clay soil. The soil was also classified as a low-plasticity clay (CL) with a liquid limit (LL) of 36 and a plasticity index (PI) of 17 according to ASTM D2487. According to previous studies, the plasticity index of a clay liner must be > 15 (Gordon et al. 1990) or > 10 (Daniel and Benson 1990), while its liquid limit should be > 30 (Gordon et al. 1990). The laboratory permeability coefficient of a compacted clay liner must be less than  $1.0 \times 10^{-7} \text{ cm/s}$  (McBride et al. 1987; Nartowska et al. 2019). Therefore, the studied soil possesses the required plasticity index, liquid limit, and permeability values.

### Effect of SIHLL on the permeability of the soil

The coefficient of permeability ( $k$ ) and total pore volume (TPV) values of the natural and contaminated soils are presented in Fig. 3. The  $k$  value of the soil contaminated with 25% SIHLL was lower ( $5.86 \times 10^{-8} \text{ cm/s}$ ) than that for the uncontaminated soil ( $8.6 \times 10^{-8} \text{ cm/s}$ ). However, the  $k$  value with 50% SIHLL ( $5.91 \times 10^{-8} \text{ cm/s}$ ) was approximately the same as that for the soil with 25% SIHLL. The  $k$  values of the contaminated soils are lower than that for the natural soil mainly because the TPV decreased from  $10.24 \times 10^{-2}$



**Fig. 3** Influence of the SIHLL concentration on soil permeability and total pore volume

to  $7.65 \times 10^{-2} \text{ cm}^3/\text{g}$  upon increasing the SIHLL concentration from 0 to 50%, respectively. The permeability and pore volume likely decreased due to the high salt levels in the SIHLL. It has been reported that pollutants and suspended solids in the SIHLL are adsorbed at the soil surface, which blocks interconnected pores in the specimen and thus decreases the hydraulic conductivity (Ma et al. 2009). Similar trends were observed by Francisca and Glatstein (2010), who noted that the leachate reduced the hydraulic conductivity of and the effective pores in the compacted soil.

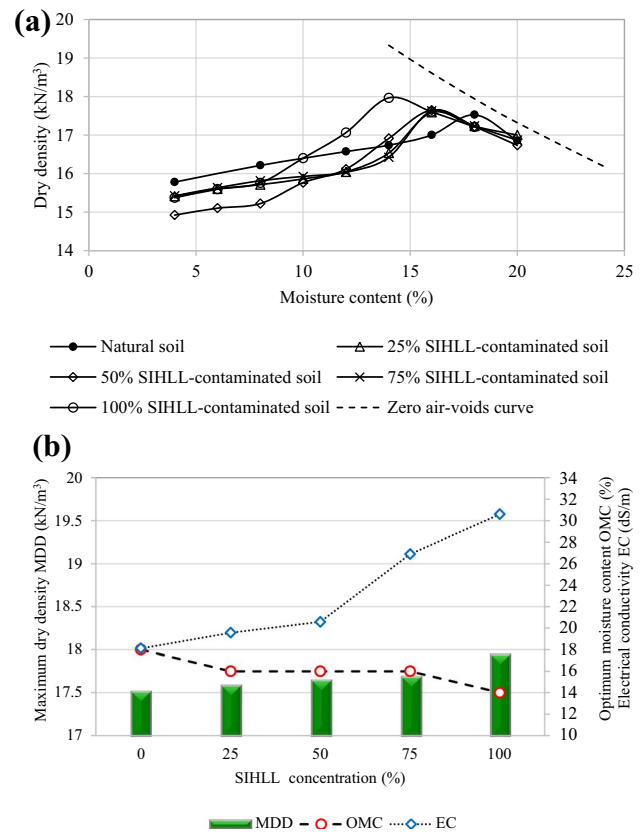
Nevertheless, in this work, increasing the SIHLL concentration further, from 50 to 100%, was found to prompt increases in  $k$  and TPV, as indicated in Fig. 3. For example, the  $k$  and TPV values increased from  $5.91 \times 10^{-8}$  to  $6.8 \times 10^{-8} \text{ cm/s}$  and from  $7.65 \times 10^{-2}$  to  $7.81 \times 10^{-2} \text{ cm}^3/\text{g}$ , respectively, upon increasing the SIHLL concentration from 50 to 75%. Nayak et al. (2007) found that increasing the leachate concentration caused the soil void ratio to increase due to chemical reactions between the leachate and the clay minerals. Strongly acidic and basic liquids dissolve clay minerals, carbonates, and iron oxides, resulting in relatively high soil permeability (Uppot and Stephenson 1989). The  $k$  and TPV of the soil contaminated with 100% SIHLL were similar to those of the natural uncontaminated soil:  $8.2 \times 10^{-8} \text{ cm/s}$  and  $9.34 \times 10^{-2} \text{ cm}^3/\text{g}$ , respectively (Fig. 3). Furthermore, the surface area of the soil with 100% SIHLL was much smaller ( $28.9 \text{ m}^2/\text{g}$ ) than that of the natural soil ( $47.2 \text{ m}^2/\text{g}$ ) because the alkaline leachate reduced the total pore space.

### Effect of SIHLL on the compaction characteristics of the soil

The compaction curves and compaction characteristics (OMC and MDD) of the natural and contaminated soils are indicated in Fig. 4a and b. It is obvious that the addition of 25% SIHLL slightly reduced the OMC from 18 to 16%.

The OMC remained constant at 16% upon increasing the SIHLL concentration to 50% and then 75%. However, there was a notable decline in the value of OMC to 14% when the SIHLL concentration was increased to 100%. This reduction in OMC may be due to a decrease in the surface area of the contaminated soil arising from the interactions between the SIHLL and the soil particles. These results for the OMC are consistent with those obtained for the MDDs of the soils contaminated with different SIHLL concentrations, as the maximum MDD ( $17.95 \text{ kN/m}^3$ ) was attained with a contaminant concentration of 100%. The MDD increased slightly from 17.52 to 17.59, 17.65, 17.69, and  $17.95 \text{ kN/m}^3$  upon increasing the concentration of SIHLL from 0% to 25%, 50%, 75%, and 100%, respectively. This reduction in OMC and slight increase in MDD with increasing contamination can likely be attributed to the increasing presence of salts and hydrocarbon compounds, which altered the soil–water characteristics (Khodary et al. 2020).

A significant rise in electrical conductivity (EC) was seen for the contaminated soils as compared to the natural soil, indicating that the salt levels in the soil increased, in accordance with the observed modification of soil characteristics following contamination. The EC increased with the SIHLL



**Fig. 4** a Compaction curves of the natural and contaminated soils. b Compaction characteristics and electrical conductivity of the natural and contaminated soils

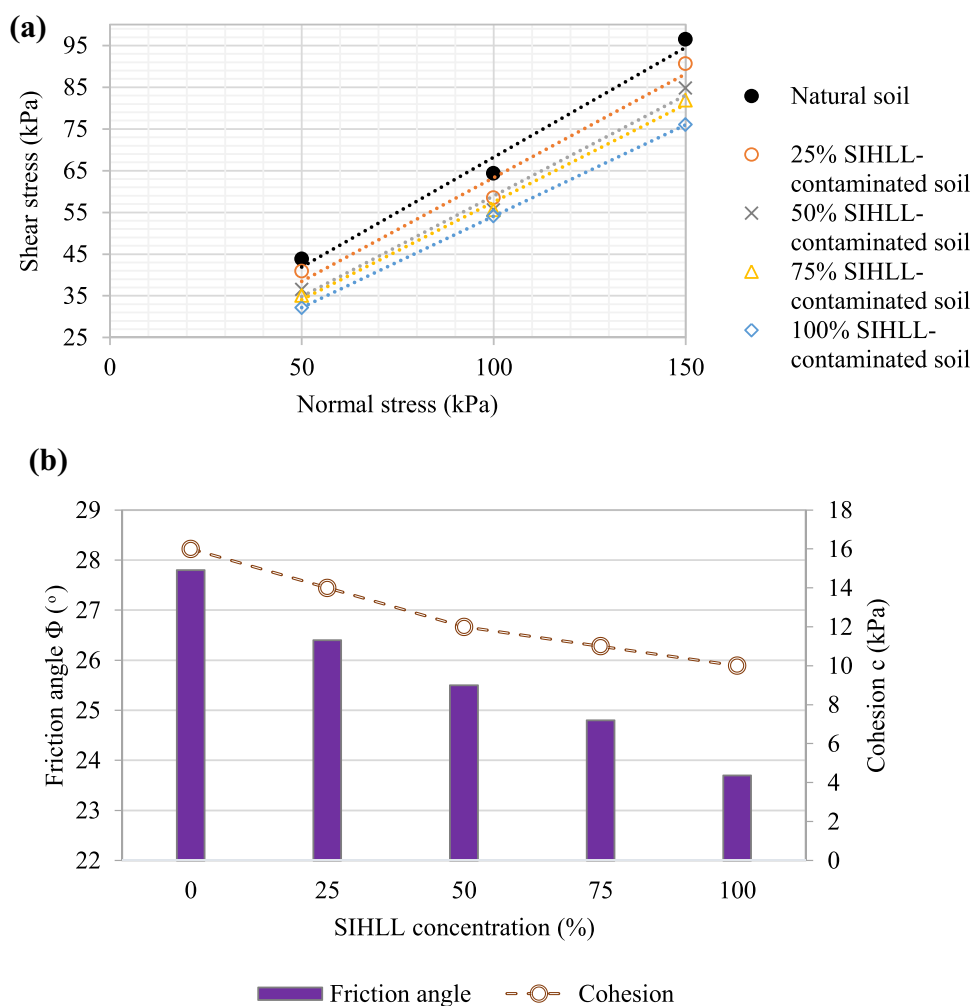
concentration and maximized at a level of 30.6 dS/m for the 100% SIHLL-contaminated soil. A previous study also indicated that adding salt to a clay soil causes a slight reduction in the OMC and a slight increase in the MDD (Raj 2005). However, this behavior was not observed in another study (Harun et al. 2013), where compaction tests of contaminated soil pointed to a drop in the MDD and an increase in the OMC upon increasing the leachate concentration from 0 to 20%. These results are consistent with those of Nayak et al. (2007), who found out that the compaction characteristics of the soil did not change much upon increasing the leachate concentration from 0% to 5%, while the MDD for the studied lateritic soil decreased from 15.47 to 14.98 kN/m<sup>3</sup> and the OMC increased from 19.52% to 25.01% when the leachate concentration was enhanced to 10%. These discrepancies between the results from this and previous studies are probably due to differences in leachate characteristics and soil type between the studies, in addition to the smaller leachate concentrations employed in the previous study.

### Effect of SIHLL on the shear strength of the soil

The normal/shear stress relationships and the shear strength parameters ( $\phi$  and  $c$ ) of the natural and contaminated soils are indicated in Fig. 5a and b. The friction angle dropped from 27.8° for natural soil to 23.7° for the soil contaminated with 100% SIHLL. This effect is likely due to the coating of the soil particles with the hydrocarbon compounds that were detected in the SIHLL, which reduced internal friction. In addition, the alkalinity of the SIHLL led to finer soil particles, and substrate dissolution reactions may also have significantly altered the internal friction.

Similarly, soil cohesion decreased with the addition of SIHLL, as presented in Fig. 5b. The cohesion of 25% SIHLL-contaminated soil was 14 kPa, as compared to 16 kPa for the natural soil. Furthermore, the cohesion of the 100% SIHLL-contaminated soil was only 10 kPa. This decrease in cohesion may be associated with the coating of the soil particles with the hydrocarbon compounds that were detected in the SIHLL.

**Fig. 5** **a** Normal/shear stress relationships of the natural and contaminated soils. **b** Shear strength parameters of the natural and contaminated soils

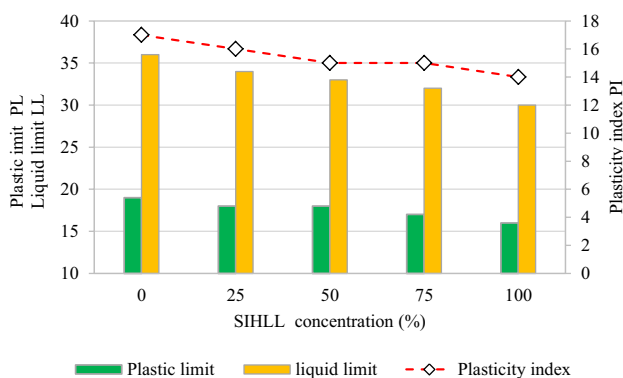


The internal friction angle of the soil is related to the geometric arrangement of the soil particles. An observed decrease in the internal friction angle of contaminated soil may be attributed to a change in particle shape. Sunil et al. (2009), who investigated the shear strength parameters of leachate-polluted laterite, found that the soil cohesion increased while the friction angle decreased as the concentration of leachate was increased. Harun et al. (2013) noted that the shear strength decreased from 156 to 55.44 kPa with increasing leachate contamination of the soil. On the other hand, a study by Li et al. (2013) indicated that increasing the leachate concentration led to a reduction in soil cohesion and an increase in the internal friction angle of leachate-polluted clay.

### Effects of SIHLL on the consistency limits of the soil

The effects of the SIHLL concentration on the plastic limit (PL), liquid limit (LL), and plasticity index (PI) of the soil are presented in Fig. 6. Marked decreases in the consistency limits were observed for the soils contaminated with SIHLL, with the PL dropping from 19 for the natural soil to 16 for the 100% SIHLL-contaminated soil. As the SIHLL concentration increased from 25% to 50% to 75%, the PL of the contaminated soil slightly decreased from 18 to 18 to 17, respectively. A similar trend was observed for the LL of the contaminated soil upon increasing the SIHLL concentration from 0 to 100%. The LL values of soils contaminated with SIHLL concentrations of 0% (natural soil), 25%, 50%, 75%, and 100% were 36, 34, 33, 32, and 30, respectively.

The reductions in the consistency limits of the soil with increasing soil contamination can be attributed to a reduction in the surface area of soil particles with contamination, which decreases water absorption and thus changes the liquid limit and plastic limit values. Moreover, the increasing salt concentration associated with contamination causes the diffuse double layer (DDL) to shrink or collapse (Bohn and Mcneal 1983). The reduced thickness of the DDL



**Fig. 6** Consistency limits for the natural and contaminated soils

surrounding the soil particles leads to less space between the soil sheets, resulting in drier soil, which in turn decreases the plastic and liquid limits. Locat et al. (1984) reported that the liquid limit was considerably reduced in marine clays.

The plasticity index (PI) of the contaminated soil gradually decreased with increasing SIHLL concentration (Fig. 6). The PI of the soil contaminated with 25% SIHLL was 16, as opposed to 17 for the natural soil, and the PI showed a further slight drop (to 14) upon increasing the SIHLL concentration to 100%. Thus, one plausible reason for the decrease in the PI for the contaminated soil is the high salinity of the leachate, given that the salts cause particle flocculation, reduce plasticity, and decrease swell potential (Mosavat and Nalbantoglu 2012). The influences of the SIHLL concentration on the total dissolved solids (TDS) and the plasticity indices are presented in Table 3. Likewise, Harun et al. (2013) reported that the PI was significantly decreased from 18.4 to 6.54 upon increasing the leachate content of soil. Additionally, a previous study indicated that there was a decrease in the PI of soil contaminated with ethylene glycol (Mosavat and Nalbantoglu 2011). Our results from the Brunauer–Emmett–Teller (BET) test revealed that the surface area of the soil with 100% SIHLL was only 28.91 m<sup>2</sup>/g, as opposed to 47.21 m<sup>2</sup>/g for natural soil.

### X-ray diffraction (XRD) and scanning electron microscopy (SEM) of the natural and contaminated soils

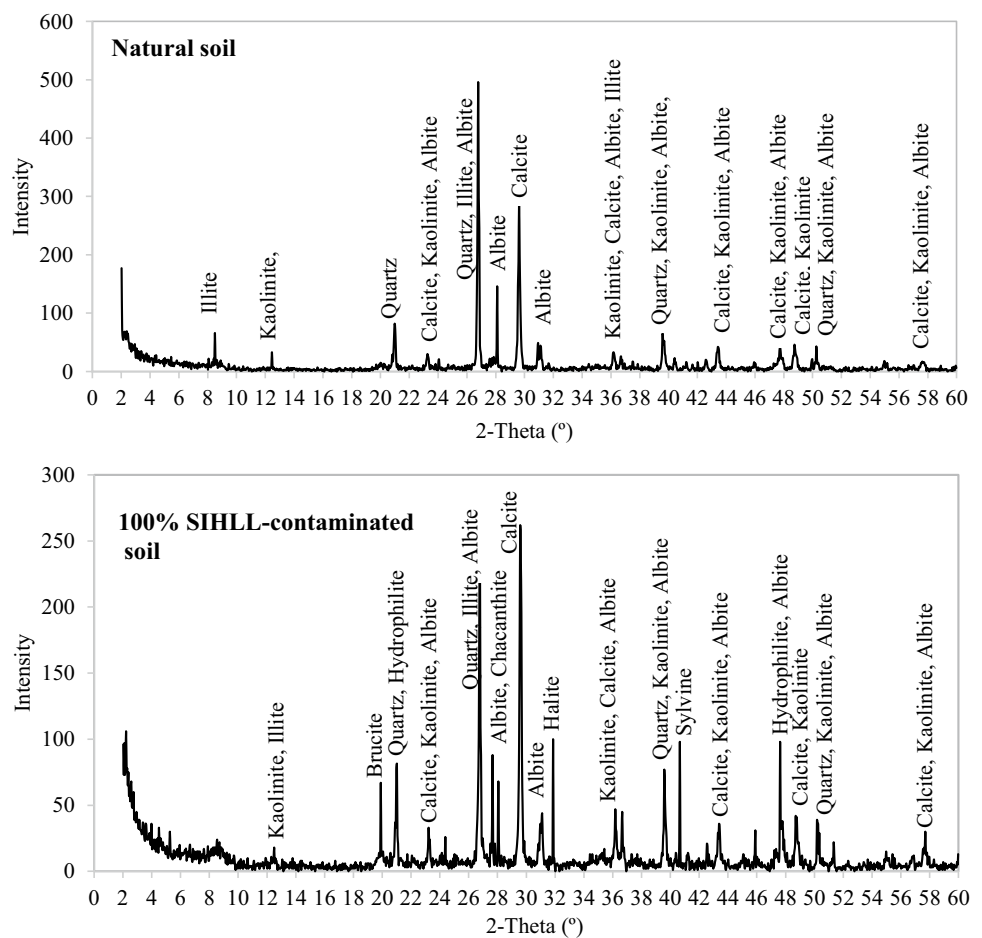
The XRD patterns for the natural and 100% SIHLL-contaminated soil samples are indicated in Fig. 7. According to this figure, leachate pollution changed the mineral content of the soil, which directly affected its properties. The major diffraction peaks from the natural samples originated from calcite ( $2\theta=23.26^\circ, 29.62^\circ, 36.18^\circ, 39.62^\circ, 43.37^\circ, 47.58^\circ, \text{ and } 56.87^\circ$ ), quartz ( $2\theta=20.95^\circ, 26.78^\circ, 36.18^\circ, 39.62^\circ, \text{ and } 50.28^\circ$ ), albite ( $2\theta=23.28^\circ, 26.78^\circ, 28.09^\circ, 31.05^\circ, 36.18^\circ, 39.62^\circ, 47.79^\circ, \text{ and } 50.31^\circ$ ), illite ( $2\theta=8.53^\circ, 12.48^\circ, \text{ and } 26.78^\circ$ ), and kaolinite ( $2\theta=12.48^\circ, 23.28^\circ, 36.18^\circ, 39.79^\circ, 50.31^\circ$ ). The peak intensities for calcite, quartz, albite, and illite were considerably weaker for the contaminated soils.

**Table 3** Influences of the SIHLL concentration on the plasticity index and salinity values of natural and contaminated soils

SIHLL concentration (%)	Plasticity index	EC (dS/m)	TDS (ppm)
0	17	18.1	11,584
25	16	19.57	12,524.8
50	15	20.58	13,171.2
75	15	26.9	17,216
100	14	30.6	19,584



**Fig. 7** XRD patterns of the natural and 100% SIHLL-contaminated soils



This was mainly due to chemical reactions between the SIHLL and the soil that led to the dissolution of minerals in the contaminated soil. In addition, brucite ( $2\theta = 19.9^\circ$ ), hydrophilite ( $2\theta = 20.99^\circ$ ,  $29.55^\circ$ , and  $47.63^\circ$ ), halite ( $2\theta = 27.65^\circ$  and  $31.87^\circ$ ), chalcantite ( $2\theta = 26.79^\circ$ ,  $28.07^\circ$ , and  $29.6^\circ$ ), and sylvine ( $2\theta = 40.66^\circ$ ) were detected in the contaminated samples. A previous study by Li et al. (2013) found that when compacted clay was infiltrated by leachate, the quartz and clay mineral contents decreased, whereas that of albite increased.

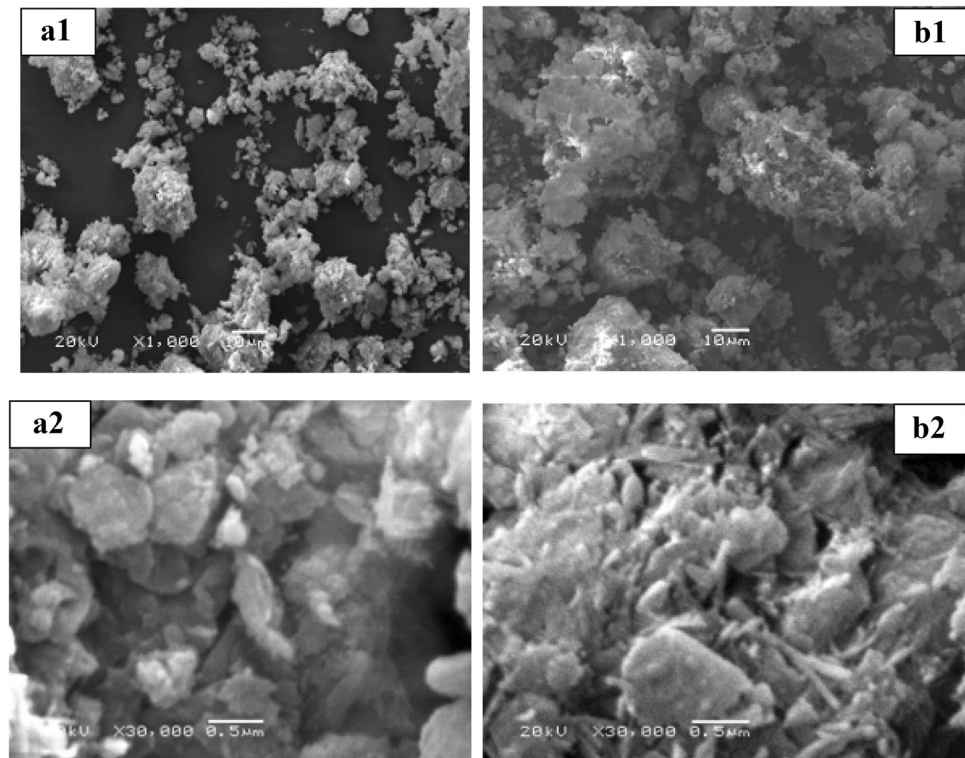
SEM photographs revealed separate aggregates with large pore spacing in the natural soil (Fig. 8a1), while Fig. 8b1 indicates that the micropores decreased significantly in size when the soil was contaminated with 100% SIHLL. This reduction was mainly due to the introduction of salts, which reduced the permeability. Significant microfabric differences between the natural and 100% SIHLL-contaminated soil samples are apparent from Fig. 8a2 and b2. Some changes in particle shape were observed for the contaminated soil, as the SIHLL distorted the particles and rearranged them in random orientations. This reorientation can be attributed to interactions between the leachate and soil minerals, and the structural changes were due to the penetration of the leachate

into soil voids. Nayak et al. (2007) observed via scanning electron microscopy that the contamination of a soil sample with an acidic leachate led to an aggregated soil structure.

## Conclusion

This study investigated the effect of saline hazardous landfill leachate (SIHLL) collected from the El-Nasreya Landfill in Egypt on the geotechnical properties of Egyptian silty clay soil via laboratory-based experiments. The following conclusions can be drawn based on this experimental work. The soil permeability coefficient and total pore volume decreased from  $8.6 \times 10^{-8}$  to  $5.86 \times 10^{-8}$  cm/s and from  $10.24 \times 10^{-2}$  to  $6.02 \times 10^{-2}$  cm<sup>3</sup>/g upon increasing the SIHLL concentration from 0 to 25%, respectively. The maximum dry density of the soil slightly increased from 17.52 to 17.95 kN/m<sup>3</sup> upon increasing the concentration of SIHLL from 0 to 100%, while the optimum moisture content reduced from 18 to 14%. This reduction in the optimum moisture content and increase in the maximum dry density with SIHLL contamination are likely attributable to the introduction of salts that alter the soil–water interaction characteristics. The plasticity

**Fig. 8** SEM images for **a** natural soil and **b** 100% SIHLL-contaminated soil at (1) 1000× and (2) 30,000×



index of the soil dropped from 17 to 14 upon increasing the concentration of SIHLL from 0% to 100%. This reduction in soil plasticity index can be attributed to a reduction in the diffuse double-layer thickness around the clay particles. The friction angle of the soil dropped from  $27.8^\circ$  for the natural soil to  $23.7^\circ$  for the 100% SIHLL-contaminated soil. This behavior may have arisen because the soil particles were coated with hydrocarbon compounds from the SIHLL. Based on measurements of soil permeability and the results of assessments of the effectiveness of the clay liner, and given its widespread availability in Egypt, the studied silty clay soil appears to be suitable for use in the construction of a new hazardous solid-waste landfill liner.

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### Compliance with ethical standards



**Conflict of interest** The authors declare no conflict of interest.

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