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# The use of Ankara Clay as a compacted clay liner for landfill sites

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ABSTRACT: Because of the current need for new landfill sites in Ankara, the suitability of Ankara Clay as a liner material for landfill sites was investigated. A mineralogical and geotechnical database was created by compiling the results of previous tests by the present authors as well as those of tests performed in the present study. The mineralogical properties of the samples were investigated by X-ray diffraction, scanning electron microscopy and methylene blue adsorption. The cation exchange capacities (CEC) of the samples vary from 12 to 35 meq/100 g soil and the dominant clay minerals are illite, smectite and kaolinite. The geotechnical properties of the Ankara Clay samples that were assessed included specific gravity, the Atterberg limits (plastic limit, liquid limit, plasticity index), particle-size distribution, compaction properties (*i.e.* maximum dry density and optimum water content) and hydraulic conductivity. Because the hydraulic conductivity of the samples was lower than the acceptable limit of $1 \times 10^{-9}$ m/s, it follows that, from a geotechnical perspective, Ankara Clay is a suitable material for use as a compacted clay landfill liner. The relationships between the mineralogical and geotechnical parameters that were investigated by regression analysis indicated that the hydraulic conductivity of the compacted soil samples decreased with increasing plasticity index, clay content, CEC, smectite content, smectite to illite ratio and decreasing illite content. According to the specifications for field construction of compacted clay liners, Ankara Clay is suitable for compaction in the field.

KEYWORDS: Ankara Clay, geotechnics, clay mineralogy, regression analysis, Ankara, Turkey.

Ankara is the capital and second largest city in Turkey with an ever-growing population of ~5 million inhabitants (according to the 2015 census) who generate a mean daily waste of 1.05 kg per person. At present, there are two main landfill sites in Ankara, at Mamak and the Çadırtepe, both of which pose serious environmental and health risks (Akgün *et al.*, 1999; Met & Akgün, 2005, 2015; Met *et al.*, 2005; Yal, 2010; Yal & Akgün, 2013, 2014). Even if strict remediation schemes were to be imposed, additional landfill sites will be required in the near future to accommodate the rate of growth of the population. For this reason, the possible use of clayey soils in the vicinity of Ankara as components of a compacted clay landfill liner needs to be investigated through assessment of their mineralogical and geotechnical properties.

The clay-rich formations of Late Miocene–Pilocene age, occurring in and around Ankara and referred to as "Ankara Clay" (Birand, 1963; Ordemir *et al.*, 1965;

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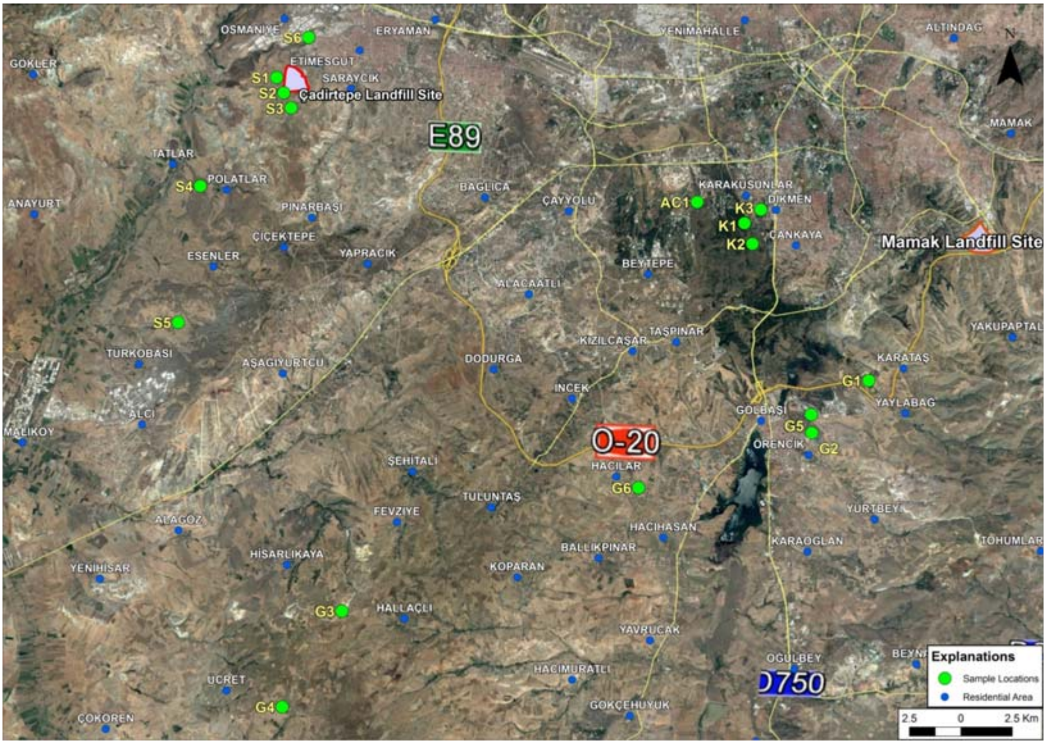


FIG. 1. Location map of the study area.

Çokça, 1991; Koçyiğit & Türkmenoğlu, 1991; Akgün *et al.*, 1999) are considered to be a major source of clay liners. The objective of the present study was to evaluate, mineralogically and geotechnically, the possible use of native Ankara Clay as a compacted clay liner, which is required as an essential component of the landfill sites to be constructed in Ankara in the near future. In order to determine the mineralogical and geotechnical properties of the Ankara Clay, a database has been created by compiling data from previous and present studies of the present authors (Sezer, 1998; Akgün *et al.*, 1999; Met, 1999; Türkmenoğlu *et al.*, 1999; Sezer *et al.*, 2003; Met *et al.*, 2005; Yal, 2010; Yal & Akgün, 2013, 2014; Met & Akgün, 2015). The locations of the clay samples that were collected from various locations around Ankara and subjected to mineralogical and geotechnical testing to investigate the suitability of Ankara Clay for use as a compacted clay liner are shown in Fig. 1. Four of the clay samples were collected from Karakusunlar (Samples K1, K2, K3 and AC1), six from Gölbaşı (Samples G1, G2, G3, G4, G5 and G6) and six from Sincan (Samples S1, S2, S3, S4, S5 and S6). Regression analysis was used to investigate the relationships between the mineralogical and geotechnical parameters. The hydraulic conductivity results were checked to assess whether they comply with the acceptable limits. Possible field construction of the compacted clay liner is described below.

## BRIEF GEOLOGY AND HYDROGEOLOGY OF THE ANKARA BASIN

Sedimentary, metamorphic and igneous rocks of Paleozoic–Quaternary age are the major geological formations that crop out in the Ankara region. The southern section of the Ankara basin is underlain by Triassic basement rocks, including dark brown greywacke, black shale and carbonate blocks which vary in size. The northern section of the basin is underlain by Upper Miocene–Lower Pliocene volcanics and fluvial-lacustrine clastic rocks and the western section is underlain by the Jurassic–Cretaceous carbonates (Koçyiğit & Türkmenoğlu, 1991). The clay-bearing fluvial clastic rocks of the

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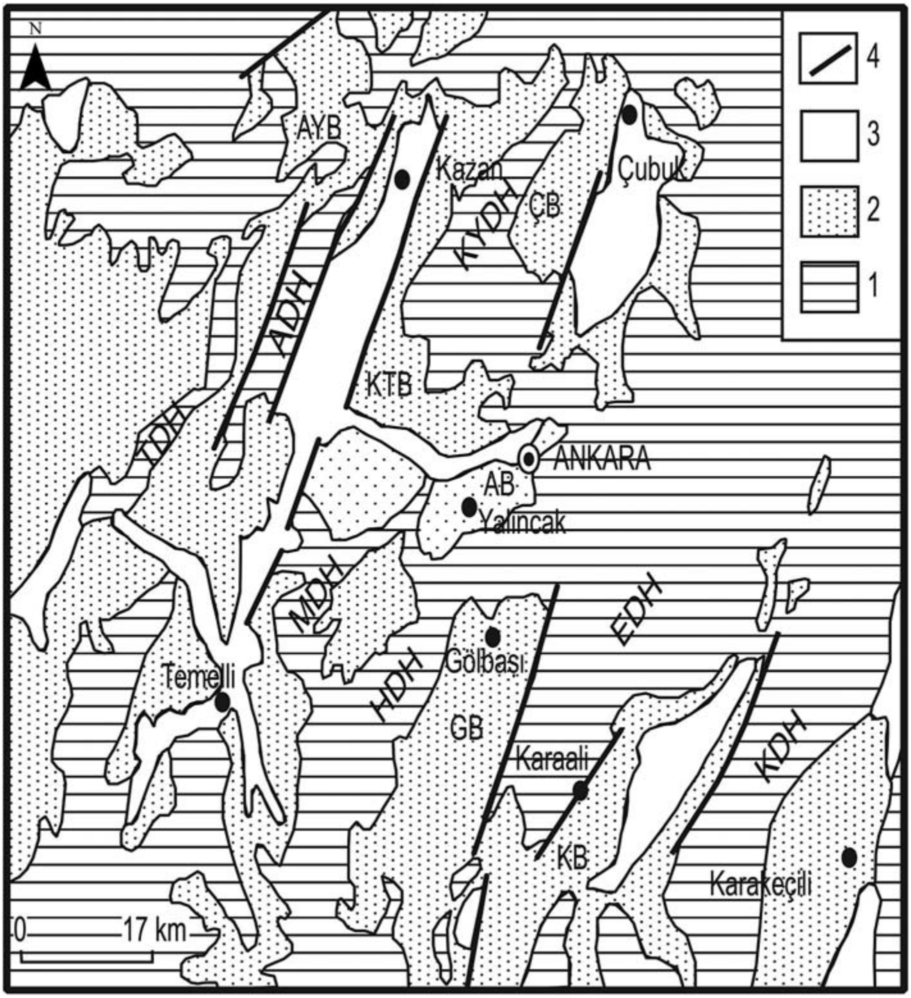


FIG. 2. Simplified geological map of the Ankara region: (1) Quaternary alluvial sediments; (2) Late Miocene–Pliocene continental basin deposits and volcanics; (3) Pre-Late Miocene basement rocks; (4) Basin margin fault. Key to abbreviations: AB – Ankara Basin, AYB – Ayaş Basin, ÇB – Çubuk Basin, GB – Gölbaşı Basin, KB – Karaali Basin, KTB – Kazan-Temelli Basin, ADH – Abdülselamdağ Highland, EDH – Elmadağ Highland, HDH – Hacılardağ Highland, KDH – Küredağ Highland, KYDH – Karyağdıdağ Highland, MDH – Meşedağ Highland and TDH – Torludağ Highland (after Koçyiğit & Türkmenoğlu, 1991).

Ankara basin are referred to as the Yalıncak formation (Koçyiğit, 1991). The generalized geology and the stratigraphy of the region are presented in Figs 2 and 3, respectively. The Yalıncak formation consists mainly of three lithofacies: the lowest part is dominated by debris-flow conglomerates of subrounded to angular pebbles with varying origins, ages and facies. These pebbles are mostly greywacke, quartzite, marble, schist, crinoidal limestone, volcanics and sandstone. This lithofacies is overlain conformably by a layer of braid plain, yellow-reddish wedge to trough cross-bedded conglomerate and sandstone. The uppermost lithofacies of the Yalıncak formation consists of the finer clastics of the floodplain, dominated by cross-bedded conglomerates and red shale, siltstone, white carbonate concretions and clay-bearing mudstone alterations. These reddish brown preconsolidated, stiff and fissured clays deposited in the flood plain environment are known as "Ankara Clay" (Ordemir *et al.*, 1965).

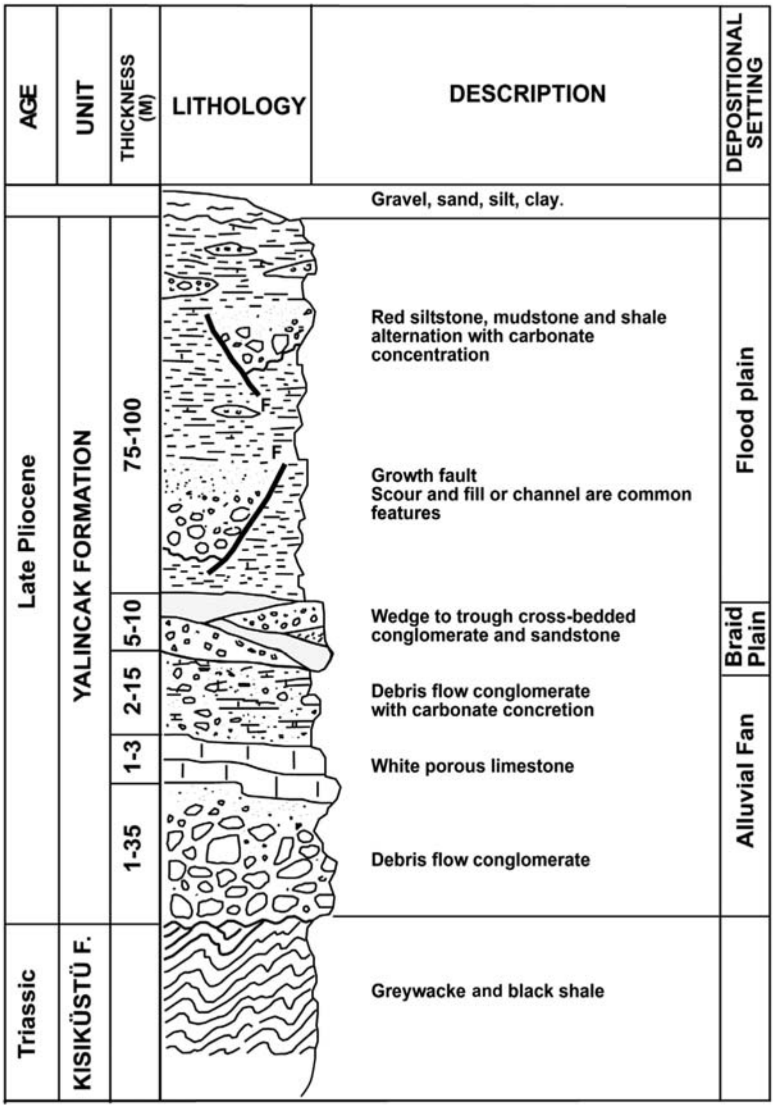


FIG. 3. Stratigraphic columnar section of the Yalıncak formation (after Koçyiğit & Türkmenoğlu, 1991).

Ankara Clay is represented by levels of clay, sand and gravel with varying thicknesses, exceeding 200 m in places (Erol, 1993). Laterally, fine lacustrine interlayers are encountered and calcareous concretions occur within the clayey levels at shallow depths (Erol *et al.*, 1980; Sezer, 1998). They appear to be preconsolidated in the upper parts due to desiccation and fissuring. Ordemir *et al.* (1977) explained the preconsolidation of these clays by the overburden caused by erosion, followed by depression in the groundwater level and sedimentation and, finally, desiccation.

Due to the resemblance of the composition of the gravel and the sand particles in Ankara Clay to the greywacke and limestone bedrock, these bedrock units are considered to be the source of the inherited clay and non-clay mineral assemblages of the red clastics of Ankara Clay (Met *et al.*, 2005). The northern and eastern parts of Ankara are confined by andesitic rocks. The presence of rock fragments of these andesites and their weathering products within Ankara Clay indicate that these andesitic rocks are also the source of Ankara Clay. Hence, the index properties of Ankara Clay possess a very heterogeneous structure and appearance, as they contain silt, sand and gravel particles in the form of layers and lenses. As the activity and clay content (CC) of these indurated stiff sediments are significant, they tend to have high plasticity and high swelling potential and are generally classified as High-Plasticity Clay (CH), Low-Plasticity Clay (CL) and partly High-Plasticity Silt (MH) according to the Unified Soil Classification System (Birand, 1963; Sürgel, 1976).

Ankara is located in the middle of the Hatip plain. Ankara creek, the main river in the area, originates from the plains to the west of Sincan and discharges to the Sakarya river. There are several formations that could possibly act as a groundwater source in the area. Among them are the Permo-Triassic limestones and the Jurassic-Cretecaous limestones which discharge their waters through fractures and joint systems only. On the other hand, the Pliocene lacustrine sediments are not capable of retaining water as they consist mostly of clayey soils thus leaving the alluvial deposits as the only formation in the area capable of retaining water (State Hydraulic Works, 1975; Erol *et al.*, 1980).

## MATERIALS AND METHODS

Clay samples from throughout Ankara were collected in order to assess their mineralogical and geotechnical properties. Investigation of Ankara Clay included the determination of the CEC and the mineralogical content of samples which were collected from three different areas, namely Karakusunlar (K1, AC1), Gölbaşı (G1, G2) and Sincan (S1, S2 and S3) with XRD and SEM coupled with Energy Dispersive X-ray analysis (SEM-EDS) (Akgün *et al.*, 1999; Sezer *et al.*, 2003). The geotechnical properties of the Ankara Clay samples that were assessed included specific gravity, Atterberg limits (*i.e.* plastic limit (PL), liquid limit (LL), plasticity index (PI)), particle-size distribution, compaction properties (*i.e.* maximum dry unit weight and optimum water content) and hydraulic conductivity.

Methylene blue (MB) adsorption tests were conducted to determine the presence of swelling clay minerals in the samples. The adsorption of a significant amount of methylene blue by soil or rock material usually indicates the presence of swelling clay minerals (Stapel & Verhoef, 1989; Rytwo *et al.*, 1991; Verhoef, 1992). In the present study, the test was conducted according to the standard ASTM C837-09. Briefly, predefined concentrations in definite volumes of methylene blue solution were added to the suspension of the fine-grained soil particles. After every addition, the saturation of the solution was checked by a stain/spot test using a filter paper. The optimum amount of MB dye absorbed was given when the sample was saturated and then the CEC of the soil sample was calculated from the total amount of methylene blue solution adsorbed by the sample (Stapel &Verhoef, 1989; Çokça, 1991; Verhoef, 1992; Çokça & Birand, 1993).

Following the CEC measurements, XRD analysis was used to investigate the presence and abundance of swelling clay minerals in the soil samples. The XRD analysis was carried out with Phillips PW3710 and PW1840 X-ray Diffractometers (40 kV, 30 mA) using Ni-filtered Cu-$K\alpha$ radiation, in order to determine the non-clay and clay mineralogy. The clay minerals were determined according to Chen (1977), Brown & Brindley (1980) and Moore & Reynolds (1997). The XRD patterns were recorded in whole-rock (random) and clay-fraction samples in natural (air-dried), ethylene glycolated and thermally treated (300 and 550°C) conditions. Semi-quantitative analysis of mineral chemistry based on the peak intensities gave information on the relative amounts of the minerals present. The semi-quantitative analysis of different clay minerals in the clay fraction was performed by using the Reference Intensity Ratio (RIR) method, which is the ratio of the highest peak intensity of a mineral to that of corundum ($Al_2O_3$) when mixed with corundum at a weight ratio of 1:1 (Chung, 1974). Therefore, the RIR method implemented in the Rigaku PDXL software program was applied and the percentages of the different clay mineral phases in the clay fraction were calculated (Rigaku PDXL Software Manual, 2010) with a small experimental error (i.e. ±3–5%). The SEM analysis was performed by using a Cambridge Stereoscan microscope, model S 4-10 with a Link Analysis to verify the chemistry of the minerals that were determined during the XRD analysis. The option to view the clay particles and the fracture surfaces directly permitted a thorough investigation of the clay morphology of the samples (Reed, 1996). A JEOL 6400 SEM equipped with an EDS system was also utilized for the semi-quantitative mineral-chemistry analysis of the Ankara Clay.

Fifteen disturbed clayey soil specimens obtained from the Ankara Clay were used for index, particle-size distribution analysis while standard compaction and falling head permeability tests were performed on 13 of those samples. Note that sample AC1 was only used for mineralogical tests. All of the soil samples were stored under ambient room conditions (22 ± 2°C, 30 ± 1%

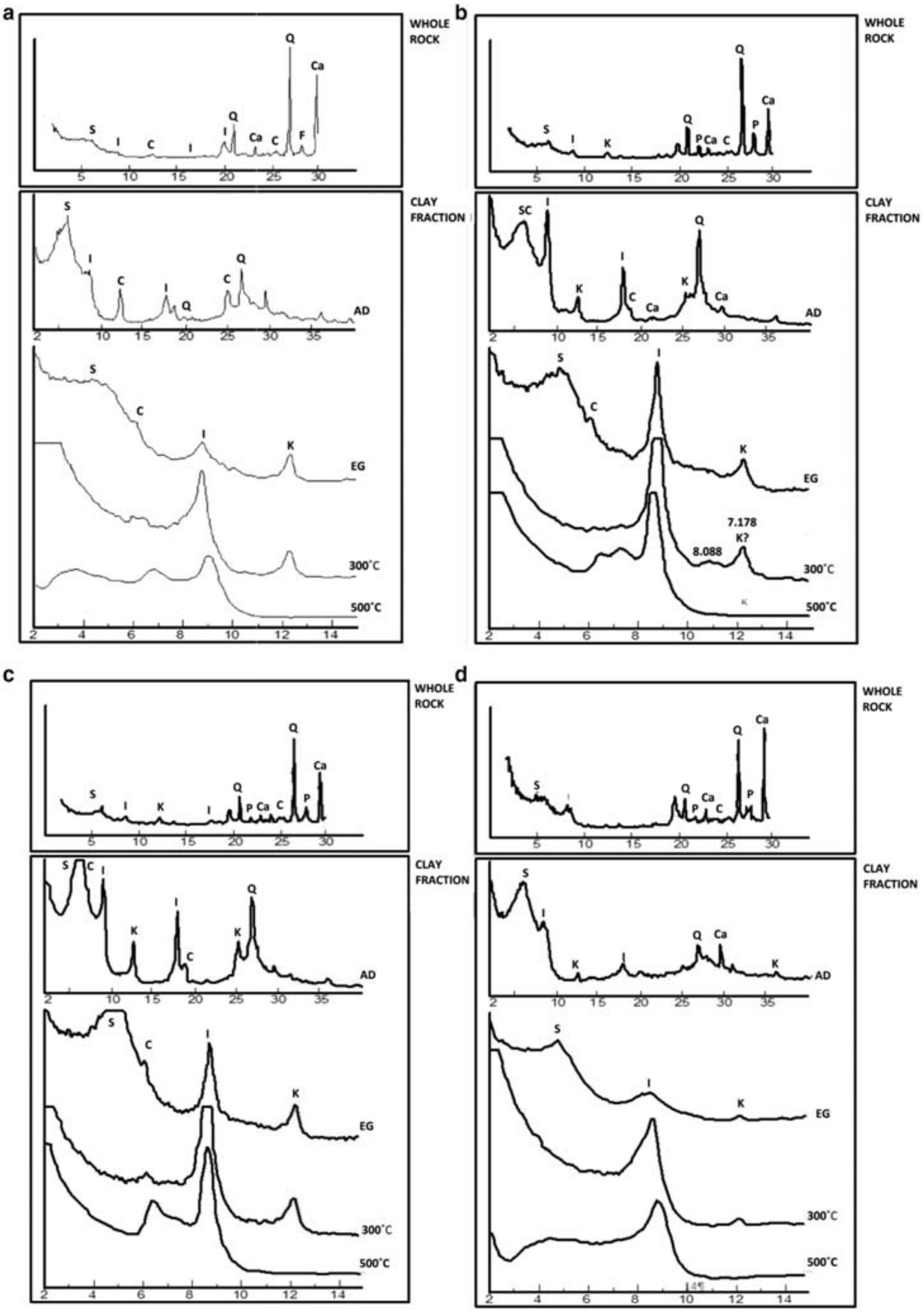


FIG. 4. XRD patterns of samples: (a) K1; (b) G1; (c) G2; (d) S1; (e) S2; (f) S3; (g) AC1. (AD: air dried; EG: ethylene glycolated; 300°C: heated at 300°C for 1 h; 500°C: heated at 500°C for 1 h, S: smectite (Sme), I: illite (Ill), C: chlorite (Chl), Q: quartz (Qtz), Ca: calcite (Cal), F: feldspar (Fsp), K: kaolinite (Kln)) (Reproduced from Met *et al.* (2005) and Met & Akgün (2015) with the permission of Springer and from Akgün *et al.*, 1999; Sezer *et al.*, 2003 with the permission of Elsevier).

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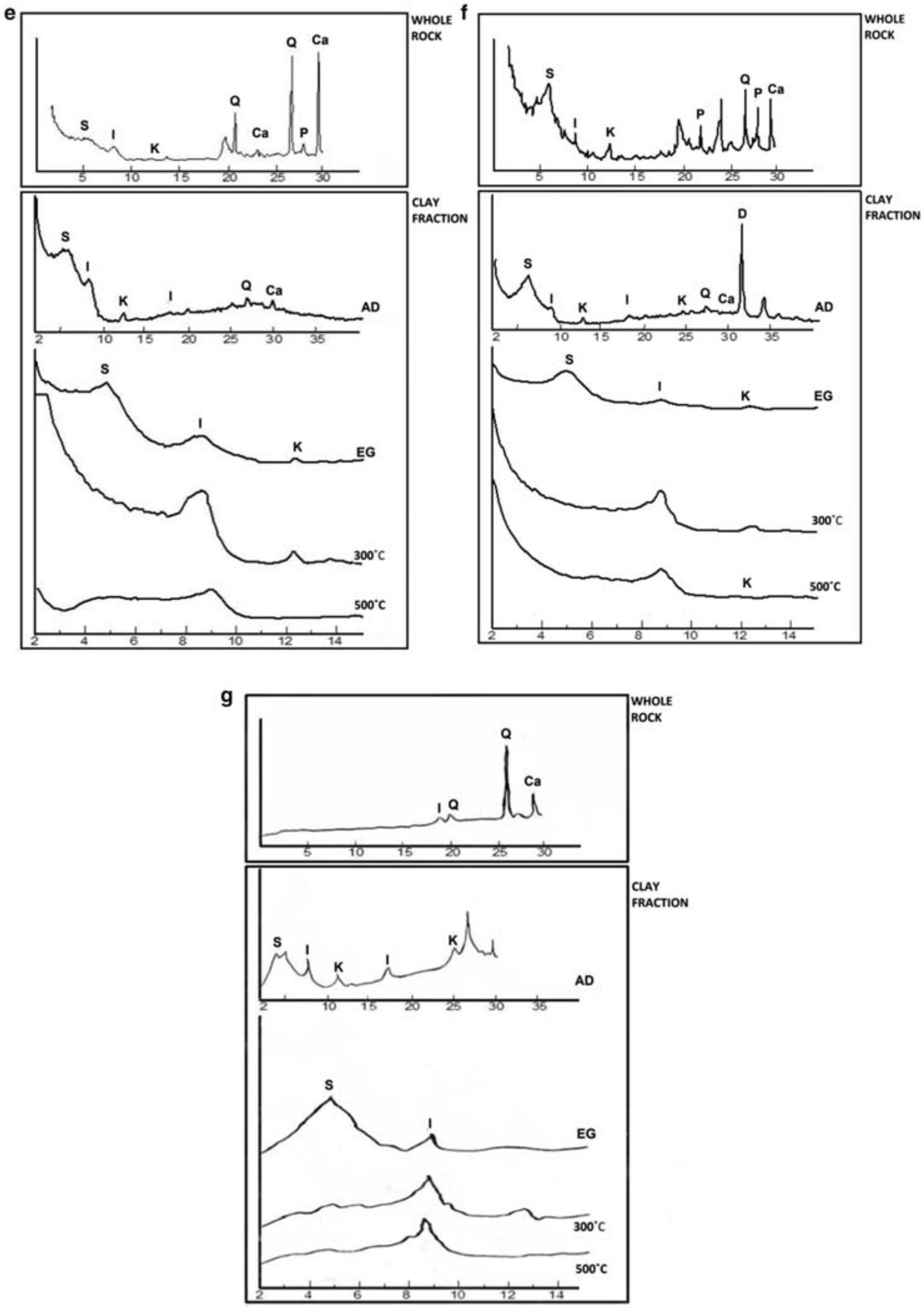


FIG. 4. Continued

relative humidity) in the laboratories of the Geotechnology Unit, Middle East Technical University (METU), Department of Geological Engineering, before testing. The locations of the samples are shown in Fig. 1.

The soil particle-size distribution, specific gravity of the solids, and Atterberg limits, namely liquid limit (LL), plastic limit (PL) and plasticity index (PI), were determined according to standard practice (ASTM

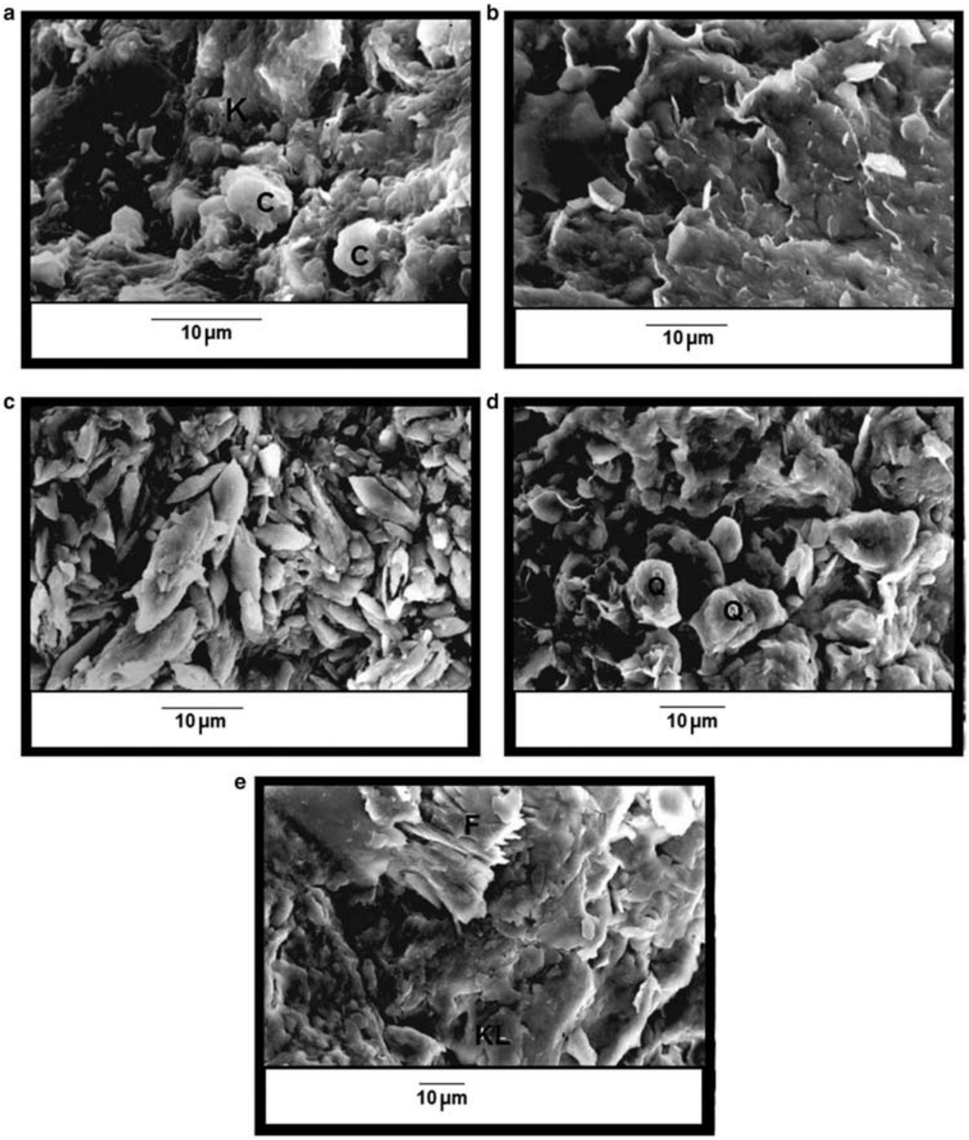


FIG. 5. SEM images of samples K1 and G1: (a) typical fine-grained, thick morphology of clay in sample K1 (K: clay, C: calcite (Cal)); (b) typical chlorite structure in sample K1; (c) C: calcite (Cal) minerals in sample K1; (d) Q: rounded quartz (Qtz) grains in sample G1; (e) KL: chlorite grains (Chl) within F, the feldspar (Fsp) matrix in sample G1 (Akgün *et al.*, 1999; reproduced from Met *et al.* (2005) with the permission of Springer).

D0422-63R07, D0854-10, D4318-10). The soil samples were classified according to their LL and PI values using the Unified Soil Classification System (USCS; ASTM D2487-10). The standard proctor compaction apparatus was used to compact the samples according to ASTM D0698-07E01 followed by placing of the compacted soil specimens in rigid-wall permeameters for hydraulic conductivity testing in accordance with ASTM D5856-95R07. The hydraulic conductivity testing apparatus consisted mainly of four compaction permeameters, de-airing tank, four burettes, a distilled water tank and a vacuum pump so that four tests could be performed concurrently. The vacuum pump was used to pump water from

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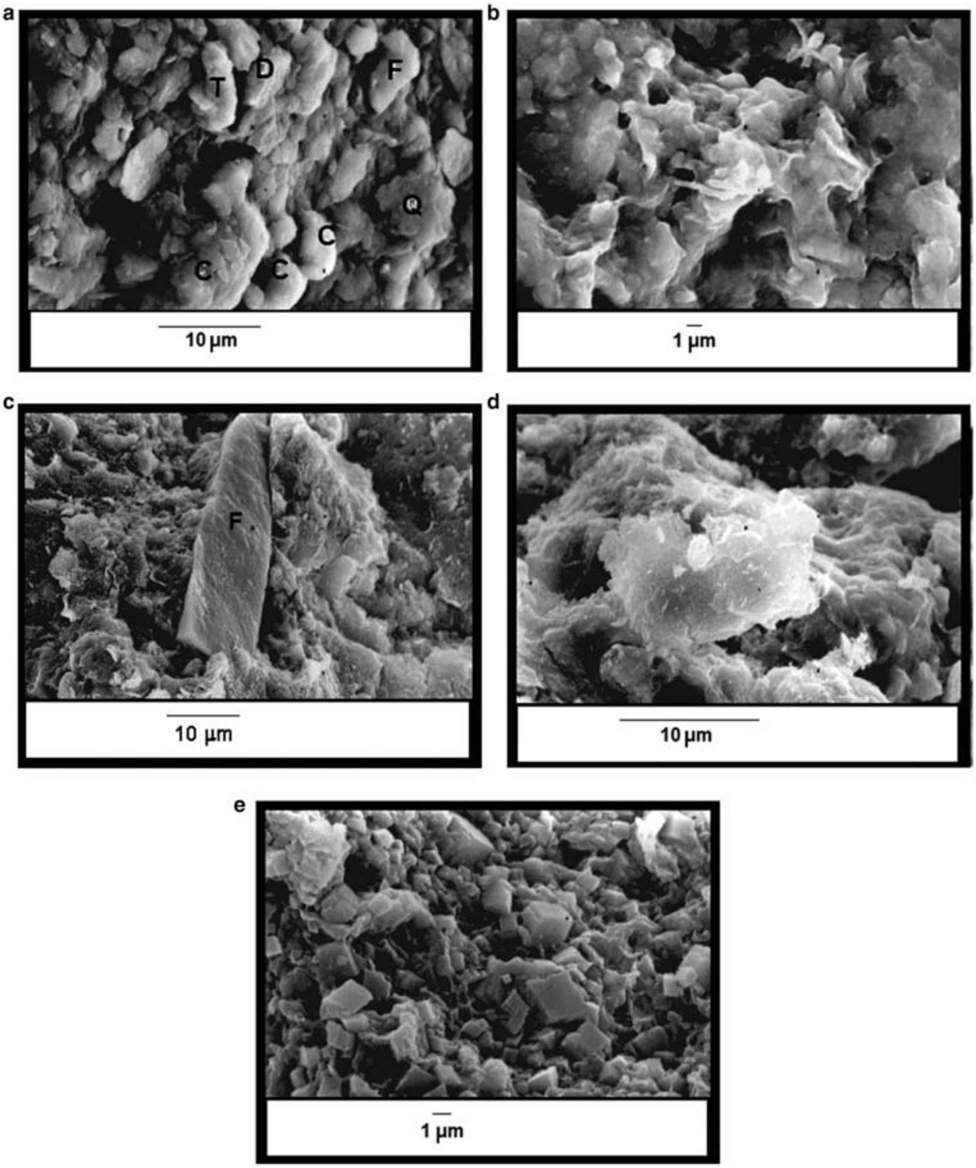


FIG. 6. SEM images of samples G2–S3: (a) titanite (T), dolomite (D), calcite (C), feldspar (F) and quartz (Q) grains within the smectitic matrix in sample G2; (b) typical smectite structure in sample S1; (c) feldspar grains (F) within an illitic-smectitic matrix in sample S2; (d) fibrous view of chlorite in sample S2; (e) rhombohedral dolomite crystals in sample S3 (Akgün *et al.*, 1999; Met, 1999; reproduced from Met *et al.* (2005) and Met & Akgün (2015) with the permission of Springer).

the distilled water tank to the de-airing tank, which freed the water of any air bubbles. The de-airing tank was connected to burettes, which were used to measure the total heads for hydraulic conductivity measurements. The evaporation burette was used to compensate for the rate of evaporation in order to correct the permeability values (where the amount of evaporation was added to the total head). Each test took place over ~45–65 days which was the approximate length of time required for the compacted samples to

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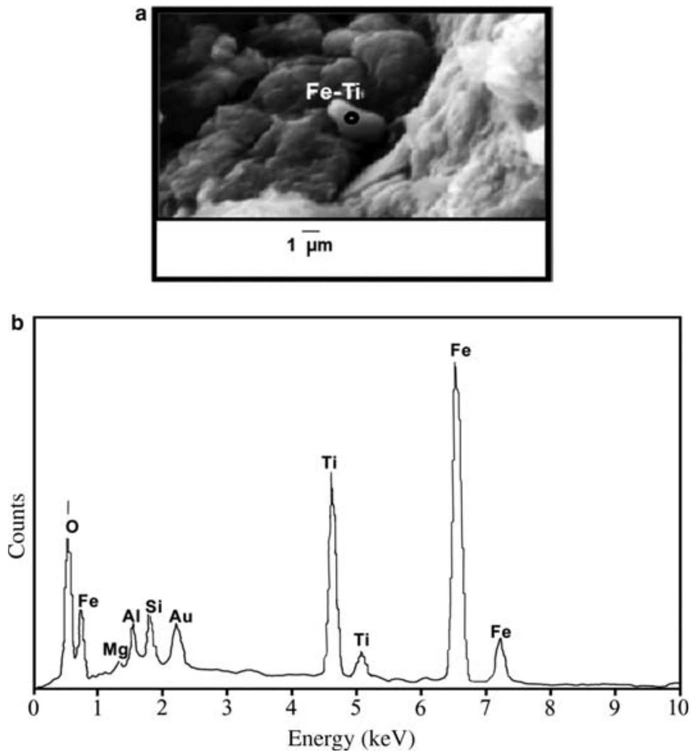


FIG. 7. (a) SEM image of an Fe-Ti mineral in the Ankara Clay and (b) EDS spectrum of the same Fe-Ti mineral (reproduced from Sezer *et al.*, 2003 with the permission of Elsevier).

attain full saturation prior to permeability testing. Completion of sample saturation was confirmed by water emanating from the water outlet portal of the compaction permeameter equipment. Distilled and de-aired water was used as the permeant.

## RESULTS OF THE MINERALOGICAL AND GEOTECHNICAL ASPECTS OF THE ANKARA CLAY

The CEC values determined from the MB adsorption test are given in Table 1. The CEC values of the soil samples ranged from 12 to 35 meq/100 g soil.

The XRD analyses of the whole-rock samples (samples K1–AC1) indicated the presence of quartz, calcite and plagioclase as non-clay minerals. Soil sample S3 differed from its counterparts, due to the presence of dolomite (Fig. 4a–g). The oriented diffraction pattern of the soil samples revealed that the dominant clay minerals were illite, smectite and kaolinite. Mixed-layer illite-smectite might also have occurred, although its presence was not proven. Soil samples K1, G1 and G2 are rich in chlorite (Fig. 4a–c) whereas chlorite is absent from the samples S1, S2 and S3 (Fig. 4d–f). The interlayer exchangeable cation in the smectite minerals observed in samples S1–S3 was mainly calcium, as was shown from the basal spacing ($d_{001}$) of the air-dried samples at ~14 Å (Fig. 4d–f). AC1 exhibits similar clay mineralogy (Fig. 4g). The smectite in the clay fraction of sample AC1 has poor crystal order suggesting a detrital origin. This sample also contains illite and kaolinite.

The results of the semi-quantitative XRD estimation of the clay minerals in the samples are listed in Table 1. Samples K1, S3 and AC1 are rich in smectite (54%, 64% and 60%, respectively). Soil samples G1, G2, S1 and S2, on the other hand, are rich in illite (77%, 54%, 66% and 69%, respectively). Chlorite is a minor mineral in samples K1, G1 and G2 (1–4%). All samples contain nearly the same amount of kaolinite (3–8%). Hence, the samples vary mainly according to their smectite to illite ratio.

Representative SEM images are shown in Figs 5–7. The SEM-EDS analysis indicated the presence of Fe-Ti

TABLE 1. Cation exchange capacity and percentage of clay minerals of samples as determined by XRD analyses.

| Sample | CEC (meq/100 g soil) | Kaolinite (%) | Smectite (%) | Illite (%) | Chlorite (%) |
|---|---|---|---|---|---|
| K1[1,2,3] | 25 | 3 | 54 | 39 | 4 |
| G1[1,2,3] | 16 | 3 | 18 | 77 | 2 |
| G2[1,2,3] | 12 | 4 | 41 | 54 | 1 |
| S1[1,2,4] | 23 | 4 | 30 | 66 | 0 |
| S2[1,2,4] | 24 | 4 | 27 | 69 | 0 |
| S3[1,2,4] | 35 | 4 | 64 | 32 | 0 |
| AC1[5] | 32 | 8 | 60 | 32 | 0 |

The sample locations are given in Fig. 1.
[1]Akgün *et al.* (1999)
[2]Met (1999)
[3]Met *et al.* (2005)
[4]Met & Akgün (2015)
[5]Sezer *et al.* (2003)

TABLE 2. Results of mean specific gravity ($G_s$) ± one standard deviation and particle-size distribution of the soil samples.

| | | Particle-size distribution | | | |
|---|---|---|---|---|---|
| Sample | $G_S$ | % Gravel | % Sand | % Fines | % Clay |
| K1[1,2,3] | 2.69 ± 0.03 (6) | 4.20 | 15.9 | 79.9 | 61.5 |
| K2 | 2.73 ± 0.07 (5) | 3.20 | 19.8 | 87.0 | 64.8 |
| K3 | 2.71 ± 0.05 (5) | 3.40 | 20.2 | 89.4 | 65.6 |
| G1[1,2,3] | 2.73 ± 0.11 (4) | 11.0 | 22.9 | 66.1 | 48.7 |
| G2[1,2,3] | 2.74 ± 0.06 (4) | 11.0 | 25.1 | 63.8 | 44.2 |
| G3[4,5] | 2.73 (1) | 4.00 | 14.0 | 82.0 | 52.0 |
| G4[4,5] | 2.78 (1) | 9.00 | 23.0 | 68.0 | 50.1 |
| G5 | 2.73 ± 0.06 (4) | 8.00 | 24.9 | 62.8 | 43.8 |
| G6 | 2.70 ± 0.04 (5) | 2.80 | 9.50 | 61.7 | 43.2 |
| S1[1,2,3] | 2.84 ± 0.07 (4) | 2.64 | 8.36 | 89.0 | 51.8 |
| S2[1,2,3] | 2.72 ± 0.06 (4) | 5.40 | 14.4 | 80.2 | 51.8 |
| S3[6] | 2.68 ± 0.06 (4) | 2.27 | 8.23 | 89.5 | 64.2 |
| S4[4,7] | 2.78 (1) | 7.00 | 21.0 | 72.0 | 60.2 |
| S5[4,7] | 2.76 (1) | 3.00 | 11.0 | 86.0 | 58.1 |
| S6 | 2.75 ± 0.08 (6) | 1.20 | 5.50 | 93.3 | 80.1 |

The sample locations are given in Fig. 1. Numbers in parentheses represent the number of tests performed.
[1]Akgün *et al.* (1999)
[2]Met (1999)
[3]Met *et al.* (2005)
[4]Yal (2010)
[5]Yal & Akgün (2014)
[6]Met & Akgün (2015)
[7]Yal & Akgün (2013)

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TABLE 3. Results of the mean values of the index tests ± one standard deviation and classification of the soil samples according to the Unified Soil Classification System (USCS; ASTM D2487-10).

| Sample | LL (%) | PL (%) | PI (%) | USCS |
|---|---|---|---|---|
| K1[1,2,3] | 53.6 ± 1.41 (4) | 18.8 ± 2.47 (13) | 34.8 ± 1.06 (4) | CH |
| K2 | 60.5 ± 1.41 (5) | 23.2 ± 1.89 (5) | 37.3 ± 1.59 (5) | CH |
| K3 | 61.6 ± 1.29 (5) | 23.4 ± 1.09 (5) | 38.2 ± 1.39 (5) | CH |
| G1[1,2,3] | 46.8 ± 0.74 (4) | 14.7 ± 3.48 (4) | 32.1 ± 2.74 (4) | CL |
| G2[1,2,3] | 42.4 ± 0.38 (4) | 16.9 ± 2.62 (4) | 25.5 ± 2.24 (4) | CL |
| G3[4,5] | 46.6 (1) | 19.2 (1) | 27.4 (1) | CL |
| G4[4,5] | 49.3 (1) | 23.0 (1) | 26.3 (1) | CL |
| G5 | 40.2 ± 0.64 (4) | 16.0 ± 2.42 (4) | 24.2 ± 2.14 (4) | CL |
| G6 | 48.8 ± 1.74 (5) | 25.0 ± 1.13 (5) | 23.8 ± 2.09 (5) | CL |
| S1[1,2,3] | 64.4 ± 0.84 (14) | 38.1 ± 2.55 (14) | 26.3 ± 1.71 (14) | MH |
| S2[1,2,3] | 72.9 ± 1.59 (8) | 43.3 ± 2.46 (8) | 29.6 ± 0.87 (8) | MH |
| S3[6] | 81.8 ± 0.89 (4) | 45.1 ± 1.13 (4) | 36.7 ± 1.71 (4) | MH |
| S4[4,7] | 58.9 (1) | 26.2 (1) | 32.8 (1) | CH |
| S5[4,7] | 47.3 (1) | 20.0 (1) | 27.3 (1) | CL |
| S6 | 55.5 ± 1.69 (6) | 26.0 ± 1.02 (6) | 29.5 ± 1.73 (6) | CH |

The sample locations are given in Fig. 1. Numbers in parentheses represent the number of tests performed. CL: Low-Plasticity Clay, CH: High-Plasticity Clay, MH: Partly High-Plasticity Silt.
[1]Akgün *et al.* (1999)
[2]Met (1999)
[3]Met *et al.* (2005)
[4]Yal (2010)
[5]Yal & Akgün (2014)
[6]Met & Akgün (2015)
[7]Yal & Akgün (2013)

oxides which may explain the typical red colour of Ankara Clay (Fig. 7).

Tables 2 and 3 summarize the results of the particle-size analysis and index tests conducted on the samples, respectively. The soil samples from Karakusunlar (samples K1 to K3) were classified as CH (high-plasticity clay), the samples from Gölbaşı (samples G1 to G6) were classified as CL (low-plasticity clay) and soil samples from Sincan (samples S1 to S6) were classified as MH (partly high-plasticity silt), CH and CL (Table 3).

The unit weight of the dry compacted soil samples initially followed an increasing trend with increasing water content until a maximum value, the optimum water content ($w_{opt}$), and the corresponding maximum dry weight ($\gamma_{dmax}$), were achieved. Then, the dry unit weight of the soil samples started to decrease with increasing water content. The results of the compaction tests are summarized in Table 4.

The hydraulic conductivity tests were performed on soil samples compacted at 2–4% on the wet sides of their optimum moisture contents to obtain greater remoulding of clods, elimination of large interclod voids and preferential re-orientation of clay particles, all of which result in smaller hydraulic conductivity values (Lambe, 1954, 1958a,b; Mitchell *et al.*, 1965; Garcia-Bengochea *et al.*, 1979; Acar & Oliveri, 1990; Benson & Daniel, 1990; Daniel & Benson, 1990; Mitchell & Soga, 2005). The results of the hydraulic conductivity tests are summarized in Table 4.

## DISCUSSION OF THE RESULTS

The mean hydraulic conductivity values of the compacted clay samples ranged from $7.70 \times 10^{-11}$ m/s to $6.83 \times 10^{-10}$ m/s with a mean value of ~$2.68 \times 10^{-10}$ m/s (Table 4). These results are comparable with the hydraulic conductivity tests performed on soils to

TABLE 4. The mean optimum moisture content ($w_{opt}$), mean maximum dry unit weight ($\gamma_{dmax}$) and mean hydraulic conductivity (*k*) values of the soil samples.

| Sample | $w_{opt}$ (%) | $\gamma_{dmax}$ (kN/m$^3$) | *k* (m/s) |
|---|---|---|---|
| K1[1,2,3] | 28.0 | 14.2 | $8.20 \times 10^{-11}$ |
| K2 | 27.6 | 14.4 | $8.12 \times 10^{-11}$ |
| K3 | 27.2 | 13.9 | $7.70 \times 10^{-11}$ |
| G1[1,2,3] | 18.0 | 17.0 | $2.94 \times 10^{-10}$ |
| G2[1,2,3] | 18.0 | 16.95 | $2.60 \times 10^{-10}$ |
| G4[4,5] | 23.0 | 14.3 | $1.93 \times 10^{-10}$ |
| G5 | 17.5 | 17.0 | $5.33 \times 10^{-10}$ |
| G6 | 21.0 | 15.8 | $6.83 \times 10^{-10}$ |
| S1[1,2,3] | 21.0 | 15.0 | $3.60 \times 10^{-10}$ |
| S2[1,2,3] | 16.0 | 13.6 | $3.00 \times 10^{-10}$ |
| S3[6] | 26.0 | 12.8 | $8.90 \times 10^{-11}$ |
| S5[4,7] | 38.5 | 13.2 | $8.36 \times 10^{-11}$ |
| S6 | 22.0 | 14.0 | $4.20 \times 10^{-10}$ |

The sample locations are given in Fig. 1.
[1]Akgün *et al.* (1999)
[2]Met (1999)
[3]Met *et al.* (2005)
[4]Yal (2010)
[5]Yal & Akgün (2014)
[6]Met & Akgün (2015)
[7]Yal & Akgün (2013)

be used as compacted clay liner materials in Tunisia and in the United States (Benson & Trast, 1995; Hamdi & Srasra, 2013). These results also suggest that the Ankara Clay may be regarded as a suitable material for a compacted clay landfill liner from a geotechnical point of view as the measured hydraulic conductivity values were less than the maximum hydraulic conductivity value of $1 \times 10^{-9}$ m/s allowed according to the environmental regulations of Turkey (Republic of Turkey, Ministry of Environment & Forestry, 2010), European Union Landfill Directive (1999) and of the United States (USEPA, 1993).

The hydraulic conductivity decreased with increasing plasticity index (PI) and with increasing clay content (Figs 8, 9). Equations 1 and 2 give the best-fit equations and the corresponding coefficient of determination ($r^2$) values for the hydraulic conductivity (*k*) as a function of plasticity index (PI) and clay content (CC), respectively. The data in Tables 2–4 were used to perform regression analysis and to obtain the best-fit equations.

$$k = 2 \times 10^{-4}(\mathrm{PI})^{-3.96}; \quad r^2 = 0.765 \tag{1}$$

$$k = 7.52 \times 10^{-2}(\mathrm{CC})^{-4.96}; \quad r^2 = 0.838 \tag{2}$$

Equations 1 and 2 show that the hydraulic conductivity decreased with increasing plasticity index (PI) and with increasing clay content (CC). Figure 10 and equation 3 show that the plasticity index (PI) increased with increasing clay content (CC) which, in turn, led to a decrease in the hydraulic conductivity.

$$\mathrm{PI} = 11.1e^{0.0182(\mathrm{CC})}; \quad r^2 = 0.787 \tag{3}$$

Equations 1–3 are comparable with those obtained in previous studies (Lambe, 1954; Mesri & Olson, 1971; D'Appolonia, 1980; Daniel, 1987; Kenney

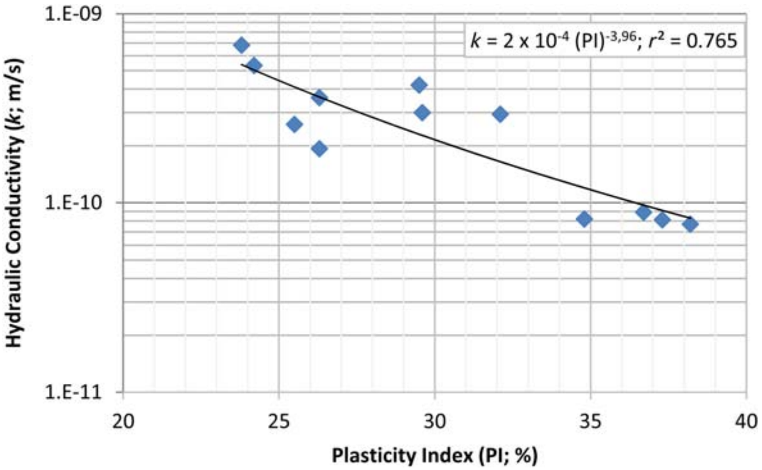


FIG. 8. Hydraulic conductivity (*k*) as a function of PI.

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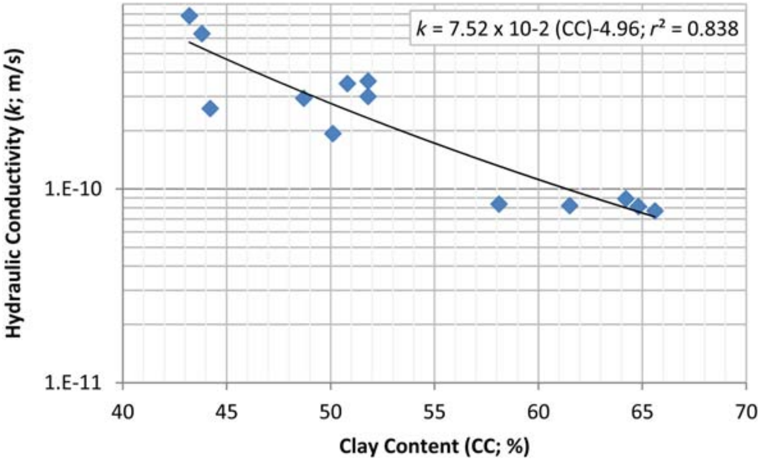


FIG. 9. Hydraulic conductivity ($k$) as a function of clay content (CC).

*et al.*, 1992; Benson *et al.*, 1994). An increase in the clay content, and in the plasticity index generally, leads to a decrease in hydraulic conductivity due to a decrease in the size of microscale pores, which controls the flow in the soils that are compacted on the wet side of the line of optimum values (Lambe, 1954; Benson *et al.*, 1994).

Tables 1 and 4 were used to investigate the relationship between hydraulic conductivity and the clay mineralogy (*i.e.* smectite content, illite content and smectite-illite ratio). The best-fit equations and the corresponding coefficient of determination ($r^2$) values for hydraulic conductivity ($k$) as a function of smectite

TABLE 5. Assessment of satisfaction of the minimum requirements for compacted clay liners (LL: mean liquid limit, PI: mean plasticity index, NS: not suggested by the researcher).

| | | | Particle-size distribution | | |
|---|---|---|---|---|---|
| Sample | LL (%) | PI (%) | % Gravel | % Fines | % Clay |
| K1 | 53.6 | 34.8 | 4.20 | 79.9 | 61.5 |
| K2 | 60.5 | 37.3 | 3.20 | 87.0 | 64.8 |
| K3 | 61.6 | 38.2 | 3.40 | 89.4 | 65.6 |
| G1 | 46.8 | 32.1 | 11.0 | 66.1 | 48.7 |
| G2 | 42.4 | 25.5 | 11.0 | 63.8 | 44.2 |
| G3 | 46.6 | 27.4 | 4.00 | 82.0 | 52.0 |
| G4 | 49.3 | 26.3 | 9.00 | 68.0 | 50.1 |
| G5 | 40.2 | 24.2 | 8.00 | 62.8 | 43.8 |
| G6 | 48.8 | 23.8 | 2.80 | 61.7 | 43.2 |
| S1 | 64.4 | 26.3 | 2.64 | 89.0 | 51.8 |
| S2 | 72.9 | 29.6 | 5.40 | 80.2 | 51.8 |
| S3 | 81.8 | 36.7 | 2.27 | 89.5 | 64.2 |
| S4 | 58.9 | 32.8 | 7.00 | 72.0 | 60.2 |
| S5 | 47.3 | 27.3 | 3.00 | 86.0 | 58.1 |
| S6 | 55.5 | 29.5 | 1.20 | 93.3 | 80.1 |
| Requirements | | | | | |
| Gordon *et al.* (1990) | >30 | >15 | NS | >50 | >25 |
| Daniel (1990) | NS | >10 | <10 | >30 | NS |

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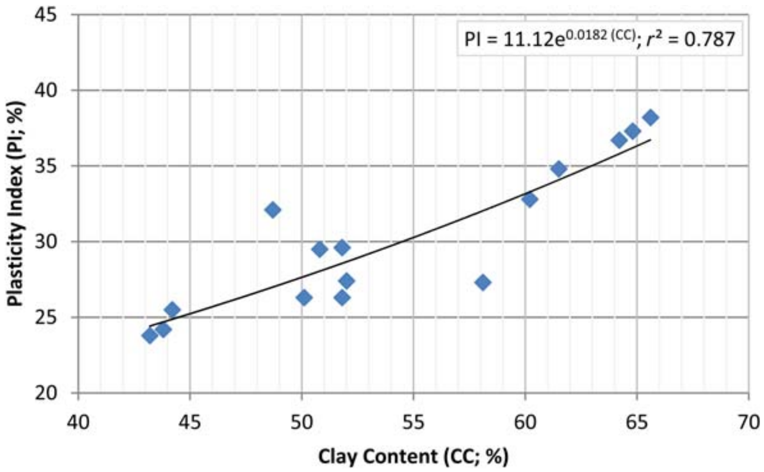


FIG. 10. PI as a function of clay content (CC).

content (S), illite content (I) and smectite-illite ratio (SIR) given by Figs 11–13 and equations 4–6 indicate that the hydraulic conductivity ($k$) decreased with increasing smectite content (S), decreasing illlite content (I) and increasing smectite-illite ratio (SIR). The relatively small hydraulic conductivity value of clayey soil samples K1 and S3 is due to their greater smectite content. As the illite percentage increased in the clay samples, the hydraulic conductivity increased slightly from $8.90 \times 10^{-11}$ m/s to $2.94 \times 10^{-10}$ m/s. In addition, the hydraulic conductivity decreased with increasing CEC (Fig. 14, equation 7). The influence of kaolinite and chlorite on the hydraulic conductivity could not be evaluated because both minerals are present in very small amounts in the clayey soil samples (*i.e.* typically <4%).

$$k = 7 \times 10^{-10} e^{-0.034(S)}; \quad r^2 = 0.796 \qquad (4)$$

$$k = 2 \times 10^{-13} (I)^{1.763}; \; r^2 = 0.864 \qquad (5)$$

$$k = 4 \times 10^{-10} e^{-0.884(SIR)}; \quad r^2 = 0.847 \qquad (6)$$

$$k = 6 \times 10^{-10} e^{-0.053(CEC)}; \quad r^2 = 0.404 \qquad (7)$$

Some compacted clayey liner materials may not satisfy the required specifications to be used as compacted clay liners, due to the presence of clods of soil and

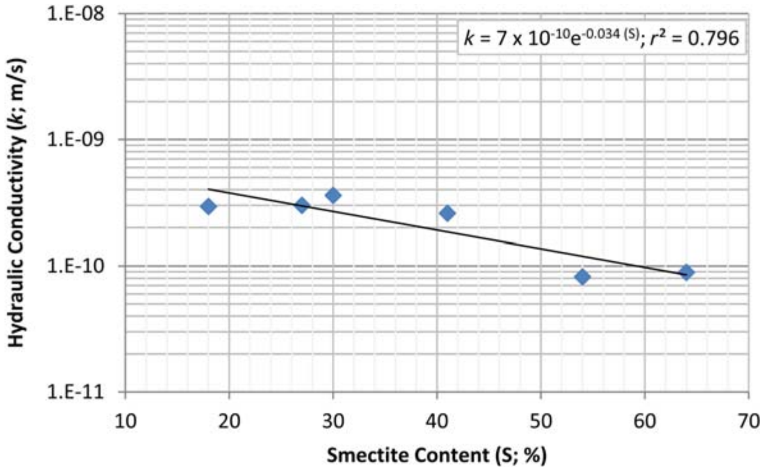


FIG. 11. Hydraulic conductivity ($k$) as a function of smectite content (S).

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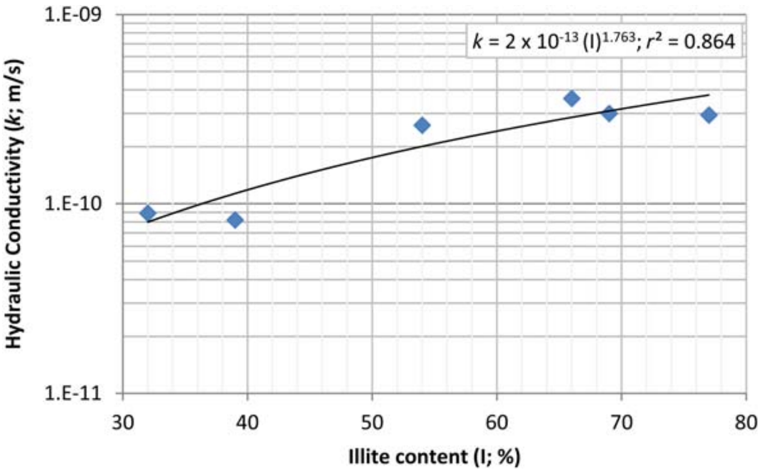


FIG. 12. Hydraulic conductivity ($k$) as a function of illite content (I).

rocks and their moisture contents. Thus, these clayey liner materials may require further processing to break down the clods of soil with tilling equipment and to sieve out the rock particles using large vibratory sieves or mechanized rock pickers passed over a loose lift of soil (Daniel, 1990; Gordon *et al.*, 1990). As is indicated in Table 5, which presents an assessment of satisfaction of the minimum requirements for compacted clay liners, clayey soil samples G1 and G2 may require sieving in the field as their sieve analysis indicated a gravel percentage of 11%, which exceeded the maximum allowed, 10%. The results of the sieve analyses of the remainder of the 13 soil samples indicated gravel percentages of <10% and hence were acceptable. The LL, the PI, the percentage of fines and the percentage of clay fractions of the 15 soil samples indicated that Ankara Clay is suitable for compacting in the field. However, even though the geotechnical properties of the samples comply with the regulations, to ensure the long term sustainability of the landfill sites, higher standards should be sought.

The quality of the clay samples to be used as compacted clay liners varies with the location of sampling. In this respect, considering the spatial variation of the quality of the samples, if logistically possible, the clay materials with the highest quality

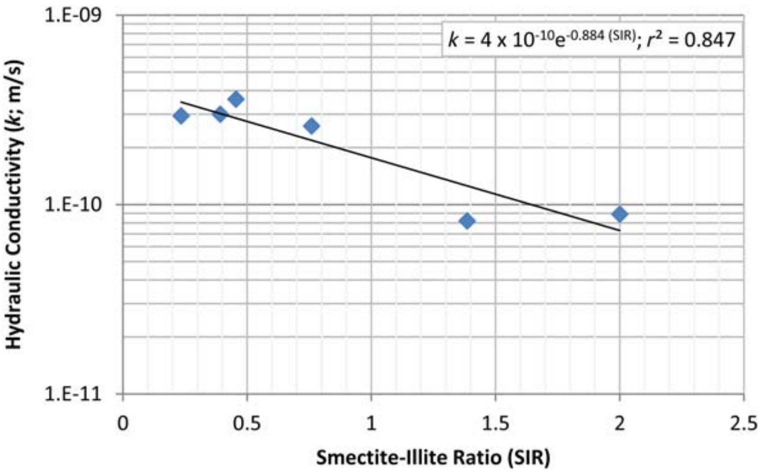


FIG. 13. Hydraulic conductivity ($k$) as a function of smectite-illite ratio (SIR).

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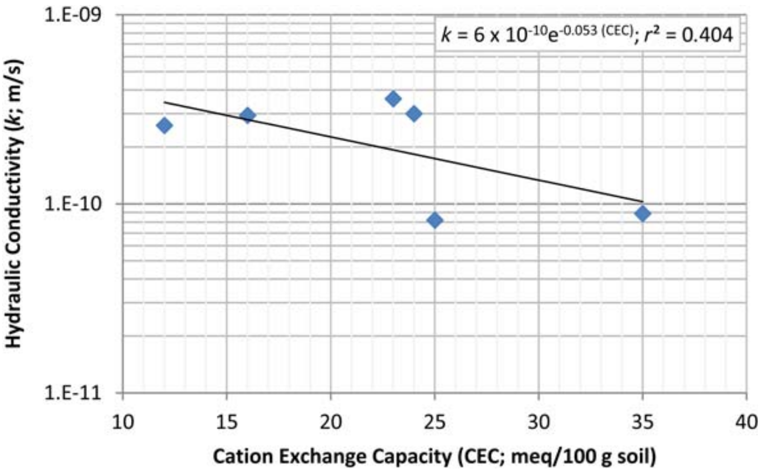


FIG. 14. Hydraulic conductivity ($k$) as a function of CEC.

should be selected for use as landfill liner materials. The clay sample S3 is considered to be of best quality for use as a compacted clay liner with a smectite content of 64%, a hydraulic conductivity of $8.9 \times 10^{-11}$ m/s, LL, PL and PI of 81.8%, 45.1% and 36.7%, respectively, and percentages of gravel, fines and clay of 2.27%, 89.5% and 64.2%, respectively.

In addition, improvement of the geotechnical properties of the clay materials through addition of bentonite, quick lime, silica fume, fly ash, cement, claystone, red mud, rubber, etc. (Çokça & Yılmaz, 2004; Kalkan & Akbulut, 2004; Kalkan, 2006; Wiśniewska & Stepniewski, 2007; Herrmann *et al.*, 2009; Travar *et al.*, 2009; Francisca & Glatstein, 2010; Musso *et al.*, 2010; Akcanca & Aytekin, 2014; Qiang *et al.*, 2014) could also be considered depending on the landfill-liner design parameters to be implemented.

A lining system consists of barrier and drainage layers where compacted clay liners (CCL) or geosynthetics such as geomembranes, geosynthetic clay liners (GCL) and/or a combination of these (composite liners composed of geomembrane liners in contact with compacted clay liners) may be used as barriers for the containment of liquids, sludges and leachate, generating solids. Compacted clay liners such as those studied here are constructed primarily from compacted natural soil materials that are rich in clay, although the liners may contain processed materials such as bentonite (Akgün & Daemen, 2012). The compacted clay liners with thicknesses generally ranging from 0.6 to 0.9 m should have a hydraulic conductivity $\leq 1 \times 10^{-9}$ m/s (*e.g.* USEPA, 1989; Koerner & Daniel, 1997; Daniel & Koerner, 2007). Geomembranes or flexible membrane liners (FML) are essentially impermeable, relatively thin sheets of polymeric materials, 0.75–3 mm thick (Qian *et al.*, 2002). A geosynthetic clay liner (GCL) is a relatively thin layer of processed clay (typically bentonite) either bonded to a geomembrane or fixed between two sheets of geotextile where a geotextile is a woven or non-woven polymeric fibre that is less impervious to liquid than a geomembrane, but more resistant to penetration damage. In GCL configurations which use a geomembrane, the clay is affixed using an adhesive whereas in GCL configurations consisting of geotextiles, adhesives, stitchbonding, needlepunching or a combination of the three is used. The main advantages of GCLs are: (1) the allocation of more landfill space for waste disposal because GCLs are not as thick as a liner system (*i.e.* ~4–6 mm thick) involving the use of compacted clay (USEPA, 2001; Qian *et al.*, 2002; Akgün & Daemen, 2012); and (2) the relatively low hydraulic conductivities of most Na-bentonite GCLs which lie in the range $1 \times 10^{-11}$–$5 \times 10^{-11}$ m/s (Qian *et al.*, 2002). Recently, it has become common practice, with the improvement of geosynthetic liner materials, to incorporate geosynthetic materials into natural clays instead of using natural clays alone in the composite clay liners (*e.g.* Katsumi *et al.*, 2001; Met & Akgün, 2005; Lorenzetti *et al.*, 2005; Travar *et al.*, 2009; Chen *et al.*, 2015). Clay-material enhancement and composite landfill liner design are beyond the scope of the present study. Note, however, that landfill liner design with Ankara Clay for various landfill liner configurations has already been performed and reported previously (Akgün *et al.*, 1999; Met, 1999; Met & Akgün, 2005,

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Table 6. Highlights of the main results.

| Sample | CEC (meq/100 g soil) | S (%) | I (%) | LL (%) | PL (%) | PI (%) | USCS | $w_{opt}$ (%) | $\gamma_{dmax}$ (kN/$m^3$) | $k$ (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| K1[1,2,3] | 25 | 54 | 39 | 53.6 | 18.8 | 34.8 | CH | 28.0 | 14.2 | $8.20 \times 10^{-11}$ |
| K2 | – | – | – | 60.5 | 23.2 | 37.3 | CH | 27.6 | 14.4 | $8.12 \times 10^{-11}$ |
| K3 | – | – | – | 61.6 | 23.4 | 38.2 | CH | 27.2 | 13.9 | $7.70 \times 10^{-11}$ |
| G1[1,2,3] | 16 | 18 | 77 | 46.8 | 14.7 | 32.1 | CL | 18.0 | 17.0 | $2.94 \times 10^{-10}$ |
| G2[1,2,3] | 12 | 41 | 54 | 42.4 | 16.9 | 25.5 | CL | 18.0 | 16.95 | $2.60 \times 10^{-10}$ |
| G3[4,5] | – | – | – | 46.6 | 19.2 | 27.4 | CL | – | – | – |
| G4[4,5] | – | – | – | 49.3 | 23.0 | 26.3 | CL | 23.0 | 14.3 | $1.93 \times 10^{-10}$ |
| G5 | – | – | – | 40.2 | 16.0 | 24.2 | CL | 17.5 | 17.0 | $5.33 \times 10^{-10}$ |
| G6 | – | – | – | 48.8 | 25.0 | 23.8 | CL | 21.0 | 15.8 | $6.83 \times 10^{-10}$ |
| S1[1,2,3] | 23 | 30 | 66 | 64.4 | 38.1 | 26.3 | MH | 21.0 | 15.0 | $3.60 \times 10^{-10}$ |
| S2[1,2,3] | 24 | 27 | 69 | 72.9 | 43.3 | 29.6 | MH | 16.0 | 13.6 | $3.00 \times 10^{-10}$ |
| S3[6] | 35 | 64 | 32 | 81.8 | 45.1 | 36.7 | MH | 26.0 | 12.8 | $8.90 \times 10^{-11}$ |
| S4[4,7] | – | – | – | 58.9 | 26.2 | 32.8 | CH | – | – | – |
| S5[4,7] | – | – | – | 47.3 | 20.0 | 27.3 | CL | 38.5 | 13.2 | $8.36 \times 10^{-11}$ |
| S6 | – | – | – | 55.5 | 26.0 | 29.5 | CH | 22.0 | 14.0 | $4.20 \times 10^{-10}$ |
| AC1[8] | 32 | 60 | 32 | – | – | – | – | – | – | – |

Cation exchange capacity (CEC), percentage of smectite (S) and illite (I) clay minerals of samples as determined by XRD analyses; mean liquid limit (LL), mean plasticity limit (PL), mean plasticity index (PI), classification of the soil samples according to the Unified Soil Classification System (USCS), mean optimum moisture content ($w_{opt}$), mean maximum dry unit weight ($\gamma_{dmax}$) and mean hydraulic conductivity ($k$) values of the soil samples. The sample locations are given in Fig. 1.
CL: Low Plasticity Clay, CH: High Plasticity Clay, MH: High Plasticity Silt.
[1]Akgün *et al.* (1999)
[2]Met (1999)
[3]Met *et al.* (2005)
[4]Yal (2010)
[5]Yal & Akgün (2014)
[6]Met & Akgün (2015)
[7]Yal & Akgün (2013)
[8]Sezer *et al.* (2003)

2015; Yal, 2010; Yal & Akgün, 2013, 2014). Met & Akgün (2015) presented a comparison between the expected leakage rates through compacted clay-only and geomembrane-compacted clay composite liners. Their results showed that the expected leakage rates for a leachate head of 1 m can be reduced by up to two orders of magnitude through the use of a composite liner which may indicate that composite liners are no more expensive than compacted clay liners when lifetimes are taken into account.

## SUMMARY AND CONCLUSIONS

The Ankara Clay, which represents the clayey levels of the Upper Pliocene deposits of the Ankara basin, is considered to be an excellent source for compacted clay landfill liners due to its low hydraulic conductivity and widespread distribution in the broader area. The present study investigated experimentally the mineralogical and geotechnical characteristics of the clayey soil samples obtained from the Ankara region. These samples possessed an average hydraulic conductivity of ~$2.68 \times 10^{-10}$ m/s which is less than the maximum value of $1 \times 10^{-9}$ m/s, according to environmental regulations in Turkey, the European Union and the United States. The major clay minerals are smectite and illite while kaolinite and chlorite are present in small concentrations. The results of the mineralogical and geotechnical tests led to decreased hydraulic conductivity ($k$) values with increased plasticity indices (PI), increased clay content, increased CEC, increased smectite content (S), decreased illite content (I) and increased smectite to illite ratio (SIR; Table 6). The relationships between the mineralogical and geotechnical characteristics were investigated by regression analyses. Investigations regarding field construction of the compacted clay liner indicated that Ankara Clay is very suitable for compacting in the field.

The mineralogical and geotechnical tests performed indicated that the material is suitable as a compacted clay landfill liner.

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