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Assessment of the geotechnical aspect of the use of paper mill sludge as landfill cover and bottom liner material

Müge Balkaya

Department of Civil Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey, email: balkayamu@itu.edu.tr

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A B S T R A C T

This study aimed to investigate the beneficial reuse of paper mill sludge as landfill cover and bottom liner material in municipal solid waste landfills. For this purpose, two-dimensional finite element analyses of a typical landfill geometry were carried out using PLAXIS finite element program. The results of the analyses were evaluated in terms of displacement and factor of safety (FS) values, and compared with those of the compacted clay. The results of this study showed that, vertical and lateral displacements of the landfill slightly increased while the FS of the landfill slopes decreased with increasing surface loading. However, for all the cases studied, lower vertical and lateral displacements and higher FS values were obtained for the landfills with paper mill sludge as the cover and bottom liner material in comparison to those of the compacted clay. Besides, for all the cases studied, FS values greater than 1.5 were obtained, indicating that the landfill slopes were stable under the proposed loadings and landfill cover and bottom liner materials. Based on these results, it can be stated that the paper mill sludge examined in this paper has geotechnical properties that are desirable for a landfill cover and bottom liner material for use as a substitute of compacted clay in municipal solid waste landfills.

Keywords: Finite element analysis; Hydraulic barrier; Landfill cover; Paper mill sludge

1. Introduction

The pulp and paper industry produces millions of tons of paper per year. This production leads to the generation and accumulation of significant amounts of waste sludge called the paper mill sludge that should be disposed of [1]. Papermill sludges are characterized by their high cellulose fiber contents. They contain wood, lignin and some organic binders as the organic components, and minerals such as kaolin and calcium carbonate, and trace quantities of heavy metals as the inorganic components [2,3].

As stated by Mabee and Roy [4], in 50 years, it was estimated that the worldwide paper mill sludge production would increase by 48%–86% over the current levels. Therefore, it is apparent that some urgent measures should be taken in terms of sludge management. Papermill sludge is generally considered as waste material. Therefore, the disposal of this sludge is a big concern all over the world. Land application and landfilling are the dominant disposal methods for paper mill sludge in most countries [4–8]. However, due to the increasing demand for landfill sites, the cost of solid waste disposal, and the stringent regulations for their disposal, burning or incineration for energy production and volume reduction have been the alternative disposal options for paper mill sludges [9,10]. On the other hand, their beneficial reuse has also been encouraged to decrease the required landfill space for their disposal, provide a more cost-effective solution compared to the other competitive materials that have economic value, and reduce the consumption of natural resources [11–16].

Although paper mill sludge can be beneficially reused in various fields of civil engineering applications such as the production of building materials [17–21], fiber additive for asphalt road pavement [22], road subbase [23,24], and soil stabilization [25–28], various researchers stated that the most favorable application for paper mill sludge is its use in hydraulic barriers in landfills since its geotechnical properties such as the permeability, cohesion, angle of internal friction, unit weight, and modulus of elasticity show similarities to those of compacted clay [12,29,30]. The important characteristics regarding the use of paper mill sludges in landfill liners are the hydraulic conductivity, water content, and the organic content of the sludge. When used in landfill liners and covers, paper mill sludge appears to have a sufficient performance in terms of geotechnical engineering. It is an attractive and economical substitute for natural clay in the construction of hydraulic barrier layers of landfills [31,32]. Besides, Carroll [33] indicated that paper mill sludge can be used as a more effective hydraulic barrier material compared to the compacted clay barrier.

In this study, two-dimensional finite element analyses of a typical municipal solid waste landfill site with different cover and bottom liner materials and surface loading conditions were carried out using PLAXIS finite element program. In the analyses, paper mill sludge and compacted clay were used as the final cover and bottom liner materials, and a 30-years-old decomposed municipal solid waste was used, simulating a closed landfill site. Closed landfill sites are generally used as recreation areas and parking lots. Therefore, the stability and displacement behavior of the modeled closed landfill site as a parking lot was also studied. The results of the analyses for the two different landfill cover and bottom liner materials (compacted clay and paper mill sludge), and surface loading conditions (0, 2, and 20 kPa) were compared in terms of displacement and factor of safety (FS) values, and the behaviors of these two materials were evaluated in terms of geotechnical engineering point of view. Although there have been numerous studies on the determination of the engineering properties of paper mill sludges and their application as landfill covers [12,29,30], to the author's knowledge, there is no published paper modeling the use of paper mill sludge as final cover and bottom liner material using finite element analysis, and comparing its geotechnical behavior with that of compacted clay. Therefore, investigating these issues was the motivation of this study.

2. Materials and methods

2.1. Statement of the problem

In this paper, two-dimensional finite element analyses of a typical landfill geometry were executed to examine the use of paper mill sludge as landfill cover and bottom liner material. A typical landfill cross-section was modeled in the analyses. Since the chosen landfill cross-section was symmetric, the analyses were performed on half of the landfill geometry. The half landfill length of the studied problem was chosen as 100 m, and the adequacy of this length was checked for minimizing the boundary effects.

In the finite element analyses, it was aimed to investigate the displacements and slope stability of a closed landfill. Therefore, the municipal solid waste studied in the analyses was chosen as a 30-years old decomposed waste, engineering properties of which are given in Table 1, consistent with Fatahi and Khabbaz [34]. The side slopes of the landfill were assumed to be 3H:1V (H = the horizontal distance, V = vertical distance). Two different landfill cover and bottom liner materials were used as compacted clay and paper mill sludge. Closed landfill sites can be used as recreation areas. Therefore, after the landfill is covered, the possible

Table 1
Material parameters used in the finite element analyses

Material model	CS	DG	CC	SPL	PMS	SiC	DW	GT	GM
	MC	MC	MC	MC	MC	MC	SSC	LE	LE
γ_{unsat} (kN/m^3)	19	18	16	18	5.3	19	11	–	–
γ_{sat} (kN/m^3)	21	21	18	21	12	21	14.6	–	–
E (kN/m^2)	40,000	100,000	20,000	50,000	3,333	150,000	–	–	–
ν	0.3	0.35	0.4	0.3	0.4	0.35	0.15	–	–
c' (kN/m^2)	17	0	24	0	0	48	11	–	–
ϕ' (°)	22	40	29	34	53	35	29	–	–
ψ (°)	0	10	0	4	13	5	0	–	–
e_{init}	–	–	–	–	–	–	0.63	–	–
C_r	–	–	–	–	–	–	0.075	–	–
C_c	–	–	–	–	–	–	0.330	–	–
C_α	–	–	–	–	–	–	0.052	–	–
EA (kN/m)	–	–	–	–	–	–	–	500	480
References	[41]	[42]	[43]	[42]	[15]	[44]	[34]	[45]	[46]

γ_{unsat}: unsaturated unit weight, γ_{sat}: saturated unit weight, E: Young's modulus, ν: Poisson's ratio, c': effective cohesion, ϕ': effective internal friction angle, ψ : dilation angle, e_{init}: initial void ratio, C_r: recompression index, C_c: compression index, C_α: secondary compression index of the soil layers, EA: axial stiffness of the geosynthetic materials.

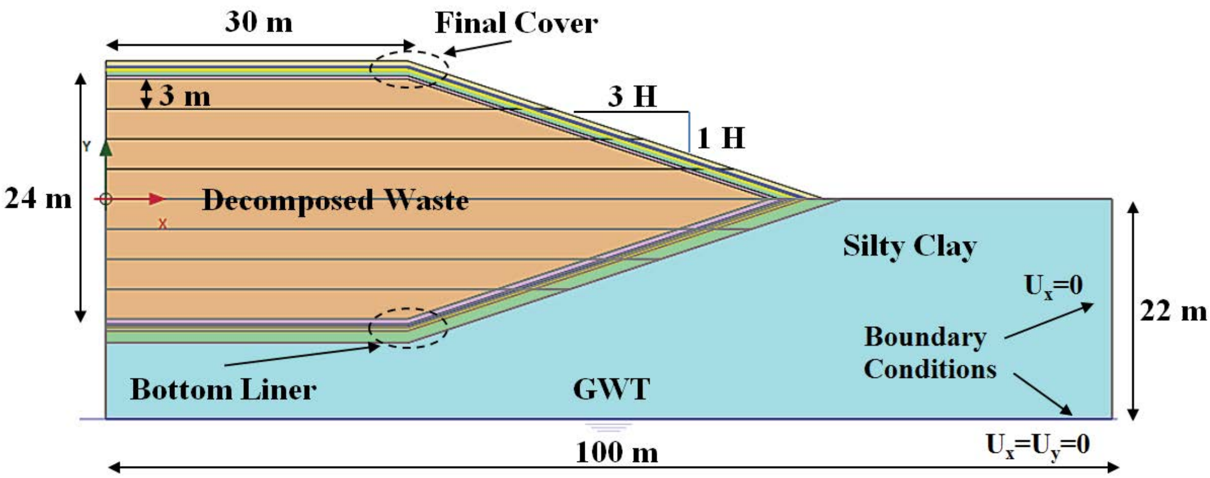

Fig. 1. Problem being analyzed.

use of this area as a parking lot was investigated with the application of 2 kPa uniformly distributed load modeling the parking lot load [35], and 20 kPa uniformly distributed load modeling the traffic load [34] over the closed landfill.

The constituents of the landfill final cover system were 0.6 m vegetative cover soil (CS), geotextile (GT), 0.3 m gravel drainage (DG) layer, geomembrane (GM), 0.6 m compacted clay (CC) or paper mill sludge (PMS), and 0.3 m sand protection layer (SPL), from top to bottom, respectively. Similarly, the bottom liner was composed of a 0.3 m SPL, GT, 0.3 m DG, GM, 0.3 m SPL, GM, and 1.2 m CC or PMS layers, from top to bottom, respectively. The final cover and bottom liner systems were selected consistent with the previously published papers [30,36,37]. The studied problem is illustrated in Fig. 1, and the details of the bottom liner and the final cover systems modeled in this study are given in Fig. 2.

Staged construction was implemented for the construction of the landfill. Taking the coefficient for lateral earth pressure $K_0 = 1-\sin\phi$ (ϕ = angle of internal friction of soil), the geostatic stresses were generated in the first step of the finite element analyses. After this step, the excavation of the natural soil, laying the bottom liner, filling the waste material, laying the final cover system, and applying the distributed loads on the covered landfill surface was simulated, respectively. After filling each layer of 3.0 m waste material, the waste was allowed to consolidate for 10 d. The selection of the lift thickness of 3.0 m was consistent with Fatahi and Khabbaz [34], and Babu et al. [36]. Once the construction of the landfill and the final landfill cover were completed, the settlement of the landfill under its self-weight was simulated by consolidation for 365 d. In order to simulate the construction of a parking lot on the closed landfill, the application of the surface loadings simulating a parking lot and the traffic load over the landfill was modeled. Safety analyses were performed after the stages modeling the surface loading conditions and one year of consolidation time.

Slope stability is an important issue in landfill design [38]. The FS for slope stability is generally taken as 1.5 [39]. In the PLAXIS finite element program, the FS against slope failure is determined by the ϕ-c reduction method, where $\tan\phi$ and c of the soil are reduced until failure at the structure takes place. The FS is obtained by the ratio of the available strength to the strength at failure.

2.2. Numerical modeling

2.2.1. Mesh design

The effects of the two different landfill cover materials on the vertical displacement (U_y), lateral displacement (U_x), and FS values of the proposed landfill were modeled using PLAXIS finite element program [40]. 15-node soil elements and 5-node geogrid elements were used for the generation of the finite element mesh. In the analyses, only the right half of the landfill was modeled due to symmetry (Fig. 3). The finite element mesh consisted of approximately 3,884 elements and was refined around the landfill to capture the rapidly varying stresses and strains around this region.

The effect of mesh refinement on the finite element analysis results was investigated for a control case (paper mill sludge as the final cover and bottom liner material, and 20 kPa surface loading). After performing several finite element analysis runs with different mesh densities, it was revealed that the maximum difference between the results was 1.49%. This showed that the different mesh densities did not have a significant effect on the displacement and FS values of the landfills investigated in this study. To reduce the size of the analysis, the mesh with the lowest computational cost that maintained sufficient accuracy was adopted in the analyses.

2.2.2. Materials used in the finite element analyses

The plane strain model was selected in the finite element analyses since the cross-section and the material properties of the landfill were assumed to be uniform along the z-direction. Linear elastic (LE) model was used for simulating the geosynthetic materials, and the Mohr–Coulomb (MC) and the soft soil creep (SSC) models were chosen for modeling the soil layers and the decomposed waste material, respectively (Table 1). Effective shear strength parameters were used in the analyses for the determination of the FS values against the instability of the landfill slopes for the intermediate and

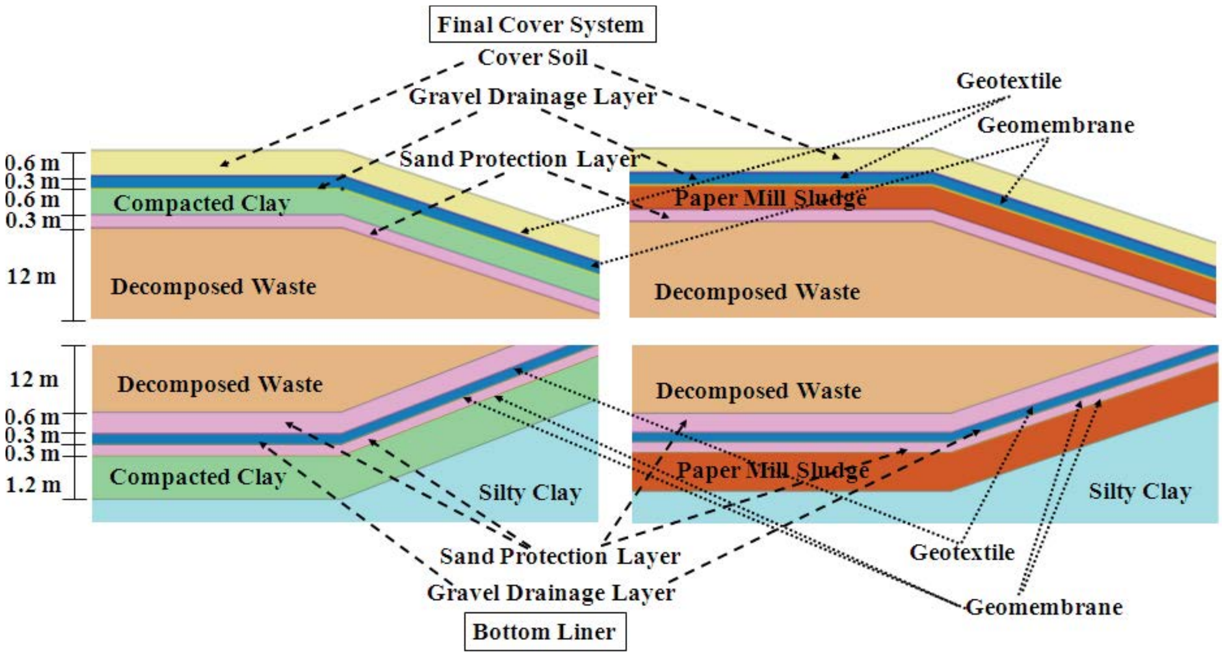

Fig. 2. Details of the final cover and bottom liner systems.

long-term conditions under different landfill cover materials, surface loading conditions, and waste consolidation cases studied in this paper.

2.2.3. Boundary conditions

Due to the symmetric landfill geometry, half of the landfill was modeled in the finite element analyses. The model dimensions were selected based on the numerous finite element analysis runs until the boundary effects became negligible. In the finite element models, $x = 0$ plane (plane of symmetry) and $x = 100$ plane were fixed against displacement in the x-direction ($U_x = 0$), while the bottom of the soil layer was fixed against displacements in the x and y directions ($U_x = U_y = 0$). The boundary conditions adopted in the analyses are given in Fig. 1.

3. Results and discussion

To evaluate the effects of different landfill cover materials and surface loading conditions due to the traffic load and the construction of a parking lot on the displacements and FS values of the investigated landfill, various configurations of these variables were studied in the finite element analyses.

As stated by Moo-Young and Zimmie [13,30], the paper mill sludge used as landfill cover and liner should be consolidated to reduce the hydraulic conductivity, and one year period is generally considered sufficient for the consolidation of the sludge to complete. Therefore, the 1-year period was selected as the consolidation duration in the analyses to examine the behavior of the paper mill sludge as the final cover and bottom liner material in comparison to the behavior of the compacted clay. Fig. 4 shows typical U_y contours of the landfill after 365 d of consolidation under a uniformly distributed load of 20 kPa. In the figure, the highest U_y values are denoted by red shading, whereas the lowest values are denoted by dark blue shading (zero displacement). As expected, the highest settlement occurred at the landfill surface, under the uniformly loaded area. It can be seen from the figure that the vertical displacement then gradually decreased downwards and became zero at the far end boundary of the geometry.

The maximum settlements occurred at the landfill surface, under the uniformly distributed surface loading. Therefore, the maximum vertical displacement (U_y) variations at the landfill surface obtained after one year of consolidation for different landfill cover and liner materials, and uniformly distributed surface loads are given in Fig. 5. These settlement values were in the same range as those predictions from the literature [34,36,47–49], corresponding to 1 year of consolidation time. As can be seen from the figure, for each loading case, higher settlement values were obtained when the compacted clay was used as the cover and bottom liner material, in comparison to those of the paper mill sludge. This settlement behavior may be attributed to the higher unit weight of the compacted clay leading to the generation of higher effective pressure, and the lower internal friction angle of the compacted clay which leads to the development of lower shear strength in comparison to that of the paper mill sludge. Almost identical settlement values were obtained for the uniformly distributed load applications of $q = 0$ kPa (no surface loading) and $q = 2$ kPa (parking lot loading). However, slightly higher settlement values were obtained for the $q = 20$ kPa (traffic load) loading case, as expected.

The maximum lateral displacements were obtained along the side slope of the landfill. The maximum lateral displacement (U_x) variations along the side slope, obtained after one year of consolidation under the compacted clay and paper mill sludge cover and bottom liner materials, and uniformly

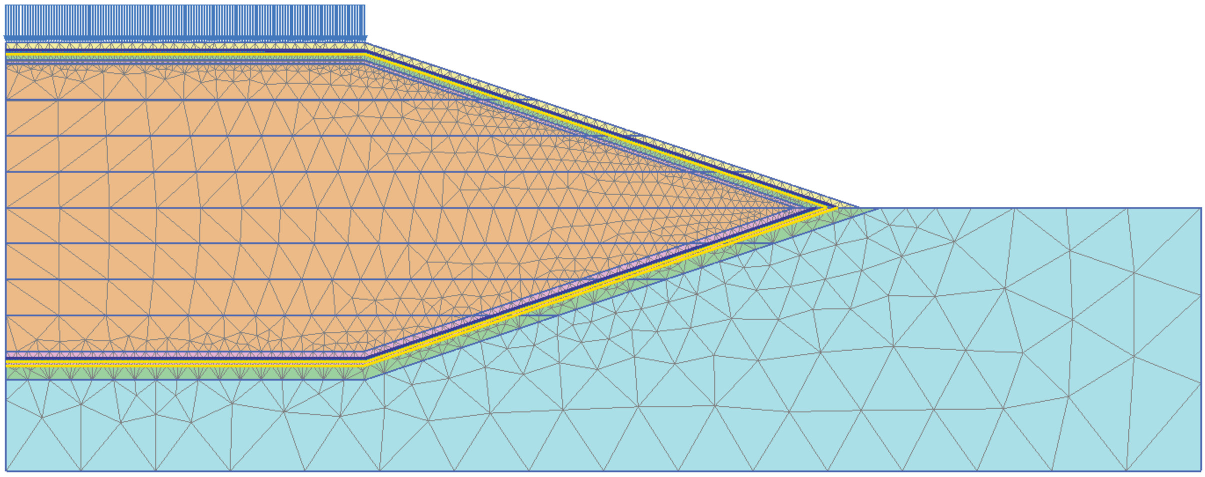

Fig. 3. A typical finite element mesh used for modeling the landfill.

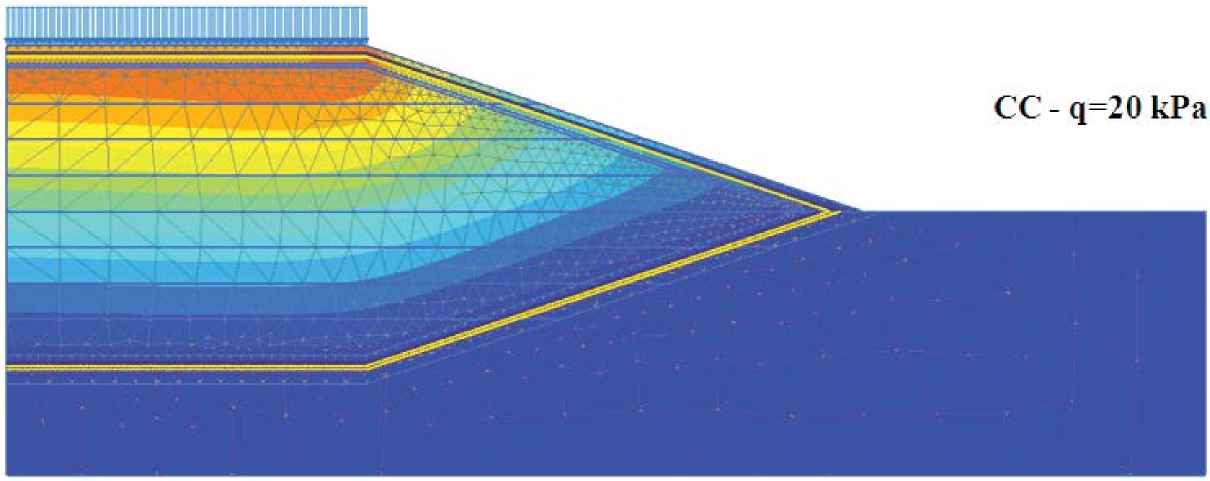

Fig. 4. Typical vertical displacement contours obtained after 365 d of consolidation.

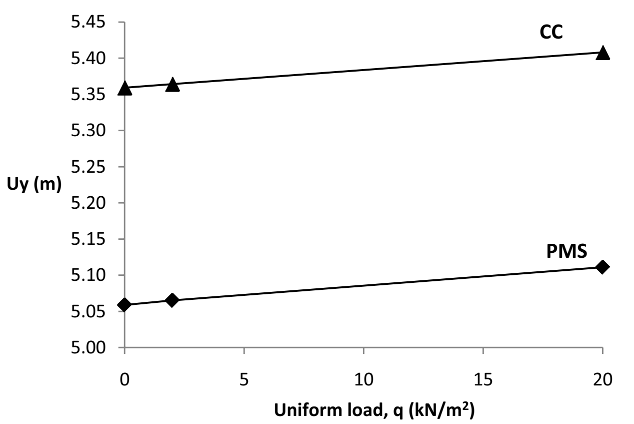

Fig. 5. Vertical displacement variations obtained after 365 d of consolidation under different landfill final cover and bottom liner materials, and distributed loads.

distributed surface loads are given in Fig. 6. The figure shows that, for the same liner and final cover design, the lateral displacement does not seem to be significantly affected by the surface loading conditions used in this study. However, for the same loading conditions, higher lateral displacement values were obtained for the compacted clay cover and liner, compared to those of the paper mill sludge. This behavior is thought to be a consequence of the higher unit weight and lower internal friction angle of the compacted clay that lead to the development of higher driving forces.

Fig. 7 shows the FS values for different landfill cover materials and surface loading conditions. As can be seen from the figure, higher FS values were obtained when paper mill sludge was used as the landfill cover and bottom liner material, compared to those of the compacted clay. The FS values slightly decreased with increasing distributed load values. However, for all the cases studied, FS values greater than 1.5 were obtained indicating that the landfill slopes were stable against sliding under these conditions. These findings were supported by Carroll [33], who stated that paper mill

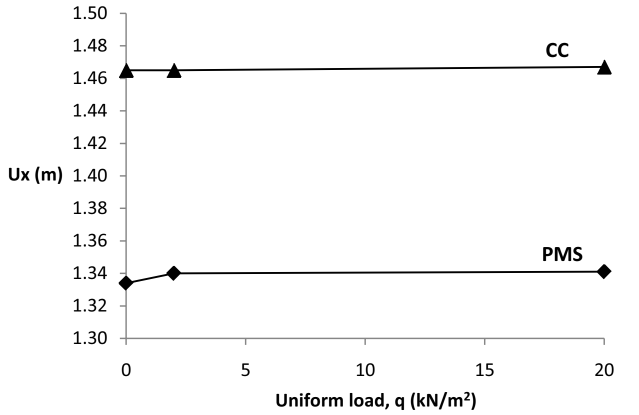

Fig. 6. Lateral displacement variations obtained after 365 d of consolidation under different landfill final cover and bottom liner materials, and distributed loads.

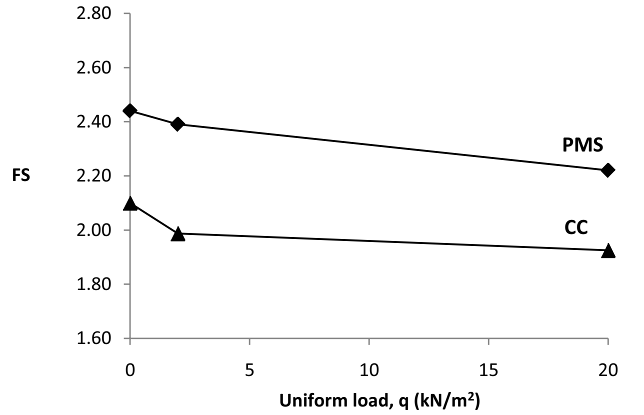

Fig. 7. FS values obtained after 365 d of consolidation under different landfill cover and bottom liner materials, and distributed loads.

sludges display adequate shear strength to withstand slopes as great as 1:4.

It is known that when designing landfills, stability and leakage are important issues that should be taken into account [50,51]. Therefore, the landfill covers and bottom liners should be composed of materials with low hydraulic conductivities, and high shear strength. The hydraulic conductivity and internal friction angle values of paper mill sludges were reported to be on the order of 1×10^{-6}–1×10^{-12} m/sec [12,13,30,31,52–54], and 25°–76.5° [13,30,52,54–56], respectively by various researchers. Therefore, it can be concluded that paper mill sludge is a material that fulfills the low permeability and high shear strength requirements for use in landfill covers and bottom liners. The behavior of this waste material resembles compacted clay in many aspects [29,30,31], which is a traditional material for use in landfill covers and liners. However, paper mill sludge has some advantages compared to clays.

While clay has commercial value, paper mill sludge can be obtained from paper mills at little or no cost. Therefore, the substitution of paper mill sludge for clay can be an economical and feasible alternative in areas that do not have a local source of clay. Besides, hydraulic barrier layers composed of paper mill sludges are reported to be less prone to construction defects caused by compaction deficiencies than do clay layers [57]. Papermill sludge is also a chemically and microbiologically stable material [12]. Since paper mill sludges are mostly composed of organic materials, they do not pose a significant environmental threat [50], which makes them a safe alternative to compacted clay. Moreover, due to their high shear strength after compaction, paper mill sludges can withstand relatively high slopes in landfill applications [33]. On the other hand, paper mill sludges are also used as adsorbent for the removal of various contaminants from wastewater, such as heavy metal [58–60], phenol [61], tricaine methanesulfonate which is a pharmaceutical product [62], and reactive dye [63]. Therefore, using paper mill sludge in landfill projects would benefit from the contaminant removal abilities of this material. Papermill sludge is also reported to be a more resistant material to freeze-and-thaw effects compared to clay [64]. Therefore, it can be said that paper mill sludge may be a better substitute for compacted clay in landfill cover systems when the freeze-thaw cycle is an issue. However, precautions should be taken when paper mill sludge is used as landfill cover material to prevent increases in the hydraulic conductivity values due to the extreme weather conditions such as desiccation and freeze-thaw cycles [13,31,33].

On the other hand, the proximity of paper mills is an important factor in the selection of this material for landfill caps and liners. Zule, et.al [12] indicated that landfills collecting municipal and industrial waste may be conveniently covered or lined by means of sludge when the sludge generation site is less than 100 km away. Therefore, this issue should be taken into consideration if paper mill sludge is to be used in landfill covers or liners.

Today, the beneficial reuse of some industrial wastes is encouraged for various reasons such as the creation of a sustainable environment, conservation of natural resources, cost-effectiveness, and decreasing the significant volumes covered by these wastes in solid waste landfills. Therefore, several researchers have investigated the use of these waste materials in various beneficial reuse applications. For example, in a two-dimensional finite element analysis study conducted by Balkaya [65], the reuse of alum sludge in municipal solid waste landfills as a hydraulic barrier layer and daily cover material was investigated. Similar to the paper mill sludge, the alum sludge is also accepted as a waste material that should be disposed of. The results of this study showed that the alum sludge used as a hydraulic barrier layer and daily cover material yielded compatible results with the ones of the compacted clay. On the other hand, the reuse of paper mill sludge in landfill liner and cover applications studied in the present paper revealed that paper mill sludge decreased the displacements while increasing the FS values in comparison to the same compacted clay that was used in the previously mentioned study by Balkaya [65]. Therefore, it can be stated that the use of waste materials such as alum sludge and paper mill sludge in landfill design can be good alternatives to the conventional compacted clay. However, due to the higher internal friction angle of the paper mill sludge that leads to higher shear strength in comparison to that of alum sludge, the paper mill sludge has a better engineering performance compared to the alum sludge.

In the light of the results of this parametric study, and the brief literature review on the physical and mechanical properties of paper mill sludge presented above, it can be stated that; considering its cost-effectiveness, high mechanical properties, sufficient hydraulic conductivities [12,13,30,31,52–54], good freeze-thaw performance [13,30,31,64,66,67], non-hazardous nature [50], and the ability to adsorb various contaminants [58–63], paper mill sludge seems to be a promising material for use in landfill liners and covers.

6. Conclusions

The results of this study showed that higher settlement values were obtained when compacted clay was used as the final cover and bottom liner material in comparison to those of the paper mill sludge, and the settlements slightly increased with increasing uniformly distributed load application. Similarly, higher lateral displacement values were obtained for the compacted clay compared to those of the paper mill sludge. When the results were evaluated in terms of slope stability, it was found that higher FS values were obtained for the paper mill sludge compared to those of the compacted clay cover, and the FS values slightly decreased with increasing distributed load values. However, for all the analyses, FS values greater than 1.5 were obtained indicating that the landfill slopes were stable against sliding under these conditions.

Within the limitations of this study, it can be concluded that the paper mill sludge examined in this paper has geotechnical properties that are desirable for a landfill cover and bottom liner material for use in a typical municipal solid waste landfill. It can also be said that the results of this investigation suggest a beneficial reuse for the huge amounts of paper mill sludge that would otherwise be disposed of in landfills as a waste material and consume landfill space, propose an economical cover and liner material alternative in places where obtaining clay would be difficult and/or uneconomical, and offer the possibility to benefit from paper mill sludge's contaminant removal abilities.

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