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Assessment of Clayey Soils and Bentonite to Use as Compacted Clay Liner for the Disposal of Municipal Solid Wastes at Lucknow City, India

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Abstract

Dumping of municipal solid wastes in a pit without liner causes groundwater contamination. Use of locally available clayey soils will be a cost-effective landfill technique. Mixing of locally available soils with bentonite reduces the permeability. To develop the liner for the disposal of municipal solid wastes generated from Lucknow city, India, the soil samples were collected from three different locations as nearby the Sagar Institute, Barabanki district; near railway crossing, Bakshi Ka Talab, Lucknow district and from Gosaiganj, Lucknow district. Different geotechnical properties such as specific gravity, particle size, liquid limit, plastic limit, plasticity index, compaction characteristics, free swell ratio and permeability of all the three soil samples were analyzed to check their suitability as a liner material. These parameters were also determined for bentonite except free swell ratio. Free swell ratio of the Gosaiganj soil sample was found under high category of expansivity. The soil of this location has the highest specific gravity, plasticity index and free swell ratio. But no any soil met the criteria of permeability to be used as a liner material. Based on the geotechnical properties, the soil of Gosaiganj was selected to use as a liner material. To meet the criteria of permeability and others, this soil was mixed with bentonite in different proportions. Bentonite was mixed in the proportion of 0%, 10%, 20%, 30% and 40% with a soil and assessed for maximum dry density, optimum water content, permeability and free swell ratio. Bentonite at 40% with a soil met the required criteria of permeability and have the highest free swell ratio. Based on the present municipal solid waste generation in Lucknow city, the size of landfill has been designed. The amount of soil and bentonite required for the construction of liner for the landfill site has also been determined in this paper

Keywords: Soil, bentonite, liner, municipal solid waste, geotechnical properties

INTRODUCTION

In developed and developing countries, managing waste management is a challenging issue. Improper handling of wastes can cause the spread of diseases, aesthetic degradation, and water, air, and soil pollution [34]. Environmental protection agencies in developing countries are facing challenges in the management of solid waste. [18].

Locally available materials have been intensively studied for developing alternative compacted clay liner soil at municipal solid waste landfill sites [28]. Various types of clay are natural materials with very low hydraulic conductivity and are commonly applied under natural conditions or after additional compaction [29]. as materials for sealing landfill liners. However, their application should be verified in compliance with local legal standards and popular technical guidelines [6]. Liners have been

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used as important components in waste disposal sites for the control of leachate [5]. The selection of materials is considered an important parameter to minimize the migration of leachate and gases surrounding the disposal site [3]. As per Ojuri et al. (2017), locally available materials can be cost-effective for liners and cover[19].

Because of their low permeability properties and ability to absorb heavy metals from leachate, clayey soils have been used for a long time [25]. Bentonite can reduce hydraulic conductivity and increase the sorption capacity of sandy soils [16]. The fine particles resulting in the micropores of bentonite and black cotton soil coupled with high surface charges contribute to low hydraulic conductivity [14]. These properties attenuate landfill leachates [33] [2].

Clay liners have been extensively used to construct barrier systems with a thickness of 1–1.5 m. Some clayey soils may not possess the minimum required hydraulic conductivity (10^{-7} cm/s). Clayey soils may exhibit low compressive strength, shrinkage, and swelling characteristics during the initial construction stages, resulting in the development of microcracks and preferential pathways [1]. Locally available soils can be amended to form a low-permeability admixed soil liner. Conventionally, clay–bentonite mixtures have been widely used as landfill liner materials [31]. To dispose of municipal solid waste generated from Lucknow City, attempts have been made to use locally available soils to develop cost-effective liners. For this purpose, soils from three different locations were collected and analyzed for their geotechnical properties to check their suitability as liner materials. Bentonite purchased from a local market was mixed with soil in different proportions to study its properties. Depending on the amount of municipal solid wastes generated in Lucknow City, the volume of landfill sites required for the disposal of waste for the next 10 years was calculated. The amounts of soil and bentonite required for the liner were also calculated for the landfill.

METHODOLOGY

Sampling Locations

Locally available materials can be used for liner and cover, which is costly [19]. Very low-permeability clay is needed for the construction of landfill liners. Locally available natural soil mixed with bentonite in various proportions can be used as soil liners for landfill applications [4]. Accordingly, clayey soils were collected from three different locations near Lucknow. The first sample was collected near the Sagar Institute of Barabanki district; the second sample was collected near a railway crossing, Bakshi Ka Talab, Lucknow district; and the third sample was collected from Gosaiganj, Lucknow district. Details of the sampling locations are presented in Figure 1 and Table 1.

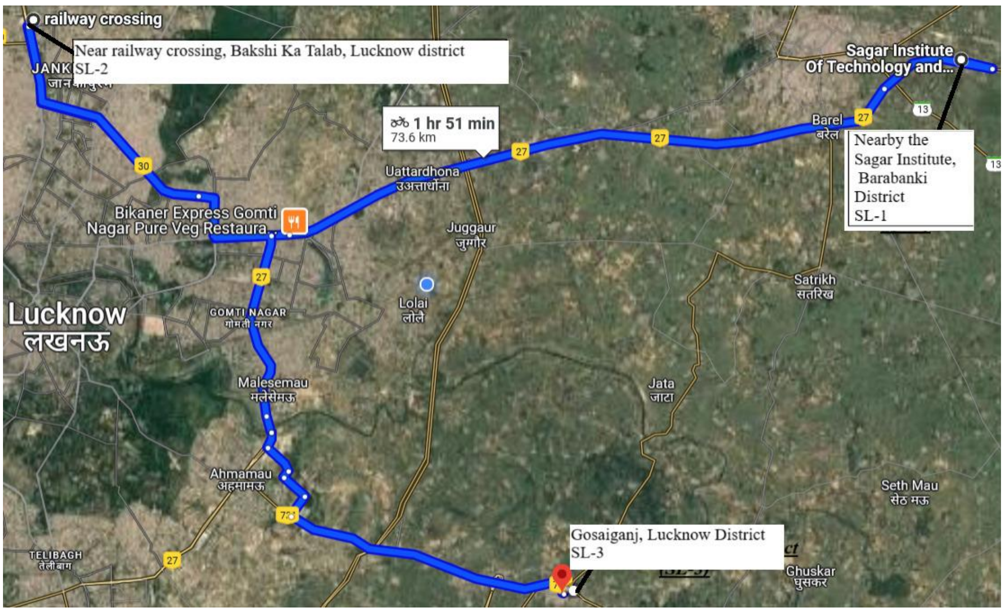

Figure 1. A view showing samples collection locations.

Figure 2. A view of collected soil samples

Table 1. Details of different sampling locations.

Name of the sampling locations	References
Nearby the Sagar Institute, Barabanki district	SL-1
Near railway crossing, Bakshi Ka Talab, Lucknow district	SL-2
Gosaiganj, Lucknow district	SL-3

Collection of Samples

After the removal of grasses, weeds, and undesirable materials, the samples were collected from a depth of 50 cm. For the sampling, tools such as trowel, spade, and auger were used. Approximately 50 kg of soil was collected from each location and stored in thick polythene bags [27]. The bags were labeled, sealed, and brought to the laboratory for analysis. The samples collected from these three locations are shown in Figure 2.

Testing of Geotechnical Properties of Soil

The collected samples were kept in the air for one week. The samples were then oven-dried for 24 hours at 105°C (IS:2720-part II, 1973). The geotechnical properties of the soils, such as specific gravity, particle size, liquid limit, plastic limit, compaction characteristics, free swell ratio, and permeability, were determined in the Geotechnical Laboratory of the Civil Engineering Department, Babu Banarasi Das University, Lucknow. The testing methods for the different geotechnical parameters are as follows:

Specific Gravity

It is defined as the ratio of the weight of dry soil to that of distilled water for the same volume of dry soil at 4^0C. The dry soil sieved through 4.75 mm sieve was used for the determination of specific gravity by density bottles [10-13,23].

Particle Size Analysis

For the determination of particle size, a set of sieves varying from 4.75 mm to 75 µm size was used. Dry soil samples (500 g) were passed through a set of sieves using a sieve shaker. The machine was operated for 10 minutes. Particles retained on different sieves were used to calculate the percentage of finer particles. The percentage finer was plotted as an ordinate (on arithmetic scale) and the particle size (opening size) as an abscissa (on a log scale) [24].

Liquid Limit

To assess the liquid limit, 120 g of dry soil was passed through a 425 µm sieve and mixed with distilled water to prepare a uniform paste. A portion of the paste was placed in the cup of the liquid limit device. A groove was formed in the paste, and the device was operated at a rate of two revolutions per second until the two parts of the soil came into contact with 12 mm at the bottom of the cup. The number of drops was recorded. Finally, the moisture content corresponding to 25 blows was considered the liquid limit (IS:2720-Part V, 1970).

Plastic Limit

A 20-gm soil sieved through a 425 µm sieve, mixed uniformly with distilled water to make it sufficiently plastic. From this paste, 8 g of soil was used to form a ball. Using the palm, the ball was rolled on a glass plate to form a 3 mm diameter thread. Rolling continued until the thread crumbled at a diameter of 3 mm. Finally, the moisture content of the crumbled thread was considered as the plastic limit (Raj, 1995).

Plasticity Index

The plasticity index is defined as the difference between the numerical values of the liquid and plastic limits, and it shows the degree of soil plasticity. Higher difference values indicate higher soil plasticity [17].

Compaction Characteristics

For the assessment of compaction characteristics, 3 kg of air-dried soil was sieved through 4.75 mm sieve. A 100 mm diameter mould was used as the percentage of soil retained on the 4.75 mm sieve was less than 20%. A mold with a volume of 1000 ml and a rammer weight of 2.6 kg was used. Because the samples were clayey in nature, therefore, 8% water were mixed in the beginning. After uniform mixing, the samples were placed in the mold into three layers. Each layer was compacted using 25 blows at a drop height of 310 mm. The moisture content and dry density of the compacted soil were determined after uniform mixing. Different values of water content and dry density were determined for the different compacted soil samples. A graph was plotted to determine the maximum dry density and optimum water content [9].

Free Swell Ratio (FSR)

It is the ratio of volume of 10 g oven-dried soil passed through a 425-micron sieve in distilled water (V_d) to that of carbon tetrachloride or kerosene (V_k). This indicated the expansivity of the soil. [30]

$$\text{FSR} = \frac{V_d}{V_k}$$

For the assessment of free swelling ratio, the soil sample with 10 g weight was mixed in 100 ml water kept in a graduated jar and another 10 g soil was mixed in100 ml kerosene oil. The volume of the sediment was measured after 24 h to determine the FSR.

Permeability

It is defined as a property of soil that permits the seepage of fluid through interconnected voids. As the soil collected for the study was cohesive in nature, the falling-head method was used to determine the permeability [8].

RESULTS AND DISCUSSION

Different geotechnical properties, such as specific gravity, particle size, liquid limit, plastic limit, plasticity index, optimum moisture content, maximum dry density, permeability, and free swell ratio, were determined for the collected soil samples. The analytical results are presented in Table 2.

Geotechnical Properties of Soils

Specific gravity

It is an index property of soil that indicates its mineralogical and chemical composition [20]. It has a history of weathering[35]. It was observed that the specific gravities of SL-3 and bentonite had similar values (Table 2). The suitability of soil as a construction material can be determined by assessing its specific gravity. A higher value can increase the strength of roads and foundations [22]

Particle Size Analysis

The grain-size distribution curve shows the distribution of particles of different sizes [15]. The grain size distribution curves are shown in Figure 3. From the curve, it was found that SL-3 had 36% percent fines (75-micron passing), indicating the suitability of soil as clay liner. According to Chinade and Yunusa (2024), percent fines ≥ 30 - 50 % is suitable as a clay liners (Table 3) [5].

Consistency Limits

Although the liquid limit for all the sampling locations was higher than 20%, the liquid limit of SL-3 (Table 2) was considered to use as a liner material because of its highest values (≥ 20 %). plasticity index of SL-3 was 18.10 %. According to Chinade, and Yunusa (2024), plasticity index >7-15 (Table 3) is suitable for clay liner. Hence, SL-3 can be used directly as a liner material for the construction of clay liners.

Table 2. Geotechnical properties of clayey soils and bentonite.

Geotechnical parameters	Soils			Bentonite
	SL-1	*SL-2*	*SL-3*	
Specific gravity	2.64	2.57	2.68	2.74
Liquid limit (%)	29.20	26.00	39.23	305
Plasticity index (%)	13.34	12.87	18.10	258
Maximum dry density (g/cm^3)	1.76	1.6	1.69	1.33
Optimum water content (%)	14	17	17	35
Permeability (cm/s)	$8.5x10^{-7}$	$7.6x10^{-7}$	$8.9x10^{-7}$	10.93×10^{-9}
Free swell ratio	1.63	1.75	2.18	-

Table 3. Specifications of liner material [7].

Property	Minimum values to attain, $k \leq 1 \times 10^{-7}$ cm/s
Liquid limit	>20
Plasticity index	>7-15
Percent fineness	Greater than 30

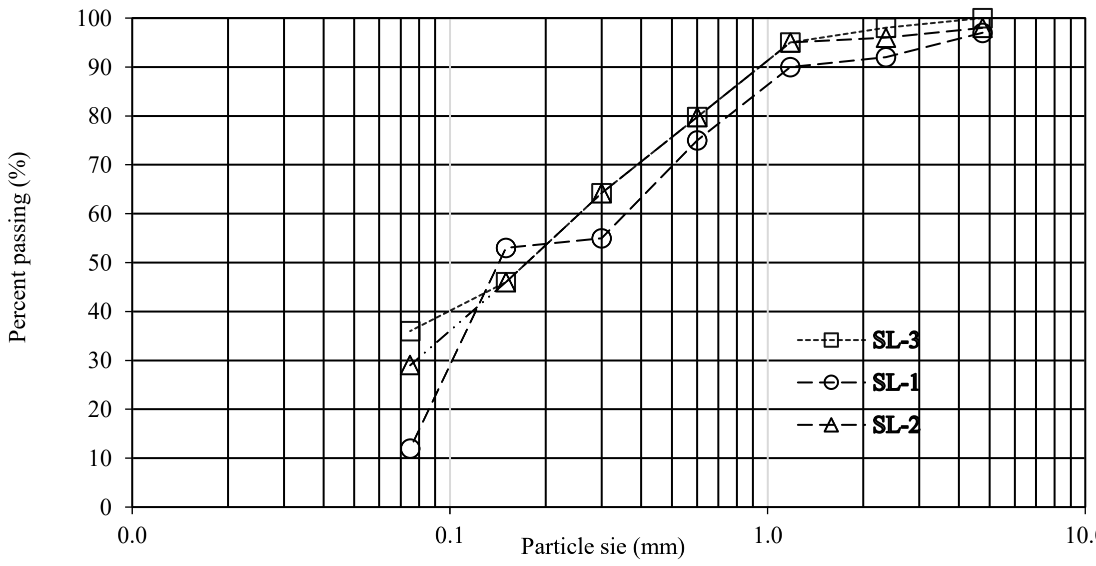

Figure 3. Particle size distribution curve.

Table 4. Classification of soils based on FSR [21].

Free swell ratio	Soil expansivity	Clay type	Dominant clay mineral type
<1.0	Negligible	Non-swelling	Kaolinitic
1.0-1.5	Low	Mixture of non-swelling and swelling	Kaolinitic and Montmorillonitic
1.5-2.0	Moderate	Swelling	Montmorillonitic
2.0-4.0	High	Swelling	Montmorillonitic
>4.0	Very High	Swelling	Montmorillonitic

Compaction Characteristics

There were no significant differences in the maximum dry density of the three soil samples. However, it was higher than that of bentonite. A higher density provided a higher linear strength.

Free Swell Ratio

Table 4 shows classification of soils based on FSR. From Table 2, FSR of the soil SL-3 is 2.18 which comes under high category of expansive soil (Table 4). Therefore, the SL-3 was chosen for mixing with bentonite to use as clay liner.

Permeability

The permeability of SL-3 was observed to be 8.9×10^{-7} cm/s (Table 2), which was higher than 1.0 x 10^{-7} cm/sec [5]. Therefore, soil SL-3 was mixed with bentonite to reduce the permeability within the prescribed values.

Suitability Assessment of Soil with Bentonite

Bentonite mainly consists of montmorillonite, which is an adsorbent of aluminum phyllosilicate. Bentonite has a high swelling ratio and a low permeability. SL-3 was chosen to enhance its properties for use as a liner after mixing it with bentonite. Bentonite was mixed in different proportions with SL-3 and the maximum dry density, optimum water content, and permeability were determined (Table 5). As the permeability of mix proportion of bentonite (40%) and SL-3 (60%) was less than 1.0×10^{-7} cm/s, therefore, this proportion was considered for the design of clay liner. In addition, this mix proportion indicates an FSR (5.75) value greater than 4 (Table 4), which is in the category of very high expansivity. The highest maximum dry density of this proportion provided better strength.

Assessment of Size of Landfill

According to Tchobanoglous (1993), the landfill area required in the future can be calculated based on the current amount of waste generated over the next 10 years, as in [32]. The details are as follows:

Current waste generation per day (W) = 1600 tons [26]

Current waste generation per year (W) = 1600 x 365 = 584000 tons

Estimated rate of increase (or decrease) in waste generation per year (x) = 1.5%.

(Use rate of population growth, for which estimates of the waste generation growth rate are not available)

Table 5. Compaction characteristics of soil and bentonite mixtures

Mix proportions		MDD (g/cm^3)	OMC (%)	Permeability (cm/sec)	Free swell ratio
Bentonite (%)	*SL-3 (%)*				
0	100	1.69	17	8.9×10^{-7}	-
10	90	1.30	34	8.79×10^{-8}	-
20	80	1.52	31	6.07×10^{-9}	-
30	70	1.79	25	3.76×10^{-9}	5.75
40	60	1.82	23	1.09×10^{-9}	5.87

Proposed life of landfill (in years) n = 10 years

Waste generation after $n\ years = Wx\left(1+\frac{x}{100}\right)^{n}$ tons

$= 584000x\left(1+\frac{1.5}{100}\right)^{10}$ = 550676.62 tons

Total waste generation in n years (T) in tons

$T = 0.5\left[W + W\left(1+\frac{x}{100}\right)n\right] x\ n$ tons

$= 0.5[584000 + 550676.62]\ x10$
= 6308769.5 tones

Total volume of waste in n years (V_w) (assumption a 0.85 t/m^3 density of waste)
$V_w = \frac{T}{0.85}$ m^3

$= \frac{6308769.5}{0.85}$
= 7422081.76 m^3

Assuming the depth of the landfill site = 10 m (H_i), the area required for landfilling (Ai)
$A_i = \frac{V_w}{H_i}$ m^2
$A_i = \frac{7422081.76}{10}$
= 742208.17 m^2

Calculation of Liner Materials

According to the EPA (1989), the thickness of the liner should vary from 1.0 m to 1.5 m. Considering the thickness of liner = 1.0 m. Taking width (B) = 450 m, the length (L) = 1649.4 m (based on the volume of waste generated after 10 years).

Dimension of the side liner (Figure 4)

Length of liner
= 2 × (long wall + 2 × side thickness) + 2 × short wall
= 2 x (1649.4 + 2 x 1) + 2 x 450
= 4202.8 m

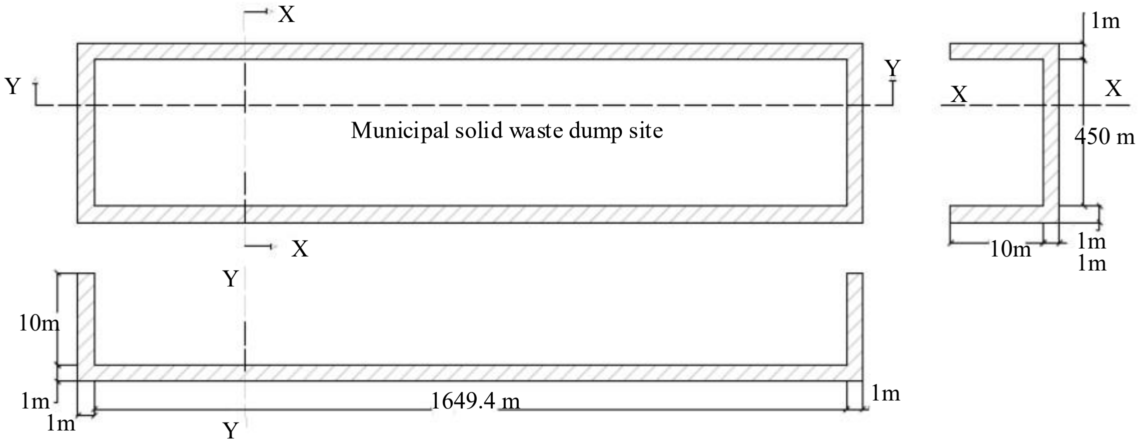

Figure 4. Proposed layout plan of landfill site.

Height of liner = 11 m
Thickness of liner = 1 m
Volume of the side liner = 4202.8 x 11 x 1 = 46230.8 m^3

Volume of bottom part of liner
= length × width × thickness.
= 1649.4 x 450 x 1 = 742208.17 m^3

Total volume clay liner material = 788438.97 m^3

Based on Table 5, considering maximum dry density (1.82 g/cm^3 = 1.82 t/m^3) of mix proportion, the amount of compacted liner material calculated as under:

Bentonite = 40% x Volume x Density = 0.40 x 788438.97 x 1.82 = 573983.57 ton

Clayey soil (SL-3) = 60% x Volume x Density = 0.60 x 788438.97 x 1.82 = 860975.35 ton

CONCLUSIONS

From the study, the conclusions drawn are as under:

- SL-3 and bentonite have similar specific gravity values. Among the three soils, SL-3 had the highest liquid limit and plasticity index. The maximum dry density of SL-3 was higher than that of bentonite indicating that it can provide more strength as a liner material. The free swell ratio of SL-3 was the highest of the three soils. Based on the free swell ratio, SL-3 falls under a high category of soil expansivity. Because the permeability of SL-3 did not meet the criteria of clay liners, it was mixed with bentonite.
- Bentonite mixed with SL-3 at the proportions of 0%, 10%, 20%, 30%, and 40%. These mixed proportions were assessed for the maximum dry density, optimum water content, permeability, and free swell ratio. permeability of mix proportion (40% bentonite + 60% SL-3) satisfied the criteria of liner. The free swell ratio of this proportion also indicates a very high expansivity of the soil. The maximum dry density increased among all proportions, indicating the strength of the liner. The optimum water content was also found to decrease at this proportion, indicating a reduction in the water content during liner construction.
- Based on the present municipal solid waste generation, the volume of waste calculated for the next 10 years is 7422081.76 m^3. Using this volume, the inside length and width of the landfill were assessed as 1649.4 m and 450 m, respectively. Considering the 1.0 m thickness liner, the amounts of bentonite and clayey soil (SL-3) were calculated as 573983.57 ton and 860975.35 ton respectively.
- By utilizing this methodology, urban planners and municipal authorities can ensure the effective management of solid waste, while minimizing environmental impacts and promoting sustainable waste disposal practices. This can achieve social acceptance and become economically affordable for local communities and governments.
- Further studies should be conducted to develop geosynthetic clay liners using soil SL-3. A study is required to determine the impact of climate and groundwater contamination at landfill sites.

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