The Permeability and Strength of Compacted Laterite Soil-Bentonite Mixtures for Landfill Cover Application

Ros N. Rosli, Mohamad R. Selamat and Harris Ramli

Abstract The most suitable soil type for landfill cover is the fine-grained soil with high clay content; however, clayey soils are also relatively low in shear strength. The laterite soils, which is regular with the Malaysian construction industry has been the main choice for landfill cover purposes in the country; however, upon investigation, the soils would normally have a permeability coefficient (k) in the order of 10^{-8} m/s or higher, thus are considered unsuitable for landfill application unless treated to meet the standard. The current study presents properties associated with permeability and shear strength of three laterite soils—LS1, LS2, and LS3—when treated by mixing with bentonite at 1, 3, and 5%. In each case, k was found reduced with increasing bentonite content. However, for LS1, a 5% bentonite treatment was required to decrease k by one order of magnitude, i.e. from 4.7×10^{-8} m/s to 9.3×10^{-9} m/s. For LS2, a 3% bentonite content was required to bring down k from 4.26×10^{-8} m/s to 6.94×10^{-9} m/s, while for LS3, only 1% bentonite was sufficient to reduce k from 3.25×10^{-8} m/s to 8.15×10^{-9} m/s. With the addition of the bentonite, the unconfined compressive strength (UCS) were found weakened to lesser than 200 kPa for all samples. Without bentonite, the UCS values for LS1, LS2, and LS3 were respectively 213 kPa, 207.84 kPa, and 156.19 kPa.

Keywords Laterite soil-bentonite mixture · Permeability · Shear strength · Landfill application

1 Introduction

Malaysia is a country with a humid tropical weather and an average temperature of 20° to 30°; rains can be expected to fall throughout the year [24]. Due to the climate, rain water that penetrates through a landfill cover and into the waste

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chamber can be a major concern when the aim is to provide long-term containment and isolation of the waste from the environment. When used as an underlay, the clayey layer should also assure that leachate will not migrate out of the repository. In most earthwork projects, strength and compaction characteristics are used to evaluate the adequacy of the design; in a landfill project however, the permeability coefficient (*k*) is the one considered most important. A cover material with a low permeability coefficient is the most sought after; thus *k* becomes the ever important criteria. The *k*-value is an expression of the rate at which a liquid passes through a porous media [18]. This criterion is widely used in the testing of soil cover and liner materials for a landfill. Based the Environment Protection Agency (EPA) standards, the most suitable soil type for a landfill cover or liner is the fine-grained soil with high clay content, and therefore with a low permeability value [9, 15, 21, 28, 36]. However, clayey soils can also give geotechnical problems due to the poor shear strength and potential high volume change. The recorded requirement for strength for performance in waste repositories has been given as UCS $\geq$ 200 kN/m^2 [5, 6]. The stated minimum UCS value required is to provide for strength to counter the overburden stress imposed by waste material such as over a landfill liner [7]. The limiting UCS is also related to soil usage as landfill cover where it correlates to shear strength that determines the stability against a slope failure occurrence in the cover.

The lateritic soils, which are abundant in Malaysia and other tropical countries, are quite clayey and they present an attractive option because of their workability and good shear strength [19, 32]. The positive experience of using laterite soil in geotechnical projects since decades ago such as for road and bases, embankment, earth dam etc. has encouraged researches in the use of the soil for landfill covers and liners [31]. However, a laterite soil can be a little high in permeability depending on the degree of weathering, the texture of the soil, and the initial void ratio [20]. Therefore, for a laterite soil to satisfy the permeability requirements and self-sealing function, an enhancement with bentonite is proposed in this study. The high swelling properties of bentonite should lead to a low *k*-value of the treated laterite soil when in contact with water. The properties of soil-bentonite mixtures have been widely studied by various researchers since decades ago [7, 29, 34, 36, 37]. Kassim et al. [25] used bentonite as an admixture to laterite soils however the studied bentonite content started with 5% and it went higher up to 20% thus the effects of using lesser than 5% bentonite on the resulting permeability and shear strength of the treated laterite soils were not evaluated. Researchers have also studied the properties of sand-bentonite mixtures for various other purposes [33, 35]. Thus, the aim of this study was to characterise the geotechnical properties of local laterite soils when treated with bentonite at low percentages for application as final cover in landfills. The required *k* of a soil qualified to be used as landfill cover or bottom liner is in the order of 10^{-9} m/s [7, 14, 16].

2 Materials and Methodology

The two main materials used in this study were the laterite soils and the bentonite. The three laterite soils were collected from Sungai Kechil, Bandar Baharu, and Relau in South Kedah with corresponding coordinates of 5.176478, 100.561557; 5.134074, 100.5679015; and 5.240605, 100.563042. The collected soils were labeled as LS1, LS2 and LS3, respectively representing the above collection sites. The soils were retrieved by excavation and transported to the laboratory for testing. The bentonite was the powdered form, typical for construction purposes, and obtained from a local supplier.

2.1 Index Properties Test

The laterite soils were air-dried before brought for the particle size distribution (PSD) test and the Atterberg limit test. The related PSD tests were carried out according to the standards, the BS1377: Part 2 [12]. The coarse portions were classified using the mechanical sieves, while the fines passing through the 63 μm sieve were evaluated using hydrometers. The Atterberg limits for the laterite soils and the bentonite were determined according to the standards, the ASTM D4318-10 and the BS1377: Part 4 [1, 13]. The specific gravities were determined according to the ASTM D854-14 [2]. The soils were classified according to the Unified Soil Classification System (USCS).

2.2 Compaction Test

The modified proctor method was carried out instead of the standard proctor as the study was associated with landfill cover application. The bentonites, at 1, 3, and 5% by weight were thoroughly mixed with the laterite soils passing the 4.75 mm sieve size. The bentonite percentages used were generally lesser than those used in the study by Kassim et al. [25] as the researchers in the earlier case started with 5% and went higher from there. The laterite samples, with bentonite already mixed in, were compacted using the 4.5 kg rammer, falling through a 450 mm height, while the mold used was the 1L British standard. For each of the 5 layers laid, 27 blows of the rammer were applied. The procedure was carried out according to the BS1377: Part 4 [13].

2.3 Permeability Test

Based on the results of the compaction tests, samples for permeability tests were prepared at maximum dry density (MDD) and optimum moisture content (OMC). The samples were soaked for at least 24 h in de-aired tap water and a steady flow was established before any result was recorded. The permeability tests carried out were of the falling head procedure, according to ASTM D5084 standard [3].

2.4 Shear Strength Test

The strength tests were carried out using the Uniaxial Compressive Test (UCT) apparatus. The soils were first remolded into cylindrical specimens, each with 38 mm in diameter and 76 mm in length, at MDD and OMC, as obtained from the compaction tests. The excesses at the top and bottom of a mold were trimmed in preparing a sample for test. Each sample was put under load until failure or occurrence of a crack.

3 Result and Discussion

The laterite soils and the bentonite were characterized individually before mixing. The results of the characterizations and the subsequent compaction, permeability, and strength tests on the laterite soils treated with the bentonite are given next.

3.1 Characterization of Laterite Soils and Bentonite

The index properties of laterite soil and bentonite are summarized in Table 1. The laterite soils used in the present study consisted of between 11.9–22.0% gravel, 32.4–53.6% sand, and 24.4–55.70% fines. Gravels and sands are considered coarse with size larger than 0.075 mm, while the fines are materials with size lesser than that given. In accordance to the Unified Soil Classification System (USCS) procedure, the soils were classified as silty sand (SM), clayey sand (SC), and high plasticity clay (CH) respectively for the LS1, LS2, and LS3 samples. The average of liquid limits (LL) obtained for the laterite soils was 46.41% while the LL for the bentonite was 215.34%. The average of plasticity indices (PI) obtained for the laterite soils was 14.13% while the PI for the bentonite was 135.14%. According to Burmister [11], the laterite soils can be described as having a medium plasticity because the PIs lie between 10 and 20%. On the other hand, the bentonite can be classified as having a very high plasticity as its PI is above 40%. A higher LL and

Table 1 Properties of laterite soil samples and bentonite

Properties	LS1	LS2	LS3	Bentonite
Gravel, % (>4.75 mm)	22.00	14.53	11.9	–
Sand, % (4.75–0.075 mm)	53.60	47.07	32.4	–
Silt, % (0.075 mm)	15.21	37.15	50.63	–
Clay, % (<0.002 mm)	9.19	1.25	5.07	–
LL, %	37.61	42.19	59.42	215.34
PL, %	35.73	28.02	46.46	80.20
PI, %	1.88	14.13	12.96	135.14
Gs	2.60	2.68	2.54	1.71
USCS	SM	SC	CH	–

PI indicates that the soil is having a greater quantity of clay particles, which in turn, reduces the permeability coefficient [22]. To qualify as a final landfill cover so that the leachate production would be low, Harshani et al. [23] stated that at least 30% of the soil should pass through sieve no. 200, which is 0.075 mm, while the LL should be over 30% and the PI should not be less than 15%. In this study, LL of all soils was above 30%, but the PIs for the laterites were less than 15% which mandates the bentonite treatment.

3.2 Compaction Characteristics of Laterite-Bentonite Mixtures

The summary of MDD and OMC of the mixtures are given in Table 2 while the compaction curves are given in Fig. 1. The additional amount of bentonite added to a laterite soil sample generally resulted in a decreased MDD and increased OMC for LS1, LS2, and LS3. In the case of LS1, the laterite soil without bentonite has an MDD of 1.95 Mg/m^3 and an OMC of 11.6% while the one with 5% bentonite had an MDD of 1.89 Mg/m^3 and an OMC of 12.9%. For LS2, the laterite soil without bentonite has an MDD of 1.92 Mg/m^3 and an OMC of 11.5% while the one with 5% bentonite had an MDD of 1.84 Mg/m^3 and an OMC of 13.0%. For LS3, the laterite soil without bentonite has an MDD of 1.70 Mg/m^3 and an OMC of 15.0% while the one with 5% bentonite had an MDD of 1.59 Mg/m^3 and an OMC of 18.0%.

Thus the trends of decreasing MDD and increasing OMC with additional bentonite amount added to the samples are similar for all samples. In addition, a sample with a higher fine content had a relatively lesser MDD and higher OMC when it was without the bentonite content. The relationships between MDD and OMC with increasing bentonite content for the cases of LS1, LS2 and LS3 are given in Fig. 2. The coefficients of determination, R^2, are all higher than 0.8, thus the correlations can be considered as very good [27]. The decreased MDD with increasing bentonite

Table 2 MDD and OMC values for laterite soil samples treated with bentonite

Bentonite content, %	LS1				LS2				LS3			
	MDD, Mg/m^3	MDD, incr., %	OMC, %	OMC, incr., %	MDD, Mg/m^3	MDD, incr., %	OMC, %	OMC, incr., %	MDD, Mg/m^3	MDD, incr., %	OMC, %	OMC, incr., %
0	1.95		11.6		1.92		11.5		1.70		15.0	
1	1.93	−1.02	12.0	3.45	1.91	−0.52	12.0	4.35	1.69	−0.59	15.5	3.33
3	1.92	−1.54	12.3	6.03	1.88	−2.08	12.5	8.70	1.66	−2.35	17.5	16.67
5	1.89	−3.08	12.9	11.21	1.84	−4.17	13.0	13.04	1.59	−6.47	18.0	20.00

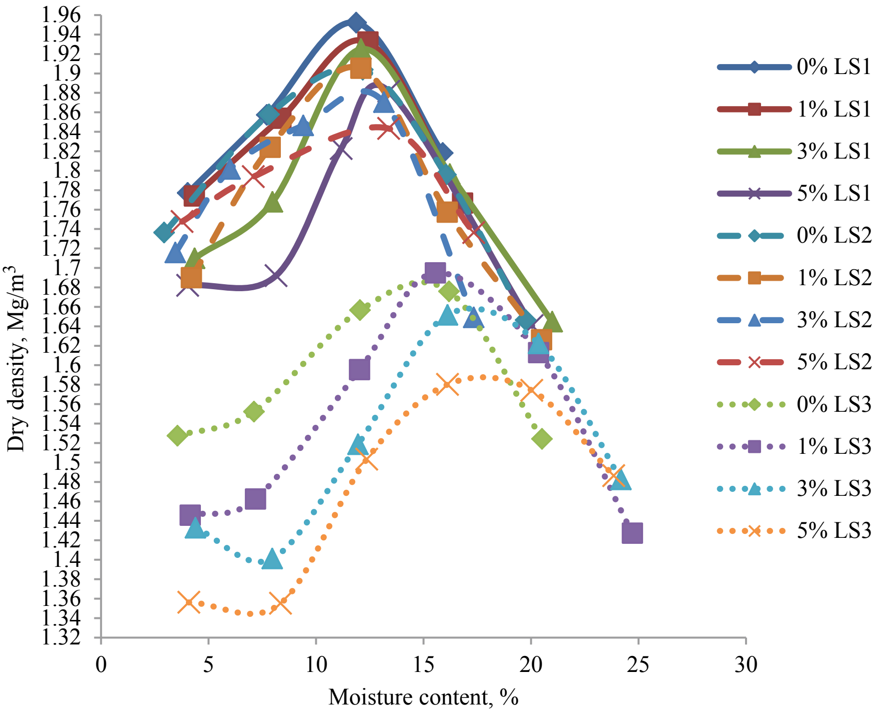

Fig. 1 Compaction curves for laterite samples, natural and with 1, 3, and 5% bentonite content

content might be caused by the high swelling characteristics of bentonite that creates gel around a soil particle. With the formation of the gel, the effective size of a soil particle increases, causing an increase in void volume and thus a decrease in dry density [10, 26, 36]. The increased OMC with increasing bentonite content is related to the increased demand for more moisture due to the hydration of fine bentonite particles with larger specific surface area [7, 17, 38].

3.3 Permeability Characteristics of Laterite-Bentonite Mixtures

The permeability coefficients (k) obtained for the cases of LS1, LS2 and LS3 are given in Table 3. Note that for all cases k were all in the order of 10^{-8} m/s when bentonite was not used as an admixture. It has been mentioned earlier that the required k of a soil qualified to be used as landfill cover or bottom liner is in the order of 10^{-9} m/s. The correlations between k and bentonite content are given in Fig. 3 which shows that k generally decreased with increasing bentonite content. The values of R^2 for the polynomial regressions obtained for the curves are all above 0.80

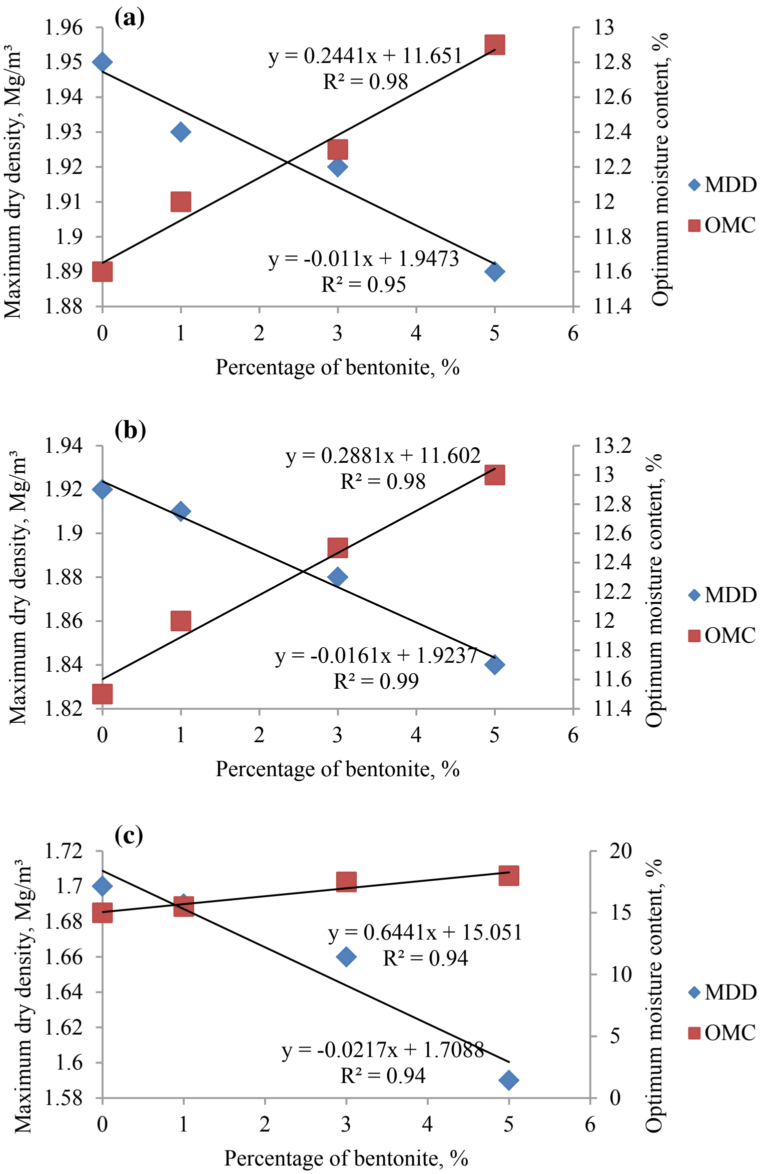

Fig. 2 Variation of MDD and OMC with bentonite content for (**a**) LS1, (**b**) LS2, and (**c**) LS3

which indicate very good correlations [27]. However, the amount of bentonite content required to bring down k by an order of magnitude, i.e. from the order of 10^{-8} m/s to the order of 10^{-9} m/s, differed between the cases. For the case of LS1, a 5% bentonite was required to reduce k from 4.7×10^{-8} m/s to 9.30×10^{-9} m/s. For the case of LS2, a 3% bentonite was required to reduce k from 4.26×10^{-8} m/s

Table 3 Coefficient of permeability (k) for laterite soil samples, natural and treated with bentonite

Percentage of bentonite, %	k value, m/s					
	LS1	Value relative to the natural, %	LS2	Value relative to the natural, %	LS3	Value relative to the natural, %
0	4.70×10^{-8}		4.26×10^{-8}		3.25×10^{-8}	
1	2.78×10^{-8}	59.15	1.62×10^{-8}	38.03	8.15×10^{-9}	25.08
3	1.11×10^{-8}	23.62	6.94×10^{-9}	16.29	3.78×10^{-9}	11.63
5	9.30×10^{-9}	19.79	2.74×10^{-9}	6.43	1.02×10^{-9}	3.14

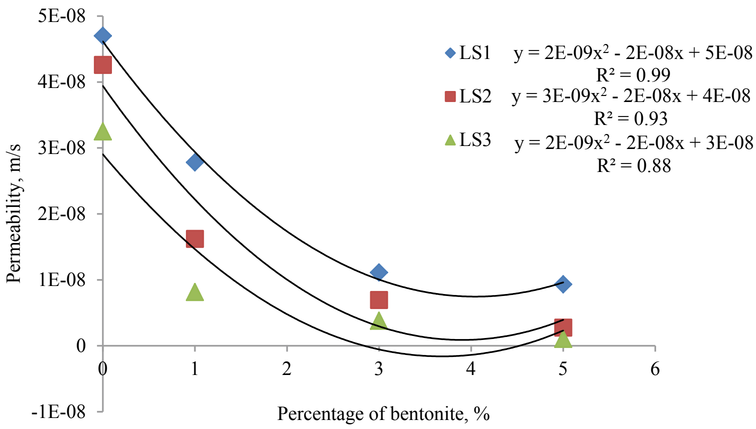

Fig. 3 Correlation between bentonite content and permeability

to 6.94×10^{-9} m/s while for the case of LS3, a 1% bentonite was required to reduce k from 3.25×10^{-8} m/s to 8.15×10^{-9} m/s. Thus the amount of bentonite required lessened with increasing fine content in the untreated laterite soil. Table 3 also shows that when 5% bentonite was added, a 3.77×10^{-8} m/s k reduction occurred in the case of LS1, a 3.99×10^{-8} m/s k reduction occurred in the case of LS2, and a 3.15×10^{-8} m/s k reduction occurred in the case of LS3. Thus the reduction in k-values due to a similar 5% bentonite use were quite the same for all cases although the laterite soils involved were of different fine contents. The general decrease in k with increasing bentonite amount again can be attributed to the very high specific surface of a bentonite particle. This characteristic allows each particle to retain the portion of water trapped in the pore space [7]. Furthermore, a saturated bentonite amount could absorb water up to 5 times of its own mass to form a gel up to 15 times of its own dry volume [4]. Thus, the decrease in k due to an addition of bentonite is associated with bentonite forming a gel or paste that fills the voids [8, 30].

3.4 Strength Characteristics of Laterite-Bentonite Mixtures

The UCS obtained for the cases of LS1, LS2 and LS3 are given in Table 4. The polynomial correlations of bentonite content versus UCS are given in Fig. 4. The values of R^2 for the polynomial regressions obtained for the curves are all above 0.80 which indicate very good correlations. For the case of LS1, the strength was reduced 11.1%, i.e. from 213.63 kN/m^2 when no bentonite was used to 189.91 kN/m^2 when 5% bentonite was used. For the case of LS2, the strength was reduced 10.98%, i.e. from 207.84 kN/m^2 when no bentonite was used to 185.01 kN/m^2 when 5% bentonite was used. For the case of LS3, the strength was reduced 6.56%, i.e. from 156.19 kN/m^2 when no bentonite was used to 145.94 kN/m^2 when 5% bentonite was used. The UCS of laterite-bentonite mixtures decreased with increasing bentonite percentage used. The bentonite particles that filled the voids between soil particles appeared to have lowered the frictional resistance between the soil particles at their contacts. With the use of 3% bentonite content and higher, the resulting UCS of the soil-bentonite mixtures did not meet the target for performance requirement in waste repositories which is UCS $\geq$ 200 kN/m^2, as

Table 4 UCS value for LS1, LS2, and LS3

Percentage of bentonite, %	UCS, kPa					
	LS1	UCS incr., %	LS2	UCS incr., %	LS3	UCS incr., %
0	213.63		207.84		156.19	
1	206.33	−3.42	195.14	−6.11	149.87	−4.05
3	197.52	−7.54	190.87	−8.16	148.00	−5.24
5	189.91	−11.10	185.01	−10.98	145.94	−6.56

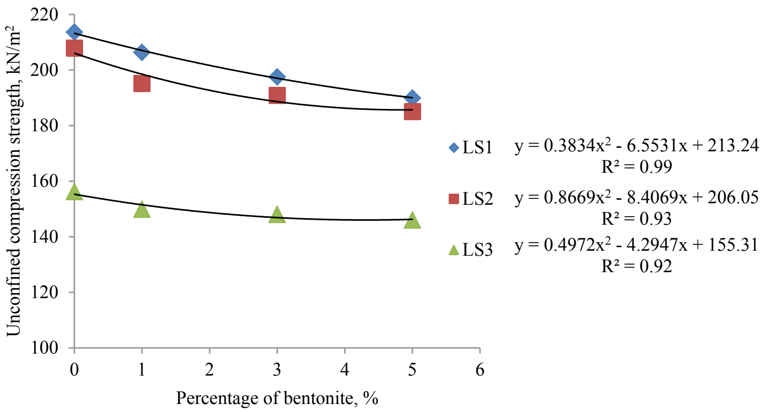

Fig. 4 Correlation between bentonite content and UCS

mentioned earlier. Thus, the laterite soils treated with 3% bentonite content and higher may not be suitable for use as a landfill liner as the stated minimum UCS value is required in order to maintain the resistance against the overburden stress imposed by the overlying waste material. However, the similarly treated laterite soils probably can still be applied for final cover given the right design which considers the shear strength required to avoid slope failure occurrences. In other words, an additional admixture probably is required to enhance the strength for the purpose.

4 Conclusion

The laterite soils sourced locally from South Kedah, named LS1, LS2, and LS3, were with different fine contents in their natural form. The soils had between 11.9–22.0% gravels content, 32.4–53.6% sands content, and 24.4–55.70% fines content. LS3 had the most fines while LS1 had the least. The LL of the soils were all above 30%, while the PI were all below 15%. LS1 soil was classified according to the USCS as SM, LS2 was SC, while LS3 was CH. Each soil was treated with 1, 3, and 5% bentonite contents and the modified proctor compaction energy. When treated with 5% bentonite, for the case of LS1, the MDD decreased from 1.95 Mg/m^3 to 1.89 Mg/m^3; for LS2 MDD decreased from 1.91 Mg/m^3 to 1.84 Mg/m^3, while for LS3 from 1.68 Mg/m^3 to 1.59 Mg/m^3. For the same 5% bentonite treatment, the OMC increased from 11.6 to 12.9% for LS1, 11.5 to 13% for LS2, and 15 to 18% for LS3. The permeability tests resulted in k generally decreasing with increased bentonite content. To reduce k by one order of magnitude, i.e. from 10^{-8} m/s to10^{-9} m/s, a 5% bentonite addition was required for LS1, a 3% bentonite addition was required for LS2, and a 1% bentonite addition was required for LS3. The standards require that a landfill cover or liner application should have a k-value in the order of 10^{-9} m/s. Despite the positive results obtained for the permeability concern, the UCS of laterite-bentonite mixtures were found decreased with increasing bentonite content. When no bentonite was used, the UCS were 213 kPa, 207.84 kPa and 156.19 kPa for LS1, LS2, and LS3 respectively. When a 3% bentonite or more was added to the laterite soils, none of the mixtures surpassed the UCS $\geq$ 200 kN/m^2 specification for landfill liner. Thus in terms of strength, a 5% of bentonite treatment to any of the soils did not pass the landfill liner requirements, and probably also the landfill cover requirements unless additional measures were taken. For future work, the use of chemical or fibrous additive could be considered for the strength enhancement. Furthermore, the microchemical reaction between a laterite soil and bentonite should be investigated in search of a better solution for the permeability and strength problems in the use of the materials.

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