A critical reappraisal of residual soils as compacted soil liners

Endene Emmanuel¹ · Vivi Anggraini¹ · S. S. R. Gidigasus²

© Springer Nature Switzerland AG 2019

Abstract

Compacted residual soils are often used as liner materials in engineered landfills, tailings dams, solar ponds, and canals, etc. to minimize the migration of contaminants into the surrounding environment and groundwater. To date, there has not been an extensive and adequate review of the suitability of different residual soil types for use as compacted liner materials. This paper reviews the suitability, merits, demerits, and possible applications of using expansive and lateritic residual soils as compacted soil liners. The review is then complemented by a study of the geotechnical properties of lateritic residual and shrinkable soils from Peninsular Malaysia. Suitability was assessed based on engineering property data for both soil types, collected from various journal papers, workshops, proceedings of conferences, and symposia from around the world. These properties were then compared with the standard requirements for use as liner materials. Descriptive statistics were employed to better assess the individual criteria of using both residual soil types as compacted soil liners. The results indicate that expansive and lateritic soils can be effectively utilized as liner materials if more acceptable materials are not readily available. The study addresses untreated soils but does not discuss the stabilization aspects.

Keywords Compacted soil liners · Residual soils · Engineering properties · Waste containment · Lateritic soils · Expansive soils

1 Introduction

In recent years, concerns about environmental degradation, groundwater contamination by leachate from landfills and tailings, seepage of chemicals from road accidents and pollution of subsurface strata from accidental spills have led to a growing worldwide interest in the development of a cost-effective and environmentally-friendly solution to minimize these problems. Among the different material techniques employed to minimize these menaces, particularly in waste containment facilities, geosynthetic clay liners (GCLs) has proven to be an easy, flexible, and reliable material technique. This is primarily because of their low hydraulic conductivity ($k_w < 10^{-10}$ m/s) [1–4]. However, under local conditions, the construction cost of using geosynthetic liner materials is exorbitant, due to the

non-existence of a local industry producing such materials. Furthermore, because of their limited thickness, these materials are subject to degradation, which affects their proper functionality as extensively discussed by [1]. Traditionally, compacted soil liners (CSLs) were used, and they are now gaining acceptance once again, either as single liners or composite liners. This is due to their low construction cost relative to their counterparts; moreover, the soils are naturally occurring and are readily available.

Over recent decades, hundreds of original research papers, technical notes, technical reports, and case studies on the application of different residual soil types as compacted liner materials in landfills, surface impoundments (e.g., mine tailings storage facilities, heap leach pads, ponds, canals) and secondary containment of above-grade fuel storage tanks, have been published

✉ Vivi Anggraini, vivi.anggraini@monash.edu; Endene Emmanuel, emmanuel.endeneche@monash.edu; S. S. R. Gidigasus, ssrgidigasus.coe@knust.edu.gh | ¹Civil Engineering Discipline, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor Darul Ehsan, Malaysia. ²Department of Geological Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

in scientific journals, conference proceedings, seminars, and academic workshops etc. [5–15]. An overview of compacted soil liners was discussed by [11, 16–21], and the advantages of compacted soil liners were discussed by [5, 8, 13, 22–26]. Despite this wealth of information, only a few studies have attempted to comprehensively review these aspects through reference to published scientific data. A possible reason for the lack of review documentation on these aspects could be that: over the past few decades, interest has shifted from CSL to GCL, owing to its peculiar advantages including; low hydraulic conductivity, low thickness, rapid installation, excellent self-healing characteristics, easy to repair, resistance to the effects of freeze/thaw cycles, greater amount of airspace, reduce overburden stress on compressible substratum, ability to withstand large differential settlement, etc. [1, 22, 27]. Nevertheless, the downsides associated with GCL as previously mentioned and discuss comprehensively by [1, 3, 28] have motivated the utilization of CSL. Consequently, the need to research and assimilate vital information on the topics above, thus addressing the knowledge gap cannot be overemphasized. Moreover, there is also a need to enhance current knowledge regarding technical information relating to the engineering properties of lateritic and shrinkable soils occurring in Malaysia through field and laboratory studies. This study, therefore, attempts to address these critical issues by presenting a summary of the core research outcomes that have occurred over previous decades, with a focus on the utilization of residual soils as compacted liner materials.

1.1 Essentialness of soil compaction

Uncompacted natural soils often consist of an amalgamation of the four basic soil particle sizes: clay, silt, sand, and gravel. They usually possess low shear and tensile strength, high porosity, high permeability, and their properties are mainly influenced by the surrounding environmental conditions [29]. Conversely, soil compaction remolds the soil into clods, thus minimizing the interclod voids and ensuring reductions in the permeability and consolidation-settlement of the compacted soil, as well as increasing tensile and shear strength [16, 30]. Therefore, the process by which air is displaced from the pores between soil grains (due to the densification caused by the application of mechanical stress) is termed soil compaction. Soil compaction is typically achieved within a precise range of moisture contents and dry densities. This specification is principally grounded in the aim of achieving a maximum dry density, therefore controlling the performance of compacted soil liners with respect to their permeability [30]. Hence, the key objectives of compacting a soil mass are to increase load-bearing capacity, prevent soil settlement

and frost damage, provide stability, and reduce water seepage, swelling, and contraction [31, 32].

1.2 Soil compaction methods

Soil compaction techniques can be grouped into various categories with different viewpoints. Commonly used laboratory methods for soil compaction include the impact, static, kneading, and vibratory methods [33]. However, based on this study, emphasis is placed on the impact and static compaction methods. Proctor testing is a common and frequently adopted impact test method [34], while the static method uses a hydraulic press or pump to compress soils to given bulk densities [35, 36]. Previous researchers including [33, 35] compared the effects of static and impact methods on soil compaction and noted different results. Crispin et al. [37] noted similar results for a silty, sandy, and clayey soils. Doris-Asmani et al. [35] achieved an increase in bulk densities and strengths when soils were compacted statically, relative to those compacted with the dynamic proctor impact method. Ekwue et al. [38] indicated that similar strength values are observed when the same soils are compacted dynamically or statically at the same bulk densities and similar moisture contents. They concluded by indicating that the method of compaction is not a determining factor in soil strength.

2 Compacted soil liners (CSLs)

2.1 Definition

Sebastian and Sindhu [31] and Chinade et al. [39] defined CSLs as low-permeability barriers constructed of cohesive soils that are compacted to increase strength and homogeneity and to reduce porosity and permeability. When properly compacted, soil liners can achieve a permeability of the order 10^{-7} cm/s or less, due to the fine particles and plastic properties of the soils. Nowadays, compacted soils are often used in conjunction with geomembranes to form a composite liner. The effectiveness of composite liners results from the advantages of the two different materials with different mechanical and hydraulic properties [40]. Moreover, encouraging conclusions from laboratory and in situ pilot tests have also proved the potential use of compacted soil liners as effective barrier materials.

2.2 Classification

Compacted soils have been utilized for many years as single or composite liner materials in solid waste containment facilities. Composite barrier systems are comprised of a geomembrane overlying either a CSL or GCL

or both [41–43]. In the last few decades, their application as composite liners has gained widespread popularity in optimizing liner system properties. There is no standard classification for compacted soils. However, the types of liner systems for which compacted soils are utilized can be accounted for. [40] classified liner systems into five major categories including double liner systems, double with bottom composite systems, double composite liner systems, single liner systems, and single composite systems (as illustrated in Fig. 1). The double liner concept was initially introduced by [44]. A double liner consists of two liners with an intervening leachate collection system (LCS) at the top and a drainage layer, called the leakage detection system (LDS), at the bottom. The drainage layer is used to detect, collect, and remove leachate between the two liners. A double liner system with a bottom composite liner consists of a single liner at the top and a composite liner at the bottom. It also includes an LCS above the top liner and an LDS between the liners. Double composite liner systems consist of composite liners as top and bottom liners. Both LCS and LDS exist above the top liner and between the liners, respectively. Such systems are usually considered in situations where a high level of environmental protection is required. A single liner system consists of only

one-liner with an LCS above the liner. The liner may consist of either a geomembrane or a low hydraulic conductivity soil [45]. A liner system consisting of two or more different, low hydraulic conductivity materials placed in direct contact with each other is termed a single composite liner system [45]. An example of this would be a geomembrane and a low hydraulic conductivity soil layer.

2.3 The evolution of compacted soil liner systems

The application of compacted soil liners commenced in the early 1970s. The first application of compacted soil liners as hydraulic barriers was in earth dams for water impoundment [20]. Since then, their specific utilization as hydraulic barriers has advanced to a wide range of applications. They have been employed in canal linings [46], landfills and surface impoundments [5, 19], sewage lagoons [47], heap leaching pads [48, 49], mine tailings dams [7, 8], chemical liquid storage ponds, and evaporation ponds [50, 51]. Among the various applications, CSLs used in municipal solid waste landfills have received the most significant attention in recent times, resulting in numerous related literature. According to [19, 52], in the USA (where many of the recent developments occurred) CSLs were not

Fig. 1 Different linear systems.
(Modified after [40])

frequently utilized until the early 1970s. Until about 1982, virtually all landfills were constructed of compacted soil liners using a single layer [53]. In 1982, their usage as single liners in landfills and other liquid storage impoundments was banned by the Environmental Protection Agency in the United States (USEPA) unless the landfill owners and operators could demonstrate that they were adequate. The ruling was based on previous studies that indicated soil liners failed to meet the USEPA requirement of zero infiltration and zero seepage of contaminants into the ground [19]. The resolution resulted from earlier findings, indicating that concentrated organic chemicals affected compacted soil liners and lead to considerable increases in liner permeability [54].

Moreover, the mediocre performance of some soil liners, due to poor construction techniques, was also a drawback [50]. In 1984, USEPA made amendments to the application of liner materials in landfills and other liquid containment facilities. The amendments stipulated the employment of double liners in these different liquid storage facilities. As such, the current environmental legislation of the USA allows the utilization of compacted soil liners in combination with synthetic geomembranes to form composite liner systems. As well as the USA, CSLs are extensively used throughout the globe. The majority of developed countries (e.g., European countries and Canada) advocate the utilization of CSLs in amalgamation with geomembranes to form a composite liner system. However, in developing countries, most landfills and other liquid impoundments still need to be lined, and CSLs appear to be the preferred choice in the case of new landfills [20]. Nonetheless, the practice of using double liner systems in sanitary landfills and other liquid impoundments is emerging in developing countries [55].

2.4 Merits of compacted soil liners

Advantages of CSLs, compared to their conventional counterparts (such as GCLs and geomembranes) are their ability to meet various design specifications and performance standards and still retain their integrity. Several researchers [5, 8, 13, 22, 24, 56] have examined the advantages of CSLs compared to conventional ones, and they are summarized below:

- Compacted soil liners can achieve a low permeability of the order 10^{-7} cm/s or less.
- High attenuation capacity.
- Excellent self-healing properties, especially those containing montmorillonite.
- Naturally occurring and readily available.
- Relatively inexpensive when present on site or nearby.
- Lower diffusive flux of contaminants.

- Possible decrease in hydraulic conductivity due to the precipitate formation, biomass growth, and solids accumulation.
- Less vulnerability to mechanical accidents (punctures).
- Better solute flux and breakthrough time.
- Good compatibility with the permeating fluid/leachate.
- Less prone to ion exchange.

2.5 Demerits of compacted soil liners

The following engineering problems are associated with using compacted soil liners.

2.5.1 Desiccation cracking

Desiccation cracking is a problem associated with compacted soil liners. Repeated wetting and drying cycles, with seasonal changes in temperature, resulting in significant dryness of the soil liner and associated cracking [24]. However, successful techniques have been identified that are capable of improving soil properties and minimizing desiccation cracks, such as the application of a surface moisture barrier above the soil layer and the use of soil additives, such as bentonite and fibers [24]. Akayuli et al. [8] and Rowe [26] indicated that some soils could naturally self-seal cracks, due to their expansive nature.

2.5.2 Material unavailability

Tropical residual soils are extensively scattered throughout the world, covering approximately 2.3 billion hectares [57]. Despite being widespread, the availability of soils with the potential properties to be used as compacted liners remains a challenge at specific sites. A common practice utilized in minimizing this problem is blending the natural soil available on or near the site with bentonite or other materials, such as polymers and waste materials, etc.

2.5.3 Difficulty of placement

The placement of CSLs in landfills and other liquid impoundments is often problematic and requires critical attention. As such, well-trained personnel are required for their placement. Various techniques and specifications are essential in achieving an excellent placement of the liner materials as outlined in [58].

2.5.4 Others

Other problems associated with compacted soil liners include but are not limited to: difficulty in withstanding differential settlement, difficulty in repairing, less airspace resulting from greater layer thickness, field hydraulic

conductivity testing is sometimes required, high cost if on-site soils are not available and a slower installation process.

2.6 Requirements of compacted soil liners

Marcos and Pejon [59] indicated that soil liners should possess the following properties (among others): low permeability ($< 10^{-7}$ cm/s), greater than 10% clay size content and a plasticity index (PI) ranging between 12 and 65%. Moreover, according to [60], the various specifications for compacted soil liners include:

- A cation exchange capacity of at least 10 meq/100 g.
- A maximum allowable permeability of the order 10^{-7} cm/s (10^{-9} m/s) or less.
- Compatibility of the leachate with the soil liner, to prevent a significant increase in permeability on exposure to leachate.
- Since diffusion is the dominant transport mechanism, a chemical flux point of 10^{-8} cm/s or less is preferable.

Declan and Paul [61] and O'Sullivan and Quigley [62] recommended the following suite of tests for evaluating the suitability of a potential source of soil liner: hydraulic conductivity, unconfined compressive strength, compaction characteristics, natural moisture content, Atterberg limits, grading, organic content, and moisture condition value. Moreover, researchers such as [15, 59] have also identified the cation exchange capacity (CEC), soil mineralogy, electrical conductivity, specific surface area (SSA), and pH as suitability criteria for assessment of soil liners. Table 1 indicates the minimum requirements for soil liner specification given by various environmental agencies and researchers. From Table 1, it is observed that the liquid limit of CSLs range from 20 to 90%. The plasticity index ranges between 7 and 65% and the activity range from 0.30 to 1.25.

3 Applications of compacted soil liners

Literature suggests that using compacted soil liners in geo-environmental engineering is feasible in different environmental protection applications including landfills, solar ponds, tailings dams, canals, waste rock storage facilities, among others. As such, their utilization has gained wide acceptance in various domains, as discussed below.

3.1 Engineered landfills

Landfills are well-engineered facilities, designed and constructed to impound municipal, hazardous, industrial, construction and demolition waste materials as well as

coal combustion residuals, among other things [42, 84, 85]. Modern landfills have liner systems incorporated to prevent the pollution of groundwater and the surrounding environment by the contaminants generated by the waste deposited on them [5, 39]. The liner system comprises a combination of one or more collection layers, drainage layers and low hydraulic conductivity barriers [40]. The low-permeability barrier could be a geomembrane, a CSL or a combination of both. As such, CSLs are used as barrier materials in landfills to segregate the waste materials from the surrounding environment, provide environmental protection and prevent groundwater contamination. Various scholars have evaluated the suitability of naturally occurring geomaterials for utilization as CSLs in landfills [5, 6, 13, 23, 86–89]. Fluet et al. [40] reported that the utilization of CSLs as single liner systems in construction/demolition debris landfills could be recommended as an effective liner material to prevent leachate migration. Also, studies by [45, 90–93] have revealed that seepage rates through geomembrane liners with holes can be greatly minimized if the geomembrane is placed in direct contact with a compacted soil layer of low permeability, to form a composite liner. Nowadays, because of the effective nature of composite liner systems, an increasing number of solid waste landfill operators and designers have resorted to this technique to ensure long-term protection of human health and the environment as well as meet the required standards for landfill liner systems [40].

3.2 Tailings dams

Riverine disposal, submarine disposal, wetland retention, backfilling, dry stacking, and storage behind dammed impoundments are the various approaches utilized for handling and storing tailings [94, 95]. Storage of tailings behind dammed impoundments (frequently called 'tailings ponds' or 'tailings dams') is the main method currently employed by large mining and mineral processing companies. Tailings dams are well-engineered facilities constructed to store the thickened, pasted, slurried or dry-stacked tailings resulting from mineral processing activities [8, 96]. By the early 2000s, the global existence of at least 3500 tailings dams (ranging from a few hectares to thousands of hectares in area) was reported by Martin and Davies [97]. Akayuli et al. [8] reported the occurrence of fine-grained rock materials and some toxic chemicals in mine tailings which are potentially harmful to the surrounding environment if not appropriately disposed of or contained. As such, the proper storage of tailings has, therefore, become a key environmental concern and hence, mineral processing companies and environmental agencies are obliged to store tailings behind specially designed tailings dams or ponds that constitute bottom

Table 1 Requirements for compacted soil liner material

Parameters	Standard requirement	References
Grain size analysis	Clay size content > 20%	[63]
	Largest grain size $\leq$ 63 mm	[64, 65]
	Silt size content $\geq$ 15%	[65]
	Largest grain size $\leq$ 50 mm	[11]
	% gravel $\leq$ 30	[11, 66]
	Clay fraction $\geq$ 10%	[61, 62, 67, 175]
	Fines content $\geq$ 30%	[61, 68]
	Fines content $\geq$ 20%	[66, 69]
	Clay fraction $\geq$ 30%	[26]
	Fines content $\geq$ 15%	[65]
Atterberg consistency limits	LL $\geq$ 30% PI $\geq$ 15%	[63]
	LL $\geq$ 20% PI $\geq$ 7%	[70]
	LL $\geq$ 30% PI $\geq$ 10%	[60]
	LL $\geq$ 30% PI > 10%	[71]
	LL $\leq$ 90%, 10% $\leq$ PI $\leq$ 65%	[61, 66]
	LL $\leq$ 90%	[62, 67]
	LL $\geq$ 30%	[72]
	PI $\geq$ 7%	[73]
	Activity $\geq$ 0.3	[60, 76]
	CL and CI	[63, 69]
Classification	CL and CH	[74]
Specific gravity	$\geq$ 2.2	[65]
	$\geq$ 2.5	[75]
Activity	$\geq$ 0.3	[60, 76]
	< 1.25	[63]
Moisture-density relationship	MDD $\geq$ 1.70 g/cm ³	[65]
	MDD $\geq$ 1.70 Mg/m ³	[14]
	> 95% proctor density	[175]
	$W_{opt} + (2-3\%)$	[69]
Thickness	300–600 mm	[22]
	$\geq$ 1 m	[61, 96]
	$\geq$ 50 cm	[77]
	0.9–1 m	[13]
Unconfined compressive strength	$\geq$ 200 kPa	[68]
Remolded undrained shear strength	$\geq$ 50 kN/m ²	[66]
Volumetric shrinkage strain	$\leq$ 4%	[68]
Coefficient of permeability	$\leq 1 \times 10^{-6}$ cm/s	[60, 77–81, 175]
	$\leq 1 \times 10^{-7}$ cm/s	[13, 22, 61, 65, 69, 75, 82, 96, 175]
	$\leq 1 \times 10^{-8}$ cm/s	[63, 83]

liner systems. The liner systems aim to minimize the migration of contaminants and toxic chemicals from the tailings into the surrounding environment and, therefore, protect the soil and groundwater from pollution. Various researchers have evaluated the suitability of naturally occurring geomaterials and waste materials for utilization as CSLs in tailings dams [7, 8, 98–101]. Depending on the geochemistry of the tailings and process solution, the tailings

may be stored within various types of liner systems. This is often done if the tailings and/or process solution contain constituents that may have a negative impact on the environment [96]. Single composite liner systems are the most frequently used. Double composite liner systems are not often utilized due to the hydraulic properties of the tailings [96]. Indeed, it is important to note that a single composite liner system can be effectively utilized

in tailings dams when the hydraulic head of the tailings exceeds 100 m. This is because of the formation of a low hydraulic conductivity layer by the tailings above the liner material [96].

3.3 Solar ponds

Solar ponds are known to be an effective and cheap technique for trapping and storing solar energy on a large scale. A salt gradient solar pond comprises three (3) zones: an upper convective zone (UCZ) of low salinity; a non-convective zone (NCZ) in the middle of the pond, with salinity that increases with depth; and a lower convective zone (LCZ) with high salinity at the bottom of the pond. A major drawback of the salt gradient solar pond is seepage through the soil, which simultaneously contaminates the soil and reduces the efficiency of the solar pond [102]. Studies have indicated that this challenge can be minimized by utilizing an effective barrier system around the inner surfaces of the pond. French et al. [103], Fynn and Short [104] and Hull and Nielsen [105], all reported the effective utilization of synthetic materials as hydraulic barriers for small prototype solar ponds. However, studies by [102] indicated that, if such synthetic liners are utilized in large solar ponds (in an area greater than 5 km²) constructed for electricity generation, the cost of the solar pond increases by as much as 30%. Under such circumstances, local clay deposits can be effectively utilized as an alternative for reducing liner costs and simultaneously preventing soil contamination, especially in developing countries [106]. A study by [107] indicated that compacted kaolinite clay had the same order of hydraulic conductivity as membrane liners for its application in large solar ponds. Compacted clay and low-density polyethylene (LDPE) were tested by [108] for their suitability as lining schemes in solar ponds. Their results revealed that an LDPE film sandwiched between two layers of compacted clay could be utilized effectively as liners for solar ponds. Researchers such as [102, 106, 107, 109, 110] indicated that utilization of compacted soils as a substitute for synthetic materials for liner applications in solar ponds could lead to a reduction in the cost of construction and the risk of pollution to the subsoil and groundwater.

4 Materials used for construction of compacted soil liners

Compacted soil liners typically consist of materials of clay size fractions, compacted in layers called lifts [39]. Commonly used materials for soil liner construction include but are not limited to: natural soils, bentonite-soil blends, fiber-soil blends, and waste materials-treated soils. CSLs

constructed from naturally occurring soils (such as expansive, lateritic and ferrallitic soils, etc.) which contain a significant amount of clay and silt size fractions are the most common and frequently used types of compacted soil liners. However, if the naturally occurring soils found around the landfill sites or liquid impoundments are not fine enough for liner application, a common practice is to blend the available soil with a suitable stabilizer to achieve the required properties [77]. Nonetheless, the focus of this study is on the suitability of natural residual soils as compacted soil liners.

4.1 Residual soils

4.1.1 Definition and characteristics of residual soils

Various researchers and institutions have defined residual soils with respect to different viewpoints, for instance, McCarthy [111] defined them as “soils form due to the accumulation of organic material or from rocks and remain at the place of formation.” Brand and Philipson [112] also defined residual soil as “soils formed by in situ weathering, but with the destruction of the original rock texture.” Blight [113] defined residual soils as “all material of a soil consistency located below the local ancient erosion surface, i.e., below the pebble marker.” Sowers [114] defined residual soil as “the product of rock weathering that remains in situ above the yet-to-be weathered parent rock.” Public Works Institute Malaysia [115] defined residual soils as “soils form in place by the breakdown of the parent material and has not been transported to any substantial distance.”

The main characteristics of residual soils include but are not limited to:

- They form a mantle of substantial thickness, which varies from place to place, depending on the factors of the formation.
- They display identifiable in situ, differential horizontal horizons and show no formation stratification.
- The nature of the parent rocks predominantly influences their composition.
- They have low strength due to bond destruction processes [116].

4.1.2 Classification of residual soils

Several efforts have been made over past decades, by various researchers such as [117–119] to devise methods for the classification of residual soils. However, despite these attempts, no generally accepted methods have been established. This is not surprising given the very diverse nature of residual soils, and it is unlikely that a universal scheme is a practical possibility. However, a grouping

of residual soils is suggested as shown in Table 2, not to create a systematic classification of residual soils but to aid engineers to identify residual soil types which can be expected to have analogous engineering characteristics. Studies have suggested that expansive and lateritic residual soils are readily available and common in most tropical countries and, as such, are used extensively for the construction of liners, hence our motivation in reviewing the suitability of both soils for compacted liner construction.

5 Suitability of expansive and lateritic residual soils as compacted soil liners

5.1 Introduction

The suitability of two typical soil liner materials, namely lateritic and expansive soils, were evaluated. Data on the

geotechnical characteristics of these soils were collected from published papers in the proceedings of conferences and professional journals. The information collated for the soils includes the results of particle size analysis, plasticity characteristics, strength, and hydraulic parameters. The literature search employed included Scopus and Google Scholar databases, complemented with Springer Link, Taylor & Francis Online, and Research Gate platforms. Information on both expansive and lateritic soils was collected from 21 countries. This was then supplemented by a study of the geotechnical properties of lateritic residual soil and shrinkable marine clay from Peninsular Malaysia. The geotechnical tests (i.e., grading, Atterberg limits, specific gravity, compaction, and unconfined compressive strength) conducted on both the lateritic residual soil and shrinkable marine clay in the current study were determined in accordance with [121] specification, while the hydraulic conductivity test was conducted using the compaction

Table 2 Classification of residual soils (Modified after [120])

Grouping system		Common pedo-logical names used for groups	Descriptive information on in situ state	
Major division	Sub-group		Parent rock	Information on structure
Group A Soils with strong mineral-ogical influence	(a) Strong macro-structure influence	Miscellaneous	Give details of type of rock from which the soil has been derived	Describe nature of structure: Stratification Fractures, fissures, faults, etc Presence of partially weath-ered rock
	(b) Strong micro-structure influence	Miscellaneous		Describe nature of micro-structure and/or evidence of it: Influence of remolding Sensitivity Liquidity index
	(c) Little or no structural influence	Miscellaneous		Indicate evidence for little or no structural effect
Group B Soils strongly influenced by normal clay minerals	(a) Smectite (montmoril-lonite) group	Black cotton Soils Black Soils Tropical Black Earths Grumusols Vertisols	Give basis for inclusion on this group. Describe any structural influences either macro-structure or micro-structure	As above
	(b) Other clay minerals?			
Group C Soils strongly influ-enced by clay minerals essentially found only in residual soil	(a) Allophane sub-group	Volcanic ash soils Andosols or andisols Andepts		
	(b) Halloysite sub-group	Tropical red clays Latosols Oxisols Ferralsols	Give basis for inclusion on this group. Describe any structural effects especially cementation effects or the sesquioxides	
	(c) Sesquioxide sub-group—gibbsite, goe-thite, hematite	Lateritic Soils Laterites Ferrallitic Soils Duricrusts		

mold permeameter under failing head condition as recommended by [122]. The data obtained from literature were analyzed using statistical package for the social sciences (SPSS) software. The analysis performed was descriptive statistics and one sample t test using a confidence limit of 0.05. Shrinkable marine clay was utilized in the current study under the category of expansive soil because the major mineral constituent of the marine clay is smectite (montmorillonite) [176], which is the main mineral in expansive soils as reported in literature. The montmorillonite clay mineral accounts for the shrink-swell behavior of the expansive soils. Figure 2a, b shows the generalized soil profiles for the lateritic and shrinkable marine soils obtained from the test pits during this study. Tables 3, 4 and 5 summarize the information retrieved for expansive and lateritic soils from the published literature, as well as those obtained from the current study, respectively.

Likewise, Tables 6 and 7 present the results of the statistical analyses for the expansive and lateritic residual soils, respectively. From the tables, generalized engineering characteristics and indices were developed for the two soil types and their suitability assessed by comparing them to the requirements of compacted soil liner materials.

5.2 Grading and textural classification of the expansive and lateritic soils

Grain size distribution is a vital component in the assessment of soil liner materials. Tables 3 and 4 show the grading, plasticity characteristics, strength and hydraulic properties of the expansive and lateritic soils, respectively. The sand content varies between 1 and 48%, silt content between 7 and 70% and the clay size content ranges from 0 to 92% for the expansive soils. For the lateritic soils,

Fig. 2 **a** Typical marine clay profile from Malaysia. **b.** Typical lateritic soil profile from Malaysia

Table 3 Summary of index and engineering properties of expansive soils

Location	Grading (%)		Fines content (%)	LL (%)	PL (%)	PI (%)	SG	Activity	Soil group		MDD (Mg/m ³)	OMC (%)	UCS (kPa)	HC (cm/s)	References
	Sand	Silt							USCS	ASSHTO					
Nigeria	10	45.0	45.0	85.0	67.5	22.8	44.7	2.36	CL	A-7-6	1.400	21.0	312.5	1.88E-8	[123]
				> 90	78.0	31.0	47.0	2.56			1.412	27.0	124.1	1.0E-9	[124]
	38	29.0	32.5	88	85.0	46.91	38.09	2.26		A-7-6					[125]
Australia	11	22	67	89	63.0	27.0	36.0	1.94	CH	A-7-6 (13)	1.34	24.0	220		[126]
	3	26	71	97	88.0	34.0	54.0	2.83	CH	A-7-5 (20)	1.538	21			[127]
Tanzania	19	31	48	79	91.0	31.0	60.0	2.84	CH	A-7-5 (20)	1.562	25.5			
	25	37	38	75	60.0	30.0	30.0	0.7			1.730	18.7			[128]
	6	54.0	40.0	94.0	73.2	29.5	43.7	1.2		A-7-6 (20)	1.260	36			
India	24	10.0	66.0	76.0	82.0	35.0	47.0	1.18	CH		1.29	35			[129]
	2	22.0	76.0	96.0	170	50.0	120	2.65			1.56	21.38	170		[130]
	19.70	18.0	63.3	81.3	85	39.0	46.0	2.68	CH		1.42	26.89	1.89E-7		[131]
Ghana	37.0	15.2	46.5	61.7	91.7	29.60	62.12	2.37	CH	A-7-6	1.61	23.98	143	3.0E-7	[8]
					74.7	26.55	48.13	2.30	CH	A-7-6	1.82	17.54			[132]
South Africa					35	21.0	14.0								[133]
Sri Lanka	40.0	26.0	34.0	60.0	44.0	19.0	25.0	2.64	CI				0.87E-8		[134]
	48.0	12.0	40.0	52.0	50.0	21.0	29.0	2.74	CI				3.2E-8		
Egypt	20.0	55.0	25.0	75.0	91.6	61.0	30.60				1.79	15.10	209		[135]
	22.3	47.5	25.7	73.2	91.6	61.0	30.60	1.22	MH	A-7-5	1.79	15.10	209		[136]
Algeria	1.0	7.0	92.0	99.1	83.7	32.8	51.0	1.98	CH		1.60	19.43	120	3.0E-9	[137]
Saudi Arabia	2.0	23.0	75.0	96.0	136	60.0	76.0	0.83	CH		1.18	32.7			[138]
Honduras	34.0	11.0	55.0	66.0	126	58.0	68.0	2.64		A-7-5 (20)					[139]
Rhodesia	3.0-12.0	25-70	18-73		72.0	24.0	48.0	0.87		A-7-6 (17)					[139]
Horn of Africa	14	32	54	86	43-103	17-49	26-54	2.4-2.5	0.6-1.1		1.108-1.278	22-49.			[140]
Morocco	19	25	56	81	56	24	32	0.59		A-7-6					[139]
	10	30	60	90	59	31	28	0.5		A-7-5					
Chad Basin	14	34	52	86	52	19	33	0.82	CL	A-7-6					[139]
	30	8	62	70	56	30	26	0.4			1.650	18.6			
Kenya	8	37	52	89	104	34	70	2.28							[139]
	4	38	56	94	72	24	48	2.47		A-7-5					
Ethiopia					109	28	81	1.36							[139]
Botswana	16	26	58	84	53-55	24-28	27-19	2.6-2.7			1.485	23			[141]
Palestine	42	58	0	58	69	27	42	2.79			1.236	22			[139]
Cameroon	19	43	38	81	64	37	27	1.7		A-7-5					[139]
					62	35	27	0.71		A-7-6					

Table 3 (continued)

Location	Grading (%)		Fines content (%)	LL (%)	PL (%)	PI (%)	SG	Activity	Soil group		MDD (Mg/m ³)	OMC (%)	UCS (kPa)	HC (cm/s)	References
	Sand	Silt							USCS	ASSHTO					
Zambia	14	35	51	49	16	33	2.58	0.65			1.802	16			[139]

LL liquid limit; PL plastic limit; PI plasticity index; SG specific gravity; MDD maximum dry density; OMC optimum moisture content; USCS unified soil classification system; ASSHTO American association of state highway and transportation official; UCS unconfined compressive strength; HC hydraulic conductivity

the sand content varies between 6 and 77%, silt content between 3 and 51% and clay size content from 1 to 66%. Grading analysis of the shrinkable marine clay and lateritic soil from Peninsular Malaysia was within the ranges reported above. Low clay size contents of 25.0% and 25.7% have been reported for some Egyptian and Algerian expansive soils, respectively [136, 137]. Also, very low clay contents of 1.2% and 3.4% were reported for Indian and Ethiopian lateritic soils, respectively [146, 154]. The expansive soils generally classify as clay, sandy-clay, silty-clay, clay-loam, silt-loam, and silty-clay-loam, on the textural classification chart (Fig. 3), while the lateritic soils are classified as clay, clay-loam, silt-loam, and sandy-clay-loam (Fig. 4).

Approximately 38% of the expansive soils had sand size contents > 20%. On the other hand, almost 91% of the lateritic soils had sand size contents > 20%, except those from Ethiopia and the USA. Hence, most of the lateritic soils are suitable for liner construction since they contain a significant quantity of sand, which would offer substantial protection from volumetric shrinkage and provide sufficient strength. It was also observed that all of the expansive soils had clay contents > 12%, except for a single sample from Cameroon. Based on the statistical analysis, the mean clay content of 50.56% for the expansive soils is significantly higher than the standard value of $\geq 10\%$ (p value < 0.05) and therefore meets the requirement. Similarly, approximately 86% of the lateritic soils had clay contents > 12%, except for soils from Ethiopia and India, which were lower. Based on the statistical analysis, the mean clay content of 29.27% for the lateritic soils is significantly higher than the standard value of 10% (p value < 0.05) and therefore meets the requirement. Therefore, both residual soil types fulfilled the recommendations of [62], who proposed a minimum clay content of 10% for soil liners. The fines contents of the expansive soils were greater than 32%, and these values fall within the recommended $\geq 30\%$ fines content proposed by [68] for liner materials. Based on the statistical analysis, the mean fines content of 80.59% for the expansive soils is significantly higher than the standard value of $\geq 30\%$ (p value < 0.05) and therefore meets the requirement. Similarly, 61% of the lateritic soils had fines content greater than 32%. Based on the statistical analysis, the mean fines content of 38.12% for the lateritic soils is higher than the requirement of $\geq 30\%$ (p value < 0.05) and therefore meets the requirement.

Hence, both residual soil types met the requirement proposed by [68]. The utilization of fine soils as hydraulic barriers was recommended by [165] due to their high specific surface area. They further indicated that, as soil texture becomes finer, leachate migration reduces. Also, [166] proposed that soil liners should contain not less than 20% fines content to achieve a

Table 4 Summary of index and engineering properties of lateritic soils

Location	Grading (%)			Fines content (%)		LL (%)	PL (%)	PI (%)	SG	Activity	Soil group		MDD (Mg/m ³)	OMC (%)	UCS (kPa)	HC (cm/s)	References
	Sand	Silt	Clay	USCS	ASSHTO												
Nigeria	59.0	9.0	30	39.0	21.6	8.0	13.9	0.46	CL		1.9	12.1	3.47E-7	[25]			
	64.0	11	22.0	33.0	42.0	18.4	23.6	1.07	CI	A-2-4	1.7	15.0	7.54E-7	[142]			
	37.0	30.0	33.0	63.0	43.0	23.0	20.0	2.7	0.60	CL	1.7	19.0	< 1.0E-7	[143]			
Hawaii	33.0	23.0	44.0	67.0	48.0	23.0	25.0	2.7	0.57	CL	1.8	18.6	2.99E-8	[144]			
	28.7	51.0	20.3	71.3	45.5	38.7	6.8	2.94	0.33		1.41			[145]			
	31.0	38.7	30.3	69.0	49.1	38.5	10.6	2.94	0.35		1.35						
Ethiopia	12.7	9.8	3.4	13.2	56.0	36.0	20.0	3.0	5.88	GM	A-2-7	1.72	23.2	553	[146]		
	6.5	9.9	4.4	14.3	56.0	38.0	18.0	2.86	4.1	GM	A-2-7	1.58	25.0				
USA	18.0	38.0	44.0	82.0	48.0	39.0	9.0	3.17	0.20						[147]		
	30.0	16.0	54.0	70.0	55.0	40.0	15.0	3.27	0.28								
Cameroon	38	32	23	55.0	57	31	26.0	2.83	1.13	GC	A-2-7	2.17	10.2		[148]		
	36.6	31.6	24	55.6	73	38	35.0	2.75	1.46	GM	A-2-7	1.94	14.5				
Ghana	36.0	4.50	40.4	44.94	59.74	23.7	36.0	0.89		CH		2.2	12.6		[149]		
	56.5	15.0	13.0	28.0	58.0	27.4	30.6	2.35		CH			13.1				
	24.0	11.0	22.0	33.0	48	19.0	29.0	2.7	1.3	CH-ML	A-2-7	2.0	18.0	600	[150]		
	22.0	11.0	26.0	37.0	52	24.0	28.0	2.7	1.1	CH-MH	A-7-6	1.9	17.0	200			
	23.0	30.0	34.0	64.0	75	41.0	34.0	2.7	1.0	MH		1.3	34.0	270	[151]		
Malaysia	77.5			21.64	58.6	52.5	6.2	2.6				1.9	13.5		[152]		
	84.10	10.3	5.87	15.90	73.0	36.50	36.50	2.84	6.2	MH		1.495	30.50	164.1	1.20E-7	[5]	
Thailand					39.1	23.2	15.9	2.8			1.9	12.6	700-800	2.26E-7	[153]		
	57.4	5.0	1.20	6.20	42.0	33.33	8.67	2.6	7.2		1.7	16.1			[154]		
India	26.9	1.3			41	26.3	14.7	2.5			1.9	15.5	124.6	2.06E-5	[155]		
					34.0	13.0	21.0	2.4			1.8	17.3	111.8	1.31E-6	[156]		
Senegal	20-30			8-14	38.8-39.8	18.5-20.8	19-20.3				A2-6	2.0	11.7		[157]		
	16-22			10-12	28.5-32.5	14.8-16.3	13.7-16.2				A2-6	2.2	6.1				
Brazil	40.0	14.0	44.0	59.0	34.0	9.0	25.0	2.6	0.57	ML		1.8	16.0		[99]		
	27.0	14.0	59.0	73.0	45.0	30.0	15.0	0.25			1.6	26.3	1.0E-7	[158]			
	28.0	6	66	72	69.5	40.9	28.6	2.73	0.43	CL	A-7-5	1.49	27.9	300	[159]		
				37.1	25	16	9.0				2.10	9.70			[160]		
Ivory Coast				21.0	48	24	24.0				2.1	10.0			[161]		
Uganda				34	38	17	22.0					13.0			[146]		
Kenya				28	45	31	14.0					19.0			[146]		
Gambia				22	36	16	20.0								[146]		
Burkina Faso				11	22	12	10.0				2.2	7.0			[162]		

Table 4 (continued)

Location	Grading (%)		Fines content (%)	LL (%)	PL (%)	PI (%)	SG	Activity	Soil group		MDD (Mg/m ³)	OMC (%)	UCS (kPa)	HC (cm/s)	References
	Sand	Silt							USCS	ASSHTO					
Tanzania			25	34	19	10.0				A-2-4	2.1	9.0			[146]
Niger			25	21	11	10.0				A-2-4	2.1	9.0			[146]
Congo				34	20	14.0					1.34	9.0			[163]
Angola				48–69	23–39	25–30					1.7–1.9	13–21			[164]

Table 5 Summary of geotechnical properties of shrinkable marine clay and lateritic soil (current study)

Properties	Shrinkable marine clay	Lateritic soil
Sand (%)	18.9	67.7
Silt (%)	43.5	7.3
Clay (%)	38.4	24.5
Fines contents (%)	81.9	28.8
Liquid limit (%)	77.8	60.9
Plastic limit (%)	34.4	34.4
Plasticity index (%)	43.4	26.5
Specific gravity	2.33	2.64
Activity	1.13	1.08
USCS	CH	MH
AASHTO	A-7-6	A-2-7
MDD (Mg/m ³)	1.496	1.38
OMC (%)	20.5	17
UCS (kPa)	210.6	235.7
Permeability (cm/s)	8.26×10^{-8}	1.74×10^{-7}

hydraulic conductivity of 1×10^{-7} cm/s or less. In conclusion, the majority of both expansive and lateritic soils met the requirements mentioned above for particle size distribution.

5.3 Specific gravity of the expansive and lateritic soils

The specific gravities of the expansive soils were found to range from 1.94 to 2.79 in the data collected, while those of the lateritic soils ranged between 2.40 and 3.27. It was found that the specific gravities of the expansive soils from Nigeria, Ghana, and Kenya are less than the 2.5 minimum recommended by the [75]. Hence, 59% of the expansive soils met the required recommendation of specific gravity for liner materials. Based on the statistical analysis, the mean specific gravity of 2.53 for the expansive soils is not significantly higher than the standard value of ≥ 2.5 (p value > 0.05) and therefore meets the requirement. Similarly, 95% of the lateritic soils met the 2.5 minimum recommended value of specific gravity for liner materials recommended by the [75], except for a soil from India which had a value that was slightly below that recommended. Based on the statistical analysis, the mean specific gravity of 2.78 for the lateritic soils is not significantly higher than the standard value of ≥ 2.5 (p value > 0.05) and therefore meets the requirement. Specific gravity values of 2.33 and 2.64 were recorded for the shrinkable marine clay and lateritic soils from Peninsular Malaysia, respectively, which both fall within the range reported in literature.

Table 6 Descriptive statistics of the expansive soils at 95% confidence interval

Property	Standard	Mean	Mean difference	<i>p</i> value	95% confidence interval of the difference		Remark
					Lower	Upper	
Clay (%)	≥ 10	50.56	40.56	0.00	33.76	47.35	The mean clay content of 50.56 is significantly higher than the standard value of ≥ 10% (<i>p</i> value < 0.05) and therefore meets the requirement
Fines content (%)	≥ 30	80.59	50.59	0.00	45.88	55.30	The mean fines content of 80.59 is significantly higher than the standard value of ≥ 30% (<i>p</i> value < 0.05) and therefore meets the requirement
LL (%)	≤ 90	76.89	− 13.11	0.01	− 22.35	− 3.87	Significant differences exist between the mean LL and the standard requirement of 30 ≤ LL ≤ 90 because <i>p</i> values are < 0.05. The LL however falls within the limits and therefore meets the requirement
LL (%)	≥ 30	76.89	46.89	0.00	37.65	56.13	
PI (%)	≤ 10	43.84	33.84	0.00	26.97	40.70	Significant differences exist between the mean PI and the standard requirement of 10 ≤ LL ≤ 65 because <i>p</i> values are < 0.05. The PI however falls within the limits and therefore meets the requirement
PI (%)	≤ 65	43.84	− 21.16	0.00	− 28.03	− 14.30	
SG	> 2.5	2.53	0.03	0.55	− 0.07	0.13	The mean SG of 2.53 is not significantly higher than the standard value of ≥ 2.5 (<i>p</i> value > 0.05) and therefore meets the requirement
Activity	≥ 0.3	0.96	0.66	0.00	0.52	0.80	The mean activity of 0.96 is significantly higher than the standard value of ≥ 0.3 (<i>p</i> value < 0.05) and therefore meets the requirement
MDD (Mg/m ³)	≥ 1.70	1.49	− 0.21	0.00	− 0.30	− 0.11	The mean MDD of 1.49 Mg/m ³ is significantly lower than the standard value of ≥ 1.70 Mg/m ³ and therefore fails to meet the requirement
UCS (kPa)	≥ 200	188.45	− 11.55	0.62	− 64.86	41.76	The mean UCS of 188.45 kPa is not significantly different from the standard value of ≥ 200 kPa, however, it is less than the standard and therefore fails to meet the requirement
HC (cm/s)	≤ 1.0E−06	7.89E−08	− 9.21E−07	0.00	− 1.03E−06	− 8.12E−07	The mean hydraulic conductivity of 7.89E−08 cm/s is significantly lower than the standard value of ≤ 1.00E−06 cm/s and hence meets the requirement

5.4 Plasticity and colloidal activity of the expansive and lateritic soils

The liquid limits of the expansive soils varied and ranged between 35 and 170%; the plasticity index ranged from 14 to 120%. The expansive soils all plotted above the A-line (Fig. 5) and were classified as clay of low to very high plasticity (CL–CH) based on the Unified Soil Classification System (USCS). Similarly, the liquid limits of the lateritic soils ranged between 21 and 75%, and the plasticity index ranged from 6 to 36%. The lateritic soils plotted above and below the A-line (Fig. 6) and classified as inorganic clay of low to very high plasticity (CL–CH) and inorganic silt of

low to high plasticity (ML–MH) based on the Unified Soil Classification System. It was observed that the study soils from Peninsular Malaysia also fall within the range of those reported in the literature. [60] recommended a liquid limit of ≥ 30% and a plasticity index of ≥ 10% for soils to be utilized in liner applications. The minimum value of the PI is because below 10% it would be highly unlikely to achieve the required low hydraulic conductivity. From Tables 3 and 4, it can be seen that the plasticity index of the expansive soils all satisfies the requirement proposed by [60]. Likewise, based on the statistical analysis, significant differences exist between the mean PI of the expansive soils and the standard requirement of 10 ≤ LL ≤ 65 because *p* values

Table 7 Descriptive statistics of the lateritic soils at 95% confidence interval

Property	Standard	Mean	Mean difference	<i>p</i> value	95% confidence interval of the difference		Remark
					Lower	Upper	
Clay (%)	≥ 10	29.27	19.27	0.00	11.28	27.25	The mean clay content of 29.27% is significantly higher than the standard value of 10% (<i>p</i> value < 0.05) and therefore meets the requirement
Fines content (%)	≥ 30	38.12	8.12	0.05	0.13	16.11	The mean fines content of 38.12% is higher than the requirement of ≥ 30% (<i>p</i> value < 0.05) and therefore meets the requirement
LL (%)	≤ 90	45.92	− 44.08	0.00	− 48.55	− 39.61	Significant differences exist between the mean LL and the standard requirement of $30 \leq LL \leq 90$ because <i>p</i> values are < 0.05. The LL however falls within the limits and therefore meets the requirement
LL (%)	≥ 30	45.92	15.92	0.00	11.45	20.39	
PI (%)	≤ 10	19.74	9.74	0.00	7.05	12.43	Significant differences exist between the mean PI and the standard requirement of $10 \leq LL \leq 65$ because <i>p</i> values are < 0.05. The PI however falls within the limits and therefore meets the requirement
PI (%)	≤ 65	19.74	− 45.26	0.00	− 47.95	− 42.57	
SG	> 2.5	2.78	0.28	0.00	0.18	0.37	The mean SG of 2.78 is not significantly higher than the standard value of ≥ 2.5 (<i>p</i> value > 0.05) and therefore meets the requirement
Activity	≥ 0.3	1.71	1.41	0.00	0.48	2.35	The mean activity of 1.71 is significantly higher than the standard value of ≥ 0.3 (<i>p</i> value < 0.05) and therefore meets the requirement
MDD (Mg/m ³)	≥ 1.70	1.82	0.12	0.02	0.02	0.21	The mean MDD of 1.82 Mg/m ³ is significantly higher than the standard value of ≥ 1.70 Mg/m ³ and therefore meets the requirement
UCS (kPa)	≥ 200	365.77	165.77	0.05	− 1.77	333.32	The mean UCS of 365.77 kPa is significantly higher than the standard value of ≥ 200 kPa and therefore meets the requirement
HC (cm/s)	≤ 1.0E−06	2.62E−06	1.62E−06	0.492	− 3.57E−06	6.81E−06	The mean hydraulic conductivity of 2.62E−06 cm/s is not significantly different from the standard value of ≤ 1.00E−06 cm/s and hence meet the requirement

are < 0.05. The PI, however, falls within the limits and therefore meets the requirement. Similarly, 86% of lateritic soils also met the requirements, the exceptions being soils from Sudan, Burkina Faso, and Niger, which had values lower than that recommended. Based on the statistical analysis, significant differences exist between the mean PI of the lateritic soils and the standard requirement of $10 \leq LL \leq 65$ because *p* values are < 0.05. The PI, however, falls within the limits and therefore meets the requirement. [62, 66, 67] recommended that soil liners should have liquid limits ≤ 90%. From the data sets, it can be observed that 73% of the expansive soils satisfied the above recommended liquid limit for use as a soil liner, while 27% had values slightly higher than those recommended. Based on the statistical analysis, significant differences exist between the mean LL of the expansive soils and the standard requirement of $30 \leq LL \leq 90$ because *p* values are < 0.05. The LL, however, falls within the limits and therefore meets the requirement.

Conversely, all of the lateritic soils satisfied the recommended liquid limit for use as a soil liner. Based on the statistical analysis, significant differences exist between the mean LL of the lateritic soils and the standard requirement of $30 \leq LL \leq 90$ because *p* values are < 0.05. The LL, however, falls within the limits and therefore meets the requirement.

Kayadelen [74] indicated that soils which are classified as low plasticity clay (CL) and high plasticity clay (CH), based on the Unified Soil Classification System, are most suitable for the construction of hydraulic barriers. Hence both soil types could be used for soil liner applications. Moreover, [12] stated that soils that lie above the A-line are suitable or marginal for use as hydraulic barriers and those below the A-line are unsuitable. Hence, all of the expansive soils tested are suitable as liners. In addition, greater proportions of the lateritic soils lie above the A-line and are, therefore, suitable for liner applications. According to

Fig. 3 Textural classification of expansive soils in literature and shrinkable marine clay in the current study. (Literature data sources: [8, 123–139, 141])

[139], expansive soils generally classify as A-7-5 and A-7-6 with group index values varying from 13 to 89 (AASHTO). From the data collected, the expansive soils classify as A-7-5 and A-7-6 and with the lowest group index value being 13. The lateritic soils, on the other hand, classify as the A-2-4, A-2-5, A-2-6 and A-2-7 groups, according to the AASHTO classification.

The activity of the expansive soils (Table 3) was found to range from 0.40 to 1.98. Likewise, the activity of the lateritic soils (Table 4) ranged between 0.2 and 7.2, thus indicating that both soils have low to high expansion potential based on the [167] criteria. Activity values of 1.13 and 1.08 were recorded for the shrinkable marine clay and lateritic soils from Peninsular Malaysia, respectively. Taha and Kabir [168] indicated that soils with higher activity are likely to consist of finer particles, have a larger specific surface area, and thicker electrical double layers. As a result, [76] noted that permeability generally decreases with increasing activity. However, [169] noted that soils with high activity are more easily affected by contaminants if utilized in containment facilities. [60, 76] recommended that soils with an activity ≥ 0.3 are suitable for liner construction and can achieve a permeability of the order 10^{-7} cm/s or less.

Hence, the expansive soils all passed the required recommendation for use as liner materials based on their activity. Based on the statistical analysis, the mean activity of 0.96 for the expansive soils is significantly higher than the standard value of ≥ 0.3 (p value < 0.05) and therefore meets the requirement. On the other hand, approximately 90% of the lateritic soils passed the required recommendation for use as liner materials based on their activity, except for soils from the USA and Brazil. Based on the statistical analysis, the mean activity of 1.71 for the lateritic soils is significantly higher than the standard value of ≥ 0.3 (p value < 0.05) and therefore meets the requirement.

5.5 Strength properties of the expansive and lateritic soils

The strength properties of both residual soil types were evaluated, based on their compaction characteristics and unconfined compressive strength. The Maximum Dry Densities (MDD) and corresponding Optimum Moisture Contents (OMC) of the expansive soils ranged from 1.10 to 1.82 Mg/m³ and 15.1 to 32.7%, respectively. The correlation between the MDD and OMC for the expansive

Fig. 4 Textural classification of lateritic soils in literature and the current study. (Literature data sources: [25, 99, 142–145, 147, 148, 158, 159])

Fig. 5 Plasticity classification of the expansive soils in literature and shrinkable marine clay in the current study. (Literature data sources: [123–129, 131–137, 139])

Fig. 6 Plasticity classification of the lateritic soils in literature and the current study. (Literature data sources: [25, 99, 141–156, 158–163])

soil (Fig. 7) shows $MDD = 2.1307 - 0.027OMC$, with a coefficient of correlation of 0.62. The MDD and OMC of the lateritic soils ranged between 1.3 and 2.2 Mg/m³ and 6.1 and 34.0%, respectively. The correlation between

the MDD and OMC for the lateritic soils (Fig. 8) shows $MDD = 2.287 - 0.0268OMC$ and with a coefficient of correlation of 0.58. The soils studied from Peninsular Malaysia also recorded values within the above ranges. From the

Fig. 7 The relationship between MDD and OMC of expansive soils in literature and shrinkable marine clay in the current study. (Literature data sources: [8, 123, 124, 126–132, 135–139, 141])

Fig. 8 The relationship between MDD and OMC of lateritic soils in literature and the current study. (Literature data sources: [25, 99, 142–144, 146, 148–163])

study, it was found that 75% of the expansive soils failed to meet the required $MDD \geq 1.70 \text{ Mg/m}^3$ limit proposed by [65] for liner materials. Based on the statistical analysis, the mean MDD of 1.49 Mg/m^3 for the expansive soils is significantly lower than the standard value of $\geq 1.70 \text{ Mg/m}^3$ and therefore fails to meet the requirement. On the other hand, 68% of the lateritic soils met the requirement. Likewise, based on the statistical analysis, the mean MDD of 1.82 Mg/m^3 for the lateritic soils is significantly higher than the standard value of $\geq 1.70 \text{ Mg/m}^3$ and therefore meets the requirement.

The unconfined compressive strength (UCS) of the expansive soils ranged between 120 and 312 kPa, while that of the lateritic soils ranged between 111 and 700 kPa. From the study, it was found that expansive soils from Ghana, Algeria, and India failed to meet the

minimum requirement of $UCS \geq 200 \text{ kPa}$ recommended for liner materials by [68]. Based on the statistical analysis, the mean UCS of 188.45 kPa for the expansive soils is not significantly different from the standard value of $\geq 200 \text{ kPa}$; however, it is less than the standard and therefore fails to meet the requirement. However, only the lateritic soil from India failed to meet the UCS requirement. Based on the statistical analysis, the mean UCS of 365.77 kPa for the lateritic soils is significantly higher than the standard value of $\geq 200 \text{ kPa}$ and therefore meets the requirement. Both soils studied from Peninsular Malaysia met the required specification for UCS for liner materials.

5.6 Hydraulic conductivity of the expansive and lateritic soils

Permeability is a key parameter for the selection of soils for use in liner applications. [170] stated that permeability decreases with increasing compactive effort because increasing compactive effort eliminates large pores. Permeability also changes with changing moisture content during molding. Soils compacted dry of optimum moisture content tend to have relatively high permeabilities, whereas soils compacted wet of optimum moisture content tend to have lower permeabilities. Increasing moisture content usually results in an increased capacity to break down clay aggregates and to eliminate inter-aggregate pores [171–173].

The permeability of the expansive soils ranged from the order of 10^{-7} – 10^{-9} cm/s , whereas the permeability of the lateritic soils ranged between the order of 10^{-5} cm/s and 10^{-8} cm/s . Likewise, the studied lateritic residual soil and shrinkable marine clay from Peninsular Malaysia also recorded values within the above ranges. The permeability of all expansive soils satisfied the requirement of a maximum acceptable limit of the order 10^{-7} cm/s or less [60, 75, 80, 174] and the order 10^{-6} cm/s [77, 78]. Based on the statistical analysis, the mean hydraulic conductivity of $7.89\text{E}-08 \text{ cm/s}$ for the expansive soils is significantly lower than the standard value of $\leq 1.00\text{E}-06 \text{ cm/s}$ and hence meets the requirement. Similarly, most of the lateritic soils satisfied the permeability requirement, except for soil from India which was slightly higher than the recommended value. Likewise, based on the statistical analysis, the mean hydraulic conductivity of $2.62\text{E}-06 \text{ cm/s}$ for the lateritic soils is not significantly different from the standard value of $\leq 1.00\text{E}-06 \text{ cm/s}$ and hence meet the requirement. In conclusion, both soils met the required limits for saturated hydraulic conductivity, which is the most critical factor for liner material assessment.

6 Summary and conclusions

This paper reviewed published literature on the recent developments in the application of residual soils as compacted soil liners in barrier systems. The study was motivated by the frequent utilization of residual soils for liner applications. Various descriptive statistics were employed to better assess the individual criteria of using both residual soil types as compacted soil liners. From the review, the following conclusions are made:

- From the grading characteristics, the expansive soils classify as clay, sandy-clay, clay-loam, silt-loam, and silty-clay loam, whereas the lateritic soils classify as clay, clay-loam, silt-loam, and sandy-clay loam. Generally, the expansive and lateritic soils had clay contents greater than the recommended $\geq 10\%$. Likewise, the fines content of all the studied expansive soils fall within the recommended $\geq 30\%$, while about 61% of the studied lateritic soils had fines content greater than the recommended.
- The liquid limits of the expansive soils vary but ranged between 35 and 170% and the plasticity index varied between 14 and 120%. The liquid limits of the lateritic soils ranged from 21 to 75%, and the plasticity index ranged between 6 and 36%. The plasticity index of the expansive soils all satisfies the minimum requirement for liner utilization. Similarly, 86% of lateritic soils also met the requirements, with the exceptions being soils from Sudan, Burkina Faso, and Niger, which had values lower than that recommended. Based on the AASHTO classification system, the expansive soils classify as A-7-5 and A-7-6, they also classify as CL-CH on the unified soil classification system. The lateritic soils, on the other hand, classify as A-2-4, A-2-5, A-2-6, and A-2-7 based on the AASHTO classification system and as CL-CH and ML-MH based on the unified soil classification system.
- The MDD and OMC of the expansive soils ranged from 1.10 to 1.82 Mg/m³ and 15.1 to 32.7%, respectively. Similarly, the MDD and OMC of the lateritic soil ranged between 1.3 and 2.2 Mg/m³ and 6 and 34%, respectively. The correlation between the MDD and OMC of the expansive soil showed $MDD = 2.1307 - 0.027OMC$, while that of the lateritic soil showed $MDD = 2.287 - 0.0268MC$. From the study, it was found that 75% of the expansive soils failed to meet the required MDD specification for liner materials. On the other hand, 68% of the lateritic soils met the requirement. The UCS of the expansive soils ranged between 120 and 312 kPa, while that of the lateritic soils ranged between 111 and 700 kPa.

From the analysis, it was found that expansive soils from Ghana, Algeria, and India failed to meet the minimum UCS requirement for liner utilization. Likewise, only the lateritic soil from India also failed.

- The permeability of the expansive soils was found to be of the order 10^{-7} – 10^{-11} cm/s, whereas those of the lateritic soils, were of the order 10^{-5} – 10^{-8} cm/s. The studied lateritic residual soil and shrinkable marine clay from Peninsular Malaysia also recorded values within the above ranges. The permeability of all expansive soils satisfied the requirement of a maximum acceptable limit of the order 10^{-6} cm/s or less. Similarly, most of the lateritic soils satisfied the permeability requirement, except for soil from India which was slightly higher.

As a general conclusion, literature showed that the majority of the studied residual soils with a few exceptions as well as the lateritic residual soil and shrinkable marine clay from Peninsular Malaysia generally possess engineering properties that make them suitable for use as liner materials in various barrier systems. However, the minority with unsuitable engineering properties can be amended by blending with suitable natural, waste, and synthetic materials to achieve the required engineering properties. Finally, we remark that environmental safety and health protection must be prioritized and warranted; hence, to this aim, any residual soil to be utilized for barrier application must undergo a thorough and careful evaluation considering the specific circumstances of the landfill site (i.e., landfill waste type and contaminant concentrations, hydrogeological and climatic conditions, etc.).

7 Future research works

It should be pointed out that, though the review of residual soils as compacted soil liners (CSL) is relatively comprehensive in this manuscript, not all the aspects regarding soil liners are discussed. Consistent with this view, future research directions on residual soils as CSL may include, evaluating and analyzing other engineering properties such as volumetric shrinkage strain, diffusion coefficient, and retention capacity that govern the suitability of geo-materials for bottom liner application, so as to better recommend the usability of residual soils as effective liner materials. Likewise, since chemical compatibility of a liner material with the percolating leachate play a vital role in assessing the long-term performance of liner materials; hence, future studies on the compatibility behavior of residual soils and leachate are necessary to better comprehend the long-term performance of the soils when utilized for liner application. Furthermore, future studies are

needed to elucidate cracking behavior (freezing–thawing behavior or wet-dry-cycles) of the residual soils, especially the expansive soil when utilized for liner application. More research is needed to understand further the potential benefits and limitations as well as cost analyses of using both residual soil types as hydraulic barriers.

Acknowledgements The authors are grateful to the Ministry of Higher Education, Malaysia for providing the financial support under the Fundamental Research Grant Scheme (FRGS/1/2017/TK01/MUSM/03/1) “Movement of leachate through compacted clay liners using local deposits: Fundamental mechanism and Suitability.” The authors also express sincere thanks to the Abunde Sustainable Engineering Group for its valuable advice. The authors also thank the anonymous reviewers for their constructive comments and suggestions which led to the improvement of the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Bouazza A (2002) Geosynthetic clay liners. *Geotext Geomembr* Rev Artic 20(1):3–17
- Najafi F, Chegenizadeh A, Nikraz H (2012) A review on GCL performance in geotechnical engineering. *Int J Biol Ecol Environ Sci* 1(3):104–107
- Feng SJ, Chang JY, Chen HX (2018) Seismic analysis of landfill considering the effect of GM-GCL interface within liner. *Soil Dyn Earthq Eng* 107:152–163
- Yu B, El-Zein A (2019) Experimental investigation of the effect of airgaps in preventing desiccation of bentonite in geosynthetic clay liners exposed to high temperatures. *Geotext Geomembr* 47(2):142–153
- Yong LL, Emmanuel E, Purwani R, Anggraini V (2019) Geotechnical assessment of Malaysian residual soils for utilization as clay liners in engineered landfills. *Int J GEOMATE* 16(58):20–25
- Kundiri AM, Osinubi KJ (2018) Reliability evaluation of two compacted tropical soils for use in municipal solid waste containment application. In: *The international congress on environmental geotechnics*. Springer, Singapore, pp 544–554
- Miguel MG, Barreto RP, Pereira SY (2017) Study of a tropical soil in order to use it to retain aluminum, iron, manganese and fluoride from acid mine drainage. *J Environ Manag* 204:563–570
- Akayuli CFA, Gidigas SSR, Gawu SKY (2013) Geotechnical evaluation of a Ghanaian black cotton soil for use as clay liner in tailings dam construction. *Ghana Min J* 14:21–26
- Amadi AA, Eberemu AO (2013) Potential application of lateritic soil stabilized with cement kiln dust (CKD) as liners in waste containment structures. *Geotech Geol Eng* 31(4):1221–1230
- Benson CH, Trast JM (1995) Hydraulic conductivity of thirteen compacted clays. *Clays Clay Miner* 43(6):669–681
- Daniel DE (1993) Clay liners. In: Daniel DE (ed) *Geotechnical practice for waste disposal*, Chapter 7. Chapman & Hall Ltd, London, pp 137–163
- Jones RM, Murray EJ, Rix DW, Humphrey RD (1993) Selection of clays for use as landfill liners. *Waste Dispos Landfill-GREEN* 93:433–438
- Kabir MH, Taha TR (2004) Sedimentary residual soils as waste containment barrier material. *Soil Sediment Contam* 13(5):407–420
- Ogunsanwo O (1996) Geotechnical investigation of some soils from SW Nigeria for use as mineral seals in waste disposal landfills. *Bull Int Assoc Eng Geol* 54(1):119–123
- Yong RN, Tan BK, Bentley SP, Thomas HR (1999) Competency assessment of two clay soil from south Wales for landfill liner contaminant attenuation. *Q J Eng Geol Hydrogeol* 32(3):261–270
- Moraci N, Busana S, Cortellazzo G, Favaretti M, Mandaglio MC, Schepis M (2018) Design and construction of a compacted clay liner in cover system of a municipal solid waste (MSW) landfill using nonstandard procedures. *Can Geotech J* 55(8):1182–1192. <https://doi.org/10.1139/cgj-2017-0371>
- Aldaef AA, Rayhani MT (2015) Hydraulic performance of compacted clay liners under simulated daily thermal cycles. *J Environ Manag* 162:171–178
- Bonaparte R, Daniel DE, Koerner RM (2002) Assessment and recommendations for improving the performance of waste containment systems. EPA—Environmental Protection Agency, Washington
- Daniel DE (1993a) Case histories of compacted clay liners and covers for waste disposal facilities. In: *3rd international conference on case histories in geotechnical engineering*, vol 2, pp 1407–1425
- Rahman F (2000) Hydraulic conductivity and chemical compatibility of some Victorian soils used as liners for waste containment. Ph.D. Thesis, School of the Built Environment, Victoria University of Technology, Australia, p 365
- Reades DW, Lahti LR, Quigley RM, Bacopoulos A (1990) Detailed case history of clay liner performance. In: *Waste containment systems: construction, regulation and performance*, vol 26. ASCE, pp 156–174
- Shankar MU, Muthukumar M (2017) Comprehensive review of geosynthetic clay liner and compacted clay liner. In: *IOP conference series: materials science and engineering*, vol 263, no 3, p 032026
- Bello A (2015) Acceptable zone for reddish brown tropical soil as liner material. *Pac J Sci Technol* 16(1):21–32
- Manoj K, Soni DK (2015) A study on the technique to improve desiccation cracks. *Int J Res Adv Eng Technol* 1(3):24–26
- Omoniyi IO (2010) Landfill site selection for municipal solid waste and assessment of soils as mineral seals around Ilorin, Southwestern Nigeria. Ph.D. Thesis, Department of Geology and Mineral Resources, University of Ilorin, Ilorin, Nigeria, p 254
- Rowe RK (2005) Long-term performance of contaminant barrier systems. *Geotechnique* 55(9):631–678
- Ozhan HO (2018) Hydraulic capability of polymer-treated GCLs in saline solutions at elevated temperatures. *Appl Clay Sci* 161:364–373
- Bouazza A (1997) Performance of geosynthetic clay liners. In: *Proceedings of the first ANZ conference on environmental geotechnics*, Melbourne, Australia, pp 307–313
- Ling IH, Leshchinsky D, Tatsuoka F (2003) Reinforced soil engineering. *Advances in research and practice*. CRC Press, Boca Raton, p 544
- Amadi AA, Eberemu AO (2012) Delineation of compaction criteria for acceptable hydraulic conductivity of lateritic soil-bentonite mixtures designed as landfill liners. *Environ Earth Sci* 67(4):999–1006
- Sebastian N, Sindhu AR (2016) Prediction of compaction of compacted clay liners. *Int J Eng Sci* 6(8):2333–2337
- Xia K (2014) Numerical prediction of soil compaction in geotechnical engineering. *CR Mec* 342(3):208–219

33. Seed HB (1954) Stability and swell pressure characteristics of compacted cays. *Clays Clay Miner* 3:483–501
34. Lambe TW (1951) *Soil testing for engineers*, 1st edn. John Wiley, New York, p 165
35. Doris-Asmani MY, Hafez MA, Nurbaya S (2011) Static laboratory compaction method. *Electron J Geotech Eng* 16:1583–1593
36. Garcia C, Alemany E, Bautista I (2012) Relationship among compaction, moisture and penetration resistance in horticultural soil. In: *Soil and water engineering. International conference of agricultural engineering-CIGR-AgEng 2012: agriculture and engineering for a healthier life*, Valencia, Spain, CIGR-EurAgEng
37. Crispin FA, Lima DC, Schaefer CE, Silva CH, de Carvalho CA, Barbosa PS, Brandao EH (2011) The influence of laboratory compaction methods on soil structure: mechanical and micro-morphological analyses. *Soils Rocks* 34(1):91–98
38. Ekwue EI, Birchb R, Chewittc J (2015) Effect of dynamic and static methods of compaction on soil strength. *West Indian J Eng* 37(2):74–78
39. Chinade AU, Umar SY, Osinubi KJ (2017) Effect of municipal solid waste leachate on the strength of compacted tropical soil for landfill liner. *Int Res J Eng Technol* 4(6):3248–3253
40. Fluet JE Jr., Badu-Tweneboah K, Khatami A (1992) A review of geosynthetic liner system technology. *Waste Manag Res* 10(1):47–65
41. Rowe RK, Quigley RM, Brachman RWI, Booker JR (2004) *Barrier systems for waste disposal facilities*. Taylor & Francis/Spon, London
42. Rubinos DA, Spagnoli G (2018) Utilization of waste products as alternative landfill liner and cover materials—a critical review. *Crit Rev Environ Sci Technol* 48(4):376–438
43. AbdelRazek AY, Rowe RK (2019) Interface transmissivity of conventional and multicomponent GCLs for three permeants. *Geotext Geomembr* 47(1):60–74
44. Giroud JP (1973) L'étanchéité des retenues d'eau par feuilles déroulées. *Annales de l'ITBTP*, 312, TP 161, Paris, Décembre, 94–112 (in French)
45. Giroud JP, Bonaparte R (1989) Leakage through liners constructed with geomembranes, part I: geomembrane liners. *Geotext Geomembr* 8(1):27–67
46. Holtz WG (1953) *Construction of compacted soil linings for canals*. US Department of the Interior, Bureau of Reclamation
47. Leroueil S, Bihan JP, Bouchard R (1992) Remarks on the design of clay liners used in lagoons as hydraulic barriers. *Can Geotech J* 29(3):512–515
48. Van Zyl D (1982) Design, construction and field testing of a heap leach clay pad. *Uranium Mill Tailings Manag* 16(24):521–537
49. Ayala R, Parra D, Valdivia R (2013) Design and construction review of a heap leach pad for safe operation. In: *Proceedings of the first international heap leach solutions conference*, pp 321–331
50. Daniel DE (1984) Predicting hydraulic conductivity of clay liners. *J Geotech Eng* 110(2):285–300
51. González-Delgado AM, Shukla MK, Stringam B, Parsheh M (2015) Evaluation of soil compaction and sealant application for compacted earthen liners. *GSTF J Agric Eng (JAE)* 2(1):1–11
52. Daniel DE (1985) Can clay liners work? *Civ Eng Am Soc Civ Eng* 5:48–49
53. Bouazza A, Van Impe WF (1998) Liner design for waste disposal. *Environ Geol* 35(1):41–54
54. Anderson DC (1982) Does landfill leachate make clay liners more permeable? *Civ Eng ASCE* 52(9):66–69
55. Scott AA, Husain N (1996) Review of MSW landfill liner design in Thailand. In: Kamon M, Balkema AA (eds) *Proceedings of the 2nd international conference on environmental geotechnics*, pp 441–446
56. Nayak PS, Singh BK (2007) Instrumental characterization of clay by XRD, XRF, and FTIR. *Bull Mater Sci* 30(3):235–238
57. Instituto Brasileiro de Geografia e Estatística (IBGE) (2005) *Technical handbook of pedology. Technical manuals in geosciences*, Rio de Janeiro, p 4. (in Portuguese)
58. Waste Permits Division (WPD) RG-534 (2017) *Guidance for liner construction and testing for a municipal solid waste landfill*, pp 1–42. https://www.tceq.texas.gov/assets/public/comm_exec/pubs/rg/rg-534.pdf
59. Marcos M, Pejon O (2006) Soils as compacted clay liners (CCL): raw material selection parameters. *IAEG* 61:6
60. Rowe RK, Quigley RM, Booker JR (1995) *Clayey barrier systems for waste disposal facilities*. E & FN Spon, London, p 390
61. Declan O, Paul Q (2009) *Geotechnical engineering and environmental aspects of clay liners for landfill projects*. Tech Pap 3:1–11
62. O'Sullivan D, Quigley P (2002) *Geotechnical engineering and environmental aspects of clay liners for landfill projects*. Fehily Timoney and Co. and Irish Geotechnical Services Ltd, Institution of Engineers of Ireland, p 11
63. Oeltzschner H (1992) Anforderung an Die Geologie, Hydrogeologie und Geotechnik beim Bau von Deponie (Requirement of Geology, Hydrogeology, and Geotechnics in the Construction of Landfills). In: Thorme-KozmienskyKJ (ed) *Abdichtung von Deponien und Altastten (Sealing of Landfills and Contaminated Site)*. E. F. Verlag fur Energie und Umwelt-technik GmbH (E.F. Publisher for Energy and Environmental Techniques), pp 53–82
64. Bagchi A (1994) *Design, construction, and monitoring of Landfills*, 2nd edn. Wiley, New York, p 361
65. ONORM S 2074 (1990) *Geotechnik in Deponiebau-Erdarbeiten*. Österreichisches. Normungsinstitut, Wein
66. United Kingdom Environmental Protection Agency (U.K EPA) (2009) *Earthworks in landfill engineering*, LFE 4, Bristol, UK, p 6
67. Arch J (1998) Clay barriers in landfills. In: *Environmental interactions of clays*, vol 2. Springer, Berlin, pp 207–242
68. Daniel DE, Wu YK (1993) Compacted clay liners and covers for arid sites. *J Geotech Eng* 199(2):223–237
69. Favaretti M, Cossu R (2018) Mineral liners. In: *Solid waste land-filling. Concepts, processes, technologies*. Chap 7.2. pp 289–312. <https://doi.org/10.1016/B978-0-12-407721-8.00016-4>
70. Qian X, Koerner RM, Gray DH (2002) *Geotechnical aspects of landfill design and construction*. Prentice Hall, New Jersey, p 717
71. Mitchell JK, Jaber M (1990) Factors controlling the long-term properties of clay liners. In: Bonaparte R (ed) *Waste containment systems: construction, regulation, and performance*. Geotechnical special publication No. 26, in Proc. ASCE, San Francisco, California, pp 84–105
72. Bagchi A (1990) *Design, construction, and monitoring of sanitary landfill*. Wiley, New Jersey
73. Daniel DE, Koerner RM (1995) *Waste containment facilities. Guidance for construction, quality assurance and quality control of liner and cover systems*. American Society of Civil Engineers, New York, p 384
74. Kayadelen C (2008) The consolidation characteristics of an unsaturated compacted soil. *Environ Geol* 54(2):325
75. United States Environmental Protection Agency (USEPA) (1982) *Hazardous waste management systems: permitting requirements for land disposal facilities*, p 126
76. Benson C, Zhai H, Wang X (1994) Estimating the hydraulic conductivity of compacted clay liners. *J Geotech Eng* 120(2):366–387
77. Ministry of Housing and Local Government, Malaysia (MHLGM) (2004) *The study on save closure and rehabilitation of landfill sites in Malaysia*. Final Rep 5:222

78. Munie J (2003) A study of the merits and effectiveness of alternate liner systems at Illinois landfills. Springfield, Illinois Environmental Protection Agency, p 46
79. Ash JS (2008) Geotechnical considerations at landfill site. Jagger. Hims Ltd, Newmarket, p 27
80. Mark Y (2002) Geology and geotechnical investigation of the proposed anterbury regional landfill Kate valley. North Canterbury Transwaste Canterbury Ltd, North Canterbury, p 147
81. Journal of Laws item 523 (2013) Regulation of the minister of environment of 30 April 2013 about landfilling of wastes. Poland's Journal of Laws, (In Polish) Sejm of the Republic of Poland, Warsaw, Poland
82. Seymour KJ, Peacock AJ (1994) Quality control of clay liners. In: Christensen TH, Cossu R, Stegmann R (eds) Landfilling of waste barriers. E and EF Spon Publisher, London, pp 69–79
83. Farquhar GJ (1994) Experiences with liners using natural materials. In: Christensen TH (ed) Landfilling of wastes: barrier. E and FN Spoon, London, pp 37–53
84. Vaverkova MD, Adamcova D, Radziemska M, Voběrková S, Mazur Z, Zloch J (2018) Assessment and evaluation of heavy metals removal from landfill leachate by *Pleurotus ostreatus*. Waste Biomass Valorization 9(3):503–511
85. Owusu-Nimo F, Oduro-Kwarteng S, Essandoh H, Wayo F, Shamudeen M (2019) Characteristics and management of landfill solid waste in Kumasi, Ghana. Sci Afr 3(e00052):1–9. <https://doi.org/10.1016/j.sciaf.2019.e00052>
86. Musso TB, Roehl KE, Pettinari G, Vallés JM (2010) Assessment of smectite-rich claystones from Northpatagonia for their use as liner materials in landfills. Appl Clay Sci 48(3):438–445
87. Oyediran IA, Iroegbuchi CD (2013) Geotechnical characteristics of some Southwestern Nigerian clays as barrier soils. IFE J Sci 15(1):17–30
88. Rahman Z, Yacob WZW, Rahim SA, Lihan T, Idris WMR, Sani WM (2013) Geotechnical characterisation of marine clay as potential liner material. Sains Malays 42(8):1081–1089
89. Yamusa YB, Ahmad K, Rahman NA (2017) Sustainable design of compacted laterite soil liner. In: Global civil engineering conference. Springer, Singapore, pp 1211–1222
90. Bonaparte R, Giroud JP, Gross BA (1989) Rates of leakage through landfill liners. Proc Geosynth 89:18–29
91. Brown KW, Thomas JC, Lytton RL, Jayawickrama P, Bhart S (1987) Quantification of leakage rates through holes in landfill liners. United States Environmental Protection Agency Report CR810940, Cincinnati, OH, p 147
92. Giroud JP, Khatami A, Badu-Tweneboah K (1989) Evaluation of the rate of leakage through composite liners. Geotext Geomembr 8(4):337–340
93. Jayawickrama PW, Brown KW, Thomas JC, Lytton RL (1988) Leakage rates through flaws in membrane liners. J Environ Eng 114(6):1401–1420
94. Lottermoser B (2007) Mine wastes: characterization. Treatment and environmental impacts. Springer, Berlin
95. Kossoff D, Dubbin WE, Alfredsson M, Edwards SJ, Macklin MG, Hudson-Edwards KA (2014) Mine tailings dams: characteristics, failure, environmental impacts, and remediation. Appl Geochem 51:229–245
96. Touze-Foltz N, Lupo J, Barroso M (2008) Geoenvironmental applications of geosynthetics. Keynote Lecture, Proceedings EuroGeo4, pp 1–98
97. Martin TE, Davies MP (2000) Trends in the stewardship of tailings dams. Tailings and mine waste. In: Proceedings of the 7th international conference, Vail, Co. Colorado State University, pp 393–407
98. Kashir M, Yanful EK (2000) Compatibility of slurry wall backfill soils with acid mine drainage. Adv Environ Res 4(3):251–268
99. Boscov MEG, Cunha II, Saito RT (2001) Radium migration through clay liners at waste disposal sites. Sci Total Environ 266(1–3):259–264
100. Agbenyeku EOE, Muzenda E, Msibi MI (2016) Chemical alterations in three clayey soils from percolation and interaction with acid mine drainage (AMD). S Afr J Chem Eng 21:28–36
101. Robbins T, Chittoori B (2017) Geotechnical evaluations of a tailings dam for use by a Molybdenum and copper mine project in Southern Idaho. In: Association of State Dam Safety Officials Annual Conference, pp 1–13. <https://damsafety.org/sites/default/files/files/Geotechnical%20Evaluations%20of%20a%20Tailings%20Dam%20-TRobbins.pdf>
102. Jubran BA, El-Baz AR, Hahmdan MA, Badran AA (1996) Experimental investigation of local clays and clay schemes as liners for solar ponds. Int J Energy Res 20(7):637–642
103. French RL, Johnson DH, Jones GF, Zangrando F (1984) Salt-gradient solar ponds. Summary of US Department of Energy Sponsored Research. DOE/SF/11592-2
104. Fynn RP, Short TH (1983) Solar ponds. A basic manual, vol 106. The Ohio State University Special Circular, Wooster, p 12
105. Hull JR, Nielsen CE (1986) Solar ponds. In: Sodha MS, Mathur SS (eds) Reviews of renewable energy resources, chap 5, vol 3. Wiley Eastern, New Delhi
106. Silva G, Almanza R (2009) Use of clays as liners in solar ponds. Sol Energy 83(6):905–919
107. Almanza R, Martinez A, Segura G (1989) Study of a kaolinite clay as a liner for solar ponds. Sol Energy 42(5):395–403
108. Raman P, Kishore VN (1990) An alternative lining scheme for solar ponds—results of a liner test rig. Sol Energy 45(4):193–199
109. Almanza R, Lozano MC (1990) Mechanical and thermal tests of a bentonite clay for use as a liner for solar ponds. Sol Energy 45(4):241–245
110. Almanza R, Castaneda R (1993) What type of clays can be used as liners for NaCl solar ponds? Sol Energy 51(4):293–297
111. McCarthy DF (1993) Essentials of soil mechanics: basic geotechnics, 7th edn. Englewood cliffs, New Jersey, p 837
112. Brand EW, Philipson HB (1985) Review of international practice for the sampling and testing of residual soils. Sampling and testing of residual soils. In: Brand EW, Philipson HB (ed) International society for soil mechanics and foundation engineering, Scorpion press, Hong Kong, pp 7–21
113. Blight GE (1982) Residual soils in South Africa. In: Engineering and construction in tropical and residual soils. ASCE, pp 147–171
114. Sowers GF (1985) Residual soils in the United States. In: Brand EW, Phillipson HB (eds) Sampling and testing of residual soils: a review of international practices. Scorpion Press, Hong Kong, pp 324–339
115. Public Works Institute Malaysia (1996) Tropical weathered in situ materials. GEOGUIDES, pp 1–5
116. Harianto R, Alfrendo S, Eng-Choon L, Yew SN, Henry TCP (2012) Variability of residual soil properties. Eng Geol 141–142:124–140
117. Bee RJ (1948) Some notes on laterite—a soil of engineering importance in the tropics. In: Conference on civil engineering problems in the colonies. Thomas Telford Publishing, pp 191–208
118. Little AL (1969) The engineering classification of residual tropical soils. Soil Mech Found Eng Conf Proc/Mexico/ 1:1–10
119. Ranganathan BV (1961) Soil structure and consolidation characteristics of black cotton clay. Geotechnique 11(4):333–338
120. Wesley LD (2009) Behaviour and geotechnical properties of residual soils and allophane clays. Obras y Proyectos 6:5–10
121. BS 1377 (1990) Methods of testing soils for civil engineering purposes. British Standards Institution, London

122. Head KH, Epps R (1980) Manual of soil laboratory testing, vol 1, no 2. Pentech Press, London, p 499
123. Oriola FOP, Moses G (2011) Compacted black cotton soil treated with cement kiln dust as hydraulic barrier material. *Am J Sci Ind Res* 2(4):521–530
124. Ola SA (1978) The geology and geotechnical properties of the black cotton soils of Northeastern Nigeria. *Eng Geol* 12:375–391
125. Amadi AA (2014) Enhancing durability of quarry fines modified black cotton soil subgrade with cement kiln dust stabilization. *Transp Geotech* 1(1):55–61
126. Osinubi KJ, Oyelakin MA, Eberemu AO (2011) Improvement of black cotton soil with ordinary portland cement—locust bean waste ash blend. *Electron J Geotech Eng* 16:619–627
127. Ingles OG, Metcalf JB (1972) Soil stabilization principles and practice. Butterworth, Sydney, p 374
128. Bucher F, Sailie E (1984) Swelling behaviour of tropical black clays. In: Regional conference for Africa, vol 8, pp 81–86
129. Sivapullaiah PV, Reddy PHP (2010) Potassium chloride treatment to control alkali induced heave in black cotton soil. *Geotech Geol Eng* 28(1):27–36
130. Bose B (2012) Geo-engineering properties of expansive soil stabilized with fly ash. *Electron J Geotech Eng* 17:1339–1353
131. Muthyalu PV, Ramu K, Raju GP (2012) Study on performance of chemically stabilized expansive soil. *Int J Adv Eng Technol* 2(1):139–148
132. Gidigasur SSR (2012) Pedology and geomechanics of problematic soils—a case study of black cotton soils from the Accra Plains of Ghana. M.Phil. Thesis, Department of Geological Engineering, KNUST, Kumasi- Ghana, p 104
133. Van Der Merwe DH (1964) The weathering of some basic igneous rocks and their engineering properties. *Civ Eng* 27(2):213–222
134. Wanigarathna D, Kurukulasuriya C, Hamamoto S, Kawamoto K (2013) Locally available expansive soils as a liner material for municipal landfills. In: Proceedings, of the 2nd international conference on sustainable built environment, special session on water and waste management, SBE/12/231. Kandy, Sri Lanka
135. Ismaiel HA (2013) Cement kiln dust chemical stabilization of expansive soil exposed at El-Kawther Quarter, Sohag region, Egypt. *Int J Geosci* 4(10):1416–1424
136. Ismaiel HA, Badry MM (2013) Lime chemical stabilization of expansive deposits exposed at El-Kawther Quarter, Sohag region, Egypt. *Geosciences* 3(3):89–98
137. Mohamedi A, Khemissa M (2015) Stabilization of an expansive over-consolidated clay using hydraulic binders. *HBRC J* 11(1):82–90
138. Mutaz E, Shamrani M, Puppala A, Dafalla M (2011) Evaluation of chemical stabilization of a highly expansive clayey soil. *Transp Res Record J Transp Res Board* 2204:148–157
139. United States Agency for International Development (USAID)/Building and Road Research Institute (BRRI) (1971) Laterite and lateritic soils and other problem soils of Africa, vol 2164. An Engineering Study Report, AID/CSD, p 290
140. Mgangira MB, Paige-Green P (2008b) Premature distress of a pavement on expansive black cotton soil in the Horn of Africa: problem soils in South Africa conference, Midrand, Gauteng, South Africa, p 7
141. Abadjieva T (2001) Chemical stabilization for low cost roads in Botswana. In: First road transportation technology transfer conference in Africa, pp 364–369
142. Omoniyi IO, Olufemi O, Abdulwahid KA (2014) Geotechnical and mineralogical evaluation of some lateritic soils from Southwestern Nigeria. *Electron J Geotech Eng* 19:301–312
143. Osinubi KJ, Nwaiwu CM (2006) Design of compacted lateritic soil liners and covers. *J Geotech Geoenviron Eng* 132(2):203–213
144. Adeoye GO, Ogunsanwo O, Ige OO (2013) Geotechnical evaluation of some soils from part of southwester Nigeria sable as Liners in waste disposal landfills. *J Civ Environ Sci* 3(7):107–114
145. Tuncer ER, Lohnes RA (1977) An engineering classification for certain basalt—derived lateritic soils. *Eng Geol* 11(4):319–339
146. Zelalem A (2005) Basic engineering properties of lateritic soils found in Nejo-Mendi road construction area, Welega. M.Sc. Thesis, Department of Civil Engineering, Addis Ababa University (AAU), Ethiopia, p 97
147. Lohnes RA, Demirel T (1973) Strength and structure of laterites and lateritic soils. *Eng Geol* 7(1):13–33
148. Onana VL, Ze ANO, Eko RM, Ntoulala RFD, Bineli MN, Owoudou BN, Ekodeck GE (2017) Geological identification, geotechnical and mechanical characterization of charnockite-derived lateritic gravels from Southern Cameroon for road construction purposes. *Transp Geotech* 10:35–46
149. Gawu SKY, Gidigasur SSR (2013) The effect of spent carbide on the geotechnical characteristics of two lateritic soils from the Kumasi area. *Int J Eng Res Technol* 6(3):311–321
150. Attoh-Okine B (1990) Stabilising effect of locally produced lime on selected lateritic soils. *Constr Build Mater* 4(2):86–91
151. Latifi N, Marto A, Eisazadeh A (2016) Physicochemical behavior of tropical laterite soil stabilized with non-traditional additive. *Acta Geotech* 11(2):433–443
152. Nik NSN, Mazidah M (2016) The effect of geopolymer to the compaction parameter of laterite soil. *Middle-east J Sci Res* 24(5):1588–1593
153. Indraratna B, Nulalaya P (1991) Some engineering characteristics of a compacted lateritic residual soil. *Geotech Geol Eng* 9(2):125–137
154. Sunil BM, Nayak S, Shrihari S (2006) Effect of pH on the geotechnical properties of laterite. *Eng Geol* 85(1–2):197–203
155. Sree D, Ajitha AR, Evangeline YS (2010) Study on amended soil liner using lateritic soil. In: Indian geotechnical conference. Geotrendz, IGS Mumbai Chapter & IIT Bombay, pp 381–384
156. Kavya MP, Anjana TR (2016) Effect of bentonite on hydraulic conductivity of compacted soil liners. *Int J Adv Res Trends Eng Technol* 3(23):74–77
157. Fall M, Sawangsuriya A, Benson CH, Edil TB, Bosscher PJ (2008) On the investigations of resilient modulus of residual tropical gravel lateritic soils from Senegal (West Africa). *Geotech Geol Eng* 26(1):13–35
158. Sandra GG, Jorge ESS, Maria EGB (2014) Heavy metal diffusion and retention in a mineral barrier of compacted lateritic soil. *Revista Brasileira de Geologia de Engenharia e Ambiental* 4(2):9–22
159. Portelinha FHM, Lima DC, Fontes MDF, Carvalho CAB (2012) Modification of a lateritic soil with lime and cement: an economical alternative for flexible pavement layers. *Soils Rocks* 35(1):51–63
160. Elarabi H, Taha M, Elkhawad T (2013) Some geological and geotechnical properties of lateritic soils from Muglad Basin located in the South-Western Part of Sudan. *Res J Environ Earth Sci* 5(6):291–294
161. Bohi ZHB (2008) Caractérisation des sols Latéritiques Utilisés en Construction Routière. Cas de la Région de l'Agnéby (Côte d'Ivoire). Thèse de Doctorat, École Nationale des Ponts et Chaussées, Paris, p 142
162. Millogo Y, Traore K, Ouedraogo R, Kabore K, Blanchart P, Thomassin JH (2008) Geotechnical, mechanical, chemical and mineralogical characterization of a lateritic gravels of Sapouy (Burkina Faso) used in road construction. *Constr Build Mater* 22(2):70–76

163. Remillon A (1955) Stabilization of laterite soils. Highw Res Board Bull 108:96–101
164. Meireles JMF (1967) Trial pavements of laterite base course. In: Proceedings of the 4th regional conference in Soil Mech & Fdn Eng Proc/South Africa
165. Brunner DR, Keller DJ (1972) Sanitary landfill design and operation. EPA report, SW—45, Washington, p 59
166. EPA (1990) Compilation of information on alternative barriers for liner and cover systems. EPA600-R-91-002. Prepared by Daniel, D.E. and Estornell, P.M. for office of research and development, Washington, DC
167. Skempton AW (1953) The colloidal activity of clay. In: Selected papers on soil mechanics, pp 106–118
168. Taha MR, Kabir MH (2005) Tropical residual soil as compacted soil liners. Environ Geol 47(3):375–381
169. Oweis IS, Khera RP (1998) Geotechnology of waste management, 2nd edn. PWS Publishing Company, New York, p 472
170. Acar Y, Oliveri L (1989) Pore fluid effects on the fabric and hydraulic conductivity of laboratory-compacted clay. Transp Res Rec 12(19):144–159
171. Benson CH, Daniel DE (1990) Influence of clods on hydraulic conductivity of compacted clay. J Geotech Eng 116(8):1231–1248
172. Garcia-Bengochea I, Altschaeffl AG, Lovell CW (1979) Relation between pore distribution and permeability of silty clays. J Geotech Eng 105(7):839–856
173. Mitchell JK, Hooper DR, Campanella RG (1965) Permeability of compacted clay. J Soil Mech Found Div 91(4):41–66
174. Fred L, Anne J (2005) Flawed technology of subtitle D Landfilling of municipal solid waste. Report of G. Fred Lee & Associates, El Macero, CA, pp 1–80. https://www.researchgate.net/profile/G_Lee3/publication/252379853_Flawed_Technology_of_Subtitle_D_Landfilling_of_Municipal_Solid_Waste/links/0f317535ef51794c88000000.pdf
175. Wagner JF (2013) Clay liners and waste disposal. Dev Clay Sci 5:663–676
176. Emmanuel E, Lau CC, Anggraini V, Pasbakhsh P (2019) Stabilization of a soft marine clay using halloysite nanotubes: a multi-scale approach. Appl Clay Sci 173:65–78

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.