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THE ACCEPTABLE COMPACTION ZONE CRITERIA BASED ON HYDRAULIC CONDUCTIVITY FOR A COMPACTED MIXTURE OF RESIDUAL SOIL WITH BENTONITE AS A SOIL LINER

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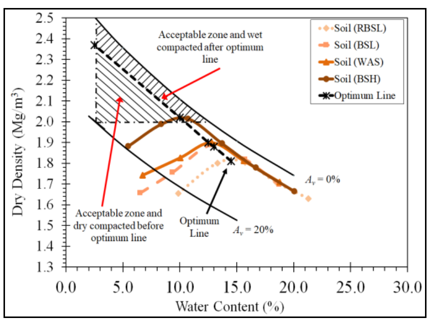
Graphical abstract



Abstract

The significant criteria for compacted clay liner in landfill construction are the compaction characteristics and hydraulic conductivity value. The primary parameter for designing an efficient soil liner is ensuring a hydraulic conductivity value below 1x10^{-9} m/s to prevent contaminated seepage into the aquifer. Therefore, the compaction criteria are crucial in controlling the construction of hydraulic barriers for liners. In this study, laboratory testing such as permeability tests at varying compaction energies, were carried out on a blend of residual soil and bentonite. The aim was to establish an acceptable compaction zone based on the allowable hydraulic conductivity value and to outline suitable design considerations for compacted residual soil mixed with bentonite as a soil liner. The design parameters investigated included hydraulic conductivity at different compaction efforts. A comparison was made between traditional, common, and modern approaches to ensure construction quality assurance for compacted soil liners mixed with bentonite. The results indicated that all methods, traditional, common, and modern, successfully met the design objectives for hydraulic conductivity, creating acceptable compaction zones on the compaction plane curve. These acceptable zones for the mixture of residual soil with bentonite align with the lower bound limit of the compaction optimum line, with the shapes of the shaded zones influenced by the soil's moisture content and compaction characteristics.

Keywords: Residual soil, bentonite, compaction, hydraulic conductivity, acceptance zone

Abstrak

Kriteria penting untuk lapisan tanah liat yang dipadatkan dalam pembinaan tapak pelupusan adalah ciri pemadatan dan nilai keupayaan hidraulik. Parameter utama untuk merekabentuk lapisan pelapik tanah yang cekap ialah memastikan nilai keupayaan hidraulik di bawah 1x10^{-9} m/s untuk mencegah resapan bahan enap tercemar ke dalam akuifer. Oleh itu, kriteria pemadatan adalah penting dalam mengawal pembinaan pelapik penghalang hidraulik lapisan tanah. Dalam kajian ini, ujian makmal seperti ujian kebolehaliran hidraulik pada tenaga pemadatan yang berbeza telah dilakukan pada campuran tanah baki bercampur dengan bentonit. Tujuannya adalah untuk menetapkan zon pemadatan yang boleh diterima berdasarkan nilai keupayaan hidraulik yang dibenarkan dan menggariskan pertimbangan reka bentuk yang sesuai untuk tanah baki yang dipadatkan bercampur dengan bentonit sebagai pelapik lapisan tanah. Parameter reka bentuk yang disiasat termasuk keupayaan hidraulik pada setiap usaha pemadatan yang berbeza. Perbandingan telah dibuat antara pendekatan tradisional, biasa, dan moden untuk memastikan jaminan kualiti pembinaan untuk pelapik lapisan tanah yang dipadatkan bercampur dengan bentonit. Hasil kajian telah menunjukkan bahawa semua kaedah, tradisional, biasa, dan moden, berjaya mencapai objektif reka bentuk untuk keupayaan hidraulik dengan tercipta zon pemadatan yang diterima pada satah lengkung pemadatan. Zon-zon yang diterima untuk campuran tanah baki dengan bentonit memadankan dengan had sempadan bawah garis optimum pemadatan, dengan bentuk zon-zon berbayang dipengaruhi oleh kandungan kelembapan tanah dan ciri-ciri pemadatan.

Kata kunci: Tanah baki, bentonit, pemadatan, kadar keberaliran hidraulik, zon penerimaan

1.0 INTRODUCTION

Typically, a compacted liner is employed as a soil liner layer in landfill areas to prevent groundwater contamination. The main factor affecting the performance of soil liner is the compaction effort as a main key in determining the hydraulic conductivity value [1]. Thus, the good compaction properties encourage the use of local materials such as residual soil as compacted clay liner (CCL) for economic use [2], [3].

Due to the inorganic clays or clay soils having low hydraulic conductivity value, it is widely used as the liners during the landfill construction. However, the main problem for residual soils in tropical climatic areas is not suitable for application as compacted clay liners due to the varies in characteristics and properties. Therefore, bentonite was used to be mixed with local soil if natural clay or clayey soils are not available. Bentonite is a versatile material for geotechnical engineering as well as their demand for different industrial applications because of the special properties [4][5]. Bentonite defined as a naturally occurring material that is composed predominantly of the clay mineral such as montmorillonite and widely used admixture for barrier layer in landfill due to their chemical durability and their performance as a long-term barrier layer. Bentonite has been previously proposed for use as sealing and buffer elements for a landfill due to the bentonite characteristics such as fine particle sizes, micro-pores, and high specific surface charges, has a large specific surface area, excellent plasticity index, possesses low hydraulic conductivity, and high adsorption capacity. The use of bentonite is widespread in industry and especially in civil engineering activities that required action as an absorbent material, hydraulic barrier, and sealant [6], [7], [8], [9].

For design purposes and construction quality assurance, hydraulic conductivity is a main criterion parameter testing for soil liner [9][10]. Therefore, compaction control plays an important role in the construction of soil liners to control hydraulic conductivity. There are two compaction principles that contribute to good quality control for soil liner was outlined by Benson & Boutwell (1992) which is common and modern compaction criteria [11]. The primary requirements for compaction for achieving the optimal moisture content and maximum dry unit weight, which varies based on the compaction efforts. In other cases, the optimal line is used as compaction control [11], [12], [13].

A critical aspect of quality control in soil liner construction, serving as a hydraulic barrier, is the compaction criterion. This criterion is essential to guarantee that compacted liners are well-constructed and function as intended. Therefore, emphasis on material specifications and methods of construction practices is essential during the design stage to ensure the effective quality for soil liner. A critical step in designing a soil liner is to estimate the optimum moisture content (OMC) and maximum dry density (MDD) of the appropriate soil liner and this determination is based on an acceptable range based on the compaction effort and named as an acceptable zone [14], [15], [16], [17]. Hence, the hydraulic conductivity value is regarded as the primary parameter to be considered in the design phase, as it is crucial to achieve the desired performance of the soil liner.

Quality control for soil liners during construction is generally based on some compaction criteria such as common criteria and modern criteria [11]. Meanwhile, for construction quality assurance, Daniel and Benson (1990) have described a modern criteria procedure to revise the common compaction control criteria through the traditional approach [1], [3], [12].

Meanwhile, Hermann & Elsbury (1987), Daniel & Benson (1990) and Benson & Boutwell (1992) stated the acceptance zone for the traditional approach by shaded position on the compaction planes was developed and established by [18], [12], [1]. For the traditional criteria, the acceptable zone was achieved at a water content between 0% - 4% from the MDD weight. While the lower bound limits correspond to 95% of the standard compaction and 90% of the modified compaction. Benson and Boutwell (1992) stated that common criterion is restricted and permits combinations of water content and dry unit weight that fall on the dry side of the optimums line and this condition dependent to the site condition compared to laboratory result hydraulic conductivities [11]. Meanwhile, the acceptance zone for modern criteria is on the compaction plane to the left of the said acceptance zone corresponding roughly to the contour of the constant degree of saturation and the minimum dry unit weight required to ensure adequate shear strength. Daniel and Benson (1990) suggested for modern criterion, the use of specified degree of saturation or the optimum line was used to define the lower moisture content bound of the acceptable zone [12]. Hence, the modern criteria aim to eliminate any potential issues by ensuring that the leftmost acceptable zone borderline does not include compaction on the dry side of the optimum line. Thus, the left side limit can be determined using the contour degree of saturation, S_r exceeds the degree of saturation at optimum, S_{ro}.

Therefore, the objective of the study outlined in the paper is to present the findings related to the acceptance compaction zone, focusing on the allowable hydraulic conductivity value for residual soil mixed with bentonite used as compacted soil liners. Through a series of laboratory tests, the study aimed to ascertain the hydraulic conductivity values under various compaction energies and effective stresses for the residual soil and bentonite mixture. The permeability tests were conducted on soil samples mixed with bentonite, compacted at the Optimum Moisture Content (OMC) for each compaction effort. These laboratory results were then utilized to define the acceptable zone based on the compaction boundaries concerning the allowable hydraulic conductivity value.

2.0 METHODOLOGY

Grade IV sedimentary residual soil was collected at Salak Tinggi, Selangor, Malaysia in a disturbed samples at an estimated depth between of 2.0 m from the ground surface to prevent soil mixed with plant roots and humus layers. Khalid *et al*. (2019) stated most of the surrounding location in Salak Tinggi area were locally prominent covered for its limestone and sandstone [19] and this is due to the formation area deposited during the Late Devonian to early Carboniferous with formations including phyllite, schist, and slate.

The sodium bentonite gray powder used in this study as the main additive is categorized as a smectic clay that contains high clay minerals namely montmorillonite. A low hydraulic conductivity characteristic of bentonite due to having a large specific surface area, excellent plasticity value, with a large specific surface area and capability of swelling during apprehension of water [20][21]. Bentonite is classified as a light material due to its low density. It has a strong alkaline material due to its high value of pH 9.6 and has extremely high value of plasticity index [21].

A mixture of soil and bentonite was mixed thoroughly and prepared using mixer before compaction testing and permeability testing were carried out. Three different mixtures samples were prepared based on the different percentages of bentonite such as 5%, 10% and 15%. The permeability mixtures samples were prepared at Optimum Moisture Content (OMC) value and were compacted according to the compaction types that were identified in this study.

Compaction tests at different energies were conducted to determine the OMC and Maximum Dry Density (MDD) for mixed soil samples. Four different compactions with different energies (E) such as Reduced British Standard Light (RBSL) with energies 336.6 kNm/m^3, British Standard Light (BSL) with energies 605.9 kNm/m^3, West African Standard (WAS) with energies 1008.7 kNm/m^3 and British Standard Heavy (BSH) with energies 2723.5 kNm/m^3 were conducted in this study as shown Table 1. The range series of compaction energies was selected as the reasonable compaction effort encountered in the field of construction. The BSH and BSL compactions efforts are equivalent to the modified proctor and standard proctor compactions respectively that stated in BS1377: Part 4:1990 [22]. Daniel and Wu (1993) stated that RBSL was the same as BSL except that only used 15 blows of the hammer were applied rather than the usual 27 blows [23]. Meanwhile, the West African Standard (WAS) classified as intermediate compaction effort and this typical energy level frequently used in the field construction [24][25]. Each procedure suggested by previous studies showed different methods of compaction efforts produced the different compaction energies.

Table 1 Compactions efforts [21][23][25]

Compaction Efforts	Hammer Weight (kg)	Drop Height (m)	No. of layer	No. of blows
RBSL	2.5	0.3048	3	15
BSL	2.5	0.3048	3	27
WAS	4.5	0.457	5	10
BSH	4.5	0.457	5	27

Table 2 shows the summarized compaction result at four different energies at each sample. It shows that the use of bentonite mixtures with different percentages has affected the values of MDD and OMC. In addition, the use of higher compaction energy resulted in higher MDD values and lower OMC values. [26].

Table 2 The results for MDD value and OMC value at different compaction types

Samples	Compaction Efforts	OMC (%)	MDD (Mg/m^3)
0B	RBSL	14.50	1.82
	BSL	13.50	1.88
	WAS	12.50	1.90
	BSH	10.00	2.02
5B	RBSL	16.50	1.76
	BSL	14.00	1.86
	WAS	13.00	1.91
	BSH	11.00	2.00
10B	RBSL	18.50	1.67
	BSL	15.00	1.78
	WAS	14.00	1.85
	BSH	12.50	1.93
15B	RBSL	19.00	1.58
	BSL	15.00	1.74
	WAS	15.50	1.78
	BSH	11.50	1.97

The permeability testing for hydraulic conductivity value determination was conducted based on the falling head conditions using a triaxial permeability cell machine as shown in Figure 1 recommended by Head (1994) [27]. The testing was operated on the cylindrical soil specimen at 70mm in diameter and 35 mm in height, accordance with standard in BS 1377: Part 6: 1990. Triaxial permeability testing methods are suitable for all types of specimens including undisturbed, remolded and compacted samples that have a hydraulic conductivity value less than 1×10^{-6} m/s [22], [27].

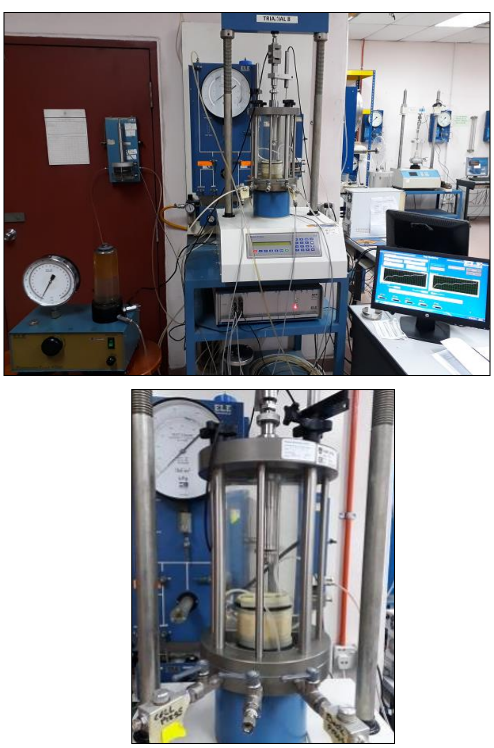


Figure 1 Triaxial machine used for permeability testing to obtain hydraulic conductivity values

The value of hydraulic conductivity was determined from the volume of water passing through in the soil specimen at a known time and at constant hydraulic gradient. The device provides a facility to maintain a water flow through a sample under a known difference pressure and to measure the water flow rate while the sample was subjected to known effective stress. The confining pressures (σ_3') at 100 kPa, 200 kPa, and 300 kPa was applied during permeability testing and this confining pressure is estimated to be encountered on liners from municipal solid waste landfills [28]. The permeability testing was repeated after the consolidation process was achieved at different effective stress values on the same sample without having to remove it.

3.0 RESULTS AND DISCUSSION

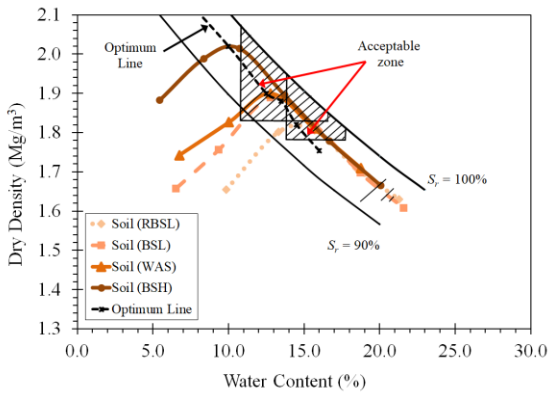
Table 3 shows the summarized result of an average hydraulic conductivity value mixture for soil with bentonite at different compaction energy and confining effective stress. It shows, the range result for hydraulic conductivity varies depending on the compaction energies used and on the confining effective stress applied.

Table 3 The hydraulic conductivity values at different compaction effort at different confining effective pressure

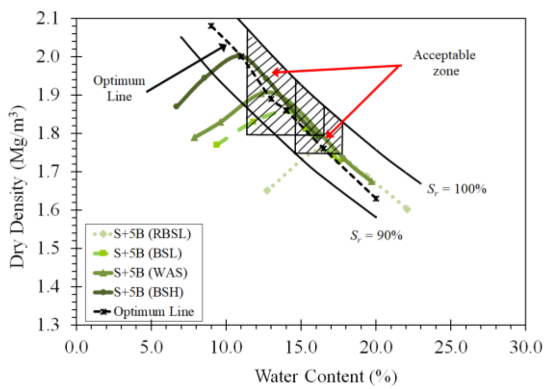
Compaction efforts	Sample	Hydraulic Conductivity value (m/s) at different confining pressure		
		σ' (100 kPa)	σ' (200 kPa)	σ' (300 kPa)
RBSL	0B	6.48E-08	2.16E-08	1.20E-08
	5B	2.14E-09	3.56E-10	8.65E-11
	10B	2.13E-10	5.91E-11	2.94E-11
	15B	1.27E-10	2.06E-11	1.63E-11
BSL	0B	3.48E-08	1.60E-08	8.31E-09
	5B	1.48E-09	3.96E-10	2.36E-10
	10B	1.35E-10	3.61E-11	1.82E-11
	15B	4.52E-11	1.40E-11	7.42E-12
WAS	0B	1.27E-08	6.01E-09	2.33E-09
	5B	3.40E-11	8.63E-11	3.13E-11
	10B	1.30E-10	3.87E-11	1.65E-11
	15B	6.90E-11	3.03E-11	1.07E-11
BSH	0B	2.40E-09	8.99E-10	4.33E-10
	5B	6.45E-10	9.96E-11	4.03E-11
	10B	1.52E-10	2.97E-11	1.46E-11
	15B	4.27E-11	1.83E-11	1.09E-11

The Acceptance Zone Using Traditional Criterion

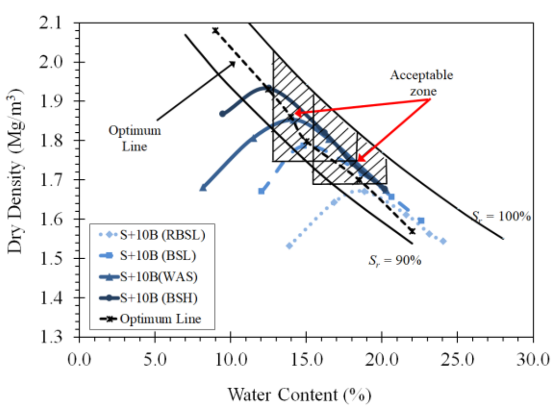
The result for acceptable zone based on traditional method for a mixture of soil with bentonite illustrated in Figure 2. The shaded area was based on the lower hydraulic conductivity value result from the BSL and BSH compaction [11], [12]. Soils compacted at wet condition (at OMC condition) was resulted in lower hydraulic conductivity compared to the soil compacted at dry condition that was resulted in higher hydraulic conductivity value. The results show a major shaded of acceptance zone occurred for mixture of soil with bentonite in between 100% and 90% at saturation line respectively. However, the acceptance zone fell further below the 90% saturation line after the soil had been mixed with 15% bentonite and this happened due to the increment of fine granule from bentonite mixture. It shows that, the shaded area for acceptance based on traditional approach meets the criteria for the allowable hydraulic conductivity value. From the graphs, the acceptance zone shaded areas was bigger with the increment of bentonite percentage use and it indicates the hydraulic conductivity value reduces with the increase with the percentage of bentonite content [11], [12], [29], [30].



(a)



(b)



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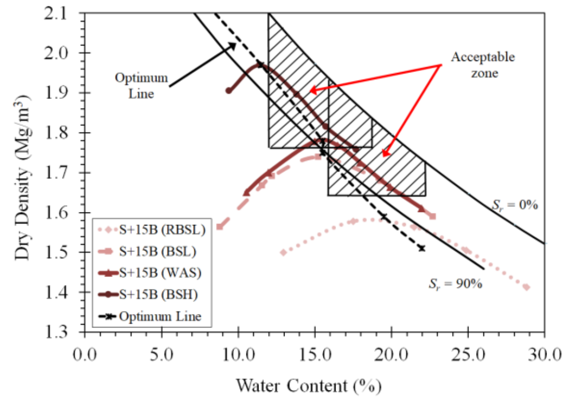


(d)

Figure 2 Acceptance zone based on traditional criterion for (a) Soil only (b) Soil+5B (c) Soil+10B and (d) Soil+15B

The Acceptance Zone Using Common Criterion

The acceptance zone using common criterion for a mixture of soil with bentonite at different compaction energies shown in Figure 3. It shows the shaded area was divided into dry side and wet side for before and after OMC, respectively. Therefore, the compacted soil in the shadowed zone has an allowable hydraulic conductivity, $k \leq 1 \times 10^{-9}$ m/s. The results show, the soil without the addition of bentonite and compacted using heavy compaction (BSH) was given a lower hydraulic conductivity value with a small shading area for wet and dry compression zones. Clearly shown in Figure 3 the improvement with hydraulic conductivity value after addition of bentonite. It shows from the Figure 3, a mixture of soil with bentonite has a larger shaded zone area for dry and wet side for all compaction energies especially for soil mixed with 5% and 10% bentonite. However, soil mixed with 10% bentonite shows the majority shaded area only at wet compacted area for RBSL, BSL and WAS plus small wet compacted area for BSH compaction. This represents, the allowable hydraulic conductivity value at all compaction energy was in the shaded zone and the increase in compaction energies were giving a low hydraulic value and the accepted hydraulic conductivity value occurs in the dry, optimal and wet OMC shaded zones [5], [11], [30], [31].

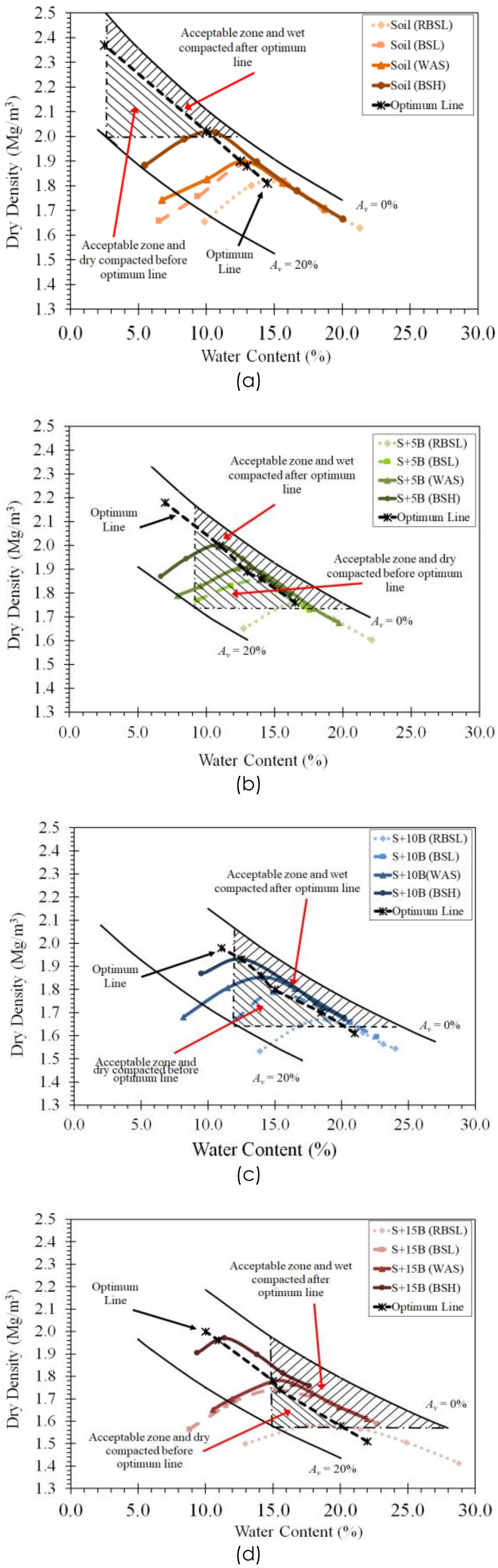
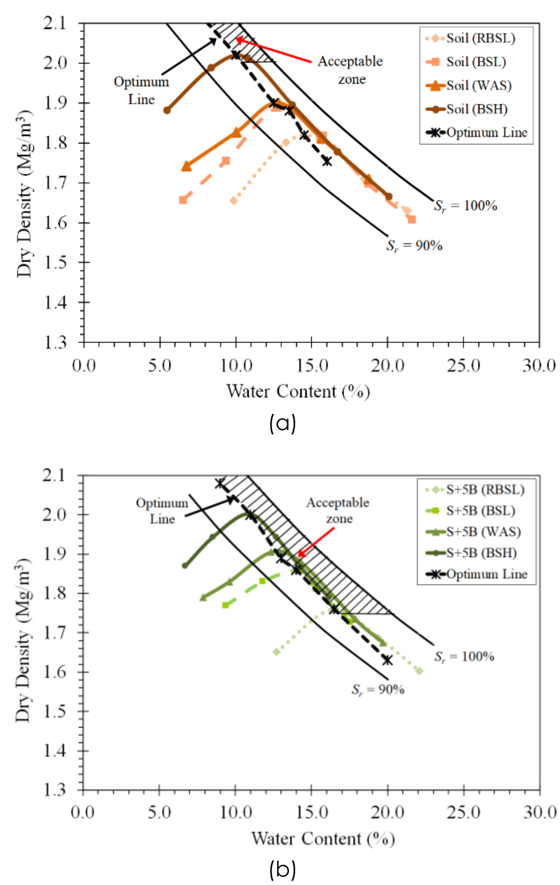


Figure 3 Acceptance zone based on common criterion for (a) Soil only (b) Soil+5B (c) Soil+10B and (d) Soil+15B

The Acceptance Zone Using Modern Criterion

The result for acceptable zone based on the modern method for a mixture of soil with bentonite was produced a sufficiently low hydraulic conductivity value shown in Figure 4. The acceptance zone on lower boundaries corresponding to the optimum lines caused by the lower hydraulic conductivity based on the water content and dry density for modern criterion [12], [30], [31]. However, a mixture of soil samples with 5% and 10% bentonites compacted at RBSL, BSL, WAS and BSH exhibits the lower boundaries falling above the 90% saturation line. Except for soil samples with 15% bentonite and compacted at RBSL and BSL has shown the limit bound located below the 90% saturations line. Therefore, its demonstrations the acceptance zone for modern criterion positioned above the 90% saturation line is allowed for soil liner construction mixed with 5%, 10% and 15% bentonite at all compaction energies excepting for a mixture of soil with 15% bentonite compacted at RBSL and BSL compaction.

The results indicate a low conductivity value depending on the position of the wet soil line at OMC which produces a compacted soil with a very small pore size and relatively identical mass. On the other hand, high conductivity in the dry zone below the optimum line produces large pores and hard and difficult to remould.



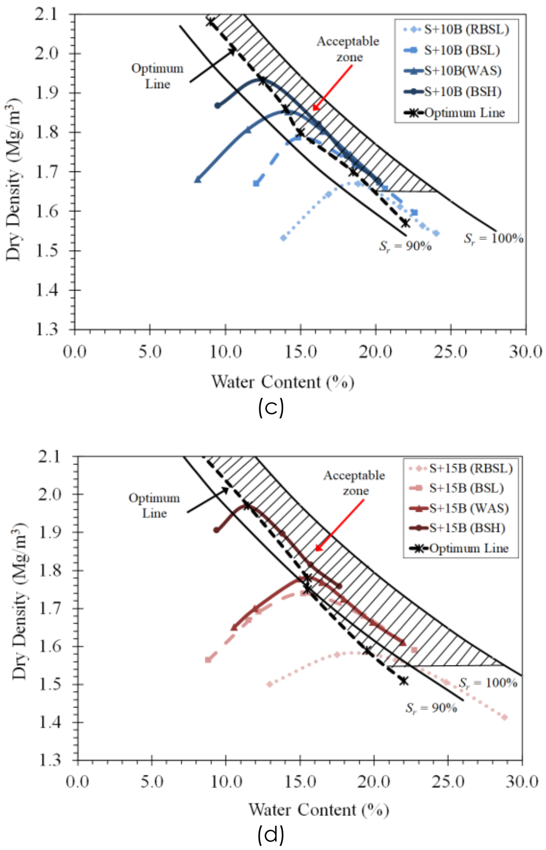


Figure 4 Acceptance zone based on modern criterion for (a) Soil only (b) Soil+5B (c) Soil+10B and (d) Soil+15B

4.0 CONCLUSION

Based on the result in this study, it clearly shows the mixture of residual soil with bentonite can be used as CCL for soil liner. It was found, the method for all compaction zone criteria based on allowable hydraulic conductivity has offered an area for acceptance zone as a compacted soil liner. Each zone has met the requirements for hydraulic values that is $k \leq 1x10^{-9}$ m/s and it shows the entire acceptance zone for a mixture of residual soil with bentonite can be designed based on traditional, modern, or common compaction control approaches depends to the flexibility and adaptability of these methods to cater to various soil characteristics and engineering requirements. By utilizing traditional, modern, or common compaction control approaches, engineers may regulate the acceptance zone to suit the specific characteristics and performance criteria of the soil-bentonite mixture, ensuring optimal compaction and hydraulic conductivity values. The lower border of the acceptance zone can be more appropriately established for each criterion by using the optimum border. However, more research needs to be conducted for the evaluation and determination of the design parameters for residual soil mixed with bentonite as a soil liner.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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