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THE PERMEABILITY AND SHEAR STRENGTH OF COMPACTED CLAYSTONE–BENTONITE MIXTURES

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ABSTRACT: A compacted claystone–bentonite mixture is proposed for use as a clay barrier. This research, in turn, focuses on the effects of bentonite mix on the permeability and shear strength of compacted claystone–bentonite mixtures. The claystone used was obtained from the Banjarbakula landfill project, approximately 10 km from Banjarbaru, the South Kalimantan Government's Administrative Center, Indonesia. The bentonite used is commercially sold in Indonesia. The claystone was mixed with bentonite at a percentage of 5%, 10%, 15%, and 20% bentonite by dry-weight bases. The mixtures were compacted at a moisture content of 10%, 15%, and 20% to reach the dry unit weight of 16kN/m^3–19kN/m^3. Permeability and unconfined compressive strength tests were performed in this study. The result showed that the permeability of mixtures decreases with increasing bentonite content. The addition of up to 20% bentonite to the mixture reduced the permeability by 4.5 times, as compared to the sample without bentonite. Moreover, the mixtures' shear strength indicated by compressive strength and cohesion increased by increasing the bentonite content to 15%. The maximum shear strength obtained was three times higher than without bentonite. The mixtures' permeability and shear strength were also significantly affected by the sample's density and moisture content. A percentage of 20% bentonite is recommended, considering the wide range of acceptability based on two criteria (i.e., permeability and shear strength).

Keywords: Claystone, Bentonite, Permeability, Shear strength, Acceptable zone

1. INTRODUCTION

Permeability is an essential parameter in determining whether a material qualifies as a clay liner, and the limits required to determine the clay liner layer vary in different countries. Austria, Belgium, Hungary, Italy, Portugal, Switzerland, and Turkey, for instance, require a permeability of 1×10^{-9} m/s [1,2], and the same value is observed for other developed countries such as the UK and the USA [1]. Meanwhile, Germany requires a permeability of 1×10^{-10}m/s with a layer thickness of ≥0.75m, and France requires a higher value of 1×10^{-6}m/s, but with a mineral barrier thickness of at least 5m [1]. Moreover, Asian countries such as Japan also require the permeability of mineral barriers to be $1\text{x}10^{-9}$m/s for type C municipal solid waste. In Indonesia, the standard landfill base layer can use a geomembrane with a thickness of 1.5–2.0cm or a clay liner with a permeability of 1×10^{-8}m/s with a total thickness of 60cm [3]. In this study, we adopted the requirement used in many countries: a minimum permeability of 1×10^{-9}m/s

Several methods are commonly applied to obtain low permeability in which compaction is the most common one [4–6]. This method leads to a reduction in soil pore volume, thereby inhibiting the flow of water in the soil. However, soils compacted at different moisture contents, despite having the same density, have different permeabilities [4,5]. Moreover, compacted clays with high water contents have smaller pore sizes despite having the same pore volume [7].

It is also possible to reduce permeability by mixing the sample with bentonite [5,8–11]. The addition of bentonite, however, has an estimated efficacy of less than 15% [12], with only negligible changes to permeability being observed. It was also reported in a previous study that 15% clay was required to obtain a permeability that met the minimum requirements of 1×10^{-9}m/s [4]. Arifin and Sambelum [5] also mixed commercial bentonite at 5–20% with local soil containing a lot of sand and silt in a landfill development project in Rikut Jawu, Central Kalimantan. The results showed that the permeability of the sample mixture met the requirements after being mixed with 50% bentonite. It is important to note that a higher density is needed to achieve the required permeability.

In several countries, a mixture of sand and compacted bentonite has also been proposed for use as a clay liner [4,8,9,12], especially at high-level waste repositories [2,6,13–17]. It involves mixing sand and bentonite at different percentages, taking into consideration how the sand's size influences the permeability of the mixture [9,18]. Moreover, different types of bentonite were used in previous studies, such as sodium bentonite [2,6,8,17–20], calcium bentonite [13,14], and others [9,11,12]. The behavior of each mixture has been found to heavily influenced by the type of bentonite used [20].

Recently, a mixture of claystone and bentonite is the most common approach for alternative barrier layers in high-level waste repositories [6,21–23]. Claystone is found in large quantities during excavation and tunnel projects. This material is usually discarded because of its unfavorable properties when interacting with water [24–28]. Claystone layers are also often believed to be the source of failures in civil constructions. However, its combination with bentonite has several advantages due to the low permeability of both bentonite and claystone. The use of 80% claystone and 20% bentonite in a claystone–bentonite mixture has been reported to reduce permeability by one order [21], showing that the presence of claystone reduced the quantity of bentonite used in the mixture.

Cui [6] reported that crushed Callovo–Oxfordian (COx) claystone behaved as an inert material, such as sand, in a swelling pressure test. Meanwhile, Zhang [22] found that a fracture in the claystone closed itself due to the development of clay minerals when filled with water. This means that the behavior of claystone depends on the clay minerals it contains due to the fact that it is usually obtained from nature. Therefore, it is necessary to investigate the behavior of claystone–bentonite mixtures to determine their optimum use as barrier layers.

Shear strength is also considered to be an important parameter in determining the suitability of clay liner materials [29,30]. The recommended minimum remolded undrained shear strength in the UK is 50 kPa (or higher for specific locations) [31]. Moreover, waste engineering properties such as shallow slope liner stability and integrity, steep slope liner stability and integrity, and cover system integrity are also considered in landfill design [32]. However, everything is directly related to the clay liner's strength, meaning that it is vital to determine the shear strength parameter.

Previous studies mostly focus on high-density samples, which are applied as barriers in the nuclear waste repositories. However, claystone–bentonite mixtures are expected to be useful in broader applications in which lower densities are required, such as landfills. Therefore, it is necessary to investigate the behavior of claystone–bentonite mixtures at different bentonite contents, densities, and moisture contents.

This research focuses on the permeability and shear strength of claystone–bentonite mixtures at different compositions. The results are expected to determine the best composition and the ranges that meet the permeability and strength criteria. The claystone was obtained from the excavation of a landfill development project in Banjarbaru City, South Kalimantan, where it was discarded. The density and moisture contents of the samples were also considered to affect the permeability of the mixture in addition to the bentonite content.

2. MATERIALS AND METHODS

2.1 Materials

The claystone used in this study was obtained from the Banjarbakula landfill development project, where over 8000m^3 was surplus to requirements. The bentonite used was from common commercial sources in Indonesia. Table 1 shows the engineering properties of the claystone and bentonite used. The bentonite had very high plasticity, with a liquid limit of 351.71% and a plasticity index of 307.03%, while the claystone had a liquid limit of 50.76% and a plasticity index of 29.81%. The dominant fractions in the claystone were clay and silt, making up 51.55% and 43.94%, respectively. In contrast, the bentonite was composed of up to 90.28% clay fractions. From Table 1, the dominant exchangeable cation in each sample was Ca^{2+}.

Table 1. Physical and index properties of the claystone and bentonite used.

Properties	Claystone	Bentonite
Specific gravity	2.60	2.71
Water content (%)	2.75	14.17
Soil compositions:		
Gravel (%)	0.0	0.0
Coarse sand (%)	0.1	0.0
Medium sand (%)	0.1	0.0
Fine sand (%)	4.3	1.4
Silt (%)	43.9	8.3
Clay (%)	51.6	90.3
Plasticity:		
Liquid limit (%)	50.76	351.71
Plastic limit (%)	20.95	44.68
Shrinkage limit (%)	9.74	41.89
Plasticity Index (%)	29.81	307.03
Exchangeable Cation:		
Na^{+} (meq/g)	0.30	0.34
Ca^{2+} (meq/g)	4.30	18.70
Mg^{2+} (meq/g)	0.10	0.20
K^{+} (meq/g)	0.30	0.58

2.2 Techniques and Procedures

2.2.1 Samples preparation

The standard Proctor compaction [33] test was conducted to obtain the optimum moisture content and maximum dry density, which were 15% and 16kN/m^3, respectively. The claystone was crushed and sieved with a mesh No. 40, and mixed with 5, 10, 15, and 20% of bentonite on a dry weight basis. The water content was used at the optimum condition of 15%, dry of optimum at 10%, and wet of optimum at 20%. Moreover, the dry volume weight of the samples was prepared at variations of 16, 17, and 18kN/m^3 to determine the dry density effect. However, high moisture content (i.e., 15 and 20%) was not applied at high densities due to the difficulty of compaction when working very close to zero air void line. The sample conditions are summarized in Table 2.

Table 2. Compositions, densities, water content, and code of samples.

Clayst. (%)	Bent. (%)	Dry unit weight (kN/m^3)	w (%)	Sample code
100	0	16, 17, 18, 19	10	100CS–w10
100	0	16, 17, 18, 19	15	100CS–w15
100	0	16, 17, 18, 19	20	100CS–w20
95	5	16, 17, 18, 19	10	95CS5B–w10
95	5	16, 17, 18	15	95CS5B–w15
95	5	16	20	95CS5B–w20
90	10	16, 17, 18, 19	10	90CS10B–w10
90	10	16, 17, 18	15	90CS10B–w15
90	10	16	20	90CS10B–w20
85	15	16, 17, 18, 19	10	85CS15B–w10
85	15	16, 17, 18	15	85CS15B w15
85	15	16	20	85CS15B–w20
80	20	16, 17, 18, 19	10	80CS20B–w10
80	20	16, 17, 18	15	80CS20B–w15
80	20	16	20	80CS20B–w20

2.2.2 Permeability and Unconfined Compressive Strength Tests

A certain amount of bentonite was mixed with claystone, and the dry weight percentage was measured. Water was added to the mixture, and the water content was evaluated. The sample was cured for 1 day and later compacted statically in a 6 cm diameter ring using a hydraulic jack to attain the density, as shown in Table 1. Meanwhile, a thin sample of 1cm was made to reach quick equilibrium as indicated by a relatively similar decrease in water level.

A thin layer of grease was applied to the tube surface to avoid leakage between the tool wall and the sample before it was inserted into the test instrument. A falling head test method was performed to obtain the permeability [34]. This method is reliable, repeatable, and quite accurate for soil permeability measurements [35]. Moreover, the water level in the burette was observed every 24 hours up to the period when there was no change in water level for each observation.

Using the same sample conditions as shown in Table 2, the claystone–bentonite mixture samples with a diameter of 47.5mm and a height of 92.4mm were also prepared by static compaction to measure the shear strength using the UCS test according to ASTM D2166 [36].

3. RESULTS AND DISCUSSION

3.1 Effect of Bentonite Content

Figures 1(a)–1(d) show the effect of bentonite content on the mixture's permeability. We considered 1×10^{-9}m/s, which is marked with gray shading, to be acceptable as it is the minimum requirement in several countries. The numbers and letters in the legend show the density and moisture contents of the sample. The highest permeability of 6.6×10^{-9}m/s was recorded in a sample with a 5% bentonite content and a density of 16kN/m^3.

Figure 1 (a) shows the reduction in permeability as the bentonite content increases. The samples with a density of 16 kN/m^3 and moisture contents of 15% and 20% were observed to meet the required permeability at 20% bentonite content. Figure 1(b) presents that permeability also decreased as bentonite content increased at a density of 17kN/m^3. Three samples met the requirement at this density, including a sample with a 15% bentonite content. A similar condition was also observed with the 18kN/m^3 sample. Meanwhile, all samples with 5-20% bentonite contents were observed to meet the requirements at the highest density of 19 kN/m^3.

These results showed that the bentonite content affected the permeability of the claystone–bentonite mixture such that at a higher percentage, there was a lower permeability. Furthermore, the permeability was not constant up to the 20% bentonite level, which is different from the findings of previous studies that showed the permeability to be constant at values more than 15% [12]. This, however, was in agreement with the results of Arifin and Sambelum [5], which showed that other parameters such as density and water contents significantly influence the mixtures' permeability. Moreover, Figure 1(d) shows that an elevated density of 19kN/m^3 is required at 10% bentonite to ensure the requirements of the mixture are met. Arifin and Sambelum [5] also predicted the need for 50% bentonite to meet the permeability requirements using standard Proctor density. Therefore, a density higher than that of the standard Proctor is required to reduce the percentage of bentonite used.

Zang [21] compacted claystone mixed with bentonite in a different composition. The findings demonstrated that the macropores in the claystone aggregate could be more densely filled with bentonite powder, leading to a low porosity. Furthermore, as water passes through the sample, the bentonite, as well as the clay fraction in the

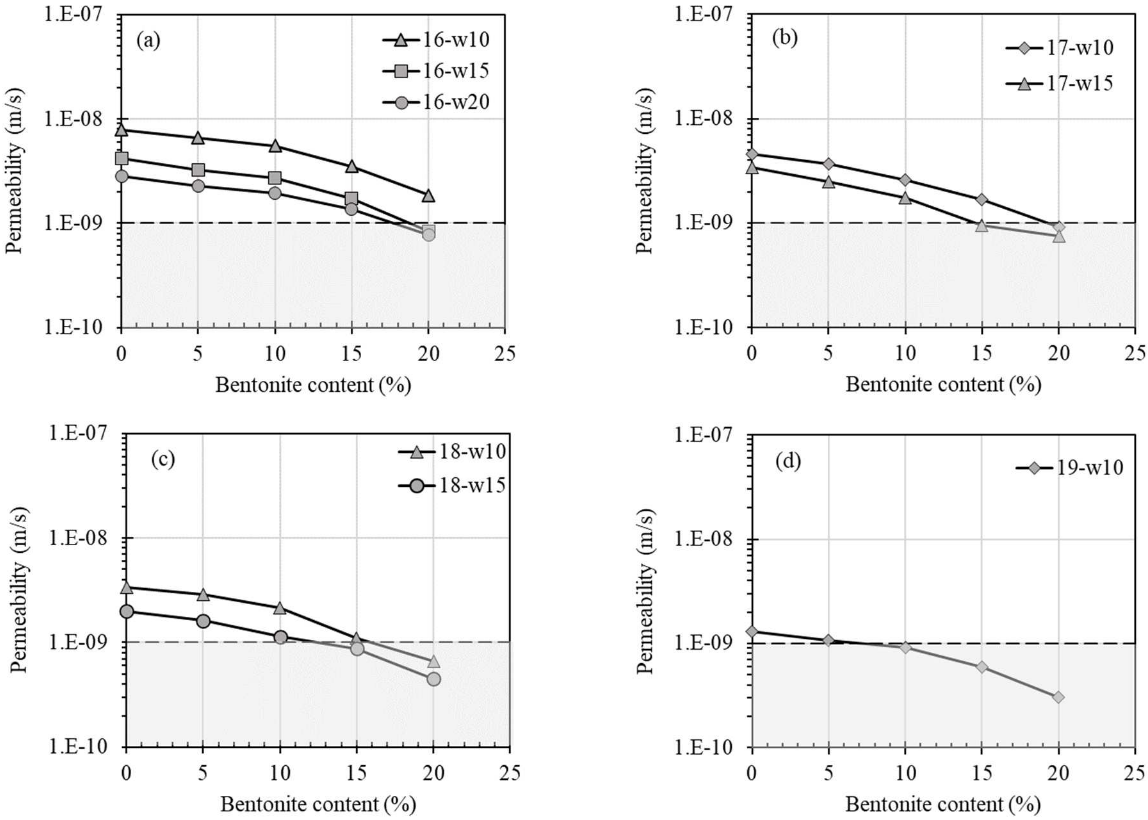


Fig.1 Effect of bentonite content on the permeability of compacted claystone–bentonite mixtures. Note: the numbers and the letters in the legend show the dry unit weight and moisture content of samples.

claystone, expands. The larger the proportion of the bentonite, the greater the extension and closing of the pores. Permeability is decreased as a result.

The change in permeability of the claystone–bentonite mixture as compared to the permeability without bentonite is summarized in Table 3. It can be seen that the permeability of claystone mixed with 5% bentonite causes a 1.2–1.4-fold decrease (with an average of a 1.2-fold decrease). This reduction continued to occur with an increasing percent of bentonite in the mixture, i.e., at an average of 1.6-, 2.6-, and 4.5-fold for the addition of 10%, 15%, and 20% bentonite, respectively.

Figure 2 shows the effect of the bentonite content on the shear strength obtained from the UCS test using a minimum compressive strength of 50kPa, as recommended by the Environment Agency [31]. This value corresponds to the medium soil consistency of 48–96kPa [34]. In the figure, the undrained cohesion is plotted as a secondary axis, which is determined as half of the compressive strength. According to Figure 2, the increase in compressive strength is accompanied by an increase in undrained cohesion caused by the addition of bentonite to the mixture.

Figure 2 also indicates that all the compressive strength samples met the required criteria, but the sample with 20% bentonite tended to have a constant or decreasing value in almost all densities, as shown in (a)–(d).

Table 3. Permeability reduction due to the addition of bentonite.

Bentonite content (%)			5	10	15	20
γ_d (kN/m^3)	w (%)	Sample code	Permeability reduction			
16	10	16-w10	1.2	1.4	2.3	4.2
16	15	16-w15	1.3	1.6	2.4	5.0
16	20	16-w20	1.2	1.4	2.0	3.6
17	10	17-w10	1.2	1.8	2.7	5.0
17	15	17-w15	1.4	1.9	3.6	4.5
18	10	18-w10	1.2	1.6	3.1	5.1
18	15	18-w15	1.2	1.8	2.3	4.5
19	10	19-w10	1.2	1.4	2.2	4.2
Average			1.2	1.6	2.6	4.5

Furthermore, the maximum compressive strength was achieved at 15% bentonite, as is apparent from the following results: 299, 456, 502,

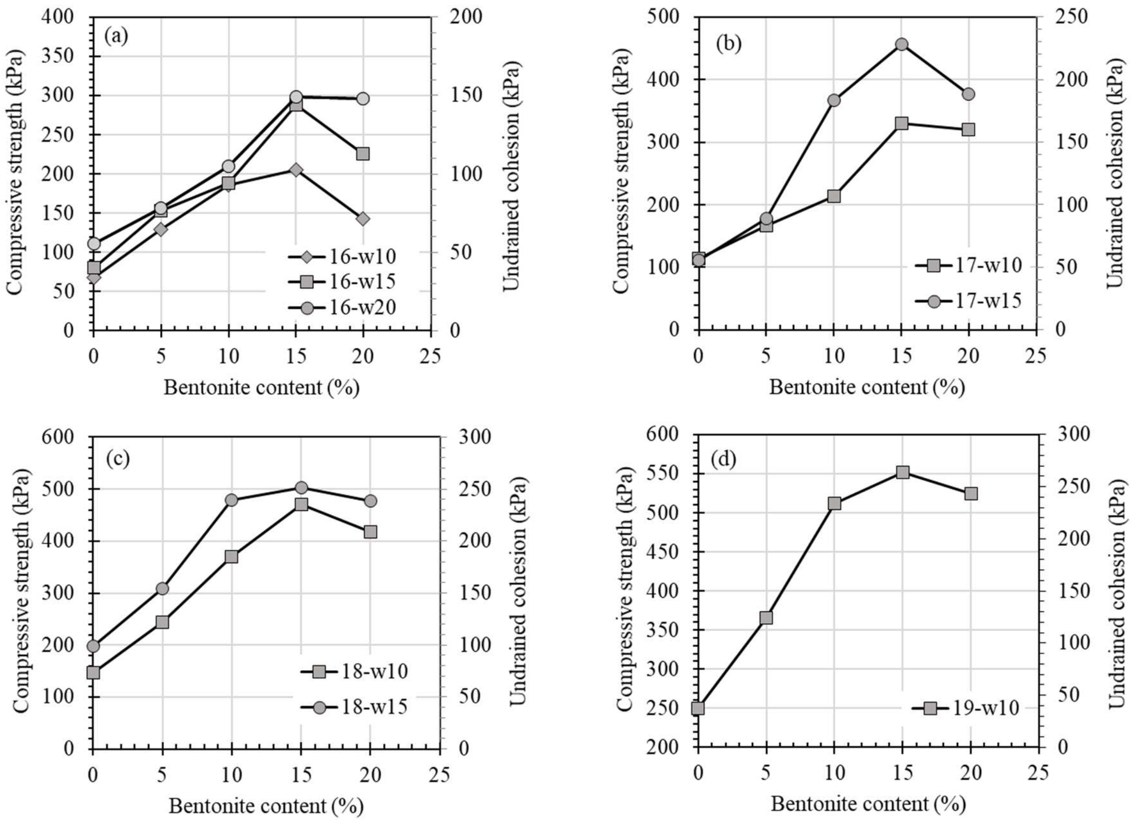


Fig. 2 Effect of bentonite content on the compressive shear strength of compacted claystone–bentonite mixtures.

and 551kPa recorded at densities of 16, 17, 18, and 19kN/m^3, respectively. This means that a higher compressive strength was obtained at a greater density, which further indicated the important influence of density on the strength of the claystone–bentonite mixtures.

Zhang [22] compacted a claystone–bentonite mixture of different compositions (i.e., 60/40 and 80/20). It was found that at the same axial stress, the 80/20 mixture resulted in a higher dry density than the 60/40 sample. This shows that the percentage of bentonite in the mixture affects the behavior of the claystone–bentonite mixture. The composition influences the density of bentonite that fills the claystone macropores. In this study, the maximum density of bentonite in claystone macropores was produced at 15% bentonite, which resulted in the maximum compressive strength and undrained cohesion of the sample. In addition to the shear strength, the final dry density of bentonite in the claystone–bentonite mixture was also found to affect the swelling pressure of the sample, as was reported by Wang et al. [23].

The addition of up to 15% bentonite content in the mixture was observed to increase the cohesion of the mixture, and the bentonite was observed to be dominant at 20%. The sample produced larger macropores at low water contents [7], which reduced the strength of the claystone–bentonite mixture. Moreover, the need for the water to reach the maximum sample density increased at higher bentonite levels, and the water added was usually absorbed more by the bentonite, causing the sample to expand. Pusch et al [37] reported that the mineral montmorillonite requires 2-3 layers of water molecules to meet the hydration force. Thickness and complete hydration layers depend on the exchangeable cation of the bentonite. Further, Sayori et al [38] observed that when water is applied to the bentonite surface, four water molecules would first be absorbed. Mitchell and Soga [39] indicated that for the complete expansion, bentonites of the sodium type with a specific surface area of 800m^2/g exceed the water content of 400% to meet the exchangeable cation hydration.

The effect that the percentage of clay in soil has on its shear strength has been widely studied. Increasing the amount of clay in soil results in an increase in cohesion followed by a reduction in the fiction angle [40–43]. The increase in cohesion is influenced by the minerals contained in the clay, i.e., montmorillonite minerals result in a higher cohesion increase as compared to kaolinite minerals [40]. In this study, the bentonite used contained montmorillonite so that an increase in the percentage of bentonite enhanced the amount of this mineral, resulting in a greater increase in cohesion.

Table 4 presents the improvement in the compressive strength of the claystone–bentonite mixture (in percent) as compared to those without bentonite. As can be seen in the table, the increase in bentonite (added to claystone) resulted in an increase in the compressive strength for all samples up to the addition of 15% bentonite. At 5% bentonite, the average increase in shear strength was 1.6-fold, and an average of 2.4- and 3.0-fold at 10% and 15% bentonite contents, respectively. As shown in Figure 2, supplementing 20% bentonite to claystone resulted in a reduction in the compressive strength of the samples. As shown in the table, a mix with up to 20% bentonite reduced the compressive strength of all samples by an average of 2.6 times.

Table 4. Shear strength changes due to addition of bentonite.

Bentonite content (%)			5	10	15	20
γ_d (kN/m^3)	w (%)	Sample code	Shear strength change			
16	10	16-w10	1.9	2.7	3.0	2.1
16	15	16-w15	1.9	2.3	3.6	2.8
16	20	16-w20	1.4	1.9	2.7	2.7
17	10	17-w10	1.5	1.9	2.9	2.8
17	15	17-w15	1.6	3.3	4.1	3.4
18	10	18-w10	1.7	2.5	3.2	2.9
18	15	18-w15	1.6	2.4	2.5	2.4
19	10	19-w10	1.5	2.1	2.2	2.1
Average			1.6	2.4	3.0	2.6

3.2 Effect of Mixture Density

Figure 3 shows the effect of density on the compacted claystone–bentonite mixtures' permeability, as indicated in samples with 5–20% bentonite with a 10% moisture content in Figure 3(a) and a 15% moisture content in Figure 3(b). The sample legend is written as the claystone percentage (CS) and bentonite percentage (B), while *w* is used as the symbol for the moisture content. Figure 3(a) shows that a higher density produced a lower permeability, as was observed in all mixture variations from 5 to 20% bentonite. However, not all mixtures met the requirements necessary for a clay liner, as indicated by the gray area. These mainly comprised 5% bentonite with a 10% moisture content. Moreover, 20% bentonite content samples were the samples that most commonly met the requirements at a density of ≥17kN/m^3, because they were compacted with more energy than the Proctor standard.

The same trend was found for samples with a higher moisture content of 15%, as presented in Figure 3(b), with an increase in density observed to cause a smaller pore number and permeability. This is in line with findings of a previous study that showed that an increase in the density reduced the macropore size and volume, while the micropores did not change much [6,7,14]. These macropores play an important role in the changes experienced in soil permeability, especially for clay soil, such that smaller and fewer macropores usually lead to a lower permeability.

This means that all the samples with a 20% bentonite content, such as 80CS20B-15, qualified as clay liners, while 85CS15B-15 was partially compliant, and neither 95CS5B-15 or 90CS10B-15 was satisfactory. These results showed that the samples compacted with Proctor Standard energy with a dry density of 16kN/m^3 satisfied the requirements at higher moisture contents. This, therefore, shows the importance of water content in compacted claystone–bentonite mixtures.

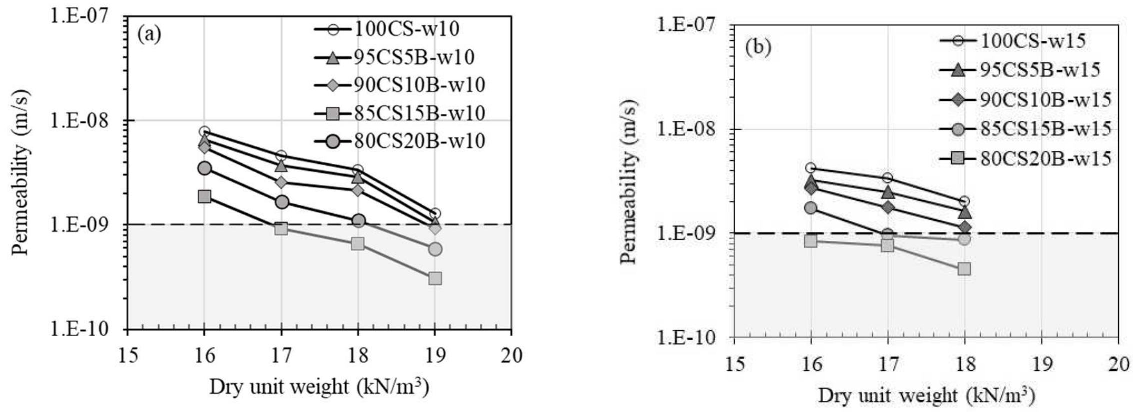


Fig. 3 Effect of density on the permeability of compacted claystone-bentonite mixtures.

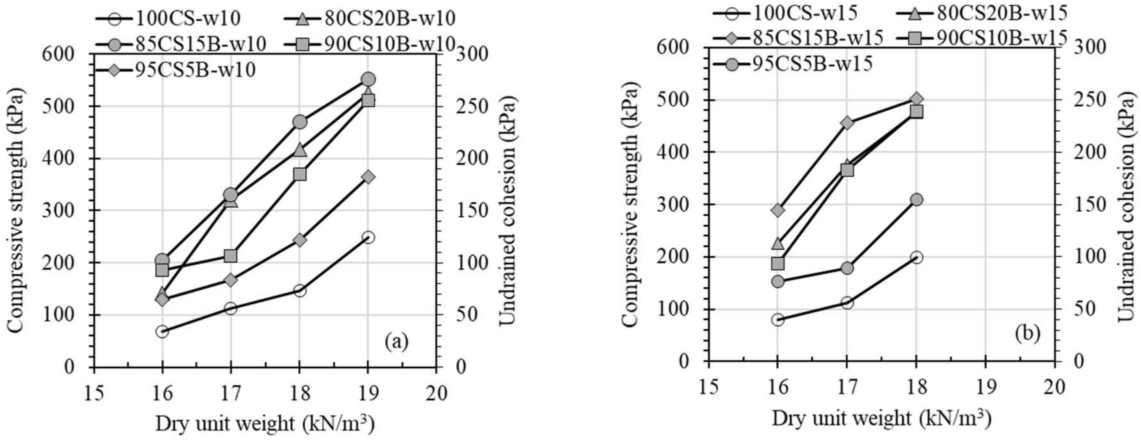


Fig. 4 Effect of density on the compressive strength of claystone-bentonite mixtures.

Figure 4 shows the compressive strength and undrained cohesion of compacted claystone–bentonite as a function of the dry density. This is demonstrated in samples with a 10% moisture content in Figure 4(a) and a 15% moisture content in Figure 4(b), which shows almost all of the densities used in this study. The sample's compressive strength and undrained cohesion were observed to increase as the density of all bentonite contents increased. The density increment caused a reduction in the size and number of macropores and increased the percentage of micropores [7], playing a role in the shear strength of clay soils.

Zhang [22] reported that the mechanical stiffness of the compacted claystone–bentonite mixtures exponentially increases with increasing dry density. Moreover, at a given dry density, the stiffness of the claystone–bentonite mixtures was higher than that of the bentonite–sand mixture. The low stiffness of the bentonite–sand mixture is due to the lower density of the bentonite matrix, which embeds the sand particles, resulting in a lower inner friction resistance [22]. On the other hand, the high stiffness of the claystone–bentonite mixture is caused by the high density of the bentonite matrix in the claystone. Claystone, unlike generally inert sand, contains clay minerals, and contact between claystone and bentonite can occur, influencing the hydro-mechanical behavior of the compacted mixture [23].

The changes in the permeability and shear strength of the claystone–bentonite mixture are summarized in Tables 5 and 6, respectively. For samples with a moisture content of 10%, as shown in Table 5, the decrease in permeability was, on average, 2.0-, 2.6-, and 6.0-fold due to an increase in density from 16kN/m^3 to 17kN/m^3, 18kN/m^3, and 19kN/m^3, respectively. When the density was increased from 16kN/m^3 to 17kN/m^3 and 18kN/m^3, the permeability decreased by an average of 1.8 and 2.0 times, respectively, for samples with a moisture content of 15%.

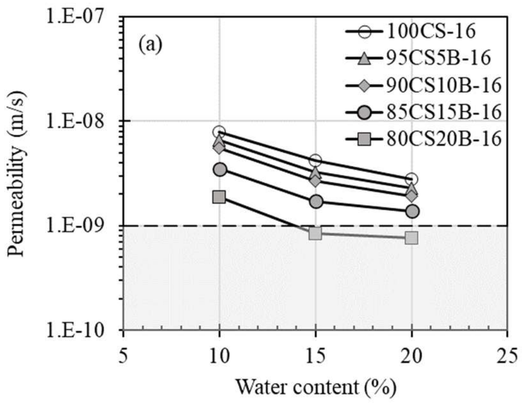
For the sample shear strength with a moisture content of 10%, as shown in Table 6, an increase in density from 16kN/m^3 resulted in an average 1.6-, 2.2-, and 3.1-fold increase after the dry unit weight increased to 17kN/m^3, 18kN/m^3, and 19kN/m^3. At a 15% moisture content, the shear strength increased by an average of 1.6 and 2.2 times, respectively, after the dry unit weight was increased from 16kN/m^3 to 17kN/m^3 and 18kN/m^3.

Table 5. Permeability change due to the increase in density.

Dry unit weight (kN/m^3)			17	18	19
Bent. content	w (%)	Sample code	Permeability change		
0	10	100CS-w10	1.7	2.3	6.1
5	10	95CS5B-w10	1.8	2.3	6.2
10	10	90CS10B-w10	2.2	2.6	6.0
15	10	85CS15B-w10	2.1	3.2	5.9
20	10	80CS20B-w10	2.0	2.8	6.1
Average			2.0	2.6	6.0
0	15	100CS-w15	1.2	2.1	
5	15	95CS5B-w15	1.3	2.0	
10	15	90CS10B-w15	1.5	2.4	
15	15	85CS15B-w15	1.8	2.0	
20	15	80CS20B-w15	1.1	1.9	
Average			1.4	2.1	

3.3 Effect of Water Content

Figures 5(a) and 5(b) show the effect of water



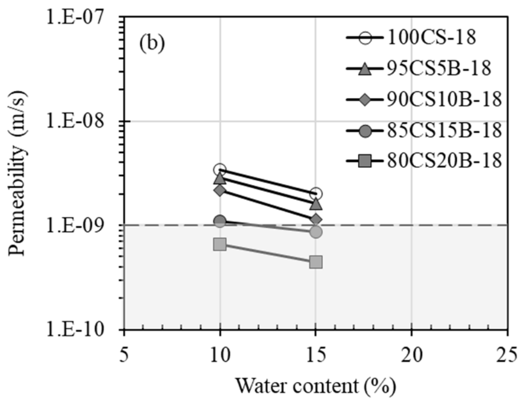


Fig. 5 Effect of water content on the permeability of compacted claystone-bentonite mixtures (a) samples with dry density of $16kN/m^3$ and (b) samples with dry density of $18kN/m^3$.

content on the permeability of the claystone–bentonite mixture sample, with the legend indicating the percentages of claystone (CS) and bentonite (B) and the density of the samples. Figure 5(a) shows the result of the sample with a density of 16 kN/m^3 using three moisture content conditions, while Figure 5(b) shows a higher density of 18 kN/m^3. The permeability of the compacted sample at the optimum water content (i.e., 15%) was observed to be lower than for the dry condition (i.e., 10%), while the value in the wet condition (i.e., 20%) was almost the same as for the optimum. Similar results were also recorded for samples with higher densities. Several researchers have previously discussed this effect [4,5].

Table 6. Shear strength change due to the increase in density.

Dry unit weight (kN/m^3)			17	18	19
Bent. content	w (%)	Sample code	Shear strength change		
0	10	100CS-w10	1.7	2.1	3.7
5	10	95CS5B-w10	1.3	1.9	2.8
10	10	90CS10B-w10	1.1	2.0	2.8
15	10	85CS15B-w10	1.6	2.3	2.7
20	10	80CS20B-w10	2.3	2.9	3.7
Average			1.6	2.2	3.1
0	15	100CS-w15	1.4	2.5	
5	15	95CS5B-w15	1.2	2.0	
10	15	90CS10B-w15	2.0	2.5	
15	15	85CS15B-w15	1.6	1.7	
20	15	80CS20B-w15	1.7	2.1	
Average			1.6	2.2	

Benson et al. [4] showed that low permeability at higher water contents was due to microstructural changes in the soil. It is important to note that a bimodal pore size distribution, including macro- and micropores, exists in dry conditions, while a unimodal pore distribution, including micropores, exists at higher moisture contents. It was also reported by Arifin and Schanz [7] that pores in dry conditions are large, while micropores are dominant at wet conditions when the samples are at the same density or void ratio. In this claystone–bentonite mixture, the claystone macropores were filled with bentonite [21]. When interacting with water, the bentonite expanded and closed these macropores. At a higher water content, in addition to the macropores filling with expanding bentonite, the dominant micropores resulted in a lower permeability.

The effects of water content on changes in permeability of the claystone–bentonite mixture are summarized in Tables 7. The data are represented by samples with densities of $16kN/m^3$ and $18kN/m^3$, as shown in Figures 5. For samples with densities of $16kN/m^3$ in Table 7, the permeability decreased by an average of 2.0 and 2.7 times when the water content increased from 10% to 15% and 20%, respectively. For samples with a density of $18kN/m^3$, an increase in the initial water content of the sample from 10% to 15% resulted in a 1.6-fold lower average.

Figure 6 shows the effect of moisture content on the compressive strength and undrained cohesion of compacted claystone–bentonite mixtures using a similar trend as for permeability, with densities of 16 and $18kN/m^3$, as shown in Figures 6(a) and 6(b), respectively. The compressive strength and undrained cohesion seemed to be relatively constant at a density of 16 kN/m^3 with a 5 and 10% bentonite content, while it was observed to increase with a moisture content of 15 and 20%. It was discovered that claystone absorbed more water at lower

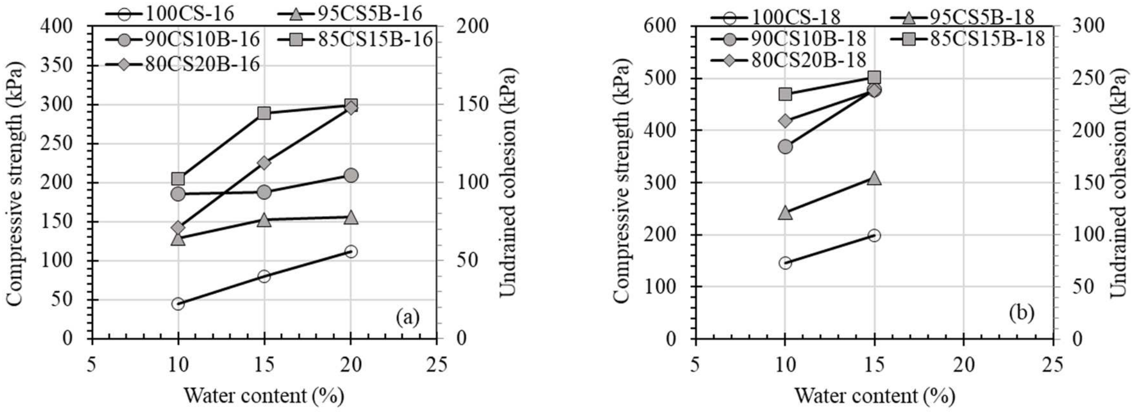


Fig. 6 Effect of water content on the compressive strength of compacted claystone-bentonite mixtures (a) samples with dry density of 16kN/m^3 and (b) samples with dry density of 18kN/m^3

bentonite levels (5–10%), and this higher water content caused a reduction in the claystone–bentonite mixture strength. This is associated with the strength usually lost by claystone when interacting with a lot of water [24–26]. Moreover, the bentonite absorbed more water at a higher content of 20%, making the sample more difficult to compact and decreasing the sample strength. Furthermore, compressive strength and undrained cohesion appeared to increase as the moisture content increased at high densities of 18kN/m^3, as shown in Figure 6(a). This was due to the compressed bentonite, which supported better bonding in the claystone–bentonite mixture.

Table 7. Effect of sample moisture content on the permeability of the claystone–bentonite mixtures.

Moisture content (%)			15	20
Bentonite content	γ_d (kN/m^3)	Sample code	Permeability change	
0	16	100CS-16	1.9	2.8
5	16	95CS5B-16	2.0	2.9
10	16	90CS10B-16	2.0	2.9
15	16	85CS15B-16	2.0	2.6
20	16	80CS20B-16	2.2	2.4
Average			2.0	2.7
0	18	100CS-18	1.7	
5	18	95CS5B-18	1.8	
10	18	90CS10B-18	1.9	
15	18	85CS15B-18	1.3	
20	18	80CS20B-18	1.5	
Average			1.6	

In general, samples compacted in dry and wet conditions produce lower shear strength than those compacted at the optimum moisture content [41,42,44]. Samples that were compacted at dry or wet moisture contents produced a dry unit weight that was smaller than those compacted at the optimum water content, following the compaction curve. In this study, the dry unit weight of the samples was prepared equally at different moisture contents. The compressive strength and cohesion obtained increased with the increasing water content, as shown in Figure 6.

Table 8 shows the shear strength change due to the alteration of the initial moisture content of the samples. As shown in the table, an increase in moisture content from 10% to 15% resulted in a 1.2-1.3-fold increase in the compressive strength and cohesion. The shear strength increased 1.5-fold as a result of increasing the water content from 10% to 20%.

Table 8. Effect of sample moisture content on the shear strength of the compacted claystone–bentonite mixtures.

Moisture content (%)			15	20
Bent. content	γ_d (kN/m^3)	Sample code	Shear strength change	
0	16	100CS-16	1.2	1.6
5	16	95CS5B-16	1.2	1.2
10	16	90CS10B-16	1.0	1.1
15	16	85CS15B-16	1.4	1.5
20	16	80CS20B-16	1.6	2.1
Average			1.3	1.5
0	17	100CS-17	1.4	
5	17	95CS5B-17	1.3	
10	17	90CS10B-17	1.3	
15	17	85CS15B-17	1.1	
20	17	80CS20B-17	1.1	
Average			1.2	

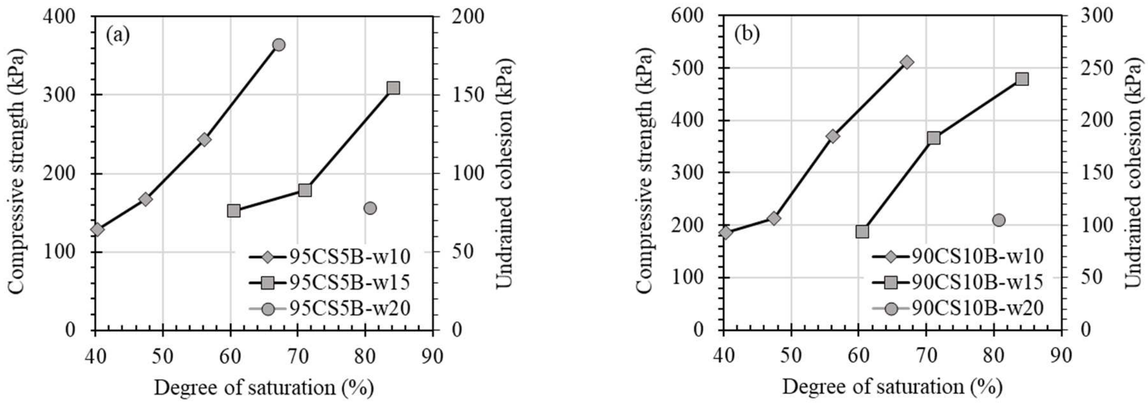


Fig. 7 Effect of degree of saturation on the compressive strength and undrained cohesion of compacted claystone-bentonite mixtures (a) 5% bentonite content, and (b) 10% bentonite content

The shear strength of sandstone and claystone fluctuates due to changes in the surrounding environment such as moisture content or relative humidity. Shakoor and Berefield [45] reported that the unconfined compressive strength of the sandstone decreases with an increasing degree of saturation. Samples were tested by allowing them to absorb water so that the degrees of saturation increase. In other words, the increase in the degree of saturation was caused by the increase in the sample moisture content. Meanwhile, Pineda et al. [46] reported the effect of the relative humidity cycle on the reduction of cohesion and friction of claystone. This decrease is due to the accumulation of strain damage that occurs during the RH cycle. Figure 7 shows the relationship between the degree of saturation and the shear strength of compacted claystone–bentonite mixtures represented by two bentonite contents, namely 5% and 10%, shown in Figures 7(a) and 7(b), respectively. Both figures show the same trend whereby compressive strength and cohesion samples increase with the increasing degree of saturation. This effect is different from the results of other studies. An increase in the degree of saturation in the study is caused by the increase in the dry density sample or a reduction in the initial sample void ratio. Moreover, the increase in water content, as seen in Figure 6, resulted in a slight increase in the shear strength of the samples. In this study, changes were made to the water content around the optimum water content of claystone (i.e., 15%) so that the shear strength at that water content is the shear strength of the maximum density of claystone.

The analysis of its microstructures using both electron scanning (SEM) and porosimetry intrusion of mercury (MIP) methods provides a more comprehensive description of the effects of supplementing bentonite to the claystone. This is directly related to the state of the mixtures, which were compacted at various moisture content levels, as well as the increase in sample density. Further investigation concerning the microstructure of compacted claystone–bentonite mixture is required.

3.4 Acceptable Zone of Clay Liner

Daniel and Benson [30] suggested a method for determining acceptable zones in clay liner designs. This method combines a zone that meets the permeability requirements and other criteria, and relates the parameters to dry unit weight and water content. Zones overlapping one another become a single acceptable zone. This method was applied to the claystone–bentonite mixture data obtained in this study, as shown in Figure 8. Two criteria were used in the figure (i.e., permeability and shear strength). The circles on the curves refer to the moisture content and density of the samples. The black symbols show the samples that meet both requirements.

Figure 8(a) shows the criteria for a sample with 5% bentonite. As seen in the figure, there is only an acceptable zone for shear strength. No permeability zone was obtained due to the absence of samples that meet the permeability criteria for 95CS5B samples, as shown in Figure 1. Moreover, Figure 8(b) shows an acceptable zone for claystone samples mixed with 10% bentonite. On the basis of the data summarized from Figures 1 and 2, only one sample met the two criteria, i.e., 90CS5B at a density of 19kN/m^3 and a water content of 10%. The overlapping zone is too small and difficult to reach in the field, especially at very high densities. Benson et al. [29] reported that only 74% of clay liners in the field met the permeability criteria of 1x10^{-9}m/s in North America. The lack of homogeneity of the mixture may fail to achieve the permeability requirements as no example met the sample's criteria with 5% bentonite.

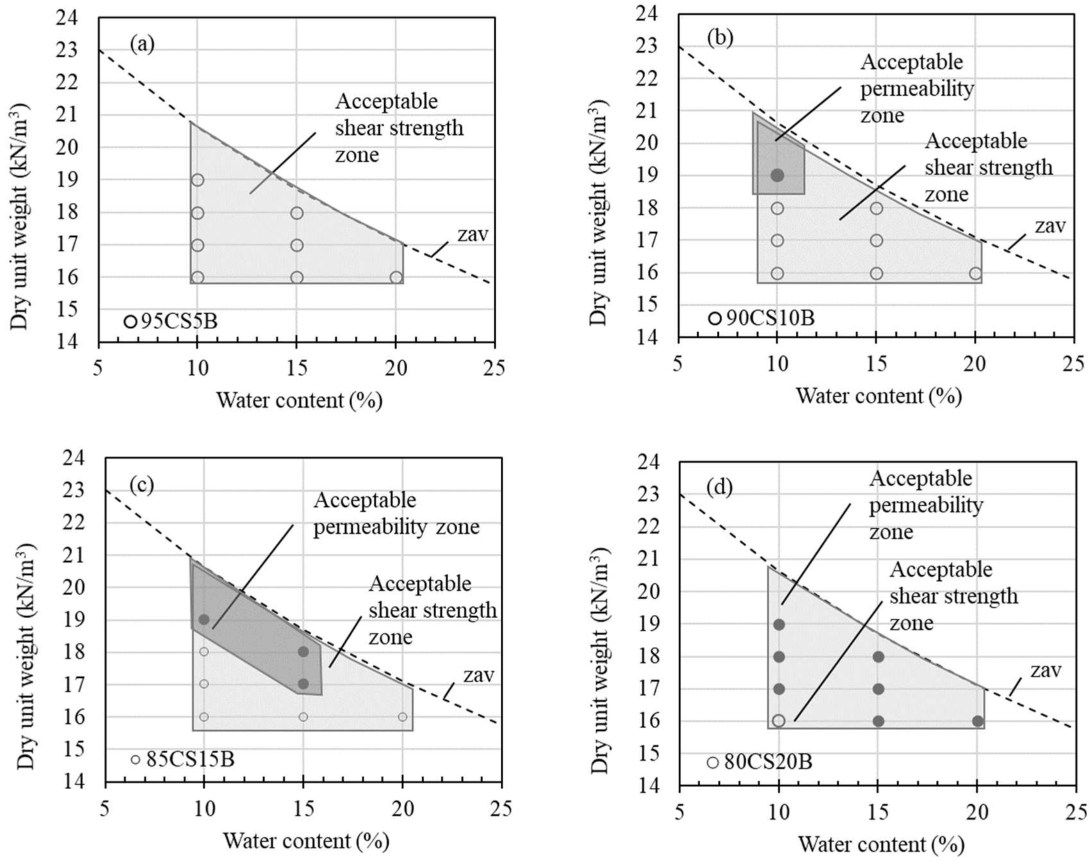


Fig. 8 Acceptable zones for the shear strength and permeability of the claystone-bentonite mixtures (a) 95CS5B, (b) 90CS10B, (c) 95CS15B, and (d) 90CS20B

For samples with a bentonite content of 15% (85CS15B), the acceptable zone is depicted in Figure 8(c). Three samples met both criteria. The overlapping zone obtained was larger than that of the 90CS10B sample, as seen in Figure 8(b). These results are consistent with previous studies that reported that an increase in the percentage of bentonite resulted in lower permeability [5,8–11]. Furthermore, seven samples with a bentonite content of 20% met the two requirements, as shown in Figure 8(d). As a result, the accepted zone became larger than those shown in previous curves. Since the size of the zone was large, the possibility of this being achieved in the field was high. The large zone also minimized the inhomogeneous effect of mixing claystone and bentonite samples. Benson et al. [29] suggested the use of a wide variety of clayey soil to achieve the permeability requirements in the field.

4. CONCLUSIONS

The effect of claystone mixed with bentonite on permeability is herein described and analyzed based on experiments. The results show that the permeability of mixtures decreases with increasing bentonite content. Mixtures of 5%, 10%, 15%, and 20% reduced the permeability of the mixture by an average of 1.2, 1.6, 2.6, and 4.5 times, respectively, compared to those without bentonite. However, not all mixtures met the clay liner permeability criteria.

Bentonite in the mixture also affects the shear strength of the sample. The compressive strength and cohesion of the mixture were increased after bentonite was added up to 15%. At 20% bentonite, the shear strength was constant or decreased. With the addition of 5%, 10%, and 15% bentonite, the shear strength of the soil was increased by an average of 1.6, 2.4, and 3.0 times, respectively, compared to those without bentonite.

The initial density and moisture content of samples also affect the permeability and shear strength of the claystone–bentonite mixtures. Increasing the density from 16kN / m3 to 19 kN / m3 reduced the sample permeability up to 6.0-fold and increased the shear strength up to 3.1-fold. Changes in the initial water content of the sample from 10% to 20% also resulted in a 2.7-fold reduction in permeability and a 1.5-fold increase in soil shear strength.

The acceptable zone based on two criteria (i.e., shear strength and permeability) increased by increasing bentonite content in the mixtures. A percentage of 20% bentonite is recommended, considering the wide range of acceptable sample conditions.

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