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Chair Person of Scientific Committee
The 6th ICSBE 2021

# Swelling Characteristics of Compacted Claystone–Bentonite Mixtures

**Abstract.** High-density claystone mixtures have been suggested as liners in radioactive waste repositories. However, this material can also be used as a liner in landfills. This study focuses on swelling characteristics of compacted claystone-bentonite at low density for landfill applications. Claystone was taken from the Banjarbakula landfill project in Banjarbaru. Furthermore, the bentonite used is a commercial in Indonesia. Claystone was mixed with bentonite with a content of 5, 10, 15, and 20% on a dry weight basis. The mixture is statically compacted with a moisture content of 10, 15, and 20% to achieve a dry density of 16 kN/m$^3$. A swell-load test was carried out using the conventional oedometer equipment to obtain swelling potential and swelling pressure of samples. The results show that the swelling potential and swelling pressure increase with the increase in bentonite content. At a bentonite content of more than 10%, both increased significantly. This research also revealed a linear relationship between swelling potential and swelling potential. **Swelling pressure maybe???**

## 1. Introduction

Claystone–bentonite mixture is a material recommended for use as a liner for radioactive waste [1–4]. Aside from the economic and environ **This sentence is not spelled correctly** ıas the advantage of containing minerals and chemical compc ɔck [1]. However, the minerals found in claystone vary depending on the region. Other materials, such as bentonite, are required to achieve the permeability requirement as a liner.

Bentonite is required because it contains the mineral montmorillonite which absorbs more water and continues to expand. When using bentonite as a sealing material, the swelling property is important. The swelling potential and swelling pressure are two important aspects of this swelling characteristic [1,5,6], [7]. The swelling potential, also known as percent swelling, is the ratio of deformation to initial sample thickness. Meanwhile, swelling pressure is the pressure required to keep the void ratio constant as the sample absorbs water [1]. By this definition, there are three methods for determining swelling pressure: the constant volume test, the swell under load test, and the swell–load test [1].

According to some researchers, different methods produce different values of swelling pressure due to differences in loading and wetting conditions [1,8]. Furthermore, swelling pressure is highly dependent on the initial dry density of the soil speciemen. The swelling pressure increases as the initial dry density increases. The swelling pressure, on the other hand, is unaffected by the initial water content. Meanwhile, both the initial dry density and the moisture content of the compacted soil influence the swelling potential [5,6], [7].

As a radioactive waste liner, a mixture of claystone and bentonite is typically recommended. As a result, it is required in materials with a high dry density. Wang et al. [1] investigated the swelling properties of a claystone-bentonite mixture with a dry density of 17-19 kN/m$^3$. Zhang [2], on the other hand, used a sample with a dry density of 18.8-19.5 kN/m$^3$. For landfills, the required density is not too high as long as the permeability requirements for Indonesia are less than $1\times10^{-8}$m/s [9][10].

This research focuses on swelling characteristics of compacted claystone-bentonite with dry density at maximum Proctor compaction (i.e., 16 kN / m3). To obtain swelling potential and swelling pressure samples, a series of swell load tests were performed. The effect of bentonite content (5-20%) and sample moisture content (10-20%) on swelling characteristics was studied.

## 2. Materials and Methods

### *2.1. Materials*

Claystone and bentonite are two materials used in this study. The claystone used arises from the Banjarbakula landfill project in Banjarbaru. It's estimated that 8000m3 of claystone was dumped during the project's construction. The claystone has a specific gravity of 2.60 and a water content of 2.75% on average in the field. The soil contains 5.5% sand, 43.9% silt, and 51.6% clay and has a liquid limit of 50.76%, a plastic limit of 20.95%, a plasticity index of 29.8%, and a shringkage limit of 9.74%. Ca2+, with a 4.3 meq/g exchangeable cation, is the dominant exchangeable cation in the claystone.

Meanwhile, the bentonite used is commercial bentonite from Indonesia. The specific gravity of the material is 2.71, with a hygroscopic water content of 14.1%. Bentonite is composed of 1.4% fine sand, 8.3% silt, and 90.3% clay. The sample has a liquid limit of 351.71%, a plastic limit of 44.68%, a shrinkage limit of 41.89%, and a plasticity index of 307.03%. The main exchangeable cation of $Ca^{2+}$ in bentonite has a capacity of 18.70 meq/g.

### *2.2. Techniques and Procedures*

#### *2.2.1. Sample preparation*

The claystone was subjected to a Proctor compaction test, which yielded an optimum moisture content of 15% and a maximum dry density of 16kN/m$^3$. This density was used in this study, along with an additional moisture content at dry of optimum (i.e., 10%) and wet of optimum (i.e., 20%). Crushed claystone was sieved with a No. 40 mesh. Bentonite was mixed in a certain weight to achieve dry weight contents of 5, 10, 15, and 20% in the mixture. After evenly mixing the claystone and bentonite, water was gradually added with a sprayer to attain a moisture content of 10, 15, and 20%. In mold with a diameter of 6.2cm and a height of 2cm, the sample was statically compacted to achieve a dry density of 16kN/m$^3$. For comparison, claystone with the same density and moisture content was tested. Claystone and bentonite are referred to as "CS" and "B" in this paper. Meanwhile, moisture content is denoted by the letter "w." Table 1 summarizes the conditions and sample codes used.

**Table 1.** Initial conditions and codes of the samples used

| Water content | Bentonite content | | | | |
|---|---|---|---|---|---|
| | 100% CS | 5% | 10% | 15% | 20% |
| 10% | 100CSw10 | 95CS5Bw10 | 90CS10Bw10 | 85CS15Bw10 | 80CS20Bw10 |
| 15% | 100CSw15 | 95CS5Bw15 | 90CS10Bw15 | 85CS15Bw15 | 80CS20Bw15 |
| 20% | 100CSw20 | 95CS5Bw20 | 90CS10Bw20 | 85CS15Bw20 | 80CS20Bw50 |

#### *2.2.2. Swelling potensial and swelling pressure tests*

The swell under load technique was used for the swelling test. In this test, the oedometer was used to obtain both swelling potential or swelling strain and swelling pressure in the same specimen. In the first step, the sample was subjected to a pressure of 6.9 kPa and inundated with water until equilibrium was reached, as indicated by no change in dial reading during testing [11]. The load was then gradually added to the load increament ratio (LIR) in the same way as in the consolidation test (i.e. LIR = 2) until the void ratio equals its initial value. Based on a swell-load test, the pressure at which the void ratio is equal corresponds to swelling pressure [12].

## 3. Results and Discussion

### *3.1. Swelling Potential*

Figure 1 depicts the swelling development over time for 100% claystone samples and claystone-bentonite mixtures with bentonite contents ranging from 5 to 20%. Figure 1(a) represents the swelling development of a sample with a moisture content of 10%, while Figures 1(b) and 1(c) exhibit the

swelling development of samples with moisture contents of 15% and 20%, respectively. As shown in the figure, the swelling strain increases over time and remains constant at a certain point. The swelling potential of samples is determined by swelling in which no noticeable difference is visible in the graph. The swelling strain was found to be constant in less than 100 minutes for 100 percent claystone samples (i.e., 100CSw10 and 100CSw15). Meanwhile, the swelling potential of other samples can be determined after more than 100 minutes, and samples with bentonite contents of 15% and 20% can be determined after more than 2000 minutes. As the percentage of bentonite in the mixture increases, the time to reach equilibrium rises.

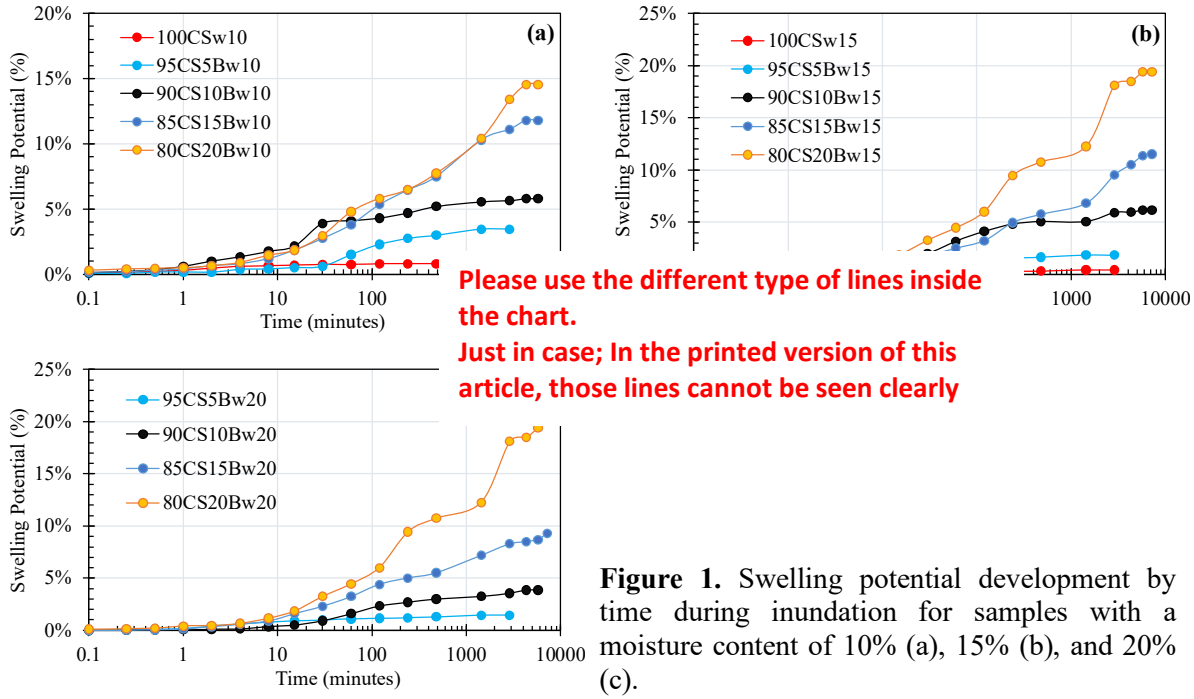


**Figure 1.** Swelling potential development by time during inundation for samples with a moisture content of 10% (a), 15% (b), and 20% (c).

Table 2 summarizes the swelling potential of the samples, which is plotted as a function of bentonite content in Figure 2. In general, as shown in Figure 2, the swelling potential increases as the bentonite content increases. If the increase in swelling per percentage of bentonite is calculated as the difference in swelling divided by the addition of bentonite content, then for samples containing up to 10% bentonite, a 0.4-0.7% increase in swelling is obtained per one percent of bentonite. Meanwhile, for samples containing more than 10% bentonite (i.e., 15-20% bentonite), the swelling addition was 1.1 percent -1.4 percent per one percent bentonite. As a result, samples with a bentonite content greater than 10% show a greater increase in swelling.

Similarly, the difference in swelling potential data for each water content is divided by the percentage of water content to investigate the effect of water content. The increase or decrease in swelling potential per one percent water content was found to be 0.1-0.3%. It can be concluded that the initial water content of claystone-bentonite mixtures has no significant effect on its swelling potential.

**Table 2.** Swelling potential of compacted claystone–bentonite mixtures

| Water content | Swelling potential (%) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 0.8 | 3.5 | 5.8 | 11.8 | 14.6 |
| w=15% | 0.4 | 1.9 | 6.2 | 11.5 | 19.4 |
| w=20% | 0.0 | 1.5 | 4.9 | 9.3 | 19.0 |

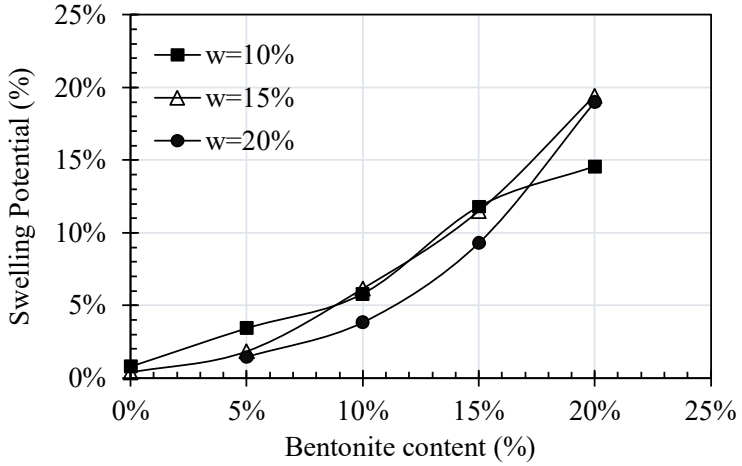


**Figure 2.** Swelling potential as a function of bentonite content

*3.2. Swelling Pressure*

The swell load test result of a claystone-bentonite mixture sample utilized in this investigation is shown in Figure 3. When the sample is inundated with water, the void ratio increases from 0.40 to 0.48, as shown in Figure 3 (a) for the 90CS10Bw15 sample, where this data is employed as the amount of the swelling potential. The void ratio decreases with increasing pressure, and the initial void ratio is intersected at 52.32 kPa. In Figure 3 (b), the sample void ratio of 80CS20Bw20 grew during the wetting process from 0.39 to 0.61, then declined with rising pressure until it intersected with the sample's initial void ratio at 183.82kPa. Swelling pressures for 90CS10Bw15 and 80CS20Bw20 are 52.32kPa and 183.82kPa, respectively.

The swell load test results are summarized in Table 3 and plotted as a function of bentonite content in Figure 4. Figure 4 shows that the higher the bentonite content, the greater the swelling pressure of the sample. The average increase in swelling pressure per 1 percent addition of bentonite was 1.4 percent, 5.87 percent, 15.15 percent, and 13.43 percent for samples containing 5%, 10%, 15%, and 20% bentonite, respectively. As a result, it can be concluded that the highest increase in swelling pressure occurs when the bentonite content exceeds 10%.

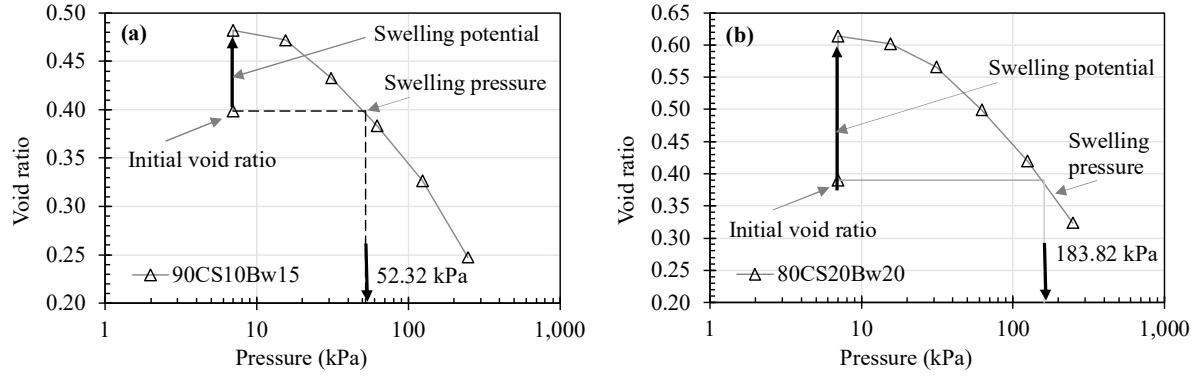


**Figure 3.** Typical swelling pressure determination from swell–load test technique (a) sample of 90CS10Bw15 dan (b) sample of 80CS20Bw20

Figure 4 also shows that specimens with a moisture content of 15% get the highest swelling pressure. This is attributed to the reason that the water content represents the optimum moisture content of the claystone sample used in this study. The swelling pressure results are influenced by the dominant claystone in the mixture. Despite having the same initial dry density, the swelling pressure obtained by the swell-load test method varies with moisture content. This is due to the fact that the microstructure

of samples compacted at various water contents results in a different macro-micro pore distribution [13]. Furthermore, because the void ratio of the samples changed during the test, the stress paths traversed by the samples were also different.

**Table 3.** Swelling pressure of compacted claystone–bentonite mixtures

| Water content | Swelling pressure (kPa) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 13.01 | 14.16 | 33.74 | 110.49 | 152.85 |
| w=15% | 15.25 | 16.46 | 52.32 | 136.42 | 229.43 |
| w=20% | 0.0 | 18.6 | 51.24 | 117.7 | 183.82 |

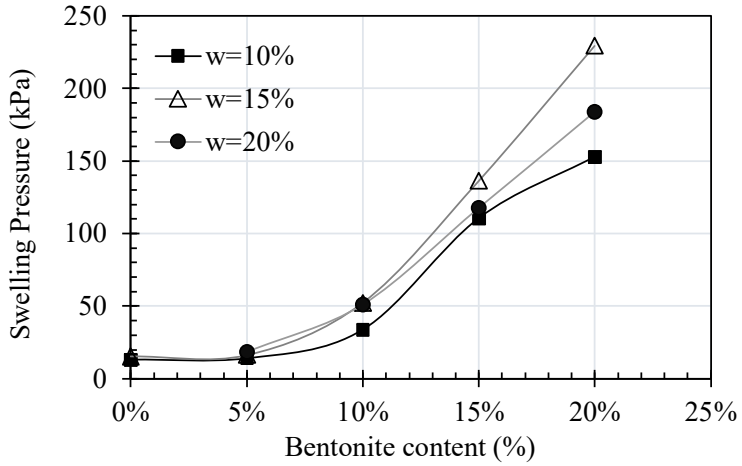


**Figure 4.** Swelling pressure as a function of bentonite content

According to Sridharan et al [12], the swelling pressure tested using the swell-load method takes a long time. Meanwhile, it tends to be faster to obtain the swelling potential. The relationship between swelling potential and swelling pressure of claystone-bentonite mixture samples obtained in this study is depicted in Figure 5. Regardless of the sample's bentonite or water content, the relationship between the two can be determined by a straight line equation with $R^2 = 0.9512$. (Equation 1).

$$P_s\ (kPa) = 10.8 S_p \tag{1}$$

where $P_s$ and $S_p$ denote swelling pressure in kPa and swelling potential, respectively.

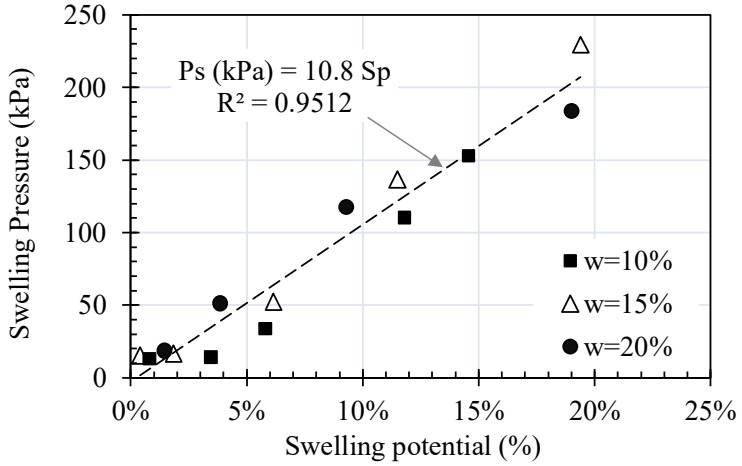


**Figure 5.** Swelling pressure and swelling potential correlation

## 4. Conclusions

The swelling characteristics of a claystone-bentonite mixture, including swelling potential and swelling pressure, have been described and analyzed. The swelling potential of the sample increases as the bentonite content increases. The greatest increase occurred in samples containing more than 10% bentonite, with 1.1-1.4% per one percent bentonite. The sample's swelling pressure rises as the bentonite content rises. The greatest increase was also observed in samples with a bentonite content greater than 10%, with an average increase of 13.3-15.3% per one percent increase in bentonite in the mixture. The water content had no significant effect on swelling potential or swelling pressure of compacted claystone-bentonite investigated in this study. Moreover, the linear swelling pressure and swelling potential relationship is accomplished using the Ps (kPa) = 10.8 sp equation, whereas Ps and Sp are swelling pressures in kPa and swelling potential.


## Acknowledgement

The authors are grateful for the financial support provided by University of Lambung Mangkurat through the "Dosen Wajib Meneliti" program in 2021.


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# Swelling Characteristics of Compacted Claystone–Bentonite Mixtures

**Abstract.** High-density claystone mixtures have been suggested as liners in radioactive waste repositories. However, this material can also be used as a liner in landfills. This study focuses on swelling characteristics of compacted claystone-bentonite at low density for landfill applications. Claystone was taken from the Banjarbakula landfill project in Banjarbaru. Furthermore, the bentonite used is a commercial in Indonesia. Claystone was mixed with bentonite with a content of 5, 10, 15, and 20% on a dry weight basis. The mixture is statically compacted with a moisture content of 10, 15, and 20% to achieve a dry density of 16 kN/m$^3$. A swell-load test was carried out using the conventional oedometer equipment to obtain swelling potential and swelling pressure of samples. The results show that the swelling potential and swelling pressure increase with the increase in bentonite content. At a bentonite content of more than 10%, both increased significantly. This research also revealed a linear relationship between swelling potential and swelling potential.

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## 1. Introduction

Claystone–bentonite mixture is a material recommended for use as a liner for radioactive waste [1–4]. Aside from the economic and environmental benefits, the use of claystone has the advantage of containing minerals and chemical compositions that are compatible with the host rock [1]. However, the minerals found in claystone vary depending on the region. Other materials, such as bentonite, are required to achieve the permeability requirement as a liner.

Bentonite is required because it contains the mineral montmorillonite which absorbs more water and continues to expand. When using bentonite as a sealing material, the swelling property is important. The swelling potential and swelling pressure are two important aspects of this swelling characteristic [1,5,6], [7]. The swelling potential, also known as percent swelling, is the ratio of deformation to initial sample thickness. Meanwhile, swelling pressure is the pressure required to keep the void ratio constant as the sample absorbs water [1]. By this definition, there are three methods for determining swelling pressure: the constant volume test, the swell under load test, and the swell–load test [1].

According to some researchers, different methods produce different values of swelling pressure due to differences in loading and wetting conditions [1,8]. Furthermore, swelling pressure is highly dependent on the initial dry density of the soil speciemen. The swelling pressure increases as the initial dry density increases. The swelling pressure, on the other hand, is unaffected by the initial water content. Meanwhile, both the initial dry density and the moisture content of the compacted soil influence the swelling potential [5,6], [7].

As a radioactive waste liner, a mixture of claystone and bentonite is typically recommended. As a result, it is required in materials with a high dry density. Wang et al. [1] investigated the swelling properties of a claystone-bentonite mixture with a dry density of 17-19 kN/m$^3$. Zhang [2], on the other hand, used a sample with a dry density of 18.8-19.5 kN/m$^3$. For landfills, the required density is not too high as long as the permeability requirements for Indonesia are less than $1\times10^{-8}$m/s [9][10].

This research focuses on swelling characteristics of compacted claystone-bentonite with dry density at maximum Proctor compaction (i.e., 16 kN / m3). To obtain swelling potential and swelling pressure samples, a series of swell load tests were performed. The effect of bentonite content (5-20%) and sample moisture content (10-20%) on swelling characteristics was studied.

## 2. Materials and Methods

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### *2.1. Materials*

Claystone and bentonite are two materials used in this study. The claystone used arises from the Banjarbakula landfill project in Banjarbaru. It's estimated that 8000m3 of claystone was dumped during the project's construction. The claystone has a specific gravity of 2.60 and a water content of 2.75% on average in the field. The soil contains 5.5% sand, 43.9% silt, and 51.6% clay and has a liquid limit of 50.76%, a plastic limit of 20.95%, a plasticity index of 29.8%, and a shringkage limit of 9.74%. Ca2+, with a 4.3 meq/g exchangeable cation, is the dominant exchangeable cation in the claystone.
Meanwhile, the bentonite used is commercial bentonite from Indonesia. The specific gravity of the material is 2.71, with a hygroscopic water content of 14.1%. Bentonite is composed of 1.4% fine sand, 8.3% silt, and 90.3% clay. The sample has a liquid limit of 351.71%, a plastic limit of 44.68%, a shrinkage limit of 41.89%, and a plasticity index of 307.03%. The main exchangeable cation of $Ca^{2+}$ in bentonite has a capacity of 18.70 meq/g.

### *2.2. Techniques and Procedures*

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#### *2.2.1. Sample preparation*

The claystone was subjected to a Proctor compaction test, which yielded an optimum moisture content of 15% and a maximum dry density of 16kN/$m^3$. This density was used in this study, along with an additional moisture content at dry of optimum (i.e., 10%) and wet of optimum (i.e., 20%). Crushed claystone was sieved with a No. 40 mesh. Bentonite was mixed in a certain weight to achieve dry weight contents of 5, 10, 15, and 20% in the mixture. After evenly mixing the claystone and bentonite, water was gradually added with a sprayer to attain a moisture content of 10, 15, and 20%. In mold with a diameter of 6.2cm and a height of 2cm, the sample was statically compacted to achieve a dry density of 16kN/$m^3$. For comparison, claystone with the same density and moisture content was tested. Claystone and bentonite are referred to as "CS" and "B" in this paper. Meanwhile, moisture content is denoted by the letter "w." Table 1 summarizes the conditions and sample codes used.

**Table 1.** Initial conditions and codes of the samples used

| Water content | Bentonite content | | | | |
|---|---|---|---|---|---|
| | 100% CS | 5% | 10% | 15% | 20% |
| 10% | 100CSw10 | 95CS5Bw10 | 90CS10Bw10 | 85CS15Bw10 | 80CS20Bw10 |
| 15% | 100CSw15 | 95CS5Bw15 | 90CS10Bw15 | 85CS15Bw15 | 80CS20Bw15 |
| 20% | 100CSw20 | 95CS5Bw20 | 90CS10Bw20 | 85CS15Bw20 | 80CS20Bw50 |

#### *2.2.2. Swelling potensial and swelling pressure tests*

The swell under load technique was used for the swelling test. In this test, the oedometer was used to obtain both swelling potential or swelling strain and swelling pressure in the same specimen. In the first step, the sample was subjected to a pressure of 6.9 kPa and inundated with water until equilibrium was reached, as indicated by no change in dial reading during testing [11]. The load was then gradually added to the load increament ratio (LIR) in the same way as in the consolidation test (i.e. LIR = 2) until the void ratio equals its initial value. Based on a swell-load test, the pressure at which the void ratio is equal corresponds to swelling pressure [12].

## 3. Results and Discussion

### *3.1. Swelling Potential*

Figure 1 depicts the swelling development over time for 100% claystone samples and claystone-bentonite mixtures with bentonite contents ranging from 5 to 20%. Figure 1(a) represents the swelling development of a sample with a moisture content of 10%, while Figures 1(b) and 1(c) exhibit the

swelling development of samples with moisture contents of 15% and 20%, respectively. As shown in the figure, the swelling strain increases over time and remains constant at a certain point. The swelling potential of samples is determined by swelling in which no noticeable difference is visible in the graph. The swelling strain was found to be constant in less than 100 minutes for 100 percent claystone samples (i.e., 100CSw10 and 100CSw15). Meanwhile, the swelling potential of other samples can be determined after more than 100 minutes, and samples with bentonite contents of 15% and 20% can be determined after more than 2000 minutes. As the percentage of bentonite in the mixture increases, the time to reach equilibrium rises.

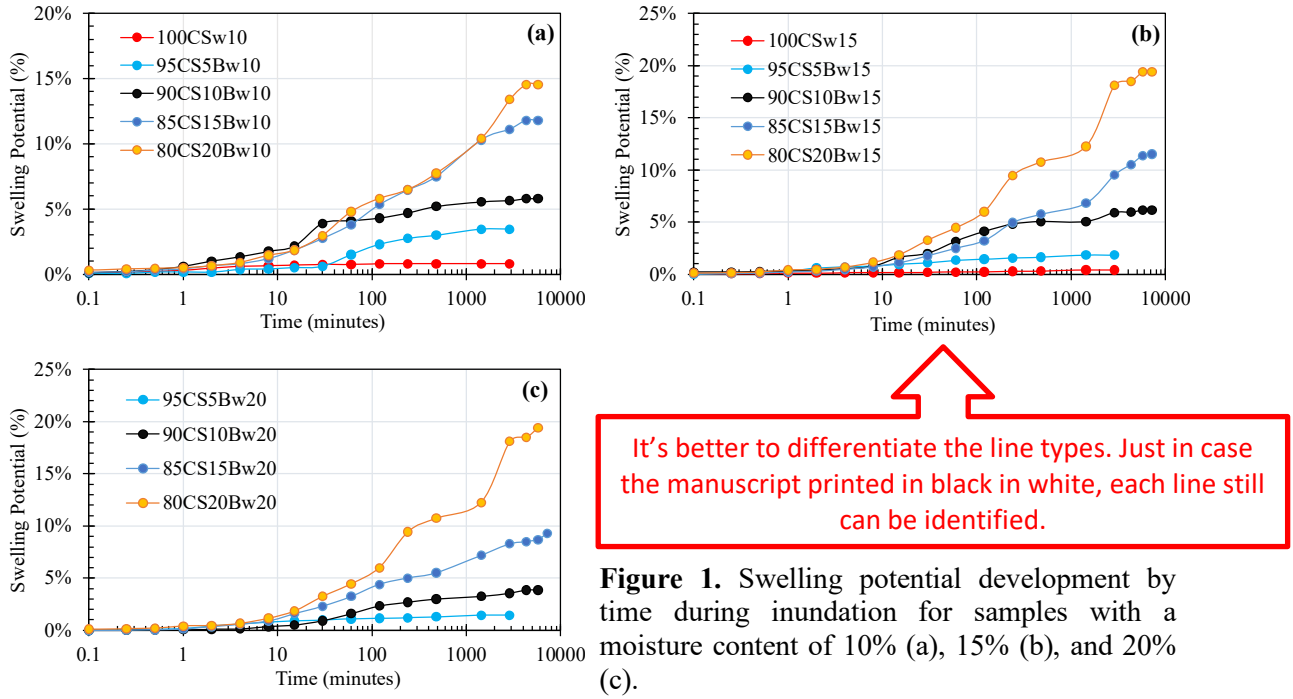


**Figure 1.** Swelling potential development by time during inundation for samples with a moisture content of 10% (a), 15% (b), and 20% (c).

Table 2 summarizes the swelling potential of the samples, which is plotted as a function of bentonite content in Figure 2. In general, as shown in Figure 2, the swelling potential increases as the bentonite content increases. If the increase in swelling per percentage of bentonite is calculated as the difference in swelling divided by the addition of bentonite content, then for samples containing up to 10% bentonite, a 0.4-0.7% increase in swelling is obtained per one percent of bentonite. Meanwhile, for samples containing more than 10% bentonite (i.e., 15-20% bentonite), the swelling addition was 1.1 percent -1.4 percent per one percent bentonite. As a result, samples with a bentonite content greater than 10% show a greater increase in swelling.

Similarly, the difference in swelling potential data for each water content is divided by the percentage of water content to investigate the effect of water content. The increase or decrease in swelling potential per one percent water content was found to be 0.1-0.3%. It can be concluded that the initial water content of claystone-bentonite mixtures has no significant effect on its swelling potential.

**Table 2.** Swelling potential of compacted claystone–bentonite mixtures

| Water content | Swelling potential (%) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 0.8 | 3.5 | 5.8 | 11.8 | 14.6 |
| w=15% | 0.4 | 1.9 | 6.2 | 11.5 | 19.4 |
| w=20% | 0.0 | 1.5 | 4.9 | 9.3 | 19.0 |

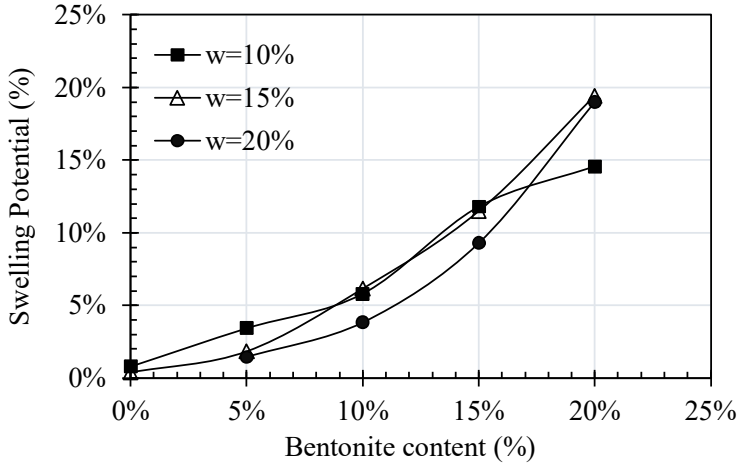


**Figure 2.** Swelling potential as a function of bentonite content

*3.2. Swelling Pressure*

The swell load test result of a claystone-bentonite mixture sample utilized in this investigation is shown in Figure 3. When the sample is inundated with water, the void ratio increases from 0.40 to 0.48, as shown in Figure 3 (a) for the 90CS10Bw15 sample, where this data is employed as the amount of the swelling potential. The void ratio decreases with increasing pressure, and the initial void ratio is intersected at 52.32 kPa. In Figure 3 (b), the sample void ratio of 80CS20Bw20 grew during the wetting process from 0.39 to 0.61, then declined with rising pressure until it intersected with the sample's initial void ratio at 183.82kPa. Swelling pressures for 90CS10Bw15 and 80CS20Bw20 are 52.32kPa and 183.82kPa, respectively.

The swell load test results are summarized in Table 3 and plotted as a function of bentonite content in Figure 4. Figure 4 shows that the higher the bentonite content, the greater the swelling pressure of the sample. The average increase in swelling pressure per 1 percent addition of bentonite was 1.4 percent, 5.87 percent, 15.15 percent, and 13.43 percent for samples containing 5%, 10%, 15%, and 20% bentonite, respectively. As a result, it can be concluded that the highest increase in swelling pressure occurs when the bentonite content exceeds 10%.

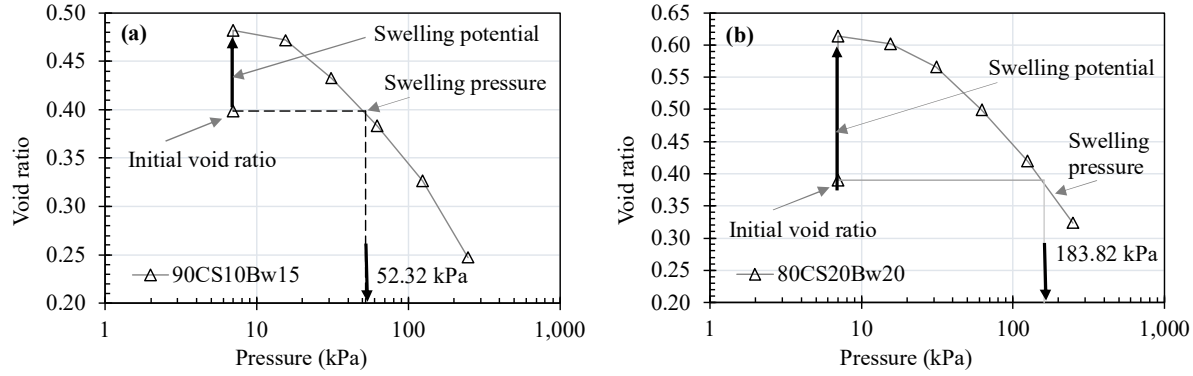


**Figure 3.** Typical swelling pressure determination from swell–load test technique (a) sample of 90CS10Bw15 dan (b) sample of 80CS20Bw20

Figure 4 also shows that specimens with a moisture content of 15% get the highest swelling pressure. This is attributed to the reason that the water content represents the optimum moisture content of the claystone sample used in this study. The swelling pressure results are influenced by the dominant claystone in the mixture. Despite having the same initial dry density, the swelling pressure obtained by the swell-load test method varies with moisture content. This is due to the fact that the microstructure

of samples compacted at various water contents results in a different macro-micro pore distribution [13]. Furthermore, because the void ratio of the samples changed during the test, the stress paths traversed by the samples were also different.

**Table 3.** Swelling pressure of compacted claystone–bentonite mixtures

| Water content | Swelling pressure (kPa) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 13.01 | 14.16 | 33.74 | 110.49 | 152.85 |
| w=15% | 15.25 | 16.46 | 52.32 | 136.42 | 229.43 |
| w=20% | 0.0 | 18.6 | 51.24 | 117.7 | 183.82 |

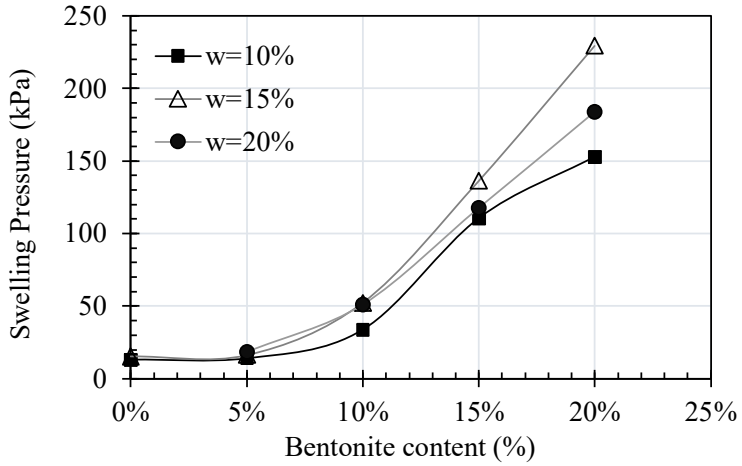


**Figure 4.** Swelling pressure as a function of bentonite content

According to Sridharan et al [12], the swelling pressure tested using the swell-load method takes a long time. Meanwhile, it tends to be faster to obtain the swelling potential. The relationship between swelling potential and swelling pressure of claystone-bentonite mixture samples obtained in this study is depicted in Figure 5. Regardless of the sample's bentonite or water content, the relationship between the two can be determined by a straightline equation with $R^2 = 0.9512$. (Equation 1).

$$P_s\ (kPa) = 10.8 S_p \tag{1}$$

where $P_s$ and $S_p$ denote swelling pressure in kPa and swelling potential, respectively.

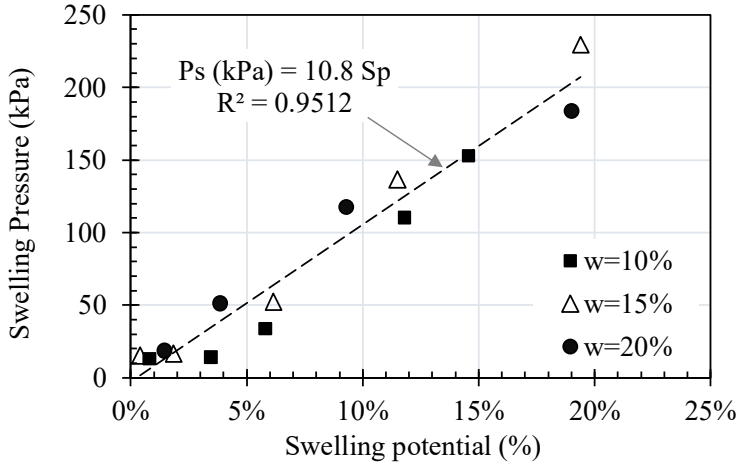


**Figure 5.** Swelling pressure and swelling potential correlation

## 4. Conclusions

The swelling characteristics of a claystone-bentonite mixture, including swelling potential and swelling pressure, have been described and analyzed. The swelling potential of the sample increases as the bentonite content increases. The greatest increase occurred in samples containing more than 10% bentonite, with 1.1-1.4% per one percent bentonite. The sample's swelling pressure rises as the bentonite content rises. The greatest increase was also observed in samples with a bentonite content greater than 10%, with an average increase of 13.3-15.3% per one percent increase in bentonite in the mixture. The water content had no significant effect on swelling potential or swelling pressure of compacted claystone-bentonite investigated in this study. Moreover, the linear swelling pressure and swelling potential relationship is accomplished using the Ps (kPa) = 10.8 sp equation, whereas Ps and Sp are swelling pressures in kPa and swelling potential.


## Acknowledgement

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# Swelling Characteristics of Compacted Claystone–Bentonite Mixtures

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**Abstract.** High-density claystone mixtures have been suggested as liners in radioactive waste repositories. However, this material can also be used as a liner in landfills. This study focuses on swelling characteristics of compacted claystone-bentonite at a low density for landfill applications. Claystone was taken from the Banjarbakula landfill project in Banjarbaru. Furthermore, the bentonite used is a commercial in Indonesia. Claystone was mixed with 5, 10, 15, and 20% of bentonite on a dry weight basis. The mixture was statically compacted with moisture contents of 10, 15, and 20% to achieve a dry density of 16 kN/m$^3$. A swell-load test was carried out using conventional oedometer equipment to obtain the swelling potential and swelling pressure of the samples. The results show that the swelling potential and swelling pressure increased with an increase in bentonite contents. At a bentonite content of more than 10%, both increased significantly. This research also revealed a linear relationship between swelling potential and swelling pressure.

## 1. Introduction

The claystone–bentonite mixture is a material recommended for use as a liner for radioactive waste [1–4]. Aside from its economic and environmental benefits, the use of claystone has the advantage of containing minerals and chemical compositions that are compatible with the host rock [1]. However, the minerals in claystone vary by region. Other materials, such as bentonite, are required to achieve the permeability requirement as a liner.

Bentonite is required because it contains the mineral montmorillonite, which absorbs more water and continues to expand. When using bentonite as a sealing material, the swelling property is important. The swelling potential and swelling pressure are two important aspects of this swelling characteristic [1,5,6], [7]. The swelling potential, also known as the percent swelling, is the ratio of deformation to the initial sample thickness. Meanwhile, swelling pressure is the pressure required to keep the void ratio constant as the sample absorbs water [1]. By this definition, there are three methods for determining swelling pressure: the constant volume test, the swell under load test, and the swell–load test [1].

According to some researchers, different methods produce different values of swelling pressure due to differences in loading and wetting conditions [1,8]. Furthermore, swelling pressure is highly dependent on the initial dry density of the soil specimen. The swelling pressure increases as the initial dry density increases. The swelling pressure, on the other hand, is unaffected by the initial water content. Meanwhile, both the initial dry density and the moisture content of the compacted soil influence the swelling potential [5,6,7].

A mixture of claystone and bentonite is typically recommended as a radioactive waste liner. As a result, materials must have a high dry density. Wang et al. [1] investigated the swelling properties of a

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claystone-bentonite mixture with a dry density of 17-19 kN/m$^3$. Zhang [2], on the other hand, used a sample with a dry density of 18.8-19.5 kN/m$^3$. For landfills, the required density is not too high as long as the permeability requirements for Indonesia are less than $1\times10^{-8}$m/s [9,10].
This research focuses on the swelling characteristics of compacted claystone-bentonite with a dry density at maximum Proctor compaction (i.e., 16 kN/m3). To obtain the swelling potential and swelling pressure of the samples, a series of swell load tests were performed. The effects of bentonite content (5-20%) and sample moisture content (10-20%) on swelling characteristics were studied.

## 2. Materials and Methods

### *2.1. Materials*

Claystone and bentonite are the two materials used in this study. The claystone used derives from the Banjarbakula landfill project in Banjarbaru. It is estimated that 8000 m$^3$ of claystone was dumped during the project's construction. The claystone has a specific gravity of 2.60 and a water content of 2.75% on average in the field. The soil contains 5.5% sand, 43.9% silt, and 51.6% clay and has a liquid limit of 50.76%, a plastic limit of 20.95%, a plasticity index of 29.8%, and a shrinkage limit of 9.74%. $Ca^{2+}$, with a 4.3 meq/g exchangeable cation, is the dominant exchangeable cation in the claystone.
Meanwhile, the bentonite used is commercial bentonite from Indonesia. The specific gravity of the material is 2.71, with a hygroscopic water content of 14.1%. Bentonite is composed of 1.4% fine sand, 8.3% silt, and 90.3% clay. The sample has a liquid limit of 351.71%, a plastic limit of 44.68%, a shrinkage limit of 41.89%, and a plasticity index of 307.03%. The main exchangeable cation of $Ca^{2+}$ in bentonite has a capacity of 18.70 meq/g.

### *2.2. Techniques and Procedures*

#### *2.2.1. Sample preparation*

The claystone was subjected to a Proctor compaction test, which yielded an optimum moisture content of 15% and a maximum dry density of 16 kN/m$^3$. This density was used in this study, along with an additional moisture content at dry of optimum (i.e., 10%) and wet of optimum (i.e., 20%). Crushed claystone was sieved with a No. 40 mesh. Bentonite was mixed at a certain weight to achieve dry weight contents of 5, 10, 15, and 20% in the mixture. After evenly mixing the claystone and bentonite, water was gradually added with a sprayer to attain a moisture content of 10, 15, and 20%. The sample was statically compacted in a mold with a diameter of 6.2 cm and a height of 2 cm to achieve a dry density of 16 kN/m$^3$. Claystone with the same density and moisture content was tested for comparison. Claystone and bentonite are referred to as "CS" and "B" in this paper. Meanwhile, moisture content is denoted by the letter "w." Table 1 summarises the conditions and sample codes used.

**Table 1.** Initial conditions and codes of the samples used

| Water content | Bentonite content | | | | |
|---|---|---|---|---|---|
| | 100% CS | 5% | 10% | 15% | 20% |
| 10% | 100CSw10 | 95CS5Bw10 | 90CS10Bw10 | 85CS15Bw10 | 80CS20Bw10 |
| 15% | 100CSw15 | 95CS5Bw15 | 90CS10Bw15 | 85CS15Bw15 | 80CS20Bw15 |
| 20% | 100CSw20 | 95CS5Bw20 | 90CS10Bw20 | 85CS15Bw20 | 80CS20Bw50 |

#### *2.2.2. Swelling potential and swelling pressure tests*

The swell under load technique was used for the swelling test. In this test, the oedometer was used to obtain both the swelling potential or swelling strain and swelling pressure in the same specimen. In the first step, the sample was subjected to a pressure of 6.9 kPa and inundated with water until equilibrium was reached, as indicated by no change in the dial reading during testing [11]. The load was then gradually added to the load increment ratio (LIR) in the same way as in the consolidation test (i.e., LIR = 2) until the void ratio equalled its initial value. Based on a swell-load test, the pressure at which the void ratio is equal corresponds to the swelling pressure [12].

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## 3. Results and Discussion

### *3.1. Swelling Potential*

Figure 1 depicts the swelling development over time for 100% claystone samples and claystone-bentonite mixtures with bentonite contents ranging from 5 to 20%. Figure 1(a) represents the swelling development of a sample with a moisture content of 10%, while Figures 1(b) and 1(c) exhibit the swelling development of samples with moisture contents of 15% and 20%, respectively. As shown in the figure, the swelling strain increases over time and remains constant at a certain point. The swelling potential of the samples is determined by the swelling in which no noticeable difference is visible in the graph. The swelling strain was found to be constant over less than 100 minutes for 100% claystone samples (i.e., 100CSw10 and 100CSw15). Meanwhile, the swelling potential of other samples could be determined after more than 100 minutes, and samples with bentonite contents of 15% and 20% could be determined after more than 2000 minutes. As the percentage of bentonite in the mixture increased, the time to reach equilibrium rose.

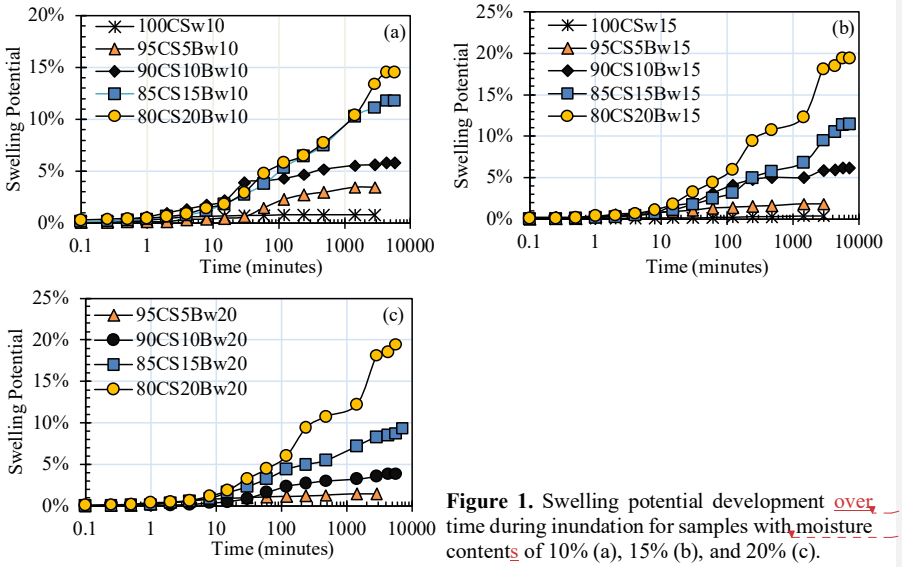


**Figure 1.** Swelling potential development over time during inundation for samples with moisture contents of 10% (a), 15% (b), and 20% (c).

Table 2 summarises the swelling potential of the samples, which is plotted as a function of bentonite content in Figure 2. In general, as shown in Figure 2, the swelling potential increased as the bentonite content increased. If the increase in swelling per percentage of bentonite is calculated as the difference in swelling divided by the addition of bentonite content, then for samples containing up to 10% bentonite, a 0.4-0.7% increase in swelling was obtained per one percent of bentonite. Meanwhile, for samples containing more than 10% bentonite (i.e., 15-20% bentonite), the swelling addition was 1.1-1.4% per one percent bentonite. As a result, samples with a bentonite contents greater than 10% showed a greater increase in swelling.

Similarly, the difference in swelling potential data for each water content is divided by the percentage of water content to investigate the effects of water content. The increase or decrease in swelling potential per one percent water content was found to be 0.1-0.3%. It can be concluded that the initial water content of claystone-bentonite mixtures had no significant effect on their swelling potential.

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**Table 2.** Swelling potential of compacted claystone–bentonite mixtures

| Water content | Swelling potential (%) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 0.8 | 3.5 | 5.8 | 11.8 | 14.6 |
| w=15% | 0.4 | 1.9 | 6.2 | 11.5 | 19.4 |
| w=20% | 0.0 | 1.5 | 4.9 | 9.3 | 19.0 |

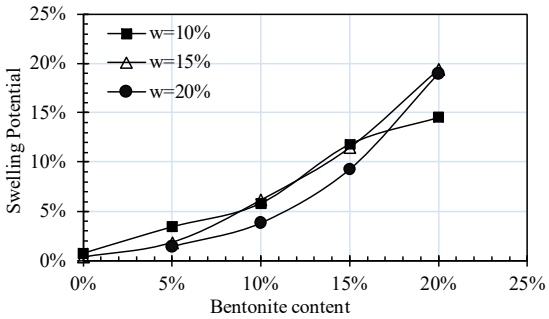


**Figure 2.** Swelling potential as a function of bentonite content.

*3.2. Swelling Pressure*

The swell load test result of a claystone-bentonite mixture sample utilised in this investigation is shown in Figure 3. When the sample was inundated with water, the void ratio increased from 0.40 to 0.48, as shown in Figure 3 (a) for the 90CS10Bw15 sample, where this data was used as the amount of the swelling potential. The void ratio decreased with increasing pressure, and the initial void ratio was intersected at 52.32 kPa. In Figure 3 (b), the sample void ratio of 80CS20Bw20 grew during the wetting process from 0.39 to 0.61, then declined with rising pressure until it intersected with the sample's initial void ratio at 183.82kPa. The swelling pressures for 90CS10Bw15 and 80CS20Bw20 were 52.32kPa and 183.82kPa, respectively.

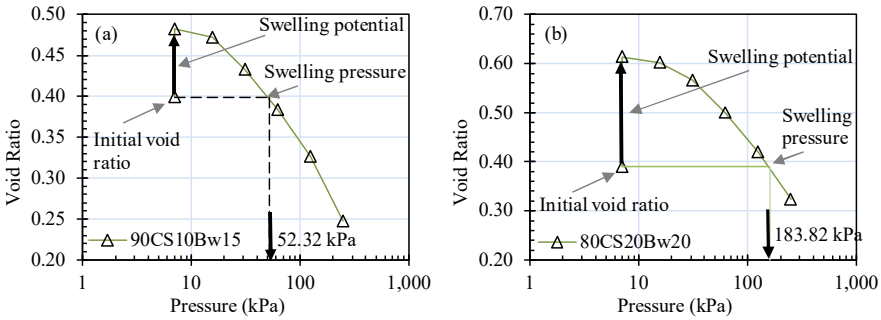


**Figure 3.** Typical swelling pressure determination from swell–load test technique (a) sample of 90CS10Bw15 and (b) sample of 80CS20Bw20.

The swell load test results are summarised in Table 3 and plotted as a function of bentonite content in Figure 4. Figure 4 shows that the higher the bentonite content, the greater the swelling pressure of the sample. The average increase in swelling pressure per one percent addition of bentonite was 1.4, 5.87,

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15.15, and 13.43% for samples containing 5, 10, 15, and 20% bentonite, respectively. As a result, it can be concluded that the highest increase in swelling pressure occurred when the bentonite content exceeded 10%.

**Table 3.** Swelling pressure of compacted claystone–bentonite mixtures

| Water content | Swelling pressure (kPa) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 13.01 | 14.16 | 33.74 | 110.49 | 152.85 |
| w=15% | 15.25 | 16.46 | 52.32 | 136.42 | 229.43 |
| w=20% | 0.0 | 18.6 | 51.24 | 117.7 | 183.82 |

Figure 4 also shows that specimens with a moisture content of 15% had the highest swelling pressure. This is attributed to the fact that the water content represents the optimum moisture content of the claystone sample used in this study. The swelling pressure results were influenced by the dominant claystone in the mixture. Despite having the same initial dry density, the swelling pressure obtained by the swell-load test method varied with moisture content. This is due to the fact that the microstructure of samples compacted at various water contents results in a different macro-micro pore distribution [13]. Furthermore, because the void ratio of the samples changed during the test, the stress paths traversed by the samples were also different.

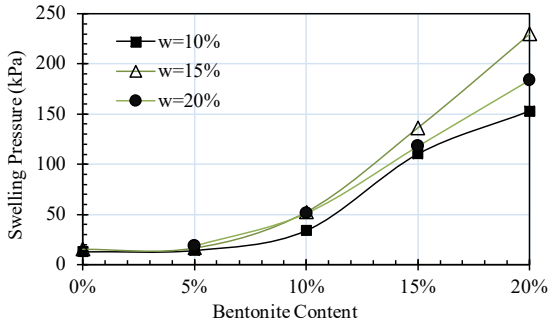


**Figure 4.** Swelling pressure as a function of bentonite content.

According to Sridharan et al [12], the swelling pressure tested using the swell-load method takes a long time. Meanwhile, the swelling potential can be obtained faster. The relationship between the swelling potential and swelling pressure of the claystone-bentonite mixture samples obtained in this study is depicted in Figure 5. Regardless of the sample's bentonite or water content, the relationship between the two can be determined by a straight-line equation with $R^2 = 0.9512$. (Equation 1).

$$P_s\ (kPa) = 10.8S_p \quad (1)$$

where $P_s$ and $S_p$ denote swelling pressure in kPa and swelling potential, respectively.

## 4. Conclusions

The swelling characteristics of a claystone-bentonite mixture, including its swelling potential and swelling pressure, have been described and analysed. The swelling potential of the sample increased as the bentonite content increased. The greatest increase occurred in samples containing more than 10% bentonite, with 1.1-1.4% per one percent bentonite. The sample's swelling pressure rose as the bentonite content rose. The greatest increase was also observed in samples with a bentonite content greater than 10%, with an average increase of 13.3-15.3% per one percent increase in bentonite in the mixture. The

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water content had no significant effect on the swelling potential or swelling pressure of the compacted claystone-bentonite investigated in this study. Moreover, the linear swelling pressure and swelling potential relationship was accomplished using the Ps (kPa) = 10.8 sp equation, whereas Ps and Sp were swelling pressures in kPa and swelling potential.

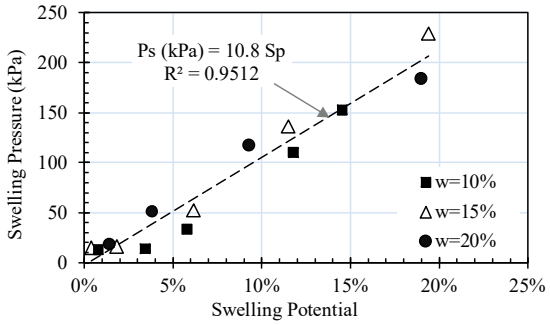


**Figure 5.** Swelling pressure and swelling potential correlation.


**Acknowledgement**

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# Swelling Characteristics of Compacted Claystone–Bentonite Mixtures

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[2] Civil Engineering Study Program, University of Lambung Mangkurat, Banjarbaru 70714, Indonesia

**Abstract.** High-density claystone mixtures have been suggested as liners in radioactive waste repositories. However, this material can also be used as a liner in landfills. This study focuses on swelling characteristics of compacted claystone-bentonite at low density for landfill applications. Claystone was taken from the Banjarbakula landfill project in Banjarbaru. Furthermore, the bentonite used is a commercial in Indonesia. Claystone was mixed with bentonite with a content of 5, 10, 15, and 20% on a dry weight basis. The mixture is statically compacted with a moisture content of 10, 15, and 20% to achieve a dry density of 16 kN/m$^3$. A swell-load test was carried out using the conventional oedometer equipment to obtain swelling potential and swelling pressure of samples. The results show that the swelling potential and swelling pressure increase with the increase in bentonite content. At a bentonite content of more than 10%, both increased significantly. This research also revealed a linear relationship between swelling potential and swelling pressure.

## 1. Introduction

The claystone–bentonite mixture is a material recommended for use as a liner for radioactive waste [1–4]. Aside from the economic and environmental benefits, the use of claystone has the advantage of containing minerals and chemical compositions that are compatible with the host rock [1]. However, the minerals contained in claystone vary by region. Other materials, such as bentonite, are required to achieve the permeability requirement as a liner.

Bentonite is required because it contains the mineral montmorillonite, which absorbs more water and continues to expand. When using bentonite as a sealing material, the swelling property is important. The swelling potential and swelling pressure are two important aspects of this swelling characteristic [1,5,6], [7]. The swelling potential, also known as percent swelling, is the ratio of deformation to initial sample thickness. Meanwhile, swelling pressure is the pressure required to keep the void ratio constant as the sample absorbs water [1]. By this definition, there are three methods for determining swelling pressure: the constant volume test, the swell under load test, and the swell–load test [1].

According to some researchers, different methods produce different values of swelling pressure due to differences in loading and wetting conditions [1,8]. Furthermore, swelling pressure is highly dependent on the initial dry density of the soil specimen. The swelling pressure increases as the initial dry density increases. The swelling pressure, on the other hand, is unaffected by the initial water content. Meanwhile, both the initial dry density and the moisture content of the compacted soil influence the swelling potential [5,6], [7].

As a radioactive waste liner, a mixture of claystone and bentonite is typically recommended. As a result, it is required for materials with a high dry density. Wang et al. [1] investigated the swelling properties

of a claystone-bentonite mixture with a dry density of 17-19 kN/m$^3$. Zhang [2], on the other hand, used a sample with a dry density of 18.8-19.5 kN/m$^3$. For landfills, the required density is not too high as long as the permeability requirements for Indonesia are less than $1\times10^{-8}$m/s [9][10].
This research focuses on the swelling characteristics of compacted claystone-bentonite with dry density at maximum Proctor compaction (i.e., 16 kN/m3). To obtain swelling potential and swelling pressure samples, a series of swell load tests were performed. The effect of bentonite content (5-20%) and sample moisture content (10-20%) on swelling characteristics was studied.

## 2. Materials and Methods

### *2.1. Materials*

Claystone and bentonite are two materials used in this study. The claystone used arises from the Banjarbakula landfill project in Banjarbaru. It's estimated that 8000 m$^3$ of claystone was dumped during the project's construction. The claystone has a specific gravity of 2.60 and a water content of 2.75% on average in the field. The soil contains 5.5% sand, 43.9% silt, and 51.6% clay and has a liquid limit of 50.76%, a plastic limit of 20.95%, a plasticity index of 29.8%, and a shrinkage limit of 9.74%. Ca2+, with a 4.3 meq/g exchangeable cation, is the dominant exchangeable cation in the claystone.
Meanwhile, the bentonite used is commercial bentonite from Indonesia. The specific gravity of the material is 2.71, with a hygroscopic water content of 14.1%. Bentonite is composed of 1.4% fine sand, 8.3% silt, and 90.3% clay. The sample has a liquid limit of 351.71%, a plastic limit of 44.68%, a shrinkage limit of 41.89%, and a plasticity index of 307.03%. The main exchangeable cation of $Ca^{2+}$ in bentonite has a capacity of 18.70 meq/g.

### *2.2. Techniques and Procedures*

#### *2.2.1. Sample preparation*

The claystone was subjected to a Proctor compaction test, which yielded an optimum moisture content of 15% and a maximum dry density of 16 kN/m$^3$. This density was used in this study, along with an additional moisture content at dry of optimum (i.e., 10%) and wet of optimum (i.e., 20%). Crushed claystone was sieved with a No. 40 mesh. Bentonite was mixed at a certain weight to achieve a dry weight content of 5, 10, 15, and 20% in the mixture. After evenly mixing the claystone and bentonite, water was gradually added with a sprayer to attain a moisture content of 10, 15, and 20%. In a mold with a diameter of 6.2cm and a height of 2cm, the sample was statically compacted to achieve a dry density of 16 kN/m$^3$. For comparison, claystone with the same density and moisture content was tested. Claystone and bentonite are referred to as "CS" and "B" in this paper. Meanwhile, moisture content is denoted by the letter "w." Table 1 summarizes the conditions and sample codes used.

**Table 1.** Initial conditions and codes of the samples used

| Water content | Bentonite content | | | | |
|---|---|---|---|---|---|
| | 100% CS | 5% | 10% | 15% | 20% |
| 10% | 100CSw10 | 95CS5Bw10 | 90CS10Bw10 | 85CS15Bw10 | 80CS20Bw10 |
| 15% | 100CSw15 | 95CS5Bw15 | 90CS10Bw15 | 85CS15Bw15 | 80CS20Bw15 |
| 20% | 100CSw20 | 95CS5Bw20 | 90CS10Bw20 | 85CS15Bw20 | 80CS20Bw50 |

#### *2.2.2. Swelling potential and swelling pressure tests*

The swell under load technique was used for the swelling test. In this test, the oedometer was used to obtain both swelling potential or swelling strain and swelling pressure in the same specimen. In the first step, the sample was subjected to a pressure of 6.9 kPa and inundated with water until equilibrium was reached, as indicated by no change in dial reading during testing [11]. The load was then gradually added to the load increment ratio (LIR) in the same way as in the consolidation test (i.e. LIR = 2) until the void ratio equals its initial value. Based on a swell-load test, the pressure at which the void ratio is equal corresponds to the swelling pressure [12].

## 3. Results and Discussion

### *3.1. Swelling Potential*

Figure 1 depicts the swelling development over time for 100% claystone samples and claystone-bentonite mixtures with bentonite content ranging from 5 to 20%. Figure 1(a) represents the swelling development of a sample with a moisture content of 10%, while Figures 1(b) and 1(c) exhibit the swelling development of samples with moisture contents of 15% and 20%, respectively. As shown in the figure, the swelling strain increases over time and remains constant at a certain point. The swelling potential of samples is determined by swelling in which no noticeable difference is visible in the graph. The swelling strain was found to be constant in less than 100 minutes for 100 percent claystone samples (i.e., 100CSw10 and 100CSw15). Meanwhile, the swelling potential of other samples can be determined after more than 100 minutes, and samples with bentonite content of 15% and 20% can be determined after more than 2000 minutes. As the percentage of bentonite in the mixture increases, the time to reach equilibrium rises.

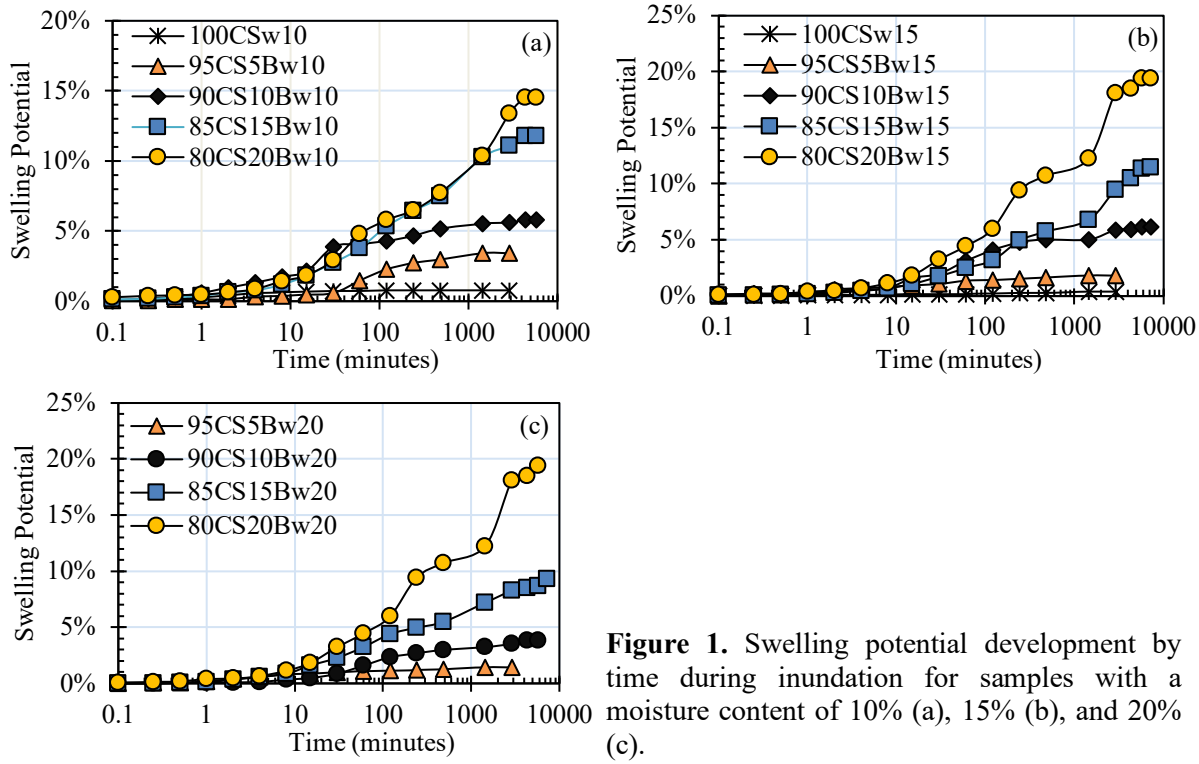


**Figure 1.** Swelling potential development by time during inundation for samples with a moisture content of 10% (a), 15% (b), and 20% (c).

Table 2 summarizes the swelling potential of the samples, which is plotted as a function of bentonite content in Figure 2. In general, as shown in Figure 2, the swelling potential increases as the bentonite content increases. If the increase in swelling per percentage of bentonite is calculated as the difference in swelling divided by the addition of bentonite content, then for samples containing up to 10% bentonite, a 0.4-0.7% increase in swelling is obtained per one percent of bentonite. Meanwhile, for samples containing more than 10% bentonite (i.e., 15-20% bentonite), the swelling addition was 1.1 percent -1.4 percent per one percent bentonite. As a result, samples with a bentonite content greater than 10% show a greater increase in swelling.

Similarly, the difference in swelling potential data for each water content is divided by the percentage of water content to investigate the effect of water content. The increase or decrease in swelling potential per one percent water content was found to be 0.1-0.3%. It can be concluded that the initial water content of claystone-bentonite mixtures has no significant effect on their swelling potential.

**Table 2.** Swelling potential of compacted claystone–bentonite mixtures

| Water content | Swelling potential (%) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 0.8 | 3.5 | 5.8 | 11.8 | 14.6 |
| w=15% | 0.4 | 1.9 | 6.2 | 11.5 | 19.4 |
| w=20% | 0.0 | 1.5 | 4.9 | 9.3 | 19.0 |

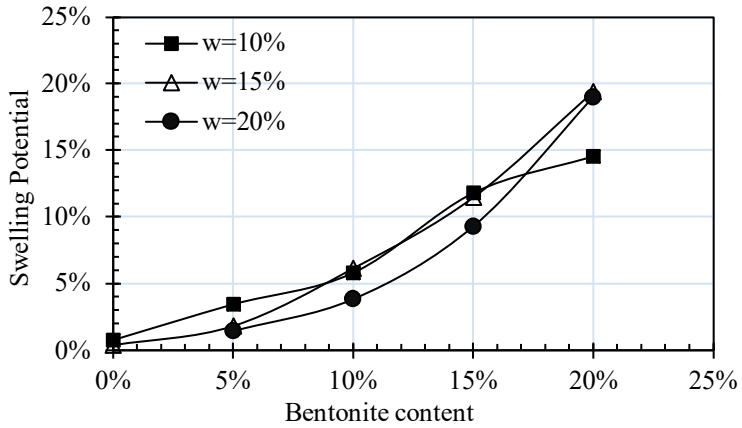


**Figure 2.** Swelling potential as a function of bentonite content

*3.2. Swelling Pressure*

The swell load test result of a claystone-bentonite mixture sample utilized in this investigation is shown in Figure 3. When the sample is inundated with water, the void ratio increases from 0.40 to 0.48, as shown in Figure 3 (a) for the 90CS10Bw15 sample, where this data is employed as the amount of the swelling potential. The void ratio decreases with increasing pressure, and the initial void ratio is intersected at 52.32 kPa. In Figure 3 (b), the sample void ratio of 80CS20Bw20 grew during the wetting process from 0.39 to 0.61, then declined with rising pressure until it intersected with the sample's initial void ratio at 183.82kPa. The swelling pressures for 90CS10Bw15 and 80CS20Bw20 are 52.32kPa and 183.82kPa, respectively.

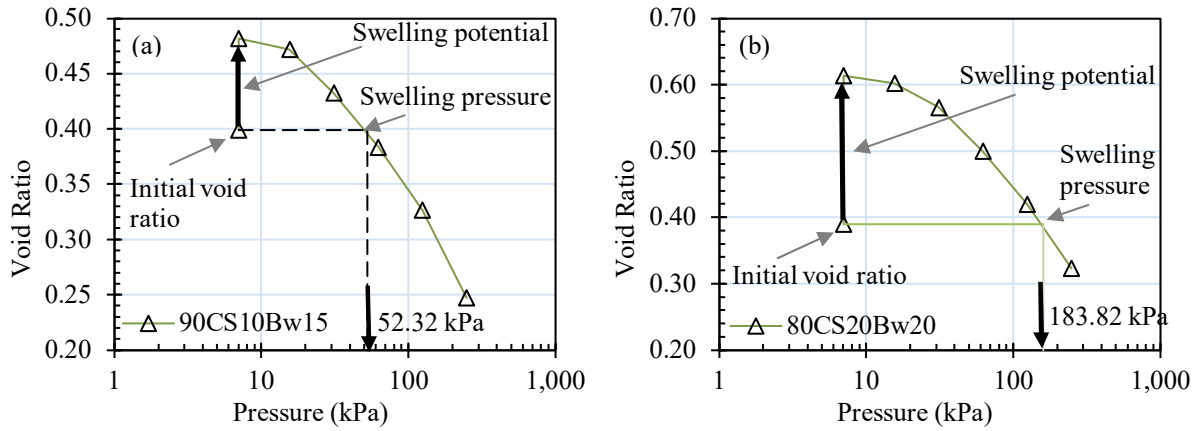


**Figure 3.** Typical swelling pressure determination from swell–load test technique (a) sample of 90CS10Bw15 dan (b) sample of 80CS20Bw20

The swell load test results are summarized in Table 3 and plotted as a function of bentonite content in Figure 4. Figure 4 shows that the higher the bentonite content, the greater the swelling pressure of the sample. The average increase in swelling pressure per 1 percent addition of bentonite was 1.4 percent,

5.87 percent, 15.15 percent, and 13.43 percent for samples containing 5%, 10%, 15%, and 20% bentonite, respectively. As a result, it can be concluded that the highest increase in swelling pressure occurs when the bentonite content exceeds 10%.

**Table 3.** Swelling pressure of compacted claystone–bentonite mixtures

| Water content | Swelling pressure (kPa) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 13.01 | 14.16 | 33.74 | 110.49 | 152.85 |
| w=15% | 15.25 | 16.46 | 52.32 | 136.42 | 229.43 |
| w=20% | 0.0 | 18.6 | 51.24 | 117.7 | 183.82 |

Figure 4 also shows that specimens with a moisture content of 15% get the highest swelling pressure. This is attributed to the reason that the water content represents the optimum moisture content of the claystone sample used in this study. The swelling pressure results are influenced by the dominant claystone in the mixture. Despite having the same initial dry density, the swelling pressure obtained by the swell-load test method varies with moisture content. This is due to the fact that the microstructure of samples compacted at various water contents results in a different macro-micro pore distribution [13]. Furthermore, because the void ratio of the samples changed during the test, the stress paths traversed by the samples were also different.

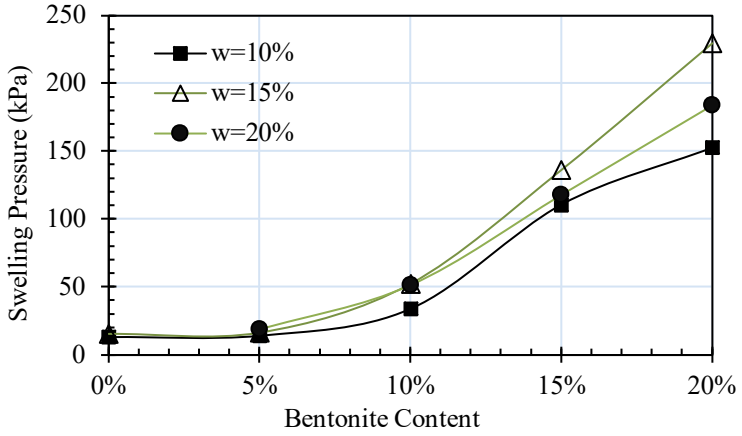


**Figure 4.** Swelling pressure as a function of bentonite content

According to Sridharan et al [12], the swelling pressure tested using the swell-load method takes a long time. Meanwhile, it tends to be faster to obtain the swelling potential. The relationship between swelling potential and swelling pressure of claystone-bentonite mixture samples obtained in this study is depicted in Figure 5. Regardless of the sample's bentonite or water content, the relationship between the two can be determined by a straight line equation with $R^2 = 0.9512$. (Equation 1).

$$P_s\ (kPa) = 10.8 S_p \tag{1}$$

where $P_s$ and $S_p$ denote swelling pressure in kPa and swelling potential, respectively.

## 4. Conclusions

The swelling characteristics of a claystone-bentonite mixture, including swelling potential and swelling pressure, have been described and analyzed. The swelling potential of the sample increases as the bentonite content increases. The greatest increase occurred in samples containing more than 10% bentonite, with 1.1-1.4% per one percent bentonite. The sample's swelling pressure rises as the bentonite content rises. The greatest increase was also observed in samples with a bentonite content greater than 10%, with an average increase of 13.3-15.3% per one percent increase in bentonite in the mixture. The

water content had no significant effect on the swelling potential or swelling pressure of the compacted claystone-bentonite investigated in this study. Moreover, the linear swelling pressure and swelling potential relationship is accomplished using the Ps (kPa) = 10.8 sp equation, whereas Ps and Sp are swelling pressures in kPa and swelling potential.

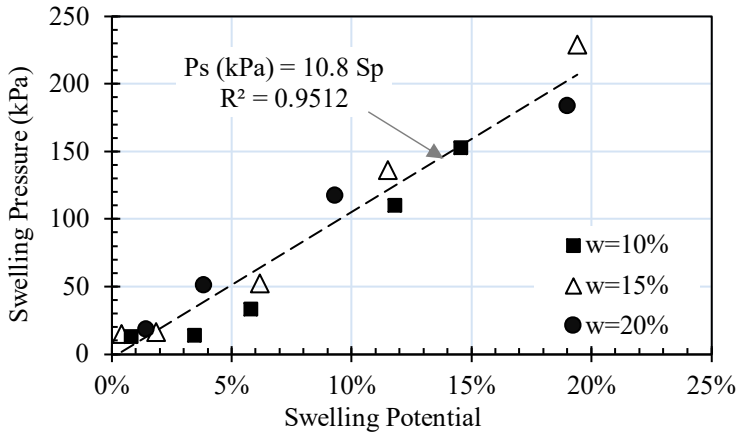


**Figure 5.** Swelling pressure and swelling potential correlation

**Acknowledgement**

The authors are grateful for the financial support provided by University of Lambung Mangkurat through the "Dosen Wajib Meneliti" program in 2021.

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*by* Yulian Firmana Arifin

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## 1. Introduction

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### *2.2. Techniques and Procedures*

#### *2.2.1. Sample preparation*

The claystone was subjected to a Proctor compaction test, which yielded an optimum moisture content of 15% and a maximum dry density of 16 kN/m$^3$. This density was used in this study, along with an additional moisture content at dry of optimum (i.e., 10%) and wet of optimum (i.e., 20%). Crushed claystone was sieved with a No. 40 mesh. Bentonite was mixed at a certain weight to achieve dry weight contents of 5, 10, 15, and 20% in the mixture. After evenly mixing the claystone and bentonite, water was gradually added with a sprayer to attain a moisture content of 10, 15, and 20%. The sample was statically compacted in a mold with a diameter of 6.2 cm and a height of 2 cm to achieve a dry density of 16 kN/m$^3$. Claystone with the same density and moisture content was tested for comparison. Claystone and bentonite are referred to as "CS" and "B" in this paper. Meanwhile, moisture content is denoted by the letter "w." Table 1 summarises the conditions and sample codes used.

**Table 1.** Initial conditions and codes of the samples used

| Water content | Bentonite content | | | | |
|---|---|---|---|---|---|
| | 100% CS | 5% | 10% | 15% | 20% |
| 10% | 100CSw10 | 95CS5Bw10 | 90CS10Bw10 | 85CS15Bw10 | 80CS20Bw10 |
| 15% | 100CSw15 | 95CS5Bw15 | 90CS10Bw15 | 85CS15Bw15 | 80CS20Bw15 |
| 20% | 100CSw20 | 95CS5Bw20 | 90CS10Bw20 | 85CS15Bw20 | 80CS20Bw50 |

#### *2.2.2. Swelling potential and swelling pressure tests*

The swell under load technique was used for the swelling test. In this test, the oedometer was used to obtain both the swelling potential or swelling strain and swelling pressure in the same specimen. In the first step, the sample was subjected to a pressure of 6.9 kPa and inundated with water until equilibrium was reached, as indicated by no change in the dial reading during testing [11]. The load was then gradually added to the load increment ratio (LIR) in the same way as in the consolidation test (i.e., LIR = 2) until the void ratio equalled its initial value. Based on a swell-load test, the pressure at which the void ratio is equal corresponds to the swelling pressure [12].

## 3. Results and Discussion

### *3.1. Swelling Potential*

Figure 1 depicts the swelling development over time for 100% claystone samples and claystone-bentonite mixtures with bentonite contents ranging from 5 to 20%. Figure 1(a) represents the swelling development of a sample with a moisture content of 10%, while Figures 1(b) and 1(c) exhibit the swelling development of samples with moisture contents of 15% and 20%, respectively. As shown in the figure, the swelling strain increases over time and remains constant at a certain point. The swelling potential of the samples is determined by the swelling in which no noticeable difference is visible in the graph. The swelling strain was found to be constant over less than 100 minutes for 100% claystone samples (i.e., 100CSw10 and 100CSw15). Meanwhile, the swelling potential of other samples could be determined after more than 100 minutes, and samples with bentonite contents of 15% and 20% could be determined after more than 2000 minutes. As the percentage of bentonite in the mixture increased, the time to reach equilibrium rose.

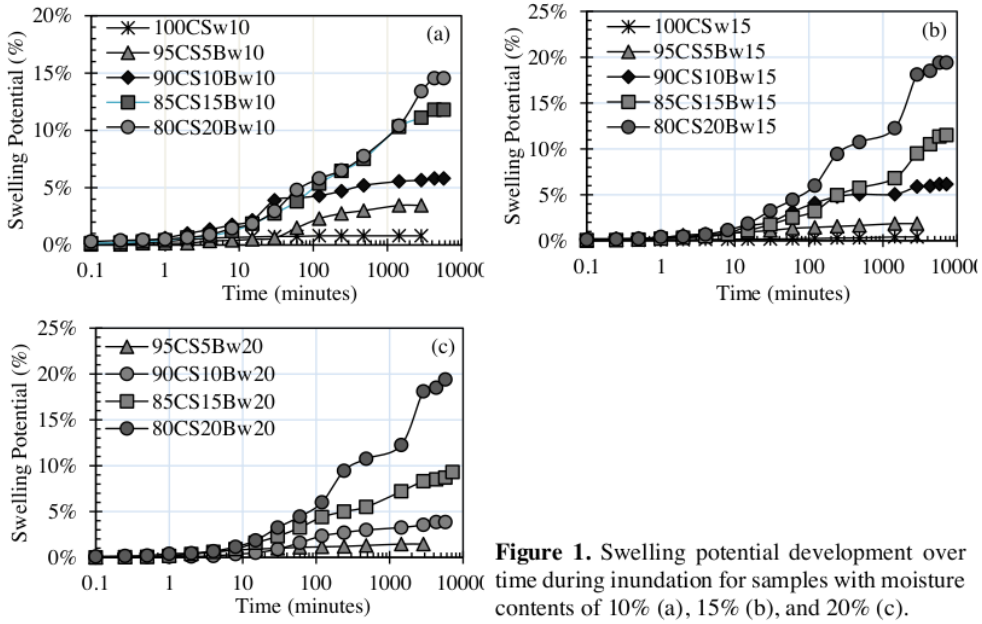


**Figure 1.** Swelling potential development over time during inundation for samples with moisture contents of 10% (a), 15% (b), and 20% (c).

Table 2 summarises the swelling potential of the samples, which is plotted as a function of bentonite content in Figure 2. In general, as shown in Figure 2, the swelling potential increased as the bentonite content increased. If the increase in swelling per percentage of bentonite is calculated as the difference in swelling divided by the addition of bentonite content, then for samples containing up to 10% bentonite, a 0.4-0.7% increase in swelling was obtained per one percent of bentonite. Meanwhile, for samples containing more than 10% bentonite (i.e., 15-20% bentonite), the swelling addition was 1.1-1.4% per one percent bentonite. As a result, samples with a bentonite contents greater than 10% showed a greater increase in swelling.

Similarly, the difference in swelling potential data for each water content is divided by the percentage of water content to investigate the effects of water content. The increase or decrease in swelling potential per one percent water content was found to be 0.1-0.3%. It can be concluded that the initial water content of claystone-bentonite mixtures had no significant effect on their swelling potential.

**Table 2.** Swelling potential of compacted claystone–bentonite mixtures

| Water content | Swelling potential (%) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 0.8 | 3.5 | 5.8 | 11.8 | 14.6 |
| w=15% | 0.4 | 1.9 | 6.2 | 11.5 | 19.4 |
| w=20% | 0.0 | 1.5 | 4.9 | 9.3 | 19.0 |

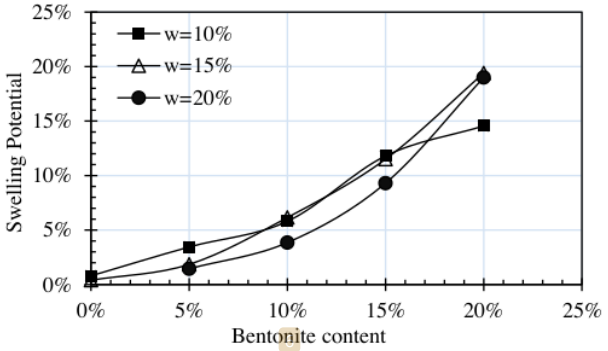


**Figure 2.** Swelling potential as a function of bentonite content.

*3.2. Swelling Pressure*

The swell load test result of a claystone-bentonite mixture sample utilised in this investigation is shown in Figure 3. When the sample was inundated with water, the void ratio increased from 0.40 to 0.48, as shown in Figure 3 (a) for the 90CS10Bw15 sample. This data was used as the amount of the swelling potential. The void ratio decreased with increasing pressure, and the initial void ratio was intersected at 52.32 kPa. In Figure 3 (b), the sample void ratio of 80CS20Bw20 grew during the wetting process from 0.39 to 0.61, then declined with rising pressure until it intersected with the sample's initial void ratio at 183.82kPa. The swelling pressures for 90CS10Bw15 and 80CS20Bw20 were 52.32kPa and 183.82kPa, respectively.

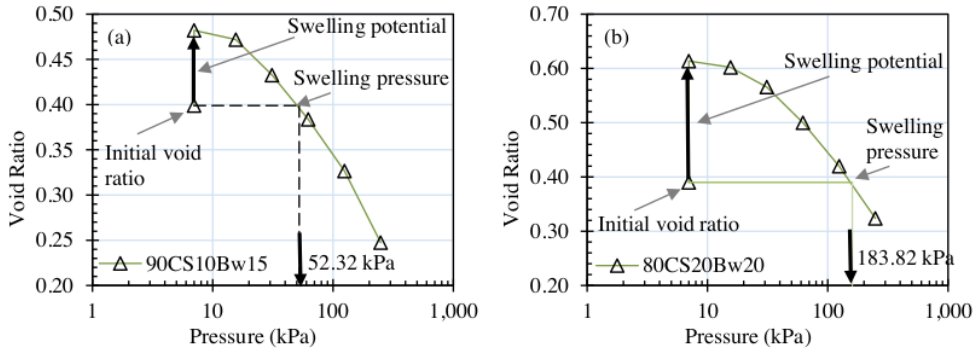


**Figure 3.** Typical swelling pressure determination from swell–load test technique (a) sample of 90CS10Bw15 and (b) sample of 80CS20Bw20.

The swell load test results are summarised in Table 3 and plotted as a function of bentonite content in Figure 4. Figure 4 shows that the higher the bentonite content, the greater the swelling pressure of the sample. The average increase in swelling pressure per one percent addition of bentonite was 1.4, 5.87,

15.15, and 13.43% for samples containing 5, 10, 15, and 20% bentonite, respectively. As a result, it can be concluded that the highest increase in swelling pressure occurred when the bentonite content exceeded 10%.

**Table 3.** Swelling pressure of compacted claystone–bentonite mixtures

| Water content | Swelling pressure (kPa) | | | | |
|---|---|---|---|---|---|
| | 100CS | 5B | 10B | 15B | 20B |
| w=10% | 13.01 | 14.16 | 33.74 | 110.49 | 152.85 |
| w=15% | 15.25 | 16.46 | 52.32 | 136.42 | 229.43 |
| w=20% | 0.0 | 18.6 | 51.24 | 117.7 | 183.82 |

Figure 4 also shows that specimens with a moisture content of 15% had the highest swelling pressure. This is attributed to the fact that the water content represents the optimum moisture content of the claystone sample used in this study. The swelling pressure results were influenced by the dominant claystone in the mixture. Despite having the same initial dry density, the swelling pressure obtained by the swell-load test method varied with moisture content. This is due to the fact that the microstructure of samples compacted at various water contents results in a different macro-micro pore distribution [13]. Furthermore, because the void ratio of the samples changed during the test, the stress paths traversed by the samples were also different.

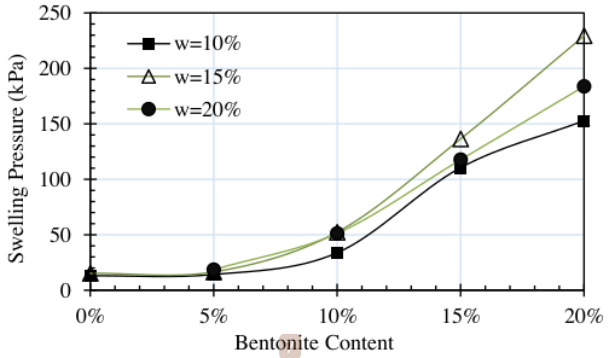


**Figure 4.** Swelling pressure as a function of bentonite content.

According to Sridharan et al [12], the swelling pressure tested using the swell-load method is time-consuming. Meanwhile, the swelling potential can be obtained faster. The relationship between the swelling potential and swelling pressure of the claystone-bentonite mixture samples obtained in this study is depicted in Figure 5. Regardless of the sample's bentonite or water content, the relationship between the two can be determined by a straight-line equation with $R^2 = 0.9512$. (Equation 1).

$$P_s\ (kPa) = 10.8S_p \quad (1)$$

where $P_s$ and $S_p$ denote swelling pressure in kPa and swelling potential, respectively.

**4. Conclusions**

The swelling characteristics of a claystone-bentonite mixture, including its swelling potential and swelling pressure, have been described and analysed. The swelling potential of the sample increased as the bentonite content increased. The greatest increase occurred in samples containing more than 10% bentonite, with 1.1-1.4% per one percent bentonite. The sample's swelling pressure rose as the bentonite content rose. The greatest increase was also observed in samples with a bentonite content greater than 10%, with an average increase of 13.3-15.3% per one percent increase in bentonite in the mixture. The

water content had no significant effect on the swelling potential or swelling pressure of the compacted claystone-bentonite investigated in this study. Moreover, the linear swelling pressure and swelling potential relationship was accomplished using the Ps (kPa) = 10.8 sp equation, whereas Ps and Sp were swelling pressures in kPa and swelling potential.

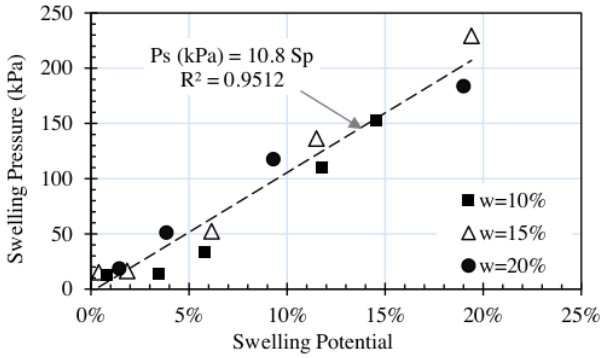


**Figure 5.** Swelling pressure and swelling potential correlation.

**Acknowledgement**

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