CHAPTER 4

TEST RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

Experimental program test results have divided into 3 parts, basic engineering properties test results, hydraulic fracture test results, and hydraulic fracture form. Basic engineering properties test results of sand-bentonite mixtures composed of sieve analysis, wet sieve analysis, relative density, specific gravity, unconfined compression test, direct shear test, standard compaction test, and hydraulic conductivity. As described in Chapter 3 about test method and application, test result of basic engineering properties such as standard compaction test, and hydraulic conductivity can apply for a construction method.

The results of hydraulic fracture tests and detachment of fine particle has discussed in this chapter.xxx

4.2 BASIC ENGINEERING PROPERTIES OF SAND - BENTONITE MIXTURE

4.2.1 Standard Compaction Test

The Standard Proctor compaction test on the mixtures was conducted in accordance with the ASTM D698 standard. Compaction procedure in landfill construction can control by compaction energy and water content. Maximum dry density and optimum moisture content of liner materials should perform in laboratory using standard compaction test before construction. Water content of material should control during compaction process, 2 – 4 % in wet side. The compaction characteristic of the mixture obtained using tap water as the pore fluid is shown in Figure4.1.

Figure 4.1shows the compaction characteristics of sand-bentonite mixtures carried out using the standard Proctor test. The percentages by weight of bentonite were 5% to 25%. Table. 4.1 summarizes the range of the maximum dry unit weight, $(\gamma_d)_{max}$, (18.6 kN/m^3 – 18.8 kN/m^3) and the optimum moisture content, w_{OPT}, (11.0 % – 13.0 %) with the percentages of bentonite in the mixture.

4.2.2 Unconfined Compressive Strength

Samples of sand-bentonite mixture were refreshed for checking their unconfined compressive strengths. Standard compaction energy and water content of sample was controlled, 18% of water content was used and then sample was kept by thin steel pipe. The dimension of the collected sample was 2.5 cm in diameter and 5 cm in height. The unconfined compressive strength apparatus in soil laboratory was used to find relation between compressive stress and vertical displacement, and then test results was calculated and plotted in relations of shear stress and displacement. 3 samples per one ratio from the same compacted mold were tested. The test results are summarized in Table. 4.2 and Figure4.2. The undrained compressive strength, S_u is increasing from 24 kPa to 85 kPa with increasing of bentonite from 5 % to 25 %.

4.2.3 Direct Shear Test

Samples of sand-bentonite mixture were refreshed for direct shear test. The sample was kept by steel ring from standard compaction mold, compaction energy and water content of sample was controlled. The dimension of the sample was 5 cm in diameter and 2.0 cm in thickness. Horizontal displacement and Horizontal pressure from dial gauge was recorded, calculated and plotted of shear stress and displacement used to determine shear at failure. Plotted of shear and stress relationship was used to find cohesion, C_{DSS} and internal friction angle, ϕ. The test results are summarized in in Table. 4.3 and Figure4.3. The direct shear test cohesion is increasing from 15 kPa to 27 kPa with increasing of bentonite from 5 % to 25 %; otherwise, the internal friction angle is decreasing.

4.2.4 Hydraulic Conductivity

The constant head permeability test was performed by applying constant pressure heads of about 50 kPa, independent on the overburden stress of the sample. Flow in water was measured with time, until flow in rate remained constant. The hydraulic conductivity was calculated by constant head test formula and presentation in form of coefficient of permeability. Remark that, the sample was not saturated. The presented of hydraulic conductivity of sample is the constant flow in rate value. Figure 4.4 shows the plot between bentonite content and the coefficient of permeability, *k*, of the mixture measured inside the chamber. Though large scattering in the measured data, the coefficient of permeability, *k*, decreases with increasing in bentonite content. For 10% of bentonite content, hydraulic conductivity less than 1 x 10^{-7} cm/s, with is minimum requirement value of landfill barrier.

Hydraulic conductivity test has performed before and after hydraulic fracture test, to compare about loss of permeable resistance of sand-bentonite mixture. Table 4.4 show summaries of hydraulic conductivity test results, before and after hydraulic fracture test. The reduce values of hydraulic conductivity depend on type of fracture form, some detachment path in sample let the flow in rate of water same as pure sand. However, for some case the hydraulic fracture caused the upper crack of sample therefore the flow in rate of hydraulic conductivity was quick (See discussions for more details).

4.2.5 Quality Control

Specimen's quality control has investigated to make uniformity of mixtures during study. Bentonite content was checked by wet sieve analysis, sample from mixing bowl was kept before compact. Water content was determined and then dry unit weight was calculated. Table 4.5 shows results of wet sieve analysis of samples. Test results show that little varies of bentonite content from design was observed. Because, mixing apparatus is small, then it easy to control the uniformity of sample. Dry sample mix before add water help more uniformity. Dry mix of sand and bentonite about 2 minute has done before squeezed water and use 3 minute for wet mix. Others quality controls were water content and compaction energy, the results were recorded in raw data. Appendix 1 shows raw data records and calculations.

4.3 HYDRAULIC FRACTURE TEST RESULTS

There are 2 types of hydraulic fracture test, horizontal and vertical plane. Two types of slot used to generate fracture plane, first horizontal plane induced by 2 circle 2-cm steel plate connected with 0.6 cm pipe, another used to induce fracture in vertical plane. Water injected in the pipe was controlled pressure by regulator, and then flow in water with time was recorded. Flow rate depend on water pressure and permeability of sample, until water pressure more than resistance of sample, high of flow rate is presented immediately. However, at the pressure which flow rate started to change was defined as breakthrough pressure, P_b. Plotted between flow rate and water pressure show defined breakthrough pressure point and trend of flow rate after fracture occurred.

Slow Rate test.

Figure 4.5 show relation between flow rate, q (cm^3/s) and water pressure, P (kPa) of Sample No. SHF01 (5% of bentonite content under 100 kPa of overburden stress - Slow rate test on horizontal plane) for slow rate test, flow rate before fracture at 50 kPa of water pressure is 2.1 x 10^{-3} cm^3/s and at breakthrough pressure, P_b (kPa) is 1.6 x 10^{-2} cm^3/s after fracture occurred at 100 kPa the flow rate is 2.4 x 10^{-1} cm^3/s, it value more than normal flow rate of 100 times (from 10^{-3} to 10^{-1}).

All relation between flow rate and water pressure, used to define breakthrough pressure was plotted, the horizontal slow rate test results show in Figure 4.7 to Figure 4.9. Figure 4.7 is the results of horizontal plane fractured of slow rate test, there are 5%, 10%, 15%, 20%, and 25% of bentonite content under 100 kPa of overburden stress. And Figure 4.8, and 4.9 show test results of horizontal slow rate test of 5%, 10%, 15%, 20%, and 25% of bentonite content under 200 and 300 kPa of overburden stress, respectively. These illustrations show the test results of all bentonite content under the same overburden stress. Figure 4.10, 4.11, and 4.12 show test results of horizontal slow rate test of 5%, 10%, and 15% of bentonite content under 100, 200 and 300 kPa of overburden stress, respectively.

All relation between flow rate and water pressure, used to define breakthrough pressure was plotted, the horizontal slow rate test results show in Figure 4.7 to Figure 4.9. Figure 4.7 is the results of horizontal plane fractured of slow rate test, there are 5%, 10%, 15%, 20%, and 25% of bentonite content under 100 kPa of overburden stress. And Figure 4.8, and 4.9 show test results of horizontal slow rate test of 5%, 10%, 15%, 20%, and 25% of bentonite content under 200 and 300 kPa of overburden stress, respectively. These illustrations show the test results of all bentonite content under the same overburden stress. Figure 4.10, 4.11, and 4.12 show test results of horizontal slow rate test of 5%, 10%, and 15% of bentonite content under 100, 200 and 300 kPa of overburden stress, respectively.

Quick Rate test.

Figure 4.6 is the test results of sample no. QHF01 (5% of bentonite content under 100 kPa of overburden stress - Quick rate test on horizontal plane) quick changed of pressure of 10 kPa / 30 sec could not showed any change of water volume in pipette, therefore at 50 kPa the flow rate value is 0.0 cm^3/s, and the same at break through pressure. Flow rate at 100 kPa of water pressure is 2.3×10^{-1} cm^3/s.

The relations between flow rate, q (cm^3/s) and water pressure, P (kPa) of hydraulic fracture tests were shown as list; Figure 4.13 hydraulic fracture test results under over burden stress of 100 kPa of quick rate test on horizontal plane, breakthrough pressure increased with bentonite content. For over burden of 200 kPa and 300 kPa, test results were shown in Figure 4.14 and Figure 4.15, respectively.

Figure 4.16 to 4.18 is the test results in vertical plane of slow rate test results, and Figure 4.19 to 4.21 is the test results in vertical plane of quick rate test results.

Table 4.6 shows summarized of hydraulic fracture test results of slow rate test on horizontal and vertical plane, the other test results of hydraulic fracture test results of quick rate test on horizontal and vertical plane show in Table 4.7.

From summarized of test results in Table 4.6 and 4.7, the relation between pressure ratio, P_b/σ_v (breakthrough pressure and over burden pressure), and bentonite content, B (%) was plotted and show in Figure 4.22 to 4.25. Figure 4.22 is the relation of horizontal plane of slow rate test, Figure 4.23 is the relation of horizontal plane of quick rate test, and the other, Figure 4.24 and Figure 4.25 is the test result in vertical plane of slow and quick rate test, respectively.

From lab test results, relation between pressure ratio and bentonite content show that breakthrough pressure value depend on bentonite content of sample and overburden stress. However, less than 15 % of bentonite content of mixtures gives the value of breakthrough pressure less than value of overburden stress, pressure ratio less than 1.0. This result can describe by the behavior during testing program, there is some bentonite particle flow out with flow out water. Ability of detachment resistance of sample is another factor, effect to the value of breakthrough pressure.

4.4 DETACHMENT OF SAND-BENTONITE MIXTURES

There is some bentonite particle flow out during hydraulic fracture tests, time and pressure was recorded but content of detachment has not recorded. For lower bentonite content than 10%, there are investigated that bentonite particle was migrated by water pressure. Some sample of 5% of bentonite content has only sand particle after hydraulic fracture test. From this observed show that the breakthrough pressure in low bentonite content is very low, some sample its lower than overburden stress, due to the resistance of detachment is lower than lateral resistance pressure, then bentonite particle was migrated before the fracture which controlled by overburden pressure occurred.

More bentonite content than 15 % by weight has increase detachment resistance, low of detachment path observed after hydraulic fracture test. The sample trend to fracture by water pressure than by detachment, crack of sample can observe. Figure 4.26 and 4.27 show the detachment path with can observed from the outside of perpex, and Figure 4.28 and 4.29 show the crack.

4.5 HYDRAULIC FRACTURE FORMS

Idealized hydraulic fractures forms typically occur as one of two general forms depending on their average dip. One form is a steeply dipping fracture that has a greater vertical than lateral dimension. This type of fracture climbs rapidly and reaches the ground surface, or vents. The other type of fracture is gently dipping and it can grow to several meters or more in the horizontal dimension, which is large enough to improve the performance of shallow wells and therefore it is useful for environmental applications (Murdoch and Slack, 2002).

During hydraulic fracture test, we can observe fracture of sample easily. Fracture form in each sample observed after finished the test. Varied of bentonite content, overburden stress, and breakthrough pressure resistance created different forms. There is more detachment path with up and down steeply dipping form in 5% bentonite content, and only up steeply dipping form with less detachment path in 10% bentonite content samples. For 15% bentonite content, gently dipping form with little detachment path at the edge of sample was observed only under overburden stress of 300 kPa, the others are steeply dipping form. However, nearly flat-lying hydraulic fractures have been created in 20% and 25% of bentonite content. Table 4.8 and 4.9 show summarize of fracture form, and the sketch of fracture plane and detachment path show in Figure 4.30 to Figure 4.36. Photo of sample was shown in Figure 4.30 to Figure 4.36.

4.6 DISCUSSIONS

From the study, test results of engineering properties and hydraulic fracture test was observed. Trend of results with bentonite content of sample has considered and presents in discussions. Trend line equation from regression method tried to present properties of mixture. However, prediction of material behaviour from test results is limitation in range of bentonite content of 5% to 25%.

Engineering Properties

The relation between unconfined compressive strength and bentonite content with plot in Figure 4.2., show the linear relation. The trend line of regression, $R^2 = 0.9976$ give linear form

$$S_u = 3.0058(\%B) + 10.654 \qquad \text{.........} (4.1)$$

However, the same type of bentonite but different sand with tested by Kowit (2002) give the relation between unconfined compressive strength and bentonite content in linear form of $S_u = 4.3949(\%B) + 3.4335$ with , $R^2 = 0.975$. The same linear relation was found with different compacted method the relation is $S_u = 1.7802(\%B) + 16.24$ with, $R^2 = 0.983$. Value of R2 show that linear trend line can use to present the relations between undrained shear strength, Su and bentonite content, %B, differential of slope of trend line depend on conditions of each sample. Compaction energy and water content is important parameter effect on slope of trend line.

The hydraulic conductivity values depend on bentonite content, while bentonite content is increase the hydraulic conductivity is decrease. Variation of hydraulic conductivity of 5% to 25% of bentonite content is 10^{-4} to 10^{-9} cm/s. The fit trend line in Figure 4.4 give the relation form of $k = 0.6(\%B)^{-6.24}$ with $R^2 = 0.84$. After fracture occurred the hydraulic conductivity was increased depend on bentonite content and detachment path. Detachment was reduce bentonite content in mixture, and increase void in sample, then observed hydraulic conductivity of some detached case is nearly of sand. In case of detachment path occur in hydraulic fracture process increase of hydraulic conductivity in 5% and 10% of bentonite content was higher than in 15%. Gently fracture form without detachment path caused little change in hydraulic conductivity the same as vertical detachment form in vertical test (See fracture form in part 4.5). This show that high operations pressure near barrier zone can cause detachment in compacted mixture, the hydraulic conductivity, which is an important factor of barrier, was reduced.

Hydraulic fracture test on slow rate test has an objective to find each value of hydraulic conductivity of water pressure supplied in starter slot. However, the flow path of water from starter slot is difficult to observed, hydraulic conductivity of starter slot can not represent the horizontal of coefficient of permeability. The hydraulic conductivity from this measured was shown in form of flow in water with water pressure. Then the results of hydraulic conductivity from hydraulic conductivity test and from hydraulic fracture test can compare in form of flow rate, q (cm^3/s). At the same water pressure of 50 kPa of 10% of bentonite under over burden stress of 100 kPa, (Slow Rate Test on Horizontal Fracture Plane) the flow rate of sample from hydraulic conductivity test is 1.6 x 10^{-7}, and from hydraulic fracture test is 3.8 x 10^{-5}.

Department of Industrial Works, Ministry of Industry, of Thailand has introduced coefficient of permeability used for impervious layer of landfill less than 1 x 10^{-7} cm/s. For 10% of bentonite content under 100kPa it seem that vertical permeability from hydraulic conductivity test is lower than horizontal permeability from hydraulic fracture test, designed of this ratio should careful.

Hydraulic fracture test results from slow rate test and quick rate test give nearly breakthrough pressure in the same conditions, slow rate test give more results of permeability before fracture. Relations between flow rate, q and water pressure, P_w show behaviour of fracture path, slow rate test normally show lower slope of graph than quick test. Quick test is suddenly fracturing, fracture resistance damaged by water pressure flow rate after fracture reach to higher like flow rate in pure sand. At higher pressure flow rate after fracture varies in range of 5 x 10^{-1} to 7 x 10^{-1} cm/s with is nearly flow rate of pure sand, however, variable should depend on water pressure and plugging of bentonite particle.

Normalization

The normalized behaviour is an integral part of all soil models based on CSSM (Critical State Soil Mechanics) concept (Wroth and Houlsby, 1985). Normalized Soil Properties concept was proposed to use in practice for saturated clay by Ladd and Foott

(1974) and Ladd et al. (1977). The normalized soil properties are S_u/σ'_{vc}, A_f, and E_u/σ'_{vc} plotted with log OCR, it unique if a soil exhibited normalized behaviour.

The Cambefort's equation developed from plane strain theory, it has some potential for relative hydraulic fracturing pressure to soil strength characteristics.

$$p_f = (1+\sin\phi)\sigma_h + C\cos\phi \qquad \text{..........}\ (4.2)$$

The empirical formula which proposed by Jaworski et al. (1981) is

$$p_f = m\sigma_h + \sigma_t \qquad \text{..........}\ (4.3)$$

where m is an empirical factor,

from equation (4.2) and (4.3)

$$m = (1+\sin\phi) \qquad \text{..........}\ (4.4)$$

$$\sigma_t = C\cos\phi \qquad \text{..........}\ (4.5)$$

Rewritten equation (4.2) in term of σ_v and normalized by C, takes the form

$$\frac{p_f}{C} = (1+\sin\phi)K_o\frac{\sigma_v}{C} + \cos\phi \qquad \text{..........}\ (4.6)$$

then,

$$m = (1+\sin\phi)K_o \qquad \text{..........}\ (4.7)$$

$$b = \cos\phi \qquad \text{..........}\ (4.8)$$

Normalized Pressure by Cohesion

The test results of cohesion and internal friction angle of mixtures show in Table 4.3. And Figure 4.3 show the relation of normalized breakthrough pressure (P_b / C) and overburden stress (σ_v / C). of 5, 10, 15, 20 and 25 percent of bentonite content by weight under 100, 200 and 300 kPa of overburden stress. The trends line equation is $y = 0.6202x + 4.5602$, while $R^2 = 0.6910$. However, behaviour of 5% to 10% of bentonite are different from the other, due to they have more detachment. Figure 4.37 shows separates trends line of 5% and 10%, with 15% to 25% of slow rate test on horizontal plane. The other show on Figure 4.38 to 4.40. The trends line equations have written in form of $y = mx + b$, and the results of m, b, and R^2 show in Table 4.10.

Normalized Pressure by Undrained Shear Strength

The test results of undrained shear strength, Su of mixtures show in Table 4.2. And Figure 4.2 show the relation of normalized breakthrough pressure (P_b / S_u) and overburden stress (σ_v / S_u). of 5, 10, 15, 20 and 25 percent of bentonite content by weight under 100, 200 and 300 kPa of overburden stress.

Rewritten equation (4.2) in term of σ_v and normalized by S_u, takes the form

$$\frac{p_f}{S_u} = (1 + \sin\phi)K_o \frac{\sigma_v}{S_u} + \cos\phi \qquad \text{..........} (4.9)$$

Figure 4.41 to 4.44 show the trend lines with normalized pressure by Undrained shear strength. The trends line equation is $y = mx + b$. Table 4.11 show the results of m, b, and R^2.

Trend Line Equations

From the hydraulic fracture test results and normalized pressure by S_u results give a good relation between breakthrough pressure and overburden pressure. The formula of trends line is

$$y = mx + b \qquad \text{..........} (4.10)$$

where,

$$y = P_b / S_u \qquad \text{..........} (4.11)$$

$$x = \sigma_v / S_u \qquad \text{..........} (4.12)$$

then equation (4.10) becomes

$$\frac{p_b}{S_u} = m\frac{\sigma_v}{S_u} + b \qquad \text{..........} (4.13)$$

or,

$$p_b = m\sigma_v + bS_u \qquad \text{..........} (4.14)$$

from Figure 4.2, the relation between bentonite content and S_u, relations of they has $R^2 = 0.998$ and can show in form of

$$s_u = 3.0058(\%B) + 10.654$$

Substitute value of m, b, from Table 4.11 and Su from equation (4.1), the relation can show in form

Horizontal fracture plane

For all results ($R^2 = 0.920$)

$$p_b = 0.572\sigma_v + 1.777S_u \qquad \text{..........} (4.15)$$

$$p_b = 0.572\sigma_v + 3.343(\%B) + 18.936 \qquad \text{..........} (4.16)$$

For 5% and 10% of bentonite content ($R^2 = 0.984$)

$$p_b = 0.633\sigma_v + 1.013S_u \qquad \text{..........} (4.17)$$

$$p_b = 0.633\sigma_v + 3.045(\%B) + 10.795 \qquad \text{..........} (4.18)$$

For 15% to 25% of bentonite content ($R^2 = 0.970$)

$$p_b = 0.854\sigma_v + 1.208S_u \qquad \text{..........} (4.19)$$

$$p_b = 0.854\sigma_v + 3.631(\%B) + 12.870 \qquad \text{..........} (4.20)$$

Vertical fracture plane

For all results ($R^2 = 0.947$)

$$p_b = 0.555\sigma_v + 1.796S_u \qquad \text{..........} (4.21)$$

$$p_b = 0.555\sigma_v + 5.398(\%B) + 19.391 \qquad \text{..........} (4.22)$$

For 5% and 10% of bentonite content ($R^2 = 0.959$)

$$p_b = 0.553\sigma_v + 1.692S_u \qquad \text{..........} (4.23)$$

$$p_b = 0.553\sigma_v + 5.087(\%B) + 18.031 \qquad \text{..........} (4.24)$$

For 15% to 25% of bentonite content ($R^2 = 0.950$)

$$p_b = 0.774\sigma_v + 1.214S_u \qquad \text{..........} (4.25)$$

$$p_b = 0.774\sigma_v + 3.648(\%B) + 12.932 \qquad \text{..........} (4.26)$$

Results of equation (4.16), (4.18), and (4.20) of horizontal fracture plane plot with test results show in Figure 4.45. and results of equation (4.22), (4.24), and (4.26) of vertical fracture plane plot with test results show in Figure 4.46.