Laboratory Tensile Strength Testing of Clay Soils using Direct Measurement

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ABSTRACT

Clay has wide application in engineered barriers, such as buffer barriers in deep geological nuclear waste disposal, clay liners in landfill, and earthen slopes and embankments, to name a few. However, most clay soils have a high potential to crack under extreme weather induced moisture loss. From a macro-mechanical view, clay tensile strength which is a critical factor governing the cracking behavior is highly dependent on the moisture content and corresponding matric suction. In this study, a series of laboratory tests on two typical clays (kaolinite and sodium bentonite) were carried out to investigate the relationship between clay tensile strength and moisture content by using a specially designed device which can measure tensile strength directly (Stirling et al. 2014, 2015). In addition, the study also investigated the effect of silica sand additive on the tensile strength of the compacted clay liner and the verification of its small value. This is reasonable if compared with the shear strength of soils.

In geotechnical design where tensile cracks contribute to instability and reduced performance in excavations, dams, riverbanks, natural slopes, hydraulic barriers, highway embankments, and other earth structures, the soil tensile strength is an essential property (Gui et al. 2012, 2016, and 2018). The tensile strength also has a vital role for slope stability analysis and the verification of desiccation cracking in the compacted clay liner of landfill (Zeh & Witt, 2007). Tensile failure is the main reason of cracking in landfill liners that normally occur due to the reduction of the water content in the liner.

In this paper, the tensile strength of two clay soils (bentonite and kaolinite) are tested and compared at various water contents and dry densities. To investigate the role of an additive on the clay tensile strength, silica sand is also added to the soils and the tensile strength of the mixtures is measured.

Keywords: clay, tensile strength, moisture content, silica sand additive.

1 INTRODUCTION

Soil tensile strength is a crucial parameter that governs the bearing capacity of soil in tension. Conventionally the tensile strength of the soil is ignored in engineering practice because of its small value in most scenarios. This value is assumed to be zero or insignificant in conventional geotechnical engineering practice due to the lack of widely available laboratory testing techniques or its relatively small value. This is reasonable if compared with the shear strength of soils.

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2 EXPERIMENTAL PROGRAM

The soil materials used in this project are kaolinite, sodium bentonite, and silica fine sand. The determination of the geotechnical engineering properties of the soils was carried out according to the British Standard BS 1377-2:1990. A particle size distribution (PSD) test was conducted on the sand and Atterberg Limits tests on the two clay soils. Table 1 lists the properties of kaolinite and bentonite, and Figure 1 shows the PSD of the silica sand.

2.1 Direct measurement equipment

For this research, the tensile strength of soil was quantified using a direct tensile strength test, the Newcastle Direct Tensile Test (NDTT) modified from a conventional Wykhan Farrance 60 mm$^2$ direct shear rig. Figure 2 illustrates the design and modification of the specimen carriage. Soil specimens were mounted between a pair of loading jaws to induce tension. No adhesive was used to avoid the introduction of any additional media as this may influence the measurement of the tensile stress and complicate the quick and easy production of the test specimens (Stirling et al., 2015). The jaws can be placed in the same carriage with which the shear box is normally fitted. This system has one big advantage that it permits the rig to be returned to its main purposes by simply lifting out the loading jaws. More details on the design can be found in Stirling et al., (2014, 2015).

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Table 1. Geotechnical engineering properties of the soils.

| Soil               | Kaolinite | Bentonite |
|--------------------|-----------|-----------|
| Soil description   | Clay      | Clay      |
| Atterberg Limits   |           |           |
| Liquid Limit (%)   | 59.4      | 404       |
| Plastic Limit (%)  | 32        | 39.3      |
| Plastic Index (%)  | 27.5      | 364.7     |

Fig. 1. Particle size distribution of the silica sand additive.

Fig. 2. The modified testing cell for the direct tensile strength measurement (a) Loading jaws and (b) Schematic of the testing rig (Stirling et al., 2015).

2.2 Testing procedure

The preparation of each soil specimen takes approximately 20 minutes, including the preparation of the mould in which the soil is prepared. The preparation of the specimens included four main steps: (1) both soils were mixed with distilled water to three different intended initial gravimetric water contents (35, 40, 45% for kaolinite and 50, 100, 150% for bentonite); (2) the mixtures of soil and water were then left to cure for a period of two weeks; (3) after that, the mould was coated with grease on its inner faces and the soils were placed into the mould; (4) soil in the mould was then subjected to a gradually increasing compressive load until 15 kN on the top of the specimen. Finally, the soil specimens were ready to be tested by the tensile strength apparatus as shown in Fig. 3. The testing process normally took about 7 to 10 minutes.

Fig. 3. Overview of the testing apparatus.

The separation of the loading jaws was led by propelling the carriage according to the motor speed. Loading is transmitted into the soil specimens via the jaws, and the load gauge reading was continually taken until complete separation of the two halves of the soil specimen, and the gauge reading was constant. During all testing, a constant loading rate of 1.2420 mm/min was applied.

Table 2 shows the soil specimen conditions prepared and tested. In total, 72 tensile tests were conducted with 36 tests for each type of soil. The intended water contents are 35%, 40% and 45% for kaolinite and 50%, 100% and 150% for bentonite. As seen in Table 2, the actual water content for each of the sample slightly deviates from the intended water content, due to the soil powder was not oven-dried before sample preparation. For each intended water content, 3 specimens were produced without any additive silica sand. To examining the effect of silica sand on the tensile strength, for each intended water content, 9 specimens were also prepared with 3 different amounts of silica sand, with 3 replicates for each. The percentage of additive silica sand used was 20%, 30%, and 30% for bentonite and 10%, 20%, and 30% for kaolinite.

The tests were terminated when the residual value was established, the specimen was then removed from the jaws and dried for 24 hours in the oven to determine the accurate water content value for each sample, as listed in Table 2.

3 EXPERIMENTAL RESULTS

3.1 Tensile force-displacement

Figure 4 shows the tensile force against the displacement of all three tests of kaolinite prepared with intended water content of 35%. As it can be seen
from the first test the displacement started with small tensile force which gradually increased until reaching the peak and then started decreasing rapidly until reaching a residual value. The second test started moving with a constant tensile force followed by dramatic increase to the peak force, then it started decreasing gradually until the residual value was reached, even though it experienced a significant drop in the process of decreasing. The third test had different behavior: the tensile force gradually increased until reaching the peak and decreased gradually as well until reaching the residual value.

Figure 5 shows the tensile force against the displacement of all three tests of bentonite prepared with intended water content of 100%. It can be seen that the tensile force applied to cause the displacement for all three tests increased linearly, gradually reaching peak stress and decreasing gradually until reaching the residual value. The value of the tensile force in the peak of the first and second test is similar. For the third test, the tensile force seems to be smaller than the first and second test, and prior to dropping to the residual value, a constant tensile force is maintained.

silica sand can significantly affect the tensile strength of kaolinite. It can be seen that the tensile strength decreases with the increase of water content in all the tests. The tensile strength tends to increase with the increase of silica sand. However, it also can be seen that most of the value of the tensile strength of kaolinite prepared with 30% of additive silica sand in all three different water content are smaller than the kaolinite prepared with 20% of silica sand. In addition, the tensile strength of the kaolinite prepared with the addition of 30% of additive silica sand is generally smaller than the kaolinite prepared with 20% of silica sand when it was prepared.

Figure 7 shows an increment of tensile strength due to sand. The value adjacent to each point is the average accurate water content calculated from all 3 tests conducted in each of the specimens prepared in the same intended water content. Generally, the tensile strength increases and then decreases with sand additives. However the optimum amount of sand is dependent on the water content of the specimens. Take the kaolinite specimens with 35% intended water content for example, its tensile strength has a significant increase from 0% to 10% of sand, and slight increase from 10% to 20% of sand and a significant decrease from 20% to 30% of sand. It is also noticed that the optimum amount of sand increase with increase of water content.

Figure 8 shows the results of bentonite tests. Similar to kaolinite, various water content and amount of silica sand additive were used. It can be seen that the tensile strength decreases with the increase of water content in all different percentage of additive silica sand. However, it generally increases with the addition of silica sand.

Figure 9 shows the increment of tensile strength with the addition of silica sand in bentonite specimens prepared with different water content. The value adjacent to each point is the average accurate water content calculated from all 3 tests conducted in each of the specimens prepared in the same intended water

3.2 Effect of water content and sand additive

Figure 6 shows the results of the tests conducted on kaolinite in all different water content. It is obvious that
content. Bentonite prepared with intended water content of 50% had a considerable increase in percentage of tensile strength from 0% to 20% of silica sand and decreases slightly from 20% to 30% of silica sand, and it had a moderate increase from bentonite with 30% to 40% of silica sand that has the average of accurate water content of 73.16%.

Fig. 7. Tensile Strength Increment after adding silica sand to kaolinite (increment percentage=tensile strength increase/tensile strength with none silica sand).

It is also shown that the bentonite prepared with intended water content of 100% had a considerable increase of tensile strength from 0% to 20% of silica sand and had a significant increase from 20% to 30% of silica sand. It also had a moderate increase from 30% to 40% of silica sand, which have average accurate water content of 134.42%. However, the tensile strength of the bentonite prepared with intended water content of 150% decreases significantly from 0% to 20% of silica sand, and it decreases slightly from 20% to 40% of silica sand.

3.3 Effect of dry density on tensile strength

Figure 10 shows the relationship between tensile strength and dry density for various sand additive values in kaolinite, it can be observed that the tensile strength of kaolinite prepared with different percentage of additive silica sand increases with the increase of dry density.

Figure 11 shows the testing results of the effect of drying density on the tensile strength. It can be seen that the relationship demonstrated in kaolinite is not followed in bentonite test. This will be discussed in section 4.

Fig. 8. Bentonite tensile strength with water content for various amount of silica sand additives.

3.4 Mode of failure

Figures 12 and 13 show the typical failure mode for...
kaolinite and bentonite, respectively, in the test. It can be seen that for kaolinite the tensile failure happens in the central section of the specimens with very rough failure surface (Fig. 12), which is perpendicular to the direction of tensile force. However, for bentonite, it can be seen that because the soil samples are too soft, and the clear failure surface does not occur.

Fig. 12. Typical failure mode of direct tensile strength test of kaolinite: a) into the device and b) out of device.

Fig. 13. Typical direct tensile strength test without the occurrence of failure surface of bentonite: a) into the device and b) out of device.

4 DISCUSSIONS

The comparisons of two soils on the relationships between the tensile strength and water content and dry density are shown in Figs 14 and 15. Comparing the two soils, generally, it can be seen that: 1) the bentonite has higher tensile strength than the kaolinite (Fig. 15); 2) the tensile strength decreases with increase of the water content (Fig. 15); 3) increasing the additive silica sand increases the tensile strength to an optimum tensile strength and then it will decrease if further increase the sand. This is particularly applicable for kaolinite (Fig. 7).

For bentonite, the tensile strength seems to have similar behavior that adding silica sand can increase its tensile strength. However, it can be seen that bentonite with 0% of silica sand have higher tensile strength than the others with 20%, 30%, and 40% of silica sand when all the test were prepared with 150% of water content (see the grey line in Fig. 9).

Even though some tests do not prove that the increase of dry density increases the tensile strength, in general, it was possible to say that dry density has an impact on the tensile strength of soil. However, comparing both soils it can be seen that the results of kaolinite had followed what Li et al., (2014) argued that with the increase of dry density, increases the tensile strength of soil, but bentonite seems not to follow the same way. It can also be seen in the Figure 15 that the kaolinite has a higher value of dry density than bentonite, but does not have a higher value of tensile strength. Dry density indicates the degree of compaction of the samples in the compaction machine.

Fig. 14. Comparison of the tensile strength of both soils.

Fig. 15. Comparison of the effect of dry density on the tensile strength of both soils.

5 CONCLUSIONS

The research was focused on the investigation and comparison of the tensile strength of two clayey soils (kaolinite and sodium bentonite). Understanding the tensile strength behaviour of soils has been studied in order to protect several issues that many geotechnical earth structures are facing. This issue is related to cracks that occurs on these geotechnical earth structures such as slopes, embankments, river banks, hydraulic barriers, and highways.

Each soil had been prepared on three different water content. For kaolinite 35%, 40%, and 45% of intended water content were used, and for bentonite, the value used were 50%, 100%, and 150% of intended water content. These differences for water content are due to the value of liquid limit, plastic limit, and plasticity index of each soil. It has seen that getting the accurate
value of each water content by analyzing after being dried, each sample had different water content, but close to the one that had been prepared.

The water content has a significant effect on tensile strength of soil: the results of all testing show that the tensile strength of each soil reduces with the increase of the water content. The tensile strength of bentonite is higher than that of kaolinite; this could also be due to the higher plasticity index (Table 1). The same conclusion had been found by Win (2006). There was obvious evidence that adding the additive silica sand on both clayey soils can change the tensile strength; it improves the mechanical properties of both soils as well as its tensile strength. The effect of dry density on the tensile strength of both soils had been analyzed: the higher dry density, the higher the tensile strength. This result is similar to the one found by Tang et al., (2015) and Li et al., (2014). Finally, this research has proven that the additive silica sand could be used as a solution to improve the mechanical properties, especially the tensile strength of both soils.

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Table 2: Intended and accurate value of water content of each sample of both soils (the first percentage number in each name of sample indicates the intended water content while the second percentage number is the percentage of sand additive).

| Type of Soil | Accurate water Content | Type of Soil | Accurate water Content |
|--------------|-------------------------|--------------|------------------------|
| Kaolinite    |                         | Bentonite    |                         |
| 35%_1        | 33.92                   | 50%_1        | 62.27                  |
| 35%_2        | 34.10                   | 50%_2        | 63.61                  |
| 35%_3        | 34.04                   | 50%_3        | 61.82                  |
| 35%_10%S_1   | 34.19                   | 50%_20%S_1   | 64.42                  |
| 35%_10%S_2   | 33.79                   | 50%_20%S_2   | 65.21                  |
| 35%_10%S_3   | 33.90                   | 50%_20%S_3   | 65.17                  |
| 35%_20%S_1   | 36.49                   | 50%_30%S_1   | 68.26                  |
| 35%_20%S_2   | 35.79                   | 50%_30%S_2   | 68.74                  |
| 35%_20%S_3   | 35.47                   | 50%_30%S_3   | 68.51                  |
| 35%_10%S_1   | 37.42                   | 50%_40%S_1   | 72.88                  |
| 35%_10%S_2   | 35.79                   | 50%_40%S_2   | 73.05                  |
| 35%_10%S_3   | 35.47                   | 50%_40%S_3   | 73.56                  |
| 35%_20%S_1   | 36.39                   | 50%_40%S_1   | 73.05                  |
| 35%_20%S_2   | 35.79                   | 50%_40%S_2   | 73.05                  |
| 35%_20%S_3   | 35.47                   | 50%_40%S_3   | 73.56                  |
| 35%_30%S_1   | 39.00                   | 100%_1       | 119.38                 |
| 35%_30%S_2   | 38.75                   | 100%_2       | 124.89                 |
| 35%_30%S_3   | 39.04                   | 100%_3       | 124.01                 |
| 40%_1        | 39.00                   | 100%_20%S_1  | 119.69                 |
| 40%_2        | 39.28                   | 100%_30%S_1  | 124.08                 |
| 40%_3        | 39.22                   | 100%_30%S_2  | 123.46                 |
| 40%_10%S_1   | 39.54                   | 100%_30%S_3  | 134.49                 |
| 40%_10%S_2   | 37.07                   | 100%_40%S_1  | 136.86                 |
| 40%_10%S_3   | 37.60                   | 100%_40%S_2  | 131.90                 |
| 40%_20%S_1   | 39.09                   | 100%_40%S_3  | 131.90                 |
| 40%_20%S_2   | 41.09                   | 100%_40%S_3  | 131.90                 |
| 40%_20%S_3   | 41.23                   | 100%_40%S_3  | 131.90                 |
| 40%_30%S_1   | 42.86                   | 100%_40%S_3  | 131.90                 |
| 40%_30%S_2   | 44.46                   | 100%_40%S_3  | 131.90                 |
| 40%_30%S_3   | 45.46                   | 100%_40%S_3  | 131.90                 |
| 45%_1        | 43.47                   | 150%_1       | 160.89                 |
| 45%_2        | 43.17                   | 150%_2       | 165.39                 |
| 45%_3        | 43.25                   | 150%_3       | 174.75                 |
| 45%_10%S_1   | 44.17                   | 150%_20%S_1  | 173.25                 |
| 45%_10%S_2   | 43.64                   | 150%_20%S_2  | 183.05                 |
| 45%_10%S_3   | 44.17                   | 150%_20%S_3  | 187.14                 |
| 45%_20%S_1   | 47.39                   | 150%_30%S_1  | 188.06                 |
| 45%_20%S_2   | 44.08                   | 150%_30%S_2  | 191.80                 |
| 45%_20%S_3   | 42.71                   | 150%_30%S_3  | 194.74                 |
| 45%_30%S_1   | 46.01                   | 150%_40%S_1  | 204.50                 |
| 45%_30%S_2   | 45.46                   | 150%_40%S_2  | 204.05                 |
| 45%_30%S_3   | 44.77                   | 150%_40%S_3  | 202.69                 |