The relationship between swelling and shear strength properties of bentonites

La relation entre les propriétés de résistance au cisaillement de l'enflure et des bentonitiques

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ABSTRACT: Clay Geosynthetic Barriers are manufactured hydraulic barriers. The mineral component usually consists of bentonite, which belongs to a group of expansive soils. The aim of this study was to establish the influence of swelling on mechanical properties of bentonites. For this purpose, granular bentonite Volclay was chosen for laboratory testing. Its mineralogical composition was predominantly montmorillonite (80% - 85% by mass). The correlation between swelling and water content on one side and changes in shear strength i.e. shear strength parameters on the other were tested using a direct shear device. During several series of testing, different levels of swelling of bentonite were simulated under the conditions of changing normal stress and hydration times. Swelling behaviour of bentonite was determined through the long-term swelling tests using oedometer, under changing normal stress. Shear strength testing show decreasing cohesion with longer hydration of bentonite. The friction angle increases with hydration that lasts from 7 to 14 days. There is no significant change in the friction angle with hydration time longer than 14 days.

RÉSUMÉ : Les géosynthétiques bentonitiques sont des produits manufacturés pour les barrages hydrauliques. La composante minérale est le plus souvent l'argile bentonitique qui appartient à la catégorie des sols gonflants. L'objectif de cette recherche est de déterminer l'influence du gonflement sur la propriété mécanique de l'argile bentonitique. Pour la recherche est choisie l'argile bentonitique en granulés Volclay, de composition minérale où domine la montmorillonite 80-85 %. La corrélation du gonflement et des changements d'humidité avec les variations de la résistance au cisaillement et les paramètres de résistance au cisaillement a été étudiée dans le dispositif de cisaillement direct. Voici la série de tests à différentes contraintes normales, à des temps variés d'hydratation, simulant divers degrés de gonflement de l'argile bentonitique. La courbe de gonflement d'argile bentonitique est définie par les expériences de gonflement prolongées à différentes contraintes normales dans l'œdomètre. Les résultats montrent une réduction significative de cohésion avec la prolongation de l'hydratation de l'argile bentonitique. L'angle de frottement augmente avec l'hydratation (de 7 à 14 jours). Il n'y a pas de changement significatif dans la valeur de l'angle de frottement lors d'une prolongation de l'hydratation supérieure à 14 jours.

KEYWORDS: Bentonite, Swelling, Direct shear test, Shear strength.

1 INTRODUCTION

Clay Geosynthetic Barriers (GBR-C) - a member of the family of synthetic materials - are extensively used nowadays as sealing barriers or their components in a wide range of engineering applications (Guyonnet et al. 2009, Kang and Shackelford 2010, Shackelford et al. 2010). In the clay geosynthetic barrier, bentonite makes the mineral component that ensures low hydraulic conductivity (Koerner 1996, Shackelford et al. 2000, Bouazza 2002, Katsumi et al. 2008), while layers of geotextile make the supporting component. Layers of geotextile are usually needle-punched or stitch-bonded in so called reinforced GBR-Cs. There are also unreinforced GBR-Cs, but their use are limited to relatively flat slope applications that do not present significant shear stress.

In deciding about the most suitable design for the sealing system, stability is one of the important factors to consider. When using clay geosynthetic barriers, it is important to pay attention to interface and internal shear strength. The interface strength is developed at the contact between the clay geosynthetic barrier and adjacent material, be it soil or other geosynthetic material. The internal shear strength is different with reinforced and unreinforced clay geosynthetic barriers. The internal shear strength of reinforced clay geosynthetic barriers depends on the strength of their components, more precisely the ultimate tensile strength of reinforcement yarns and the shear strength of bentonite. Hydrated bentonite has very low shear strength, which is why its impact on the internal shear strength will be reduced. The internal shear strength of unreinforced clay geosynthetic barriers is identical to the shear strength of bentonite clay (Gilbert et al. 1996, Kovačević Zelić 2000, Zornberg and McCartney 2009, Fox 2010).

Bentonite clays fall into the group of expansive soils. It was the bentonite clay swelling property the key mechanism that ensures very low levels of hydraulic and gas conductivity, and therefore its role of the clay geosynthetic barrier's sealing component. The cause for swelling is found in the fact that smectite clay minerals are the main component of bentonite, with montmorillonite as the predominant mineral. Electrical charge and the colloidal particle size are the reasons why this group of minerals is hydrophilic. Their ability to attract molecules of water allows them to increase volume several times, and it plays an important part in the mechanical properties of bentonite, including strength, deformability and hydraulic conductivity. What contributes further to the low hydraulic conductivity of bentonite is an increase in the content of montmorillonite; specific surface area (decrease in the size of particles); electrical charge deficit and sodium content (Na^+) in the system of exchange (Mitchell and Soga 2005, Guyonnet et al. 2009). The influence of these factors on the quality of bentonite can mostly be seen macroscopically through increases in ion exchange capacity, plasticity and swelling capacity (in the presence of fluid), against decreases in hydraulic conductivity and strength. It should be stressed here that sodium bentonite clays demonstrate a very low level of hydraulic conductivity and a high swelling capacity.

For the purpose of quantifying the role of bentonite within the clay geosynthetic barrier, laboratory tests were conducted with samples of Volclay granular bentonite, using direct shear and oedometer tests. As a part of this study, a detailed characterization of bentonite was carried out. Mineralogical composition of bentonite was: montmorillonite 80-85%, cristobalite around 5%, quartz around 5%, plagioclase 5%. Index properties of bentonite were as follows: liquid limit

437.0%, plastic limit 52.86%, specific surface area 700 m2/g and ion exchange capacity 88.63+/-6.51 meq/100g. The influence of swelling and water content of bentonite samples on the measured values of total shear strength and shear strength parameters was observed using the direct shear device. In a series of tests, under conditions of varying effective stress, hydration times were changed depending on the results of oedometric tests in order to simulate different levels of bentonite swelling. Swelling behavior of bentonite was defined through long-term oedometer tests with varying effective stress. In order to prevent the change in chemical and mineralogical composition of bentonite, demineralised water was used as the test fluid. Shear displacement rate was 1 mm/min. This displacement rate enables relatively short shear stage in relation to previously finished hydration stage, that is, the reduced impact of additional hydration and creep during shear stage on the test results.

2 OEDOMETER SWELL TEST

Bentonite swelling tests were performed using standard oedometer cells of 74 mm in diameter. The placement procedure was relatively simple i.e. pouring of granular bentonite into the oedometric cell was performed without the application of external loading. The initial water content (as-received) of granules was approximately 12%. Identical amounts of bentonite were used for all specimens, making sure that the bentonite is not compacted, but only slightly flattened. After installation, the specimens were loaded to normal stress levels of 50, 100 and 200 kPa. The next step was to add demineralised water into the cell, leaving the specimens to swell under applied normal stress levels for the next 276 days. At the end of experiments, specimens were taken out of the device, and final moisture content was determined.

Test results showed the highest level of swelling and relative vertical deformation for those specimens that were under the lowest levels of normal stress. Therefore, the intensity of swelling decreased as normal stress level increased. It is evident on the basis of the swelling curves that relative vertical deformation (swelling) of specimens after the period of 276 days was 65.80% (6.787 mm) under normal stress of 50 kPa; 38.54% (3.945 mm) under normal stress of 100 kPa and 13.93% (1.339 mm) under normal stress of 200 kPa.

The analysis of time required for the primary swelling stage indicates that these times were identical for all normal stress levels (Figure 1). In this particular case, the time for completion of the primary swelling was approximately 31 days, looking at all three series.

On the basis of analysis of vertical deformation development for these specimens upon completion of the primary swelling stage, it is evident that in the period which remained the stage of secondary compression started. Following conclusions were drawn by observing vertical deformations over the remaining period of 245 days during which there was secondary compression of the specimens:

- with specimen subjected to normal stress intensity of 50 kPa, there was compression by 0.092 mm, resulting in vertical deformation of 0.54%;
- with specimen subjected to normal stress intensity of 100 kPa, there was compression by 0.196 mm, resulting in vertical deformation of 1.36%;
- with specimen subjected to normal stress intensity of 200 kPa, there was compression by 0.203 mm, resulting in vertical deformation of 1.82%.

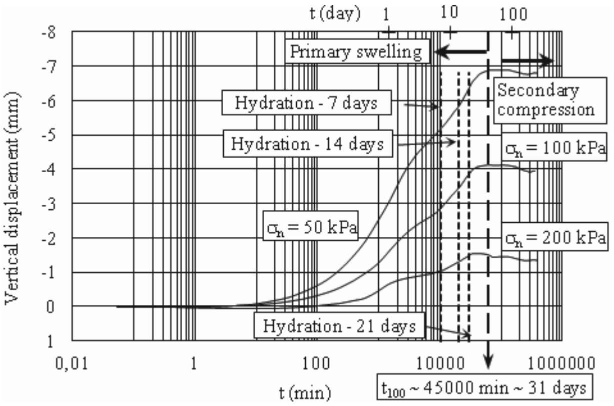

Figure 1. Bentonite swell tests.

Therefore, same as with the primary swelling, the rate of vertical deformation in the stage of secondary compression and how it develops with time also depends on normal stress levels, but in this case the intensity of secondary compression increases with the increase of normal stress level.

The specimens were subjected to secondary compression over a long period of time, so it is assumed that the impact of changing temperature in the laboratory on the vertical deformation curves is possible during the period of secondary compression. A combination of very low vertical deformations and variable temperatures in the laboratory during measurement may lead to a change in the rate of vertical deformation increment during secondary compression. Some changes in temperature in the laboratory were expected, and it is assumed that they affect measuring sensors used in this test.

3 DIRECT SHEAR TEST

3.1 *Laboratory testing program*

Clay geosynthetic barriers are composite materials. Considering the specific form of clay geosynthetic barriers, their shear strength is mainly tested using modified direct shear devices. This test was aimed at quantifying the performance of bentonite clay component within the clay geosynthetic barrier. It was conducted on a sample of granular bentonite, not including the geosynthetic component. The shear strength tests on some unreinforced and particularly on reinforced clay geosynthetic barriers indicate that special attention is required relating to the size of specimen. However, the specimen size is not crucial when testing the shear strength of bentonites. Therefore, a standard direct shear device with box dimensions of 60×60 mm was used in this study.

Previous studies of the shear strength of bentonite indicate that the key influence on its behavior comes from the property of swelling i.e. moisture content in the specimen. In order to establish the influence of bentonite swelling on its shear strength, specimens were tested in three series under normal stress of 50, 100 and 200 kPa, with varying hydration times (7, 14 and 21 days).

The specimen placement procedure consisted of pouring bentonite into the shear box. The as-received water content level in granules was approximately 12%. The same amount of granulated bentonite was always used, making sure that the bentonite is not compacted, but only slightly flattened. The described procedure ensured approximately identical initial values for thickness, dry mass and dry density of all specimens (their thickness was approximately 8 mm). This kind of procedure was believed to provide a representative simulation for the conditions under which bentonite is used as part of clay geosynthetic barriers. After the placement, normal stress loading was applied on the specimens immediately followed by the initiation of hydration procedure. After finished hydration procedure lasting 7, 14 and 21 days for three series of testing, specimens were sheared in the shearing stage by the same rate of shearing. Normal stress levels remained unchanged in both stages.

3.2 *Test results*

Measured vertical displacements in the shear stage indicate consolidation under all normal stress levels and hydration times. The displacement rate in these tests was 1 mm/min and the assumption was that compression during the shear would cause pore pressure inside the specimen to increase.

Table 1 shows the results of testing in the shear stage. Residual values of shear strength were obtained at specimen relative deformation of 15%, and this was also the maximum horizontal shear that could be obtained in the standard shear box. Shear strength values were constantly growing with the increase of normal stress and with decrease of final moisture content. With specimens subjected to stress levels of 50 and 100 kPa, longer hydration times caused higher values of final moisture content and decreasing shear strengths. With specimens subjected to stress level of 200 kPa, final moisture content and shear strength of bentonite did not change irrespectively on hydration times.

Table 1. Summary of direct shear test results.

Hydration time	Normal stress (kPa)	Shear strength		Final moisture content (%)
		Peak (kPa)	Residual (kPa)	
7 days	50	21.4	17.3	113.12
14 days	50	19.4	12.9	124.32
21 days	50	17.2	11.8	140.26
7 days	100	32.2	25.6	85.36
14 days	100	29.2	21.4	97.82
21 days	100	27.5	20.0	104.05
7 days	200	51.1	38.0	71.33
14 days	200	52.0	37.6	69.66
21 days	200	49.4	36.2	71.91

Table 2 shows the value of shear strength parameters obtained by shearing of bentonite specimens. Peak and residual strength envelopes are shown in Figures 2 and 3.

Table 2. Shear strength parameters.

Hydration time	Peak parameters		Residual parameters	
	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)
7 days	11.99	11.23	11.05	7.80
14 days	8.04	12.47	4.79	9.38
21 days	6.32	12.27	3.63	9.31

By observing peak (Figure 2) and residual (Figure 3) strength envelopes, it is evident that the specimens sheared after 14 and 21 days of hydration have almost identical values of peak and residual friction angle, while peak and residual values of cohesion were decreasing as specimen hydration times were increased. In the case of specimen hydrated for seven days, there was obvious change in behavior, in comparison with specimens hydrated for 14 and 21 days. This specific specimen shows significantly higher values for peak and residual cohesion and somewhat lower values for peak and residual friction angle, in comparison to specimens hydrated for 14 and 21 days.

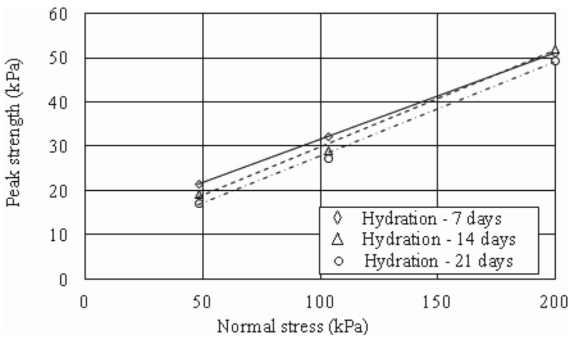

Figure 2. Peak strength envelopes.

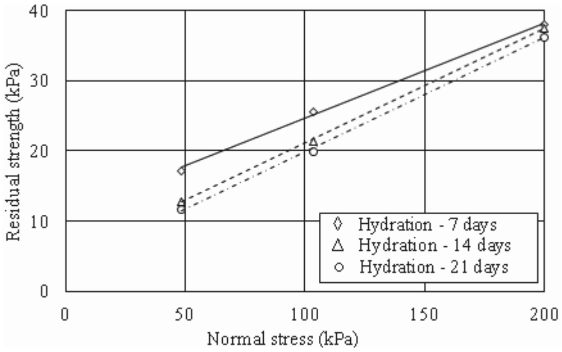

Figure 3. Residual strength envelopes.

Figure 4 presents the influence of final moisture content on the test result values for peak and residual shear strength. It is evident that, irrespectively to the normal stress level, shear strength has tendency to decrease as final moisture content increases.

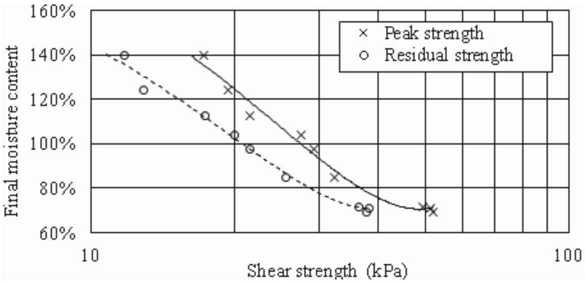

Figure 4. Final moisture content vs. shear strength.

Figure 5 presents the correlation between peak and residual friction angles and the time of hydration. For hydration times in this test, a change in the friction angle was visible up to the 14th day of hydration. After that, the friction angle decreased insignificantly.

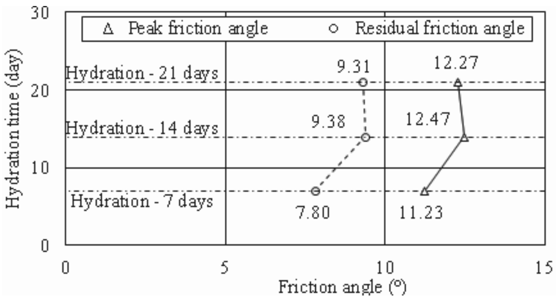

Figure 5. Hydration time vs. friction angle.

Figure 6 presents the correlation between peak and residual cohesion and the time of hydration. Observing the change in cohesion, it is evident that cohesion decreases constantly with longer hydration times.

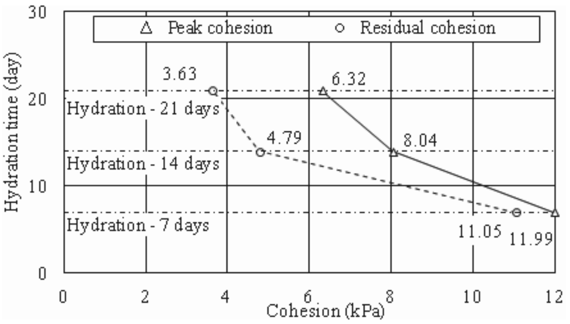

Figure 6. Hydration time vs. cohesion.

Friction angle and cohesion values were normalized and expressed in percentages in relation to the parameter values after seven days of hydration. It is evident that a 14-day hydration causes peak friction angle to increase by around 10%, while extended hydration time results in insignificant decrease of the friction angle (Figure 7). The increase is higher with the residual friction angle – by around 20% after 14 days of hydration, while after that it decreases insignificantly.

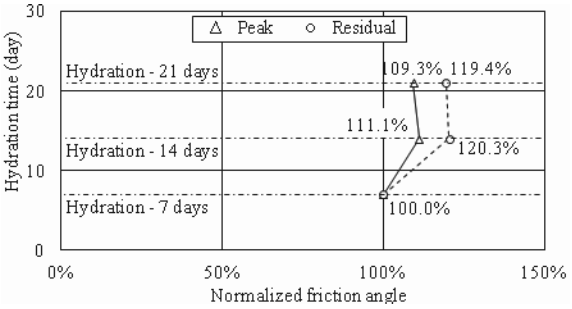

Figure 7. Hydration time vs. normalized friction angle.

Cohesion values continuously decrease with the increase of hydration time, and this is particularly evident with residual cohesion, where this reduction is more obvious (Figure 8). Specifically, the value of peak cohesion equals 67% of normalized value (in comparison to 7-day hydration) after 14 days of hydration and 52.7% after 21 days of hydration; the value of residual cohesion equals 43.3% of normalized value, which is by 13.7% higher reduction in residual cohesion. After 21 days of hydration, the value of residual cohesion equals 32.9% of normalized value, which is by 9.8% less in comparison with peak cohesion.

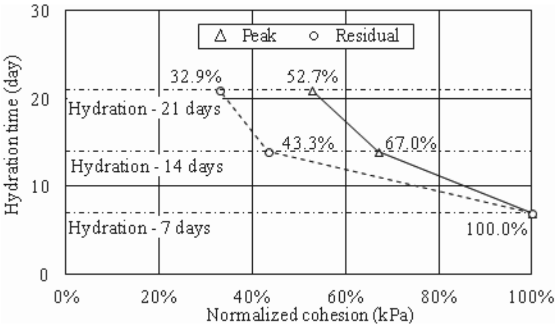

Figure 8. Hydration time vs. normalized cohesion.

4 CONCLUSIONS

Test results show that the swelling of bentonite clay is a long-lasting process. Tests carried out on the Volclay sample have shown that the primary swelling stage is completed after 31 days, regardless of the normal stress intensity. After primary swelling, the stage of secondary compression and creep develops. The extent of swelling and secondary compression depends on the normal stress levels.

The analysis of shear strength parameters of specimens hydrated for 7, 14 and 21 days shows decreasing cohesion with extended times of hydration. When hydration time is longer than 14 days, the intensity of change in cohesion decreases. The intensity of change in residual cohesion in the first 14 days of hydration is higher than for peak values, presumably as a result of increasing pore pressure during the shear stage.

With extended hydration time (from 7 to 14 days), the friction angle initially increases, but further extension of hydration (to more than 14 days) produces almost no change in the friction angle value. Peak and residual friction angles change in line with this pattern, but the extent is somewhat smaller for the residual friction angle.

Knowing the process of swelling of bentonite is important from the aspect of shear strength of bentonite and clay geosynthetic barriers. Also, the displacement rate influences peak and residual values of bentonite shear strength. Lower displacement rate means a longer test duration overall, and consequently more time for hydration/swelling in case of normal stress levels that are smaller than the bentonite swelling pressure. Potential continuation of the hydration process in the shearing stage will depend on the stage of swelling that the specimen is in. If the time required to finalize primary swelling has been reached, it can be assumed that hydration of the specimen would end, and that after this the specimen would enter the stage of secondary compression

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