The Correlation between the CBR and Shear Strength in Unsaturated Soil Conditions

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Abstract

In pavement design, the CBR and direct shear tests are two very common laboratory investigations for predicting the strength of a subgrade layer. The relationship between the CBR and water content has been commonly presented in analyses, with the result of the direct shear being expressed from the aspect of effective cohesion and the internal friction angle. Even though most natural soil is in an unsaturated condition, the effect of soil suction on CBR has not been taken into account in practice. The information on the CBR based on soil suction is very rare. A new CBR test technique using suction measurement was recently implemented by the authors, namely the suction-monitored CBR test. The aim of this study is to make a correlation between the unsaturated CBR measurement and the unsaturated shear strength of a subgrade layer. The data was taken from suction-monitored CBR tests and suction-monitored direct shear tests on sand and sand-kaolin clay mixtures. The results indicate that there is a positive correlation between the CBR and the unsaturated shear strength. By using this correlation, the suction-affected CBR of a particular soil can be predicted using the suction-monitored direct shear test.

Keywords: CBR-shear strength correlation, sand-kaolin clay mixtures, unsaturated shear strength

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1. Introduction

In pavement design, the California Bearing Ratio (CBR)is a very commonly used laboratory test for predicting the strength of a subgrade layer. The CBR has been used for some time as a semi-empirical approach towards predicting the bearing capacity of subgrade layers. This method was first introduced into the California State Highway Department in the 1920's. The US Army Corps of Engineers then adapted the method in the 1940's for military airfields. After the Second World War, the CBR was also used in the UK and its use spread to European countries (Ashworth, 1972; Croney and Croney, 1991). Due to its simplicity and relatively low cost, this method has been widely used across the world for flexible pavement design. Even though most near-surface soil layers are in an unsaturated condition, the effect of suction on the results of the CBR test has not been taken into consideration in practice. Recently, a laboratory study was carried out by the authors. This study on suction-affected CBR, namely the suction-monitored CBR test, was conducted on artificial soil consisting of sand and kaolin clay mixtures. At the same time, a laboratory study of suction-affected shear strength, namely the suction-monitored direct shear test, was also carried out. The results of these techniques were combined to develop correlation between the CBR and the shear strength of soil in unsaturated conditions.

2. The Effect of Suction On Soil Behavior

Vital as According to Houston et al. (1994), soil suction is one of main parameters used in unsaturated soil mechanics. The role of this parameter is as vital as pore water pressure measurement of effective stress in saturated soil mechanics. Suction is defined as the ability of soil to absorb additional water [Murray and Sivakumar, 2010]. It is the attraction of water to transform a soil water molecule from the liquid phase into the vapour phase [Bulut and Wray, 2005].There is a relationship between water content and soil suction; the higher soil water content, the lower suction in the soil. The change of water content in the soil is responsible for the changes in suction. In all geotechnical problems, the change in soil suction is responsible on the change of the behavior of unsaturated soil.

3. Existing CBR Correlations

A number of studies and investigations such asin-situ or laboratory tests have previously been carried out to make correlations between the CBR and other soil properties. The CBR-bearing capacity correlation from a static cone penetrometer, the CBR-DCPIcorrelation from a dynamic cone penetrometer, and the CBR-Young modulus from a falling weight deflectometer (FWD) were amongst such CBR correlations made from in-situ testing. The CBR has also been correlated with laboratory test results such as those of the undrainedshear strength of the soil. Most of the correlations were applied according to the particular circumstances of the soil such as soil type, dry density, soil consistency andegree of saturation. Some of the correlations are presented as follows:

Scala was one of the first investigators who developed the correlation between the CBR and soil strength. He undertook a considerable number of tests in Australia for obtaining the CBR,using static/dynamic cone penetrometers(DCP)[Scala, 1956]. The correlations were presented in blows/inch-CBR curves from DCP tests, and the bearing-capacity-CBR curve from static cone penetration tests. Other than Scala, studies regarding the CBR and DCP impact on various types of soil have also been conducted by researchers such as kleyn(1975), Smith and Pratt (1983), Harrison (1986) and Webster et al. (1992). The difference between the results of all of these studies was not significant. One of the correlations was presented below in Eq. (1):

$$\log CBR = 2.465 - 1.12 \log (DCP) \qquad (1)$$

Black (1961) and Black (1962) developed a correlation between the CBR and the ultimate bearing-capacity (q_u) of inorganic cohesive soil. Black suggested that the relationship between the CBR and q_u was dependent on the type of soil and method of compaction (static or dynamic). The proposed correlation was:

$$CBR = \frac{q_{u\,(kPa)}}{70} \qquad (2)$$

A laboratory study on artificial soil was conducted to correlate the unsoaked CBR and undrained shear strength S_u as reported by Danistan and Vivulanandan(2009), and Danistanand Vipulanandan(2010). They proposed the correlation in Eq. (3)for CH soil and

Eq. (4) for CL, CH and SC respectively:

$$S_u = -0.426\,(CBR)^2 + 2.212\,(CBR) \tag{3}$$

$$CBR = 0.56\,S_u^{1.07} \tag{4}$$

The CBR has also been correlated with the modulus of subgrade,E_s as reported by Powell et al. (1984), and shown below:

$$E_s\,(MPa) = 17.58 \times CBR^{0.64} \tag{5}$$

Chen et al. (2005)reported that Eq. (6) was adopted by AASHTO (1993) as the soaked CBR-subgrade modulus correlation for fine-grained soils.

$$E_s(MPa) = 10.34 \times CBR \tag{6}$$

Rao et al.(2008) reported the correlation between the CBR and the Young modulus (in MPa) obtained fromportable falling weight deflectometers (PFWD) on lateritic subgrade soil as:

$$CBR = -2.7543 + 0.2867\,(E_{PFWD}) \tag{7}$$

The study was carried out to correlate the CBR and the unconfined compression strength σ_c(MPa) by Behera and Mishra(2012)on fly ash-lime mixture at 7 and 28 day curing periods. The correlations proposed are written in Eq. (8) and (9) respectively:

$$CBR = 108.8\,\sigma_c + 14.14 \tag{8}$$

$$CBR = 56.45\sigma_c + 39.12 \tag{9}$$

The effect of unsaturated conditions has been taken into consideration by Black (1962)who proposed the correlation between the unsaturated and saturated CBR (CBR_u and CBR_s) for remoulded inorganic cohesive soil as:

$$CBR_{unstauretd} = CBR_{saturated}\,x\ (Degree\ of\ saturation)^{2.3} \tag{10}$$

Ampadu(2007)carried out an experimental study on decomposed granite in unsaturated conditions and found that the CBR of unsaturated conditions (CBR_u) can be predicted using saturated CBR (CBR_s) values, suction (u_a- u_w), and air entry values u_e of the specimen. He proposed the correlation:

$$CBR_u = CBR_s\ x\ \left[\frac{u_a - u_w}{u_e}\right]^n \tag{11}$$

where: the value of n is dependent on dry density.

In short, all of the correlations were applied to a particular soil type in either a saturated or unsaturated condition. There are many other correlations of the CBR with other soil parameters such as resilient modulus, maximum dry density, fines content, plasticity index and grading modulus.

4. Material Properties

Artificial specimens of sand, kaolin clay and sand-kaolin clay mixtures of 95:5 and 90:10 proportions by weight were used in this study. The index property tests carried out on them were based on ASTM D 854 for specific gravity, D 422/63 for grain size analyses, D 4318 for the Atterberg limits test, and D-2487 for soil classification. The results are summarized in Table 1.

The standard compaction test was performed on sand, 95:5 and 90:10 mixtures based on ASTM D 698 to obtain their compaction characteristics. Additional compaction tests were also performed on 80:20, 60:40, and 100:0 (kaolin clay) mixtures to obtain a broader range of proportions from 0% to 100 % of kaolin clay content. The results were used as a reference for specimen preparation for the direct shear and CBR tests. The results are presented in Figure 1.

For this poorly graded sand, the densification due to compaction was mainly caused by rearrangement amongst their particles. During compaction, particles of sand move to fit in the best position. The voids become narrower and the specimen becomes denser and more compact. However, due to the lack of smaller particles, the pore spaces in poorly graded sand remain relatively unfilled. To some extent, the addition of kaolin clay to sand could produce a new material with better properties such as dry density. The presence of kaolin clay, to some extent, will cause an increase in dry density and a decrease in void ratio. These results agree well with the results of Mullin and Panayiotopoulos (1984a)(1984).

5. Suction Monitored Direct Shear Test

5.1. Working principles

The suction-monitored direct shear apparatus is a device for unsaturated shear strength testing. Tarantino and Tombolato (2005), Jotisankasa and Mairaing (2010) were amongst the researchers who developed this device. It is basically made by modification of the conventional direct shear by attaching tensiometer(s) on some parts of the shear box. The tensiometer is placed in such a way that its ceramic surface has a good contact with the specimen. During the shear, suction is monitored. Fig. 2 shows the cross section of the suction-monitored direct shear apparatus.

Table 1. Summary of index properties of specimens

Specimen	Source	G	LL	PL	PI	C	C	Classification
Kaolin day	Uni min, WA	2.58	31	58	N.A	27	N.A	CH
Sand	Bal divi, WA	2.63	N.A	N.A	N.P	2.53	SP	0.99
mix ture 95:5	N.A	2.63	N.A	N.A	N.P	3.43	SP	1.3
mix ture 90:10	N.A	2.63	15.4	21.3	22.55	5.9	SC-SM	5.88

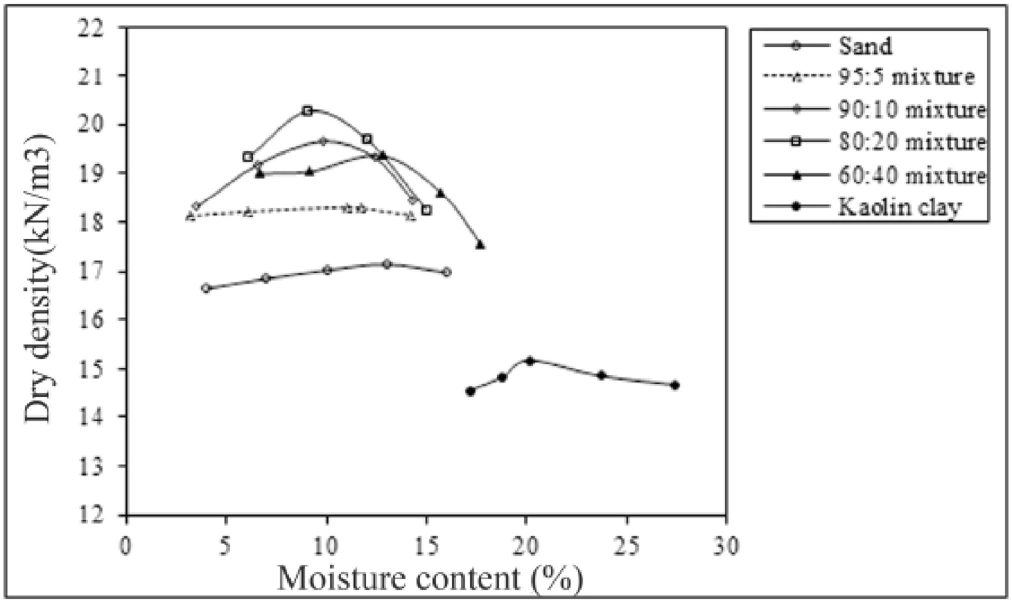

Figure 1. Compaction curves of specimens

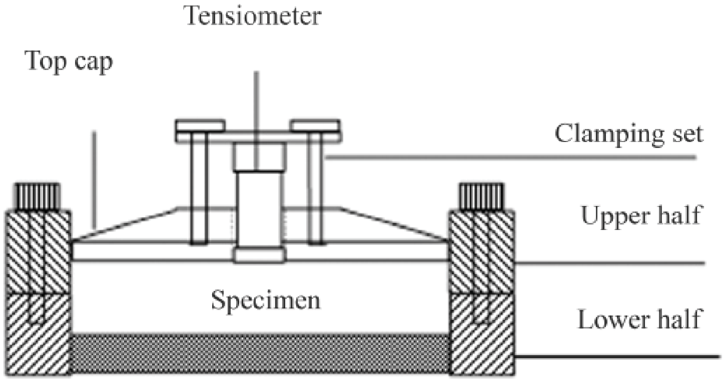

Figure 2. Cross section of suction-monitored direct shear apparatus(Purwana et al., 2011)

5.2 Test Result

The final results of the suction-monitored direct shear test is presented by a family of curves describing the relationship between suction and shear strength, as shown in Fig. 3 (a), (b), and (c). In this study, due to the limited capacity of the tensiometer, the curve was finalized at a suction point of below 80 kPa. It can be observed that all curves exhibit a bilinear form, providing equation y1 and y2 for the first and second line respectively.

A single failure envelope was created from a series of saturated and unsaturated direct shear tests with the application of different levels of suction pressure on the specimen, using three variations of initial net normal stresses. In this method, the different levels of suction pressure were generated naturally by adjusting the specimen's water content using the air-drying method; the drier the specimen, the higher the suction.

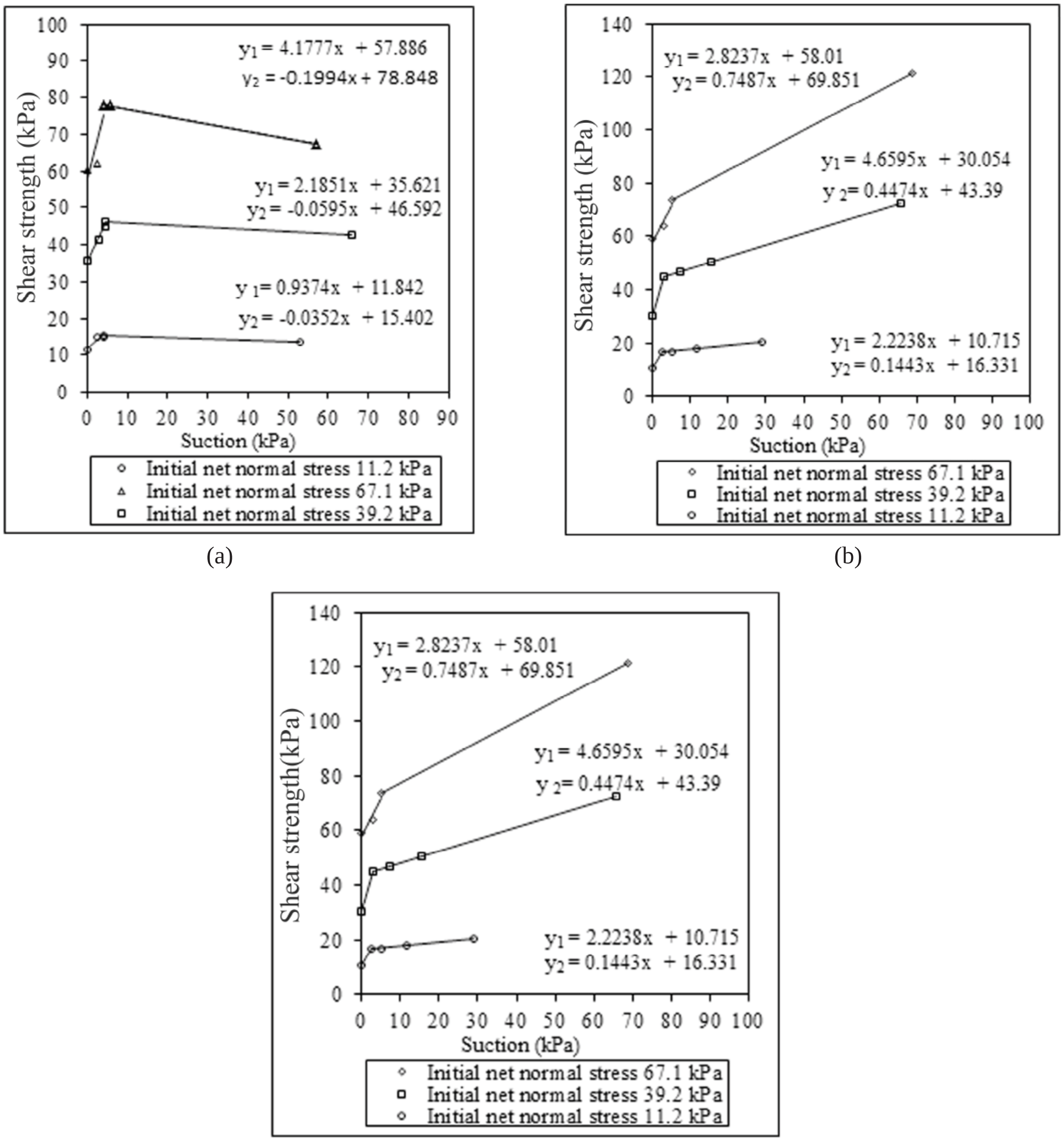

Figure 3. Failure envelopes of unsaturated specimens; (a) sand, (b) 95:5 mixture, and (c) 90:10 mixture

6. Suction-Monitored CBR Test

6.1 Working Principles

The working principles of the suction-monitored CBR test are similar to the suction-monitored direct shear test. In this test, tensiometers were attached to some parts of the CBR mould in such a way that during penetration, suction was monitored continuously using a data logger or another digital device. In this study, a tensiometer was placed on a surcharge weight (T_1) and 2 tensiometers were attached to the CBR mould (T_2).
A number of experimental laboratory tests were carried out on sand and sand-kaolin clay mixtures with similar proportions to the specimens used in the suction-monitored direct shear test. Compaction was performed according to method C of the ASTM D 698. Compaction was carried out layer by layer @ 56/layer in a 6 in. (152 mm) mould with a 5.5 lb. (2.5 kg) standard hammer falling 304.8 mm to achieve 100% maximum dry density. The CBR tests were conducted in soaked and unsoaked condition representing saturated (or near saturated) and unsaturated conditions.

Three types of specimens were prepared to obtain saturated and unsaturated specimen with different values of suction. The worst field conditions were simulated by the saturated or near saturated conditions. The unsaturated specimens with different water content were prepared to simulate natural “in-field” conditions when it underwent a water content reduction due to air-drying after compaction. There was no special treatment given to this category of specimen. For this, the surface of the compacted specimen was left to have contact with the free air in order for some of the pore water to evaporate. During this period, the weight of the specimen was recorded to predict its water content. When the desired water content was achieved, the air-drying was stopped. Prior to CBR penetration, this specimen was covered with a plastic sheet to avoid further evaporation. Fig. 4 shows the cross-sectional set up of the suction-monitored CBR test.

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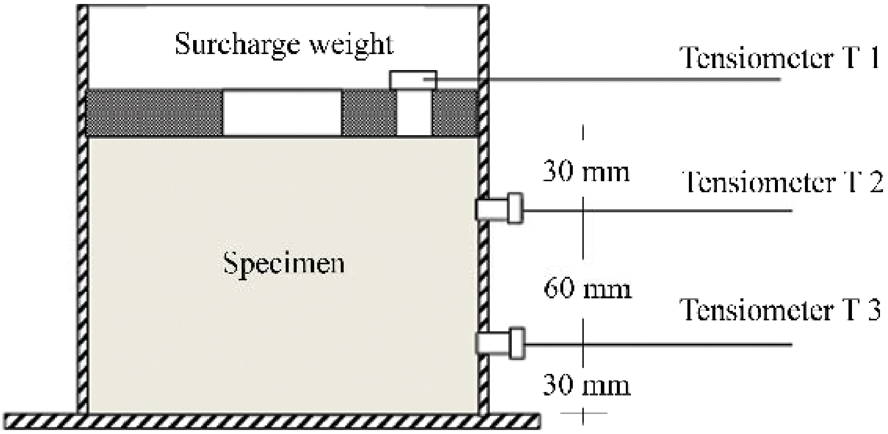

Figure 4. Schematic cross-sectional setup of the CBR test (Purwana et al., 2012)

6.2 Test Results

Fig. 5 shows the plots of suction versus CBR of all specimens. It can be observed from the figure that for those particular soils with a particularly low range of suction, all curves exhibit a bilinear form. The first part of the curve starts from near zero suction (saturated sample) to near air entry value (AEV) with a significant increase in the CBR. The second part starts from near AEV with a relatively slower increase in the CBR. Suction did not ever attain a zero value even though the sample was soaked for 4 days. For simplicity, the equation of each line of each failure envelope is displayed in each figure.

7. CBR- Shear Strength Correlation

The CBR and shear strength tests, in which suction was taken into consideration, were time-consuming and costly. The laboratory procedure associated with the devices and specimen preparation was complex. The correlation between their parameters was then beneficial.

In this study, the data was obtained from both suction-monitored CBR and suction-monitored direct shear tests on sand, 95:5, and 90:10 sand-kaolin clay mixtures. This correlation may only be valid for the range of suction from zero to 80 kPa and may only be applicable to sand and sand with small amounts of fine-grained material. The correlation was developed by plotting the failure envelopes of sand from Fig. 3 (a) and the suction-CBR curve of sand from Fig. 5. By using a 5 kPa interval of suction, the curves of unsaturated CBR versus unsaturated shear strength were plotted as shown in Fig. 6. It can be seen that a single value of CBR can be obtained from at least one of the curves, either from an initial normal stress of 11.2 kPa, 39.2 kPa, or 67.1 kPa. The good range of R-square values between 0.87 and 0.92 indicated that these correlations were reasonable.

It can be observed from Fig. 6 that the unsaturated CBR value of sand can be predicted using the unsaturated shear strength (τ_u) result from the unsaturated direct shear test. It is possible to add some more curves amongst them to accommodate initial normal stresses other than 11.2 kPa, 39.2, kPa or 67.1 kPa. For example, a curve of an initial normal stress of 25 kPa can be constructed roughly between the first and the middle curves as shown in that figure (dashed line). A similar method was adopted to correlate the CBR and the unsaturated shear strength for the 95:5 and 90:10 mixtures. The equations and R-square values are presented in Figures 7 and 8 respectively. The high R-square values of these equations indicated a positive correlation between the CBR and unsaturated shear strength.

Table 2 summarizes the correlations for all type specimens.

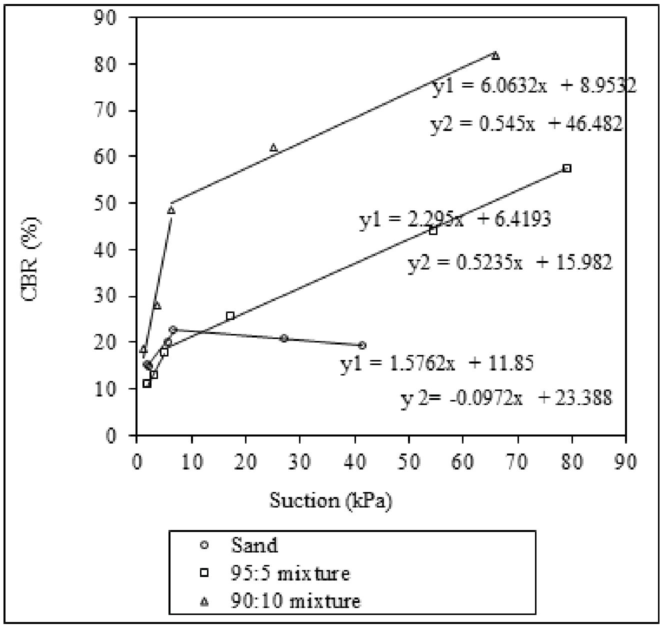

Figure 5. Suction versus CBR plot (modified from Purwana et al., 2012)

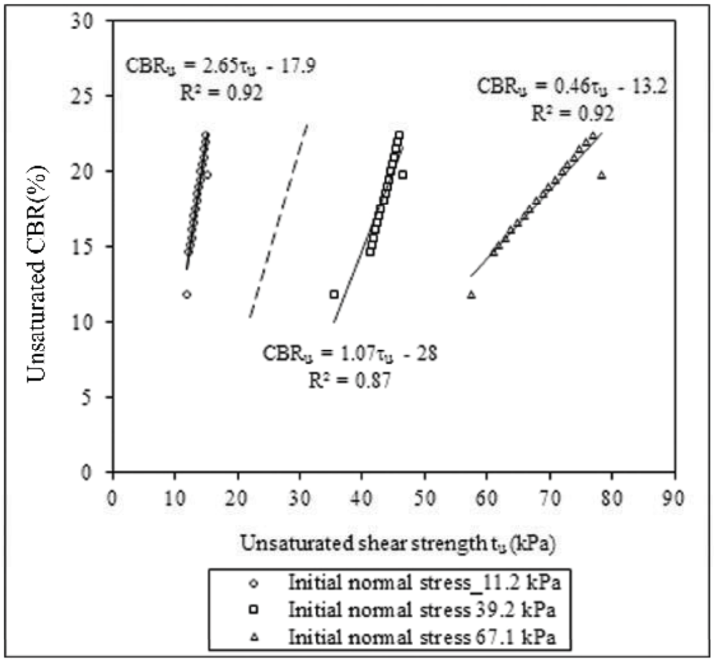

Figure 6. Plot of unsaturated strength versus unsaturated CBR for sand

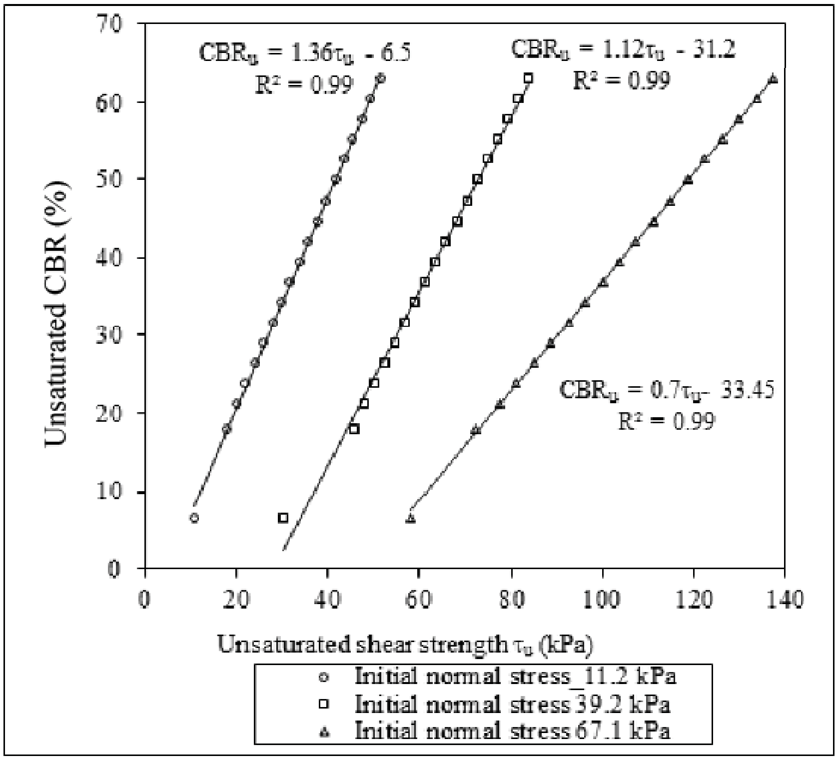

Figure 7. Plot of unsaturated strength versus unsaturated CBR for 95:5 mixture

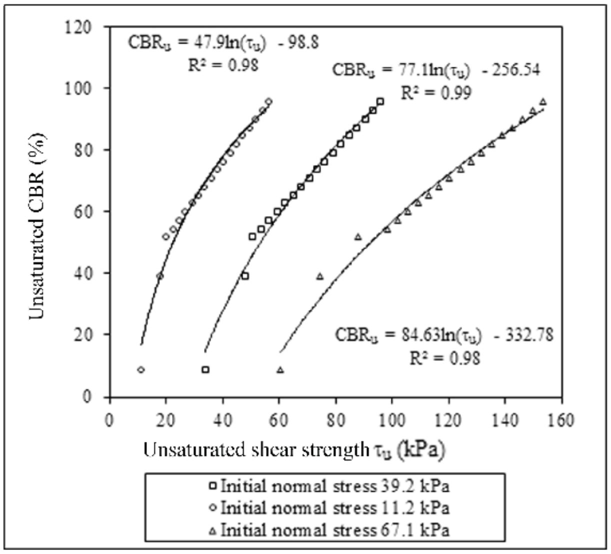

Figure 8. Plot of unsaturated strength versus unsaturated CBR for 90:10 mixture

Table 2. Summary of correlations for all specimens

Specimen	σ_n(kPa)	Correlation	Equation
Sand	11.2	$CBR_u = 2.7\tau_u + 17.9$	(12 a)
	39.2	$CBR_u = 1.07\tau_u + 28$	(12 b)
	67.1	$CBR_u = 0.46\tau_u + 13.2$	(12 c)
95:5 mixture	11.2	$CBR_u = 1.36\tau_u + 6.5$	(13 a)
	39.2	$CBR_u = 1.12\tau_u + 31.2$	(13 b)
	67.1	$CBR_u = 0.7\tau_u + 33.45$	(13 c)
90:10 mixture	11.2	$CBR_u = 47.9ln(\tau_u) + 98.8$	(14 a)
	39.2	$CBR_u = 77.1ln(\tau_u) + 256.54$	(14 b)
	67.1	$CBR_u = 84.63ln(\tau_u) + 332.78$	(14 c)

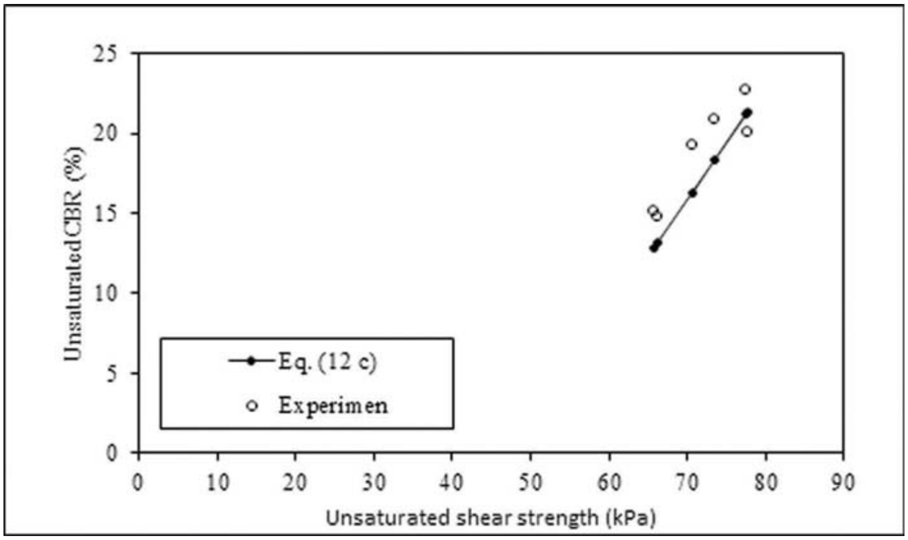

Figure 9. Curve showing the comparison of the experimental and correlation results of sand

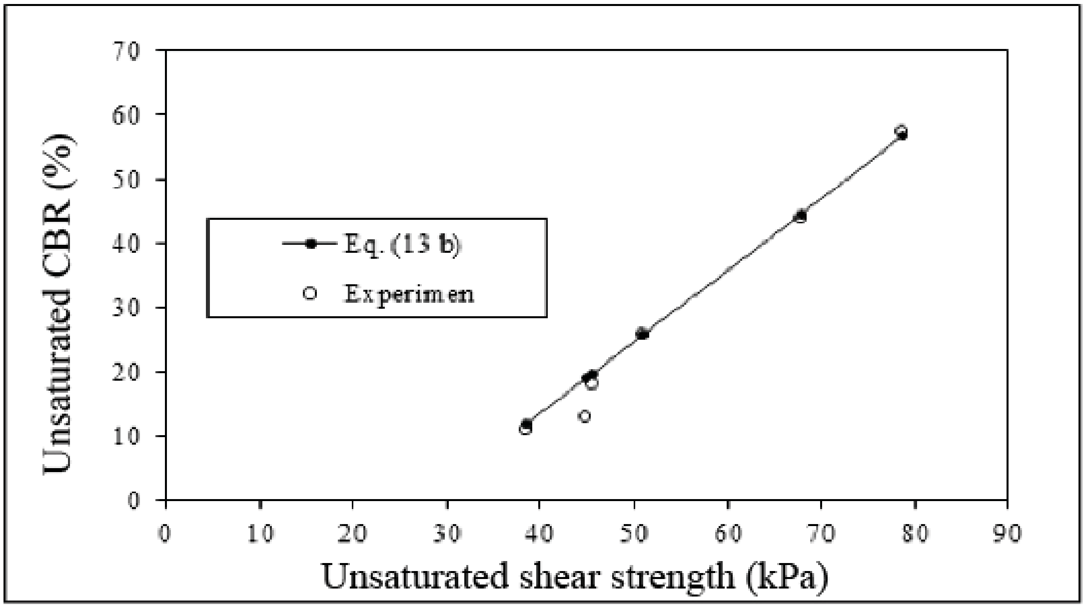

Figure 10. Curve showing the comparison of experimental and correlation results of 95:5 mixture

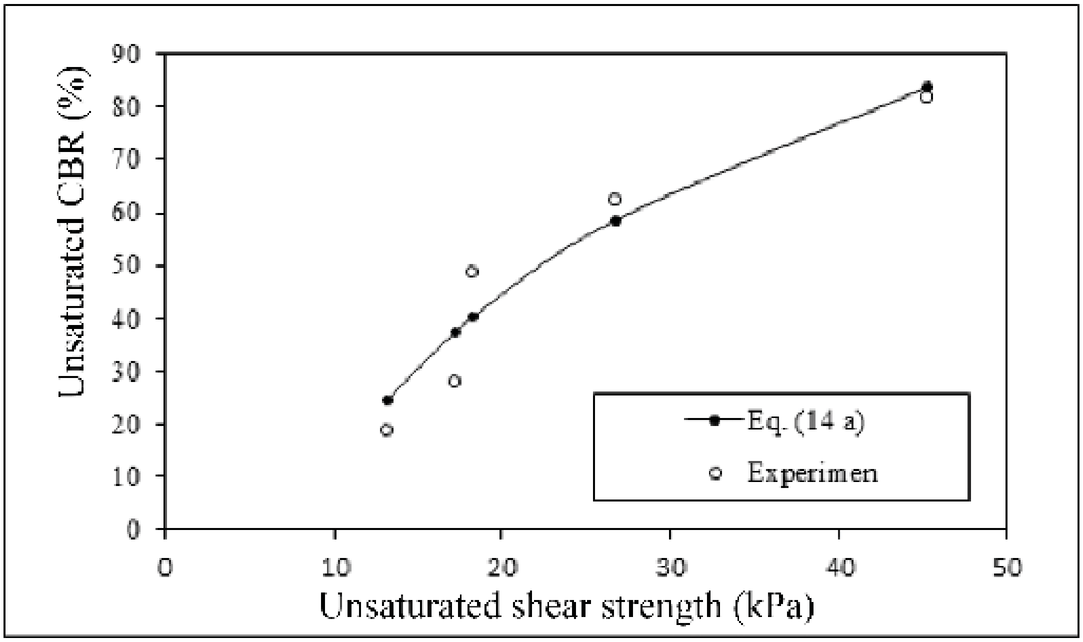

Figure 11. Curve showing the comparison of experimental and correlation results of 90:10 mixture

8. Conclusions

A correlation between unsaturated shear strength and unsaturated CBR has been discovered. This correlation may only be applicable to a very low range of suction (up to 80 kPa), and only for particular sand and sand kaolin clay mixtures with low proportions of clay. The high R-square values of the equations indicate that the correlations are valid.

9. Acknowledgments

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