Influence of Matric Suction on Resilient Modulus and CBR of Compacted Ballina Clay

Sin-Mei Lim[b], Buddhima Indraratna[c], Ana Heitor[d], Kai Yao[a*], Dalong Jin[e], Wael M. Albadri[f], Xia Liu[g]

[a] *School of Qilu Transportation, Shandong University, Jinan 250002, China.*
[b] *NUS Environmental Research Institute (NERI), National University of Singapore, 21 Lower Kent Ridge Road, Singapore 119077, Singapore.*
[c] *Faculty of Engineering & Information Technology, University of Technology Sydney, Broadway, NSW 2007, Australia.*
[d] *School of Civil Engineering, University of Leeds, LS2 9JT, UK.* [e] *Department of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China.*
[f] *Department of Mechanical Power Technical Engineering, Al—Amara University College, Misan 62001.*
[g] *Jining Hongxiang Highway Survey Design & Research Institute Co. Ltd, Jining 272000, China.*

***Corresponding author (Kai Yao)**
Email addresses: drsinmei@gmail.com (Sin-Mei Lim), Buddhima.Indraratna@uts.edu.au (Buddhima Indraratna), A.Heitor@leeds.ac.uk (Ana Heitor), yaokai@sdu.edu.cn (Kai Yao), jindalong@163.com (Dalong Jin), w_m120@yahoo.com (Wael M. Albadri), 838052903@qq.com (Xia Liu)

Abstract: Road infrastructure is often built above the groundwater table. The materials used are usually compacted and thus generally remain under unsaturated conditions throughout their service life. This paper presents experimental results that highlight the influence of matric suction on the resilient modulus (MR) and California bearing ratio (CBR) of a compacted subgrade Ballina clay (typically found in NSW, Australia). The soil specimens were prepared in a range of water contents and dry unit weights, tested using a series of repeated load triaxial tests and CBR tests, and the associated matric suction was measured using the filter paper method. The tests were complemented by the study of the macrostructure of the compacted specimens using X-ray computed tomography (CT). Test results show that there are intimate relationships between the soil suctions and resilient modulus as well as CBR on the compacted clay at different moisture contents and that both parameters can be defined empirically through matric suction. A linear trend was established between matric suction and M_R with a high coefficient of correlation of 0.99. CT scan results reveal that increasing soil moisture increased the inter-pores volume and the aggregations became more compressible and present probable matrix-dominated macrostructure during compaction. While soils compacted at the dry side of optimum moisture content yield distinct aggregations owing to the flocculation and aggregation of soil structure.

Keywords: Compaction; Matric suction, CT-Scan; CBR, Resilient modulus

Introduction

The mechanical behaviour of an unsaturated pavement subgrade is significantly influenced by the variation of the soil suction [1], with is also known as negative soil pressure due to the cooccurrence of air and water in the soil fabric [2]. It implicitly measures the effect of soil-water interaction forces on the deformation characteristics of the pavement materials [3]. For an unsaturated soil, the association of the soil suction with the surface tension between water and the soil particles is a state variable essential for assessing the mechanical response to loading, in particular under repeated traffic loading [4]. Thus, one of the key mechanical properties for determining the response of pavements under repeated traffic loading according to the Mechanistic-Empirical Pavements Design Guide [5] is the resilient modulus (M_{R}), along with its susceptibility to changes in water which is corresponding to changes in matric suction. Another most widely used parameters in the design of pavement subgrade is the California bearing ratio (CBR), where the bearing ratio and deformation of the subgrade layers are greatly affected by the changes of matric suction of the soil [6]. Over and above this, field dry unit weight is also another mechanical parameter essential in quantifying the compaction quality of the pavement subgrade, while the associated water content affects the magnitude of matric suction, this successively influence the effective stress of the compacted soil [4]. However, there have been limited studies on the influence of soil suction on CBR in relation to its M_R under the whole range of water content across the compaction curve.

Mirzaii and Negahban (2016) [6] discussed extensively on the effects of soil suction with CBR on clayey sand. Recent studies [7, 8] attempts on investigating the effect of matric suction (ψ_{m}) on resilient modulus (M_{R}) and found that an increase in ψ_{m} contributes to the enhancement of soil stiffness for a compacted soil. On the other hand, Kim and Kim (2007) [9] evaluated the resilient modulus of the compacted sandy-silty Indiana subgrade soils prepared at different water contents. Similar nature of research was done by Nowamooz et al. (2011) [10] in investigating the resilient behaviour of a natural compacted sand prepared at various moisture contents, without correlating with soil suction or CBR value. Furthermore, Sawangsuriya et al. (2008) [11] studied the effect of matric suction on M_R of fine-grained subgrade soils compacted at optimum moisture contents (OMC) and note that the M_R increases with the increase in soil matric suction. Several studies were attempted in correlating M_R with CBR on various unsaturated soil type [12-13]. Among others, Garg et al. (2009) [14] opined that a relationship between M_R and CBR can be established but there is a wide divergence from the experimental value. Whereas Leung et al. (2013) [15] re-examined the prediction of M_R with CBR for compacted saprolitic subgrade soils using several models established by past researchers but the result shows that the predicted relationships were either limited to different ranges of compaction density or were excessively conservative for adoption. Leung et al also further emphasize the importance of saturation and moisture ratio, inextricably correspond this to the soil suction that are useful in estimating M_R and CBR. Notwithstanding this, most of the aforementioned studies focuses solely on the correlation of either the soil suction with CBR or M_R, or the relationship of CBR and resilient modulus, these studies did not consider the influence of soil suction on both CBR and M_R arising from the variation in water contents and density in the compacted soil, and its interrelationship.

This study investigates the influence of soil suctions on the resilient modulus and CBR properties of Ballina clay in its compacted state and their interrelationships through a series of laboratory testing. The study reveals that there is an intimate relationship between the soil suction and resilient modulus as well as CBR arising from its compaction characteristics (i.e. moisture content and dry unit weight). A one-to-one relationship was also observed with the M_R and CBR across the evolution plane based on matric suction. The tests were complemented by the study of the macrostructure of the compacted specimens using X-ray computed tomography (CT).

Materials and Testing Strategy

The soil selected for this study was collected from a site close to the Pacific Highway in Ballina which runs along the east coast of Australia between Sydney and Brisbane (Fig. 1). This site, located in a low-lying flood plain, consists of mostly highly compressible and saturated clays. Ballina clay has a liquid limit (LL) of 96%, a plasticity index (PI) of 63% and a specific gravity of 2.63. The particle size distribution of the Ballina clay (Fig. 2) represents approximately 67% sand, 17.25% silt and 11% clay size fraction whereas the uniformity of coefficient(C_u) is 9.83 and curvature coefficient (C_c) is 1.14. Thus, based on the index properties and the grain-size distribution, the soil is classified as high-plasticity clay, CH [16]. Ballina clay can also be classified as CE according to British Soil Classification System (BSCS) where C is defined as clay and E is defined as extremely high (LL > 90%). The soil properties of Ballina clay have also been studied in detail by Indraratna et al. (2014) and Pineda et al. (2016)[17-18] and the basic soil properties are given in Table 1.

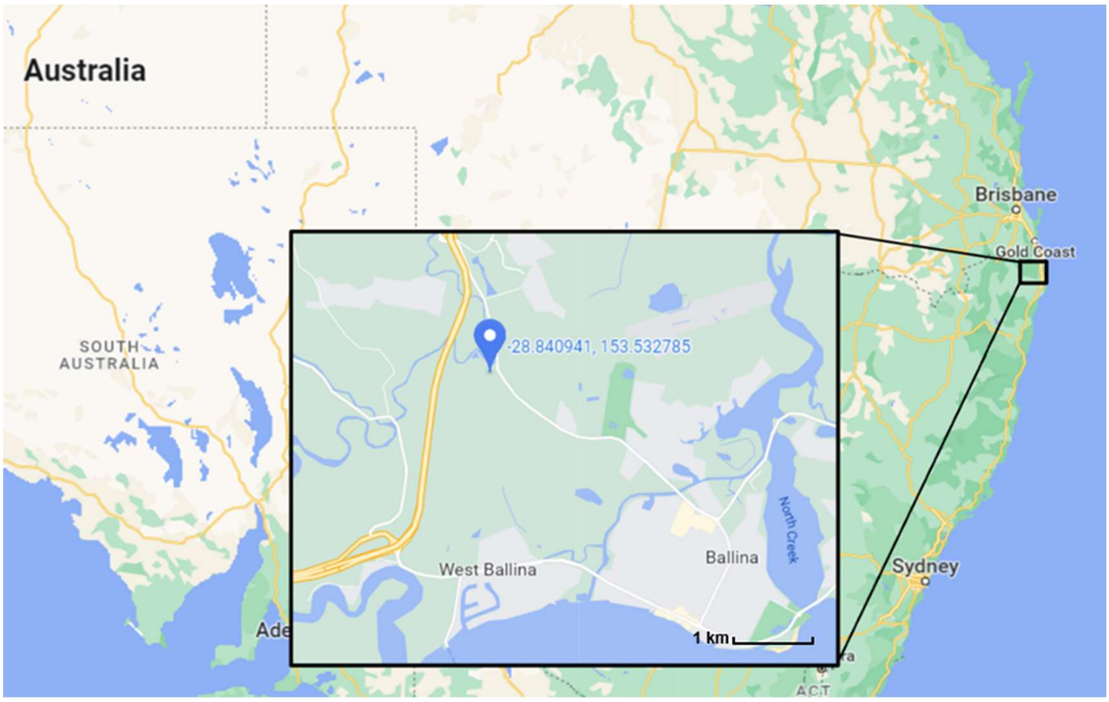


Fig. 1. Location of Ballina, New South Wales, Australia (inset: Ballina soil sampling location at 28°50’24.2”S and 153°31’58.3”E) [19]

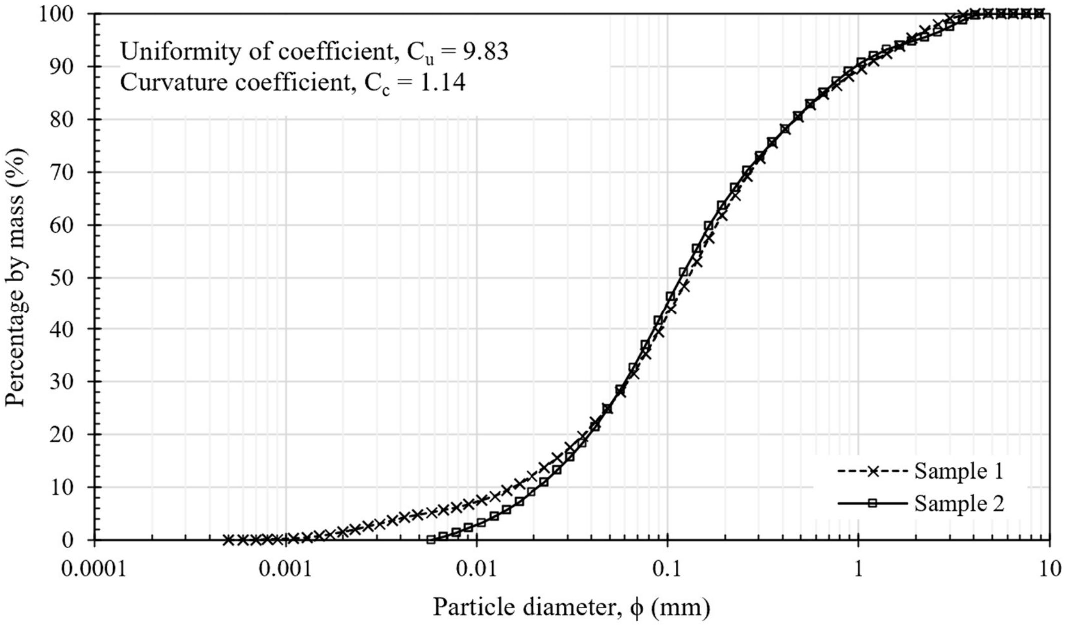


Fig. 2. Particle size distribution of Ballina Clay.

Table 1

Soil properties of Ballina Clay.

Parameters	Unit	Values
Liquid limit, LL	%	94.7
Plastic limit, PL	%	32.2
Plasticity Index, PI	%	62.5
Water content, w	%	92.6
Specific gravity	-	2.63
Void ratio	-	2.36
Wet unit weight, γ_w	kN/m^3	16.5

Before compaction, the soil sample was air dried prior to mixing with the required amount of water using ORIMAS Universal mixing machine that had a 20L capacity, 240V, and at speed of 91 rpm for 2 minutes. Any visible moisture lumps were then disaggregated before placing the moist mixture in a plastic bag kept for moisture equilibration (e.g. under constant temperature and humidity conditions).

The compaction characteristics were determined using a Standard Proctor compaction test in accordance to [20]. To determine the maximum dry unit weight and optimum moisture content of Ballina clay, a total of 9 compacted specimens were prepared so that a range of different dry densities could be attained in terms of water content. All the specimens were compacted on the same day to prevent curing differences due to air temperature and humidity fluctuations, which at times can be significant. Compaction energy of E = 595 kJ/m^3 was adopted for all tests with water content in the selected specimens varied across the compaction plane (12.1% to 25.2%). These specimens were then utilized to mould the material for the CBR test and for the resilient modulus tests using a cyclic triaxial apparatus (e.g. 50mm diameter by 100 mm high specimens, following the procedure described by Chen et al., 2015[21]. Additional specimens were prepared for determination of soil suction and used for CT-scanning. Soil suction was measured using the filter paper method which is a method that is valuable in deriving both total and matric suction [22]. It should be noted that at least 3 replicate samples were prepared for every test conducted in this study.

Resilient modulus and California bearing ratio

The resilient modulus (M_R) values are obtained to measure the degree to which a soil can recover from stress levels commonly placed upon soils by traffic [23]. The aim is to provide a relationship between stress and deformation of a soil material that can be used for the structural analysis of layered pavement systems. The test was conducted at constant water content to simulate typical field conditions. In this study, the resilient modulus is defined as:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

where M_R is the resilient modulus, σ_d is the cyclic deviator stress, ε_r is the recoverable axial strain. As indicated in Eq. (1), the larger the recoverable deformation, the smaller the resilient modulus. A constant all-around confining pressure (20kPa) is applied on the specimen to simulate the lateral stress caused by the overburden stress and applied wheel load. The suggested level of confining stress on top of the subgrades was in the range of 13.8 kPa to 27.6 kPa which is appropriate for determining M_R for the design of pavement [9]. The confining pressure was controlled using a GDS instruments water pressure controlled (accuracy 1 mm^3 and 1 kPa) Resilient modulus tests were carried out by applying a cyclic load having haversine-shaped pulse with duration of 0.1 second and rest period of 0.9 seconds. For ensuring the accuracy of the cyclic test results (i.e. axial stress and strain), the data was sampled at a relatively high rate and 20 data points were recorded for each cycle.

Compacted specimens were loaded according to ASTM D5311[24] method. Fig. 3(a) shows a typical deformation response of Ballina clay under repeated loading. At the initial stage of the test, at a relatively small number of cycles ($n<100$, Fig. 3c), there is a considerable permanent deformation occurring indicated by the plastic strain. The M_R is calculated as the mean of the last five cycles considering the recoverable axial strain and cyclic deviator stress as shown in Fig. 3(b). The loading involves conditioning, which attempts to establish steady-state or resilient behaviour labelled as 'stable' shown in Fig. 3(c), through the application of a large number of cycles (i.e., 3000 cycles). In the similar figure, it can be seen that the recoverable strains occur after numerous load repetitions, it is important to note that the deviator stress applied should not exceed the shear strength of the soils. The bearing capacity of compacted Ballina clay was determined with CBR test. The soil samples were compacted using proctor compaction method (1L mould) and the test procedures followed were in accordance with ASTM D1883-05 standard [25].

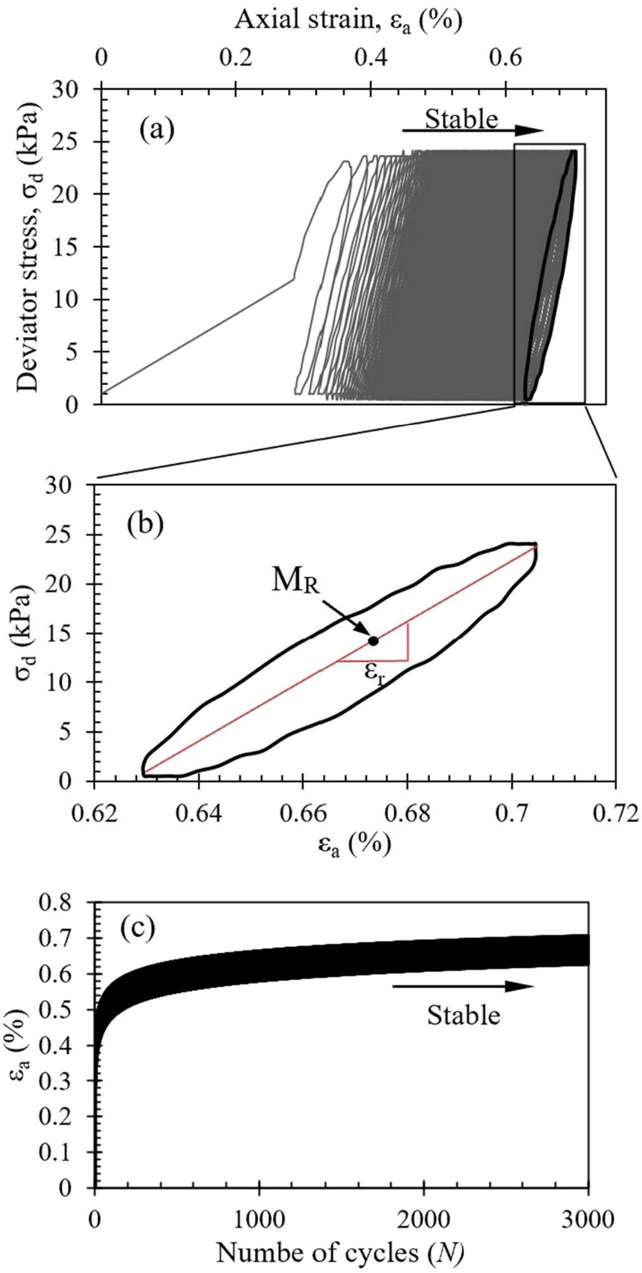


Fig. 3. A typical resilient modulus measurement technique. Cyclic loading results showing soil specimen with γ_d=15.9 kg/m^3 and w=15.5%.

Water retention behaviour

The suction-moisture content relationship was obtained using the filter paper technique in accordance with ASTM standard D5298 [26]. The 55 mm Whatman No. 42 ashless filter paper was used in this technique. Two methods were adopted for measuring suction, i.e. non-contact and contact method for determining total and matric suction, respectively. In the non-contact method, the filter paper is placed either on a disc above the soil in an airtight container for at least seven days whereas in the contact method, the filter paper disks are placed in direct contact with the soil. A minimum of two filter papers determinations were carried out for determining the soil suction for each compacted specimen prepared at a given water content and dry unit weight (see Fig. 4) and the average suction value was considered. In this technique, the soil suction is determined based on the filter paper water content on the basis that a filter paper will come to equilibrium with respect to moisture flow with the soil after 7 days [27]. ASTM D5298[26] only provides one calibration curve for both matric and total suction determinations, however there have been many studies that showed that for Whatman 42 filter paper, two sets of calibration should be adopted for matric and total suction respectively [28].

Thus, in this study, soil suction calibration equations follow those proposed by [34]:

$$\text{Log}\ \psi = a - b\ w_f \qquad (2)$$

Where log ψ is the logarithm of suction (kPa) in base 10, a and b are constants and w_f is the filter paper water content at present.

The equation was further used and modified through extensive research work carried out by Leong et al. (2002)[28]. The experimental evidence reported by Leong et al. (2002)[28] indicates that separate equations, i.e., Eq. (3) to (6) should be used to determine the matric and total suction.

Total suction:

$$w_f < 26; \quad \log \psi = 5.31\text{-}0.0879\ w_f \qquad (3)$$

$$w_f \geq 26; \quad \log \psi = 8.778\text{-}0.222\ w_f \qquad (4)$$

Matric suction:

$$w_f < 47; \quad \log \psi = 4.945\text{-}0.0673\ w_f \qquad (5)$$

$$w_f \geq 47; \quad \log \psi = 2.909\text{-}0.0229\ w_f \qquad (6)$$

Where w_f is the water content of filter paper and ψ is soil suction. Eq. (3) to (6) was used in this study to determine the total and matric suction.

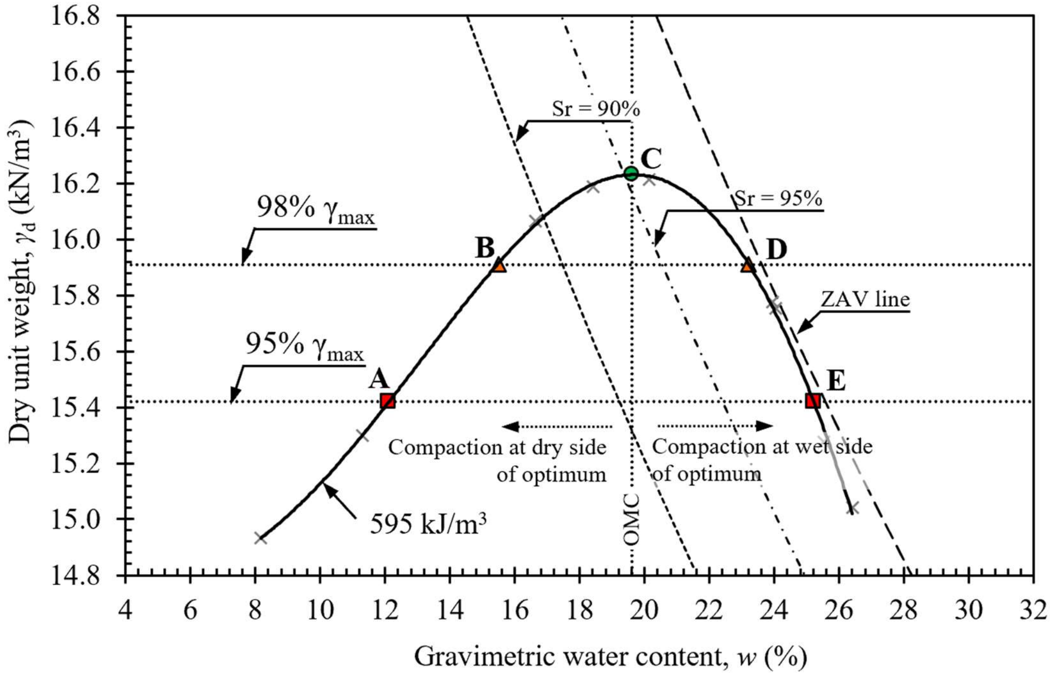


Fig. 4. Compaction curves of Ballina Clay at compaction energy of E = 595 kJ/m³.

Medical grade computed tomography-scanner testing

Computed tomography (CT) scanning systems use X-rays to visualize thin, cross sections of specimens. During CT scanning, high voltage X-rays generated from a source located at one side of the gantry, are attenuated through the test specimen and then registered by a series of detectors placed in the opposite direction. As the X-rays penetrate through the test specimen, some of them are absorbed. The different rates of absorption reflect changes in the specimen density [29]. The tests were carried out using an X-ray CT scanner (Toshiba Asteion S4). The reconstruction function adopted in this study enabled the correction of image artefacts that could result from the absence of lower energy X-rays. The X-ray tube current and voltage was 200 mA and 135 kV, respectively. The X-ray beam was as per soil slice thickness which is 2 mm wide, the exposure time was allowed at 1 second, and the field of view (FOV) was 75 cm that enable a zooming factor of four. The compacted soil specimens were scanned horizontally at 2-mm interval and the resulting CT scans were then used to create images along vertical planes at a range of 16mm through the center of the soil cylinder. The CT-scan images were analyzed using medical radiology software DicomWorks v. 1.3.5. The images not only portray well with the general arrangement of the soil structure but this technique also allows for the specimens to be tested non-intrusively and in "as-compacted" state, without damaging the soil structure.

Results and Discussion

Soil suction and degree of saturation for compacted specimens

Fig. 4 shows the compaction curve for compacted Ballina clay at compaction energy of 595 kJ/m^3. The gravimetric water content varied from 12% to 25% at 95% dry unit weight. The maximum dry unit weight and optimum moisture content is 16.2 kN/m^3 and 19.6%, respectively. For the compaction energy level adopted, the dry unit weight increases as the moisture content increase to the OMC. Beyond this point (i.e. compaction at the wet side of optimum), the dry unit weight decreases with increasing water content. The water retention curves were plotted in Fig. 5 for sample compacted across different water content. As expected, an increase in soil moisture content leads to a decrease in both total and matric suction. As the Ballina clay soil is of marine origin, the difference between matric and total suction is wordy of note in Fig. 6. The presence of some degree of salinity in Ballina Clay is responsible for the difference between total and matric suction as also known as osmotic suction (ψ_π). Interestingly, a hysteretic behaviour is observed where the ψ_π value decreased as the S_r increased indicating that as the soil is closer to saturation and the salt concentration in the soil is likely reduced and hence a lower osmotic suction is obtained. For higher degree of saturations, which is shown beyond the dashed line Se, when most of the soil pores are filled with water, the effect of salt concentration is likely to be less, and therefore both matric and total suction are of similar magnitude. In contrast, for specimens that were prepared at drier water contents this difference becomes larger. The matric suction of all the 5 specimens ranged from 29 kPa to 567 kPa. Vullient et al. (2002)[30] stressed that the mechanical stress level is affected by the soil suction and greatly influences the hydric behaviour.

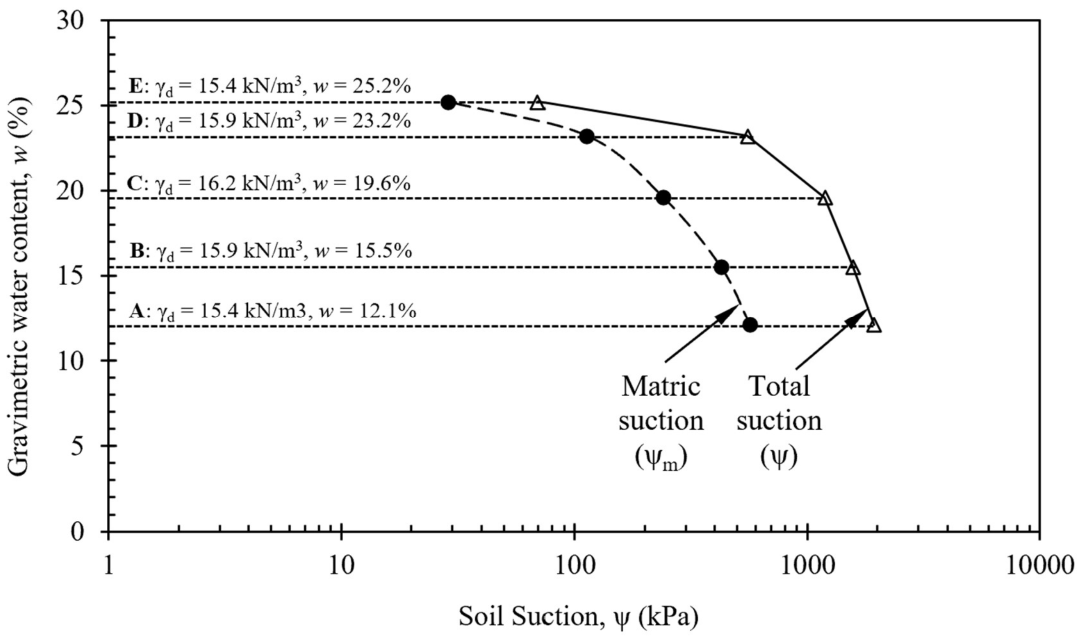


Fig. 5. Water retention curves of compacted Ballina clay at specific dry density and water content measured using filter paper method.

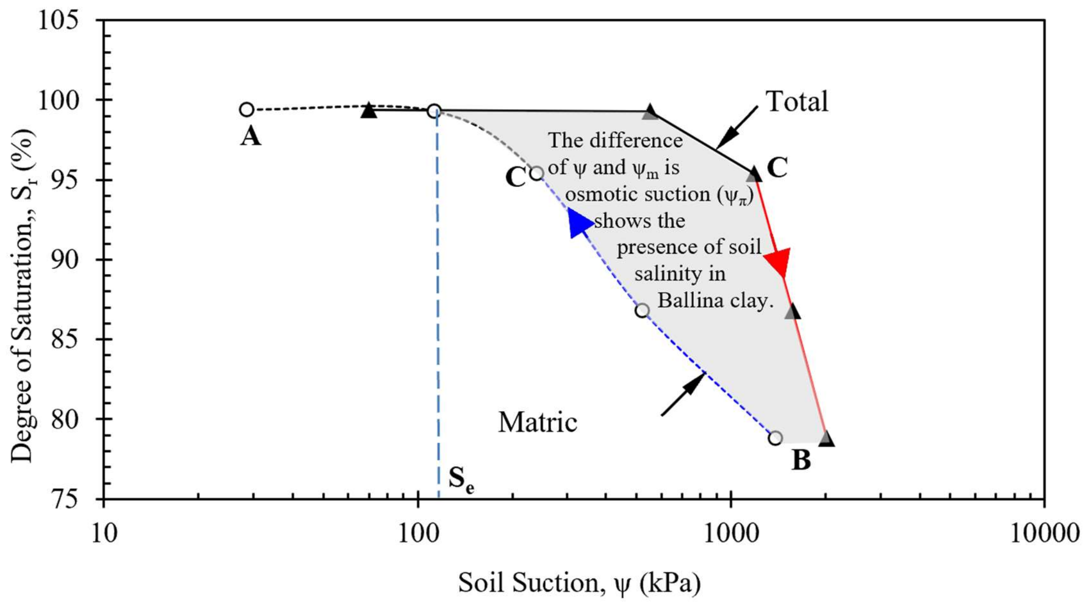


Fig. 6. Variation of soil suction with degree of saturation.

The Influence of Matric Suction on California Bearing Ratio (CBR)

The CBR test was carried out to examine the effect of soil moisture content on the bearing capacity of compacted Ballina clay. It can be seen from Fig. 7 that the curves for samples compacted at the dry side of optimum moisture content (OMC), i.e. A and B tend to concave up at the beginning for penetrations typically smaller than 1.5mm. This is likely due to surface irregularities and therefore zero point was adjusted to obtain the accurate CBR value. A bilinear trend was also observed from the load-penetration curves for sample A and B. At relative dry conditions which is below OMC, there was a marked increase in CBR values due to the increase of dry soil unit weights and the CBR reaches a value of 28 and 22.9%, respectively for sample A and B. For a 3.1% decrement of water content for sample B from sample A, the CBR value has a percentage increment of approximately 18%. When the water content increases from 15.5% for sample B to optimum moisture content (19.6%) at pronounced critical points for soil compacted at maximum dry unit weight, the value of CBR decreases to 9.9.

The gradient of the load on piston decreases when moisture content of the soil increases. However, the effects became much lesser for specimens prepared on the wet side of the OMC. For specimen D and E, when the moisture content is higher than that of the OMC, the gradient of the load on piston decreases quite steadily to almost constant. On the dry side of OMC, the CBR reaches a value of 28 and 22.9%, respectively for sample A and B. For a 3.1% decrement of water content for sample B, the CBR value has a percentage increment of approximately 18%. Soil compacted at moisture content above OMC could rarely reach a CBR of 5% or above, therefore soil compacted at its OMC was often regarded as competent materials by many design standards [15]. Sample type A and E compacted at the same dry unit weight (γ_d = 15.4 kN/m^3) but at different moisture content i.e. 12.1% and 25.2%, respectively shows an exceptionally large difference in its CBR value, 3.4 compared to 22.9. This indicates that soil water content and associated soil structure on the dry and wet sides of OMC (e.g., [31]) plays the predominant role in the soil strength response evaluated through CBR. Similar observations can be made for specimen B and D. The aforementioned trends observed in this study were corresponding to the findings ascertained by Cabalar & Mustafa (2017)[32].

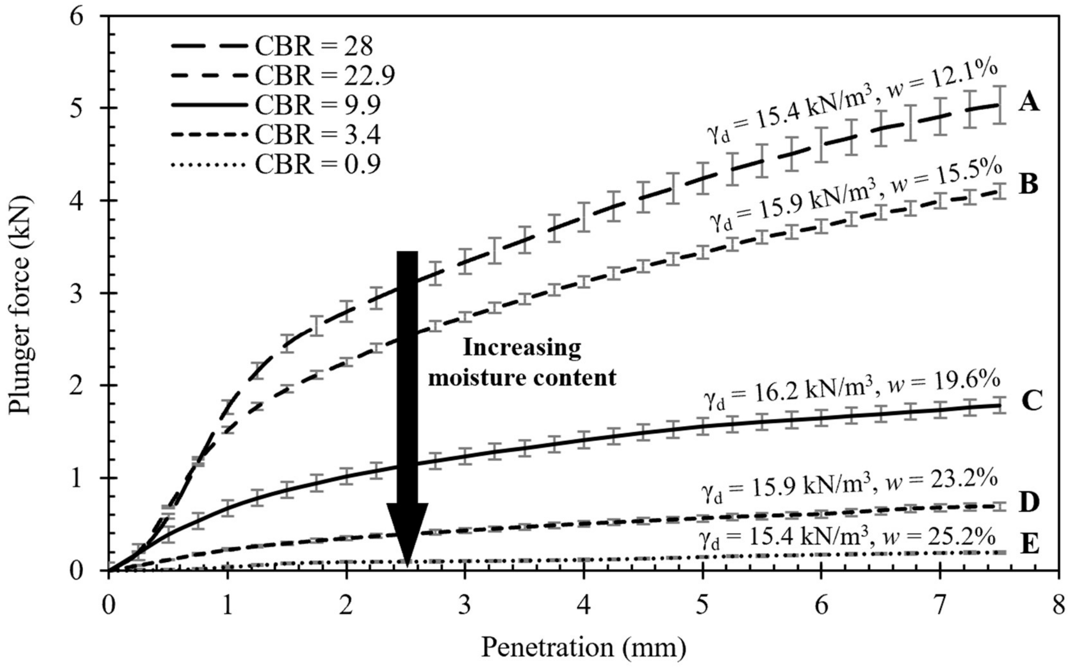


Fig. 7. California Bearing Ratio (CBR) test result curves.

While CBR decreased with increasing water content, an opposite trend was observed for matric suction (Fig. 8). This is not surprising as previous studies indicated that suction governs the strength behaviour of compacted soils [3, 33]. Further, there seems to be a linear trend established between the matric suction and CBR, showing a high coefficient of correlation of 0.99. This can be used to readily estimate CBR along the compaction plane provided that matric for the compacted materials is measured. Notwithstanding this, it is worthy of noting the nonlinear relationship observed from the inset of the figure for CBR plotted against the degree of saturation. On the dry side of OMC, the CBR remains approximately around the same order whereas sharply decreases once OMC is exceeded. This behaviour is likely due to the concurrent suction decrease and dry unit weight increase from point A to B (see Fig. 4) and concurrent decrease of suction and dry unit weight that occurs once OMC is exceeded. These observations are in agreement with findings reported by Heitor et al. (2013)[34] for the small-strain shear modulus.

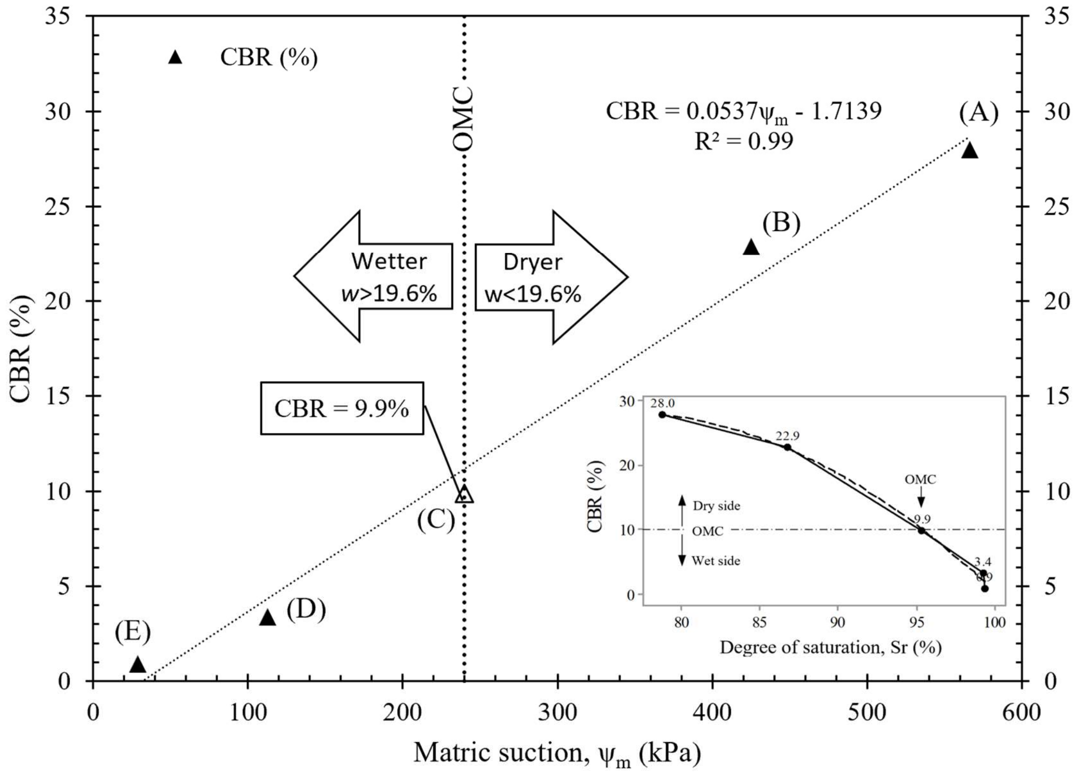


Fig. 8. Evolution of the CBR values based on matric suction at five different water contents: (A) w = 12.1%, (B) w = 15.5%, (C) w = 19.6%, (D) w = 23.2% and (E) w = 25.2%.

The Influence of Matric Suction on Resilient Modulus

Fig. 9 shows the variation of M_R as a function of S_r and ψ_m, respectively. It was observed that the M_R of the compacted materials have significant relation to the soil suction in terms of soil moisture content. Two empirical relationships are proposed for the prediction of M_R through S_r and ψ_m with high coefficient of determination of 0.95 and 0.90, respectively. The matric suction possesses a better relationship with M_R compared to soil degree of saturation. This phenomenon is in agreement with findings reported by Sawangsuriya et al. (2008) [11] and Dong et al. (2020)[8]. Although the dry unit weight of the specimen compacted as dry side of OMC (15.4kN/m^3) is smaller than that of specimen compacted at OMC (16.2kN/m^3), the value of M_R is higher which is 56.5MPa compared to M_R value of 39.3MPa at OMC. This appears to be caused by capillary suction which contributes to an increase in the effective stress by attracting particles towards one another and thus exhibiting higher particle contact force that results in higher M_R values [9]. Moreover, the gradual increase in matric suction indicates the increase in capillary menisci between the solid particles, resulting in an increase in inter-capillary forces [2] and, therefore the M_R. Fig. 10 (a) and (b) illustrates the past literature [2] on resilient modulus with matric suction and degree of saturation, respectively. Despite of lower M_R values obtained for the Ballina clay used in this study, it shows the same trend with other types of material used. It also seems that there is a much less variation at the wet side that coming to a platoon. Similar trend has been observed by [2] and it seems that the platoon extends for the other type of soils.

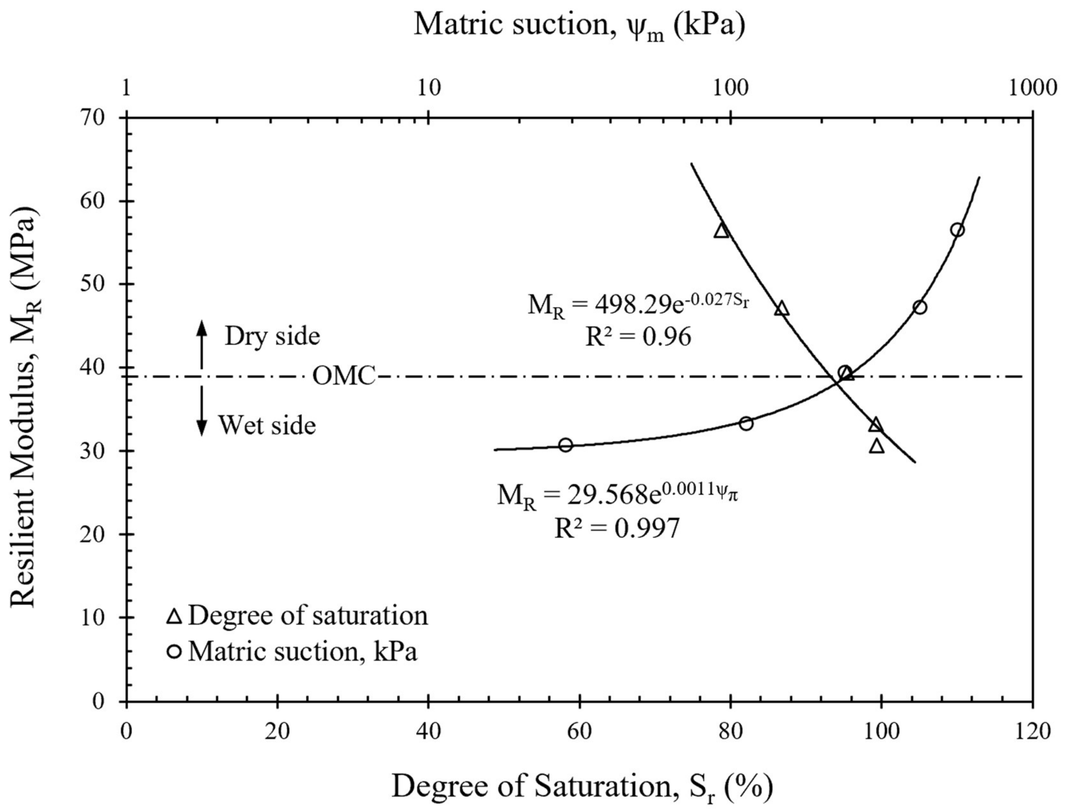
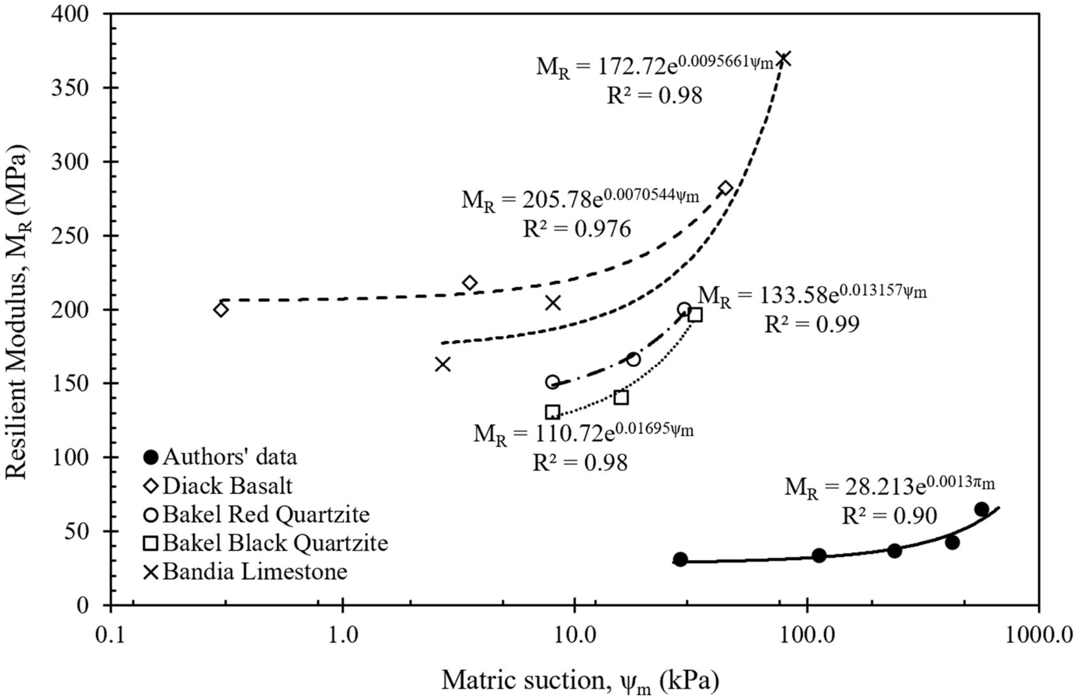
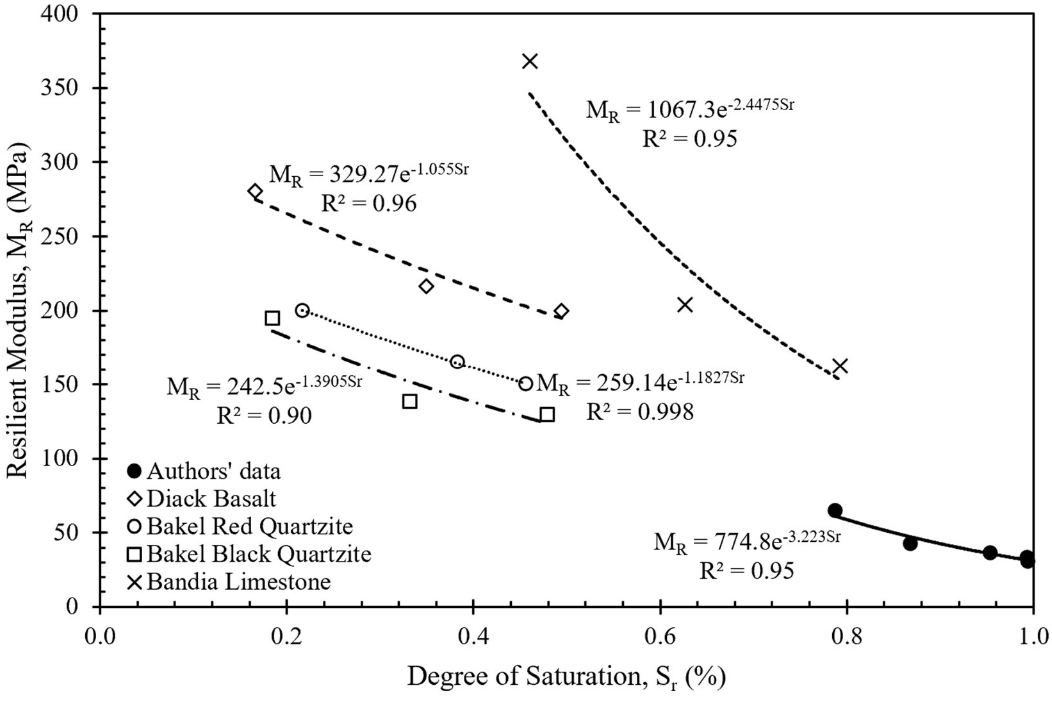


Fig. 9. Resilient modulus as a function of degree of saturation and matric suction on a semi-logarithmic scale.



(a)



(b)

Fig. 10. Resilient modulus as a function of (a) matric suction and (b) degree of saturation.

Resilient Modulus and CBR Relationships

The evolution of the CBR and resilient modulus values based on matric suction was drawn as presented in Fig. 11. Linear regression was observed for both CBR and M_R against matric suction. At the wetter region prior to compacted at OMC, CBR and MR values were increasing gradually at 30.65% and 33.24%, respectively. However, when the soil was compacted at water content dryer than OMC, the CBR and MR value increase tremendously to 28 % and 56.45 MPa, respectively. This seems that the change in both M_R and CBR values are more sensitive toward the dry side. Thus, it is interesting to note that the increment percentage for both CBR and M_R values are almost similar at the wetter and dryer region of matric suction. Both CBR and M_R values are expected to increase linearly beyond the compacted matric suction of 566.6 kPa. This finding is comparable to [6] for compacted kaolin. A one to one relationship was also observed from this figure, with the reduction of M_R and CBR values across the plane, it seems there is a consistent reduction in both parameters when it move to the wet side. If the soil is compacted at the slightly dry side of the compacted range lie within the 98% of maximum dry unit weight, the small change in the moisture content (~3.5%) have substantial change in the results of M_R.

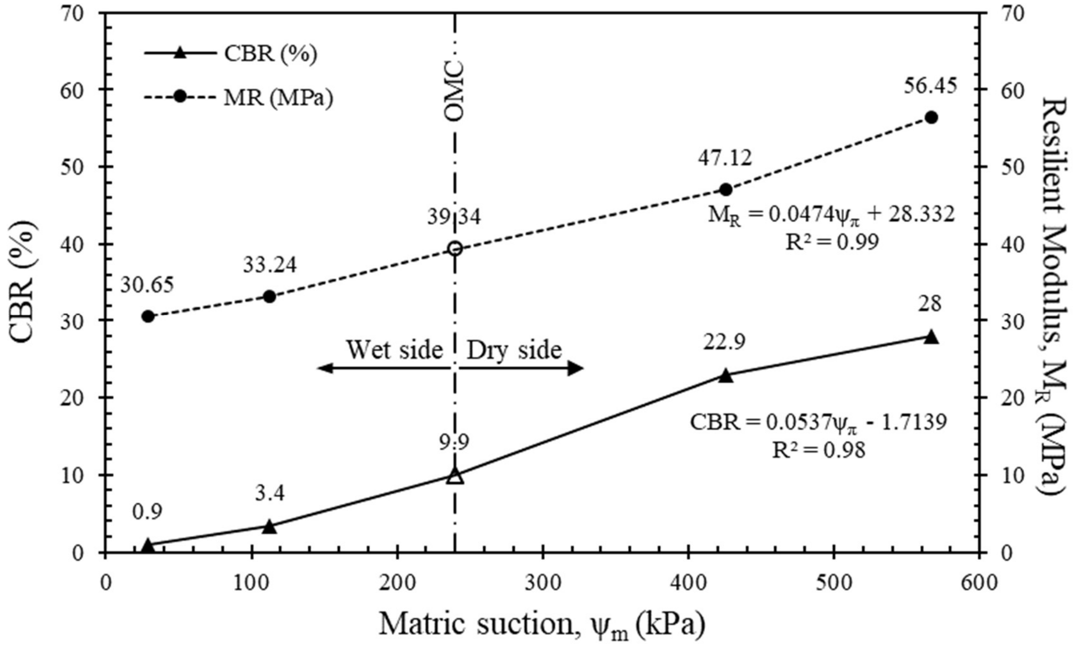
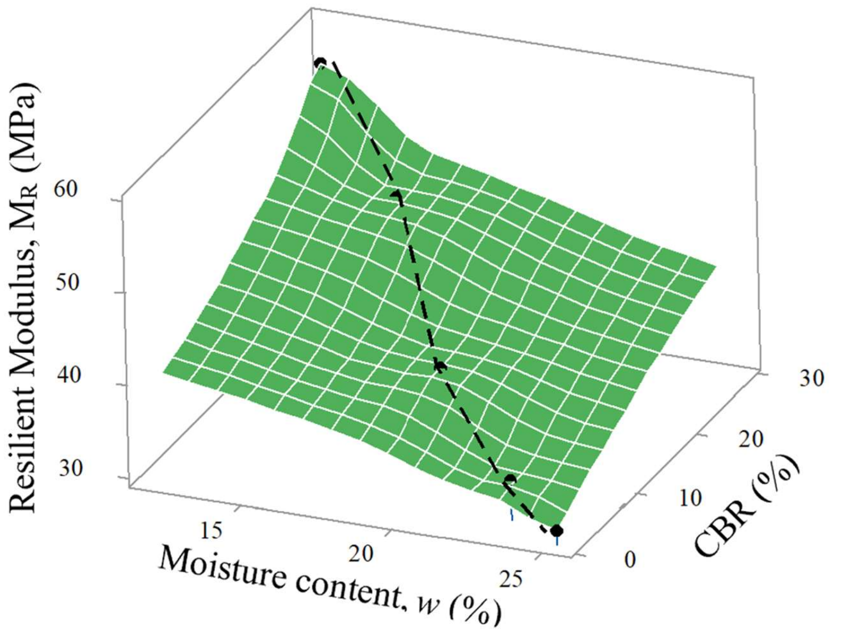
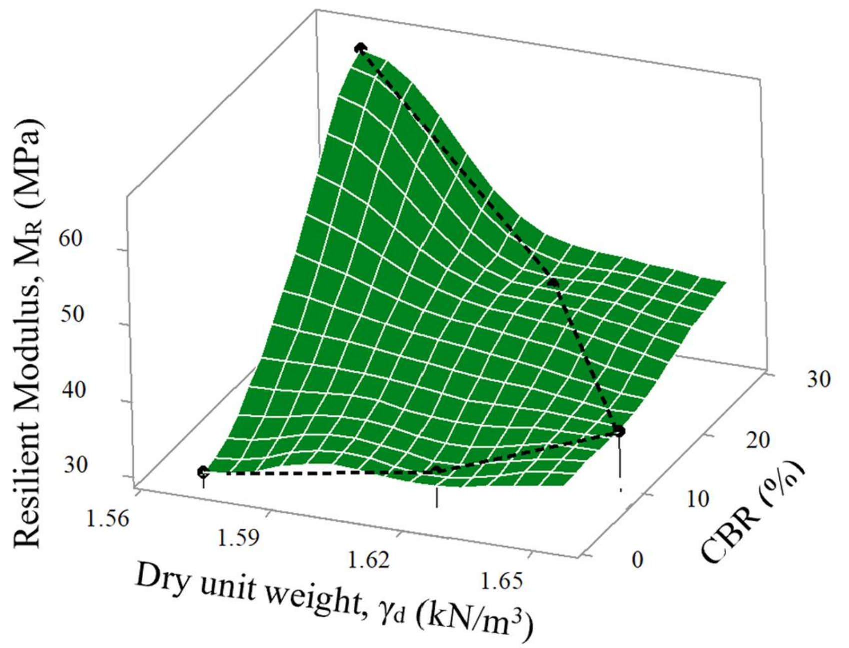


Fig. 11. Evolution of the CBR and M_R values based on matric suction at five different moisture contents.

The discussion from the above findings can further established through multilinear regression model. The relationship of moisture content, dry unit weight, CBR and M_R was plotted in 3D surface plot shown in Fig. 12 (a) and (b). To explore the potential relationship between these three variables, the 3D surface plot was interpolated using MINITAB 17 statistical software. Minitab 17 surface plots response (z) values at the x-y intersections of an evenly-spaced mesh. If the x- and y-values are evenly spaced, Minitab 17 plots the z-values at the x-y intersections. If the x- and y-values are not evenly spaced, Minitab interpolates (estimates) the z-values at the intersections of a regular 15 by 15 mesh with the same x- and y-ranges as the data. In the case of this study, the three variables are not evenly space, therefore Minitab 17 interpolates the data using Distance method instead of Akima's polynomial method. Distance method works well in for this analysis as it estimate z within the range of the dataset for x and y. Whereas Akima's polunomial method does not give desired effect for this analysis as it uses a fifth-order polynomial which can only estimate z-values at x-y positions beyond the avaliable dataset that are too large or small. M_R is the response values represented by z-axis whereas CBR and moisure content were plotted on the x- and y-scales, respectively as the predictor factors. Fig. 12 (a) shows a rising ridge surface of CBR and moisutre content which have substantial effect on the resilient modulus. It can also be observed that when either factors (CBR or moisture content) were increasing at the same time leads to an increase in M_R. This phenomenon does not occur in the case for dry unit weight. Both M_R and CBR values decreased moderately to 39.34 MPa and 9.9 %, respectively for soil compacted at wet side of OMC, regardless of the dry unit weight imparted. Fig. 12 (b) shows the 3D surface plot for three different variables (M_R, γ_d and CBR) where resileint modulus and CBR values are not entirely influenced by dry unit weight. As can be seen from this figure, specimen prepared at the same dry unit weight was observed to have very significant different in the resilient modulus and CBR values. In spite of compacted at the similar dry unit weight over a wide range of moisture content, the strength and potentially its stiffness of the compacted soil can behaved very differently.



(a)



(b)

Fig. 12. Surface plot of three variations on: (a) Resilient modulus, moisture content and CBR; (b) Resilient modulus, dry unit weight and CBR.

These 3D surface plots are useful for establishing the regression model for M_R value. The nonlinear multiple regression model established for M_R as a function of

CBR and w {$M_R = f$ (CBR, w)} as shown in Eq. (7) is having coefficient of determination of 0.99.

$$M_R = 75.1 + 0.063\ \text{CBR} - 1.81w \tag{7}$$

Where w and CBR value are presented in percentage.

Conversely, the nonlinear regression analysis of the three parameters for $M_R = f$ (CBR, γ_d) yields the following equation {*vide* Eq. (8)} with a high coefficient of determination of 0.97, which is above 0.7 indicating relatively good fit according to Lim (2015).

$$M_R = 52.4 + 0.864\ \text{CBR} - 1.41\ \gamma_d \tag{8}$$

These factors are further summarized graphically in the polar chart shown in Fig. 13. The five axes represent five different type of soil specimen prepared at different moisture content and dry unit weight and tested with CBR and M_R with lowest value moving towards the graph's centre and highest value appear towards the periphery. It can be seen that with the decrease in soil matric suction, both CBR and M_R value tend to move further away from the periphery indicating a decrease in the value. The red circle with dashed line presenting the soil parameter compacted at optimum moisture content and maximum dry density, whereas the yellow cluster indicate the drying side and green cluster indicate the wetter side.

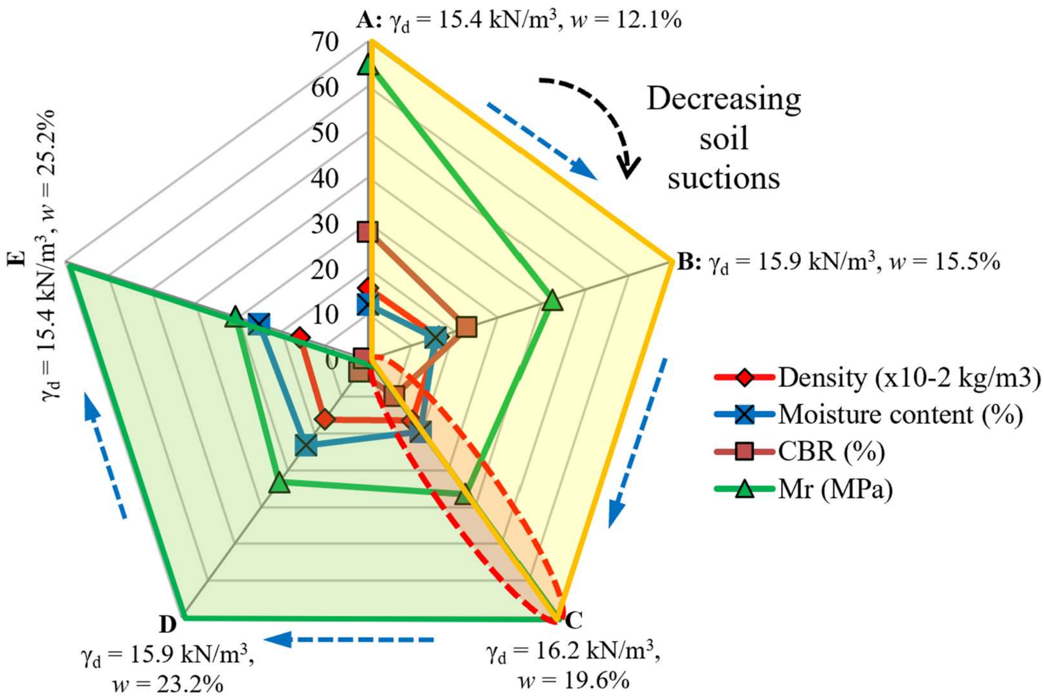


Fig. 13. Polar chart. The five axes represent five types of specimens prepared at different moisture content and dry density and tested with CBR and M_R with lowest value moving towards the graph's centre and highest value appear towards the periphery.

Soil Macrostructure

The CT-scanning has been carried out in this study to examine the macrostructural changes of soil compacted at different moisture content and dry unit weight. The CT-scanning was performed on the soil surface on both side of the sample. The structural changes observed in the compacted soils were evaluated in terms of macroporosity (inter-aggregate pores), by examining the differences in the greyscale of the images. Varying grayscale values represent sediment, water and void space. Presented herein, denser materials are represented as lighter grayscale values with the voids showing the darkest. For instance, white and grey areas correspond to sand particles and aggregations, respectively. Whereas dark areas correspond to air-filled and water-filled pores. Similar technique was adopted by [35]. As illustrated in Fig. 14, specimen (A) compacted at 12.1% of water content shows distinct aggregations (grey areas) with large interpores (a mixed of water- and air-filled areas). While as the water content increases to 15.5% for specimen (B), aggregations were observed with less air-filled areas. There is an improved orientation of particles and a corresponding reduction in size of voids as water content increase from specimen (A) to (B) as shown in the CT-scan images. As the soil compacted to its OMC, water replaces the pores and this further leads to a flocculation of the soil particles as shown in (C). This phenomenon is observed to be in agreement with the findings hypothesized by Ajdari et al. (2013)[7] and Lim et al. (2021)[42] . With higher bearing capacity and stiffness values observed at the dryer site where compacted soils were observed to be flocculated (compressibility reduces) through quantitative analysis, this phenomenon thus further justify and in congruent with the findings reported in Lim et al. (2021)[36].

When the soil is compacted at wet side of optimal, as illustrated in (D) and (E), these compacted soils have the opposite characteristics of the soil compacted at dry side of the optimum water content. Soil compacted at water content higher than the optimum water content results in a relatively weak matrix soil structure. At this point, the aggregations fused slightly to form a more “matrix-dominated” macrostructure during compaction. This gives a significant reduction in CBR and resilient modulus values. These compacted soils exhibit a soil structure dominated by large amount of macropores (i.e. the whiter areas). As soil compacted to a higher water content of 0.252 as shown in CT-scanned image (E), the micropores are observed to have moderately lost to nearly absent. The studying of specimen prepared beyond the optimum moisture content reveals a decrease in the number of connected voids filled with air, consequently, matric are developed as a result.

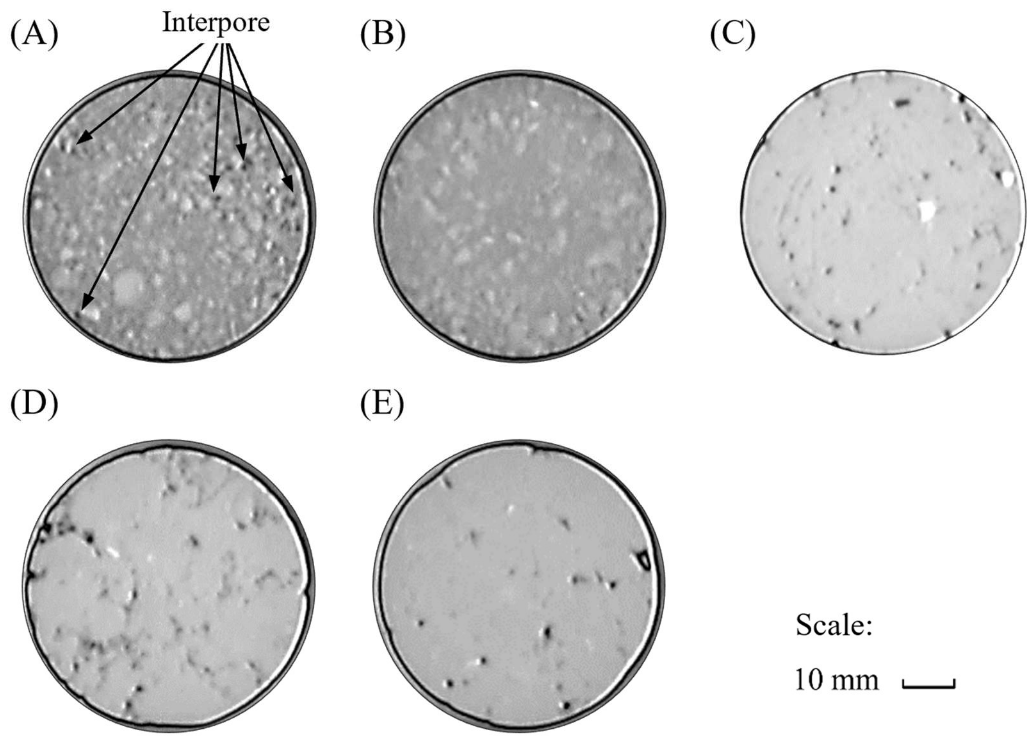


Fig. 14. CT-scan images of compacted specimens at different moisture content: (a) w = 12.1%, (b) w = 15.5%, (c) w = 19.6%, (d) w = 23.2%, (e) w = 25.2%, representing five distinct of regions of aggregation.

Regardless of the effect of compaction, increasing soil moisture increased interpore volume [37]. When soils were compacted at the wet side of OMC, with the increased in moisture content, the aggregations become deformable and gradually tend to be more matrix-dominated macrostructure during compaction [34]. When the soils are compacted at dry side of OMC, distinct aggregations were observed, typically results in a flocculated and aggregated soil structure having random particle orientations, this mirrors the observations in considerable higher matric suction and higher CBR as well as resilient modulus values discussed above. It is thus worth noting that macrostructure changes associated with the increase in moisture content under different dry densities are possibly the reasons for the increase in the soil suction, M_R

and CBR values. This indicates that M_R and CBR exhibits a strong dependency on the soil structure, as outlined in studies on compacted soil by Heitor et al. (2013[34]. Nonetheless, it is recommended that the physical characterisation of compacted soil using CT scan should be quantitatively analysed in terms of its saturated hydraulic conductivity (K-Sat, cm h^{-1}), air permeability (K-Air, cm^2) and relative diffusivity for He [38], among others for further research study.

Conclusions

Under unsaturated conditions, the effect of matric suction on the behaviour of soil resilient modulus and CBR are of key importance. The results of a laboratory testing programme allowed to examine the hysteretic behaviour of the soil suction on resilient modulus and CBR of compacted Ballina clay along dryer and wetter region across a compaction energy. The study also reiterates a common assumption in practice that there is intimate relationship between the compaction characteristics (i.e. moisture content and dry unit weight), soil suction and resilient modulus as well as CBR. It was also noted that the stiffness of the compacted soil was significantly affected by the water content. There is a one-to-one relationship observed with the reduction of M_R and CBR across the evolution plane based on matric suction. This seems there is a consistent reduction in both parameters when it moves to the wet side (w>19.6%). Both M_R and CBR are relatively insensitive at the wet side. If small water content is change in the field, it is expected not likely to affect strongly on the value of M_R and CBR (9 MPa and 8%, respectively). However, if small change (~3.5%) in the water content in the dry side, a dramatic change will be expected for both M_R and CBR values (18 MPa and 18 CBR, respectively). This also reveals that matric suction in soil contribute significantly to the stiffness and strength of the soil. However, suction is lost when soil absorbs water. This occurs in the field through water infiltration during rainfall. CT scan results reveals that increasing soil moisture increased the interpores volume. Soils compacted at the wet side of OMC impart that the aggregations became more compressible and present probable matrix-dominated macrostructure during compaction. While soils compacted at dry side of OMC yield distinct aggregations owing to the flocculated and aggregated soil structure with random particle orientations which mirror the observations in considerable higher matric suction and higher CBR as well as resilient modulus values. Generally, notable correspondence can be found between the soil suction, the water content, resilient modulus and CBR of compacted Ballina clay. This study is limited to evaluating the variation of CBR and resilient modulus of compacted Ballina clay as a function of total suction and matric suction in the laboratory. Further investigation is required to study the influence of soil suction on CBR and resilient modulus on soil compacted at different energy level.

Acknowledgment

This study has been conducted under the auspices of a funded Australian Research council project. Authors gratefully acknowledge financial assistance. This study was conducted while the first author was at the University of Wollongong, the use of the facilities of the Centre for Geomechanics and Railway Engineering are gratefully acknowledged. The first author would also like to thank Probase Manufacturing Sdn. Bhd. for the main financial support for her study carried out in Australia. This work was also supported by Shandong Excellent Young Scientists Fund Program (Overseas) (2022HWYQ-016) and Shandong Provincial Natural Science Foundation (ZR2021QE254).

References

[1] Wan, A. W. L., Gray, M. N., and Graham, J. 1995. On the relation of suction, moisture content, and soil structure in compacted clays*, in proceeding of the First International Conference on Unsaturated Soils*, UNSAT-95, Paris, pp. 215–222

[2] Ba, M., Nokkaew, K., Fall, M., & Tinjum, J. M. (2013). Effect of matric suction on resilient modulus of compacted aggregate base courses. *Geotechnical and Geological Engineering*, *31*(5), 1497-1510.

[3] Vanapalli, S. K., & Han, Z. (2014). Application of the unsaturated soil mechanics in the design of pavements. In *Proceedings of the 6th International Conference on Unsaturated Soils, Sydney, Australia* (pp. 1799-1805).

[4] Kim, H., Ganju, E., Tang, D., Prezzi, M., & Salgado, R. (2015). Matric suction measurements of compacted subgrade soils. *Road Materials and Pavement Design*, *16*(2), 358-378.

[5] Transportation Officials. (1993). *AASHTO Guide for Design of Pavement Structures, 1993* (Vol. 1).

[6] Mirzaii, A., & Negahban, M. (2016). California bearing ratio of an unsaturated deformable pavement material along drying and wetting paths. *Road Materials and Pavement Design*, *17*(1), 261-269.

[7] Ajdari, M., Habibagahi, G., & Masrouri, F. (2013). The role of suction and degree of saturation on the hydro-mechanical response of a dual porosity silt–bentonite mixture. *Applied Clay Science*, *83*, 83-90.

[8] Dong, X. X., Chen, Y. G., Ye, W. M., & Cui, Y. J. (2020). Effect of initial suction on the stiffness and strength of densely compacted Gaomiaozi bentonite. *Applied Clay Science*, *194*, 105696.

[9] Kim, D., & Kim, J. R. (2007). Resilient behavior of compacted subgrade soils under the repeated triaxial test. *Construction and Building Materials*, *21*(7), 1470-1479.

[10] Nowamooz, H., Chazallon, C., Arsenie, M. I., Hornych, P., & Masrouri, F. (2011). Unsaturated resilient behavior of a natural compacted sand. *Computers and Geotechnics*, *38*(4), 491-503.

[11] Sawangsuriya, A., Edil, T. B., & Bosscher, P. J. (2008). Modulus-suction-moisture relationship for compacted soils. *Canadian Geotechnical Journal*,*45*(7), 973-983.

[12] Sukumaran, B., Kyatham, V., Shah, A., & Sheth, D. (2002, May). Suitability of using california bearing ratio test to predict resilient modulus. In *Proceedings: Federal aviation administration airport technology transfer conference* (p. 9).

[13] Mendoza, C., & Caicedo, B. (2018). Elastoplastic framework of relationships between CBR and Young's modulus for granular material. *Road Materials and Pavement Design*, *19*(8), 1796-1815.

[14] Garg, N., Larkin, A., & Brar, H. (2009). A comparative subgrade evaluation using CBR, vane shear, light weight deflectometer, and resilient modulus tests. In *Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields* (Vol. 5, pp. 57-64).

[15] Leung, G. L. M., Wong, A. W. G., & Wang, Y. H. (2013). Prediction of resilient modulus of compacted saprolitic soils by CBR approach for road pavement subgrade: a re-examination. *International Journal of Pavement Engineering*, *14*(4), 403-417.

[16] Howard, A. K. (1984). The revised ASTM standard on the unified classification system. *Geotechnical Testing Journal*, *7*(4), 216-222.

[17] Indraratna, B., Perera, D. and Rujikiatkamjorn, C. & Kelly, R. (2014). Soil disturbance analysis due to vertical drain installation. *Proceedings of the Institution of the Institution of Civil Engineers – Geotechnical Engineering,*

[18] Pineda, J. A., Suwal, L. P., Kelly, R. B., Bates, L., & Sloan, S. W. (2016). Characterisation of Ballina clay. *Géotechnique*, *66*(7), 556-577.

[19] Google Maps, 2017. *Anglia Ruskin University: Chelmsford Campus*, 1:1.500. Google Maps [online] Available through: ARU Library <http://library.aru.ac.uk> [Accessed 6 August 2022].

[20] AS 1289.5.1.1:2003, Methods of Testing Soils for Engineering Purposes – Determination of the Dry Density/Moisture Content Relation of a Soil Using Standard Compactive Effort, Standards Australia.

[21] Chen, Q., & Indraratna, B. (2015). Deformation behavior of lignosulfonate-treated sandy silt under cyclic loading. *Journal of Geotechnical and Geoenvironmental Engineering*, *141*(1), 06014015.

[22] Su, Y., Cui, Y. J., Dupla, J. C., & Canou, J. (2022). Soil-water retention behaviour of fine/coarse soil mixture with varying coarse grain contents and fine soil dry densities. *Canadian Geotechnical Journal*, *59*(2), 291-299.

[23] Davish P., Labuz J.F., Guzina B., Drescher A. Small strain and resilient modulus testing of granular soils (Final Report). Minesota Departmet of transportation research services section, 2004.

[24] ASTM (2013). Standard test method for load controlled cyclic triaxial strength of soil. ASTM D 5311/D5311-M-13, American Society of Testing materials. West Conshohoken, PA.

[25] ASTM (2005). Standard test method for California bearing ratio of laboratory-compacted soils. ASTM D1883-05. American Society of Testing materials. West Conshohoken, PA.

[26] ASTM (2003). Standard test method for measurement of soil potential (suction) using filter paper method. ASTM standard D 5298 Annual Book of Standards. American Society of Testing Materials. West Conshohoken, PA.

[27] Fredlund, D. G. and Rahardjo, H. (1993). Soil mechanics for unsaturated soils. *New York: John Wiley & Sons*, Inc.

[28] Leong, E. C., He, L., & Rahardjo, H. (2002). Factors affecting the filter paper method for total and matric suction measurements. *Geotechnical Testing Journal*, *25*(3), 322-333.

[29] Alshibli, K. A., Alramahi, B. A., & Attia, A. M. (2006). Assessment of spatial distribution of porosity in synthetic quartz cores using microfocus computed tomography (μCT). *Particulate science and technology*, *24*(4), 369-380.

[30] Vulliet, L., Schrefler, B., & Laloui, L. (2002). *Environmental Geomechanics*. EPFL Press.

[31] Delage, P., & Graham, J. (1996). Mechanical behaviour of unsaturated soils: understanding the behaviour of unsaturated soils requires reliable conceptual models. In *PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE ON UNSATURATED SOILS/UNSAT'95/PARIS/FRANCE/6-8 SEPTEMBER 1995. VOLUME 3*.

[32] Cabalar, A. F., & Mustafa, W. S. (2017). Behaviour of sand–clay mixtures for road pavement subgrade. *International Journal of Pavement Engineering*, *18*(8), 714-726.

[33] Liang, W. Y., Yan, R. T., Xu, Y. F., Zhang, Q., Tian, H. H., & Wei, C. F. (2021). Swelling pressure of compacted expansive soil over a wide suction range. *Applied Clay Science*, *203*, 106018.

[34] Heitor, A., Indraratna, B., & Rujikiatkamjorn, C. (2013). Laboratory study of small-strain behavior of a compacted silty sand. *Canadian Geotechnical Journal*, *50*(2), 179-188.

[35] Rees, E. V., Priest, J. A., & Clayton, C. R. (2011). The structure of methane gas hydrate bearing sediments from the Krishna–Godavari Basin as seen from Micro-CT scanning. *Marine and Petroleum Geology*, *28*(7), 1283-1293.

[362] Lim, S. M., Yao, K., Jiang, Y., Lim, Z. C., & Bakar, I. H. (2021). Geotechnical characteristics of lateritic clay admixed with biomass silica stabiliser. *Journal of Cleaner Production*, *321*, 129008.

[37] Menon, M., Jia, X., Lair, G. J., Faraj, P. H., & Blaud, A. (2015). Analysing the impact of compaction of soil aggregates using X-ray microtomography and water flow simulations. *Soil and Tillage Research*, 150, 147-157.

[38] Grevers, M. C. J., JONG, E. D., & St. Arnaud, R. J. (1989). The characterization of soil macroporosity with CT scanning. *Canadian Journal of Soil Science*, *69*(3), 629-637.