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Undrained Response of a Sand with Addition Mica Particles

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Abstract: This study presents an experimental work on coarse rotund sand- mica mixture and availability of a stepwise regression (SR) method for formulation of the results. An intensive laboratory study of saturated coarse rotund sand (Leighton Buzzard Sand) and fine (mica) mixtures with various mix ratios is investigated by a series of oedometer and triaxial compression tests. The experimental database used for SR modelling is based on a laboratory study of saturated coarse rotund sand and mica mixtures with various mix ratios under a 100 kPa effective stresses in triaxial tests. In the tests, deviatoric stress (q), pore water pressure generation (u) and strain levels (ε) have been measured in a 100 mm diameter conventional triaxial testing apparatus. The input variables in the developed SR models are the strain and mica content and the outputs are deviatoric stress, pore water pressure generation and undrained Young's modulus. The performance of accuracies of proposed SR models are quite satisfactory. The proposed SR models are presented as simple explicit mathematical functions for further use by researchers.

Key words: Leighton Buzzard Sand · Mica · Triaxial testing · Oedometer tests · Stepwise regression

INTRODUCTION

The presence of platy mica particles in coarse rotund sands alters the mechanical behavior of sandy soils. The mechanical response of micaceous sands has been subject to intensive research in soil mechanics [1-6]. As early as 1925, Terzaghi [1] stated that much more experimental works were required for the foundation settlements prediction, as particle size alone was not enough to estimate a reasonable indication for the foundation settlements prediction. Gilboy [2] studied the influence of mica content on the compressibility of sand and concluded that an increase in mica content resulted in an increase in the void ratio of the uncompressed material as well as an increase in compressibility. The observations, first made by Gilboy [2], that any system of analysis or classification of soil which neglects the presence and effect of the flat-grained constituents will be incomplete and erroneous. Olson and Mesri [4] concluded that for all apart from the most active of reconstituted clays, mechanical properties were the governing factors in determining compressibility. A recent experimental study by Theron [7] was conducted on mixtures of mica and sand and demonstrated the enormous impact of particle shape on the mechanical properties.

Most current basic soil mechanics text show that mica particles; (i) cause undrained strength anisotropy from a brittle response in triaxial extension tests to a ductile behaviour in triaxial compression tests [6], (ii) decreases strength [8], (iii) alters internal shear mechanism [9] and (iv) increase compressibility [10]. Micaceous sands are deemed unacceptable for earthworks because of the reasons raised above. Actually, a number of slope failures have been attributed to the presence of mica [8]. The behaviour of micaceous sands was studied in connection with flow slides that occurred during construction of river training for the Jamura Bridge in Bangladesh [6] and Merriespruit gold tailings dam in South Africa which failed in such a catastrophic fashion in 1994 [11, 12]. Interestingly, the behaviour of mica is clay-like, but particle size analyses and the origins of the geomaterial provide that they contain little clay-sized material and do not have colloidally-active minerals. This study presents an alternative approach for modeling of coarse rotund sand- mica mixtures based on experimental results using Stepwise Regression (SR). Three different SR models are proposed for deviatoric stress (q), pore water pressure (u) and undrained Young's Modulus (Eu).

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Void Ratio and Texture of Sandy Soils: The term "volume of voids" in the definition of void ratio refers to the space that is not filled by the mineral grains [13]. When a sandy soil or a reconstituted mixture with some amount of fines is studied, the volume of voids can further be grouped into two subcategories as (i) voids due to skeleton particles (e.g. Leighton Buzzard Sand grains in this study) and (ii) voids due to finer grains (e.g., mica particles in this study) [14-16]. In a similar way, the grain matrix can also be grouped as finer grain matrix and coarser grain matrix. These matrices are expected to be influenced by each other and influence the overall macro behavior [17].

For example, Kenney [18] showed that the residual strengths of mixtures composed of crushed quartz and different clay minerals depend on the relative volumes of clay mineral matrix and massive minerals. It was also showed that as the volume of the massive mineral exceeds about 50% of the total volume of the mixtures, the residual strength of the mixture is approximately equal to that of the massive mineral. Skempton [19] postulated for the clays that if the clay fraction is less than approximately 25%, the mixture behaves much like a sand or silt rather than a clay, however residual strength is controlled almost entirely by sliding friction of the clay minerals when the clay fraction is above 50%. Georgiannou *et al.* [20] stated that up to a 20% fraction, clay does not significantly decrease the angle of shearing resistance of the granular component. From the conducted tests by Salgado *et al.* [21], it was indicated that fines fully control soil response in terms of dilatancy and shear strength beyond 20% of content. Vallejo and Mawby [22] showed that the shear strength of the sand–clay mixtures would be governed by the sand when fines content is less than 25%. Kumar and Wood [23] reported that it is the clay matrix that controls the overall behavior of the clay–gravel mixtures for granular volume fractions being less than approximately 45%. Whereas, Vallejo [24] indicated for gravel–sand mixtures based on the direct shear tests by glass beads that coarser grains control the shear strength of the mixtures if the finer grain concentration is less than 30%.

The parameters of skeleton void ratio [21-25], granular void ratio [9-20], intergranular void ratio [15-13-17], or void ratio of the granular phase [26], in fact all of which are the same concepts, were studied by some researches in the sense of shear strength of soils containing fines. Additionally, the study by Monkul and Ozden [17] on granular soils with contain a considerable amount of clay investigate the compression behavior of clayey sands from the perspective of intergranular void ratio concept by defining the transition fines content and granular compression index parameters that are based on experimental evidence obtained during the interaction between fine (clay) and coarse grain (sand) matrices.

It is considered that the fines contents' contribution is secondary, if the size of the fines are very small with respect to the pore sizes of the coarse grains and the amount of fines is within a certain margin. The coarser grain matrix is therefore dominant in the transfer of contact forces [15]. It is also postulated that at low fines contents (FC), finer grain matrix in the intergranular void spaces would be relatively high compressible [10]. From the previous laboratory experiences by many researchers, intergranular void ratio (es) can be defined as the ratio of volume of the intergranular voids to the volume of granular solids [17]

$$e_S = \frac{(V_V + V_f)}{V_S} \quad (1)$$

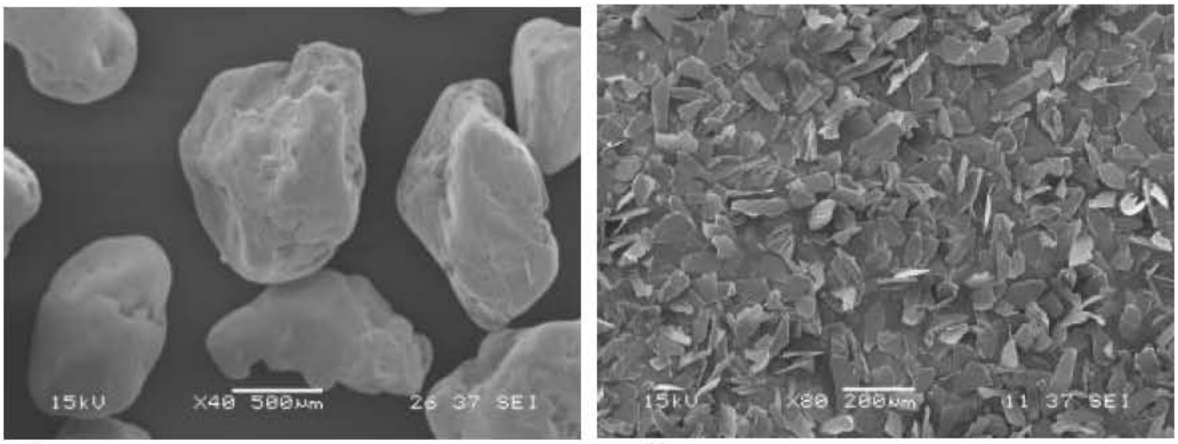
Where V_v, V_f, V_s are the volume of voids, fines and sand, respectively. Hence V_v+V_f is the volume of intergranular void space.

MATERIALS AND METHODS

Two different geomaterials were used in the experimental work; these were Leighton Buzzard Sand and mica. The Leighton Buzzard Sand used in the experiments was a fraction B supplied by the David Ball Group, Cambridge, U.K., confirming to BS 1881-131:1998. Its specific gravity, minimum and maximum dry densities were found to be 2.65, 1.48 g/cm^3 and 1.74 g/cm^3 respectively. As can be seen from the Fig. 1a and 2, more than 90% of the coarse sand particles, which are rounded and mainly quartz, are between (around) 0.6 mm and 1.1 mm.

Mica used in the experiments 52-105 micron muscovite mica supplied by Dean and Tranter Ltd. It's specific gravity, minimum and maximum dry densities were found to be 2.9, 0.725 g/cm^3 and 0.916 g/cm^3 respectively [7]. Figure 1b and 2 show the SEM picture and size gradation for the mica particles respectively.

Leighton Buzzard Sand and mica were mixed at various percentage of mica. The percentage of mica meant in this study refers to the dry weight of mica relative to the total dry weight of the mixture. Two mica percentages were considered, namely; 5%, 15% and then all results were compared with the clean Leighton Buzzard Sand.



(a) (b)

Fig. 1a,b: a: SEM Picture of the Leighton Buzzard Sand used in the experimental study, b: SEM Picture of mica used in the experimental study

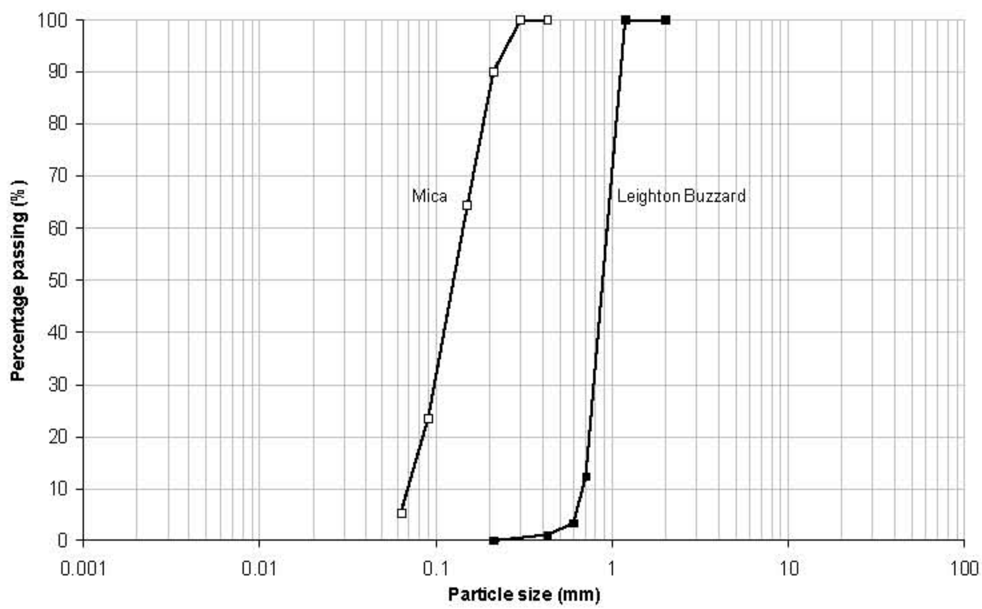


Fig. 2: Grain size distributions of Leighton Buzzard Sand and mica

Testing Apparatus and Procedures

Oedometer Tests: The consolidation test method carried out during the investigation is the standard method of measuring consolidation properties (ASTM D 2435-96), which involves the incremental loading of soil specimens. Incremental loading is to apply daily increments of vertical load to a submerged container in a rigid ring, with draining permitted through porous stones at the bottom and top. Oedometer samples were tested in 7.5 cm diameter rings. Loadings were initiated from 5kPa and were doubled each day, that is, the ratio of load increment to existing load is usually 1.

Triaxial Tests: The tests were performed in a conventional 100-mm-diameter Wykeham Farrance compression triaxial machine. Strain controlled loading was applied using a digitally controlled STALC 4958 type internal load cell at a constant rate of displacement. In order for the cell and the back pressures to be measured, two pressure transducers, PDCR 810 produced by Druck Limited, were used. Pairs of strain gauges were submersible LVDTs produced by R.D.P. Electronics Ltd., which were employed to measure the axial displacement in the middle third of the specimen in diametrically opposite positions.

Leighton Buzzard Sand, water and mica were mixed in the desired proportions to produce a uniform paste. A cylindrical membrane was attached to the bottom endplate using two o-rings and the split mould was placed around the endplate. Prepared uniform paste was then gently spooned into the split mould on the pedestal. Great care was taken to ensure that no vibration was employed. When the mould was completely filled, the excess sand particles were removed and the weight of the specimen was recorded. The top end plate was attached with two o-rings and 20 kPa suction was applied to the inside of the specimen. The split mould was carefully split to prevent any disturbance to the specimen. The test cell was then assembled and filled with water to apply cell pressure. After the test cell was completely assembled, the loading frame was placed. The suction inside the specimen was decreased while the gradually increasing the cell pressure by the desired value was achieved.

A series of isotropically consolidated undrained triaxial compression tests were carried out on the specimens at 100 kPa effective consolidation stress. During the consolidation process, the pore-pressure, cell pressure, volume, strain measurements were closely examined and recorded. Following the consolidation, the drainage valve to the specimen was closed and then compressive load was commenced at a constant displacement rate of 0.015 mm/min.

RESULTS AND DISCUSSION

Oedometer Tests: The test results on mica and Leighton Buzzard Sand show that the characteristics of the sands tested is ascribable to the presence of the flat grains in the samples tested in oedometer. From the 1-D compression results, it was found that the presence of platy particles in the specimens tested had a marked effect on the compressibility of the material under load. In the light of Theron [7], the author postulates that mica particles occupy the voids between coarse rotund sand particles. Based on the amount of mica particles present, the Leighton Buzzard Sand particles are in contact with each other and the behaviour of the samples tested are controlled by Leighton Buzzard Sand particles. When the contacts between the Leighton Buzzard Sand particles reduce, the behaviour of the samples becomes to clay like. Global void ratio with fines content and oedometer stress are shown in Fig. 3. As can be seen from Fig. 3, initial void ratios for the samples are scattered between 0.61 and 0.95 because of their initial conditions.

The governing role of either finer or coarser grain matrices on the overall behaviour of the sample should be expected to change during one dimensional compression. The interchange of this governing role can be expressed using intergranular void ratio concept. Monkul and Ozden [17] proposed an equation for calculation of the intergranular void ratio as follows:

$$e_s = \frac{e + \dfrac{G \cdot FC}{G_f \cdot 100}}{\dfrac{G}{G_s} \cdot \left(1 - \dfrac{FC}{100}\right)} \quad (2)$$

G_s and G_f in the above equation are the specific gravity of coarser and finer grain matrice forming the soil respectively. G is the specific gravity of soil itself, which is assumed to be the weighed average of the specific gravities of grains matrices forming the mixtures. FC denotes the fines content. Using the equation above, intergranular void ratios for the same samples in this study are found to be kept in a larger band (i.e. 0.61- 1.39) (Fig. 4).

Coarser (Leighton Buzzard Sand) and finer (mica) grain particles can rearrange themselves into various modes as shown in Fig. 5 depending on the initial conditions and applied stress. From the study by Monkul and Onal [17], establishment of direct grain contacts of the coarser grain matrix can be assumed to initiated when intergranular void ratio of the mixture becomes equal to the maximum void ratio of the host granular material, which is Leighton Buzzard Sand in this study (i.e., e_s=e_{max}). The fines content, at which this condition occurs, was named as "transition fines content, FC_t" by Monkul and Ozden [13]. Variation of intergranular void ratio with fines content under various oedometer stresses is shown in Fig. 6. Transition fines contents (mica contents) varying with effective stresses can be determined by the intersection of the dashed line with curves.

Transition fines content (FC_t) values vary between 6.1% and 12.5% depending on the applied stress (Table 1). FC_t values increase as the effective stress increase. That means, under higher stress, transition arrangement of the Leighton Buzzard Sand grain matrix takes place at higher values of mica content. The same intergranular void ratio (e_s) can be observed at different combinations of the fines content (FC) and global void ratio (e) [16]. In other words, intergranular void ratio value of 0.71 (e_{max}), where transition occurs, can be can be observed with a higher transition fines content and a

Table 1: Transition fines contents for the specimens under different oedometer pressures

Effective stress, (kPa)	FCt (%)
5.88	6.1
14.94	6.7
28.53	7.0
52.53	7.5
76.53	7.7
124.53	8.2
220.53	9.0
412.53	9.5
604.53	10.4
831.83	11.3
1059.13	11.7
1244.43	12.2
1429.73	12.5

lower global void ratio combination with increase in effective stress. Intergranular void ratio, fines content and applied stress can be seen in a 3-D plot in Fig. 7.

Fabric change mechanism during 1-D compression for a sample of certain fines content can be further investigated with Fig. 5. For example, the initial state of the fabric of the sample with 10% mica (shown by triangular points in Fig. 4) can be represented by Fig. 5a. The Leighton Buzzard Sand grains get closer to each other as the oedometer pressure increases. At the beginning, active contacts between Leighton Buzzard Sand grains are not generated. Further loading towards 500 kPa should start to generate contact points among Leighton Buzzard Sand grains. Additional stress increment results in a steady decrease of the intergranular void ratio causing formation of strong contact points as illustrated in Fig. 5b.

The border represented by the dashed line in Fig. 4 shows the upper limit, under which the Leighton Buzzard Sand matrix forms a continuous framework with grain to grain contacts. Hence, the compressional characteristics are also expected to deviate under this border. In order to better understand the arrangement of Leighton Buzzard Sand grain matrix, the granular compression index (Cc-s) parameter can be utilized [13]. The definition of granular compression index is very similar to the definition of compression index (Cc). The Cc-s is expressed as decrease of intergranular void ratio with effective stress, which is shown as below.

$$C_{c-s} = \frac{\Delta e_s}{\Delta \log \sigma'} \quad (3)$$

Alteration of global compression index (Cc) and granular compression index (Cc-s) with fines (mica) content is shown in Fig. 8 and 9. Cc and Cc-s values are calculated for 28 kPa and 124 kPa effective stresses. Compression indices of both sets of data increase relatively linearly with fines (mica) content. However, granular compression indices of the same set of data show a non-linear behaviour. Compression behaviour of Leighton Buzzard Sand – mica mixtures can be examined in two stages shown by different zones in Fig. 8 and 9. The dashed lines in the figures show the transition fines contents (FC_t) for the pressure ranges (Table 1). Through the zone left of the FC_t Leighton Buzzard Sand grain matrix can be thought to have almost a continuous force chain with grain to grain contacts and mica grains are mostly located in the intergranular voids. Therefore, a less compressive behaviour is seen. However, initiating from the FC_t values, Leighton Buzzard Sand grain contacts start to decrease because of the filling mica. Therefore, a sharp increase in the slope of granular compression index curve can be observed. With further increase in fines content, Leighton Buzzard Sand grains become more dispersed so that there is almost no grain contact between them. At this zone, the compressibility of the soil is expected to be mainly governed by the mica grain matrix. Therefore, the difference between granular compression and global compression index increases with an increase in mica content.

Triaxial Tests: The study provides an additional data set to compare the Leighton Buzzard Sand- mica mixtures in a triaxial apparatus. The test results show that the characteristics of the Leighton Buzzard Sand tested may be principally ascribable to the presence of the flat grains. The author postulates that platy particles occupy the voids between Leighton Buzzard Sand particles. Depending on the amount of platy particles present (i.e., mica), the Leighton Buzzard Sand particles are either in contact with each other and the behaviour of the samples tested are controlled by Leighton Buzzard Sand particles, or they are separated by platy particles.

In the light of Clayton *et al.* [10], the shape of particles controlling the mechanical behaviour of the Leighton Buzzard Sand-mica mixtures seems to be dependent on the contact mechanism between the Leighton Buzzard Sand particles. When the Leighton Buzzard Sand particles are in clear contact to each other and the mica particles only partially fill the pores, the mechanical behaviour of the mixes under these situations

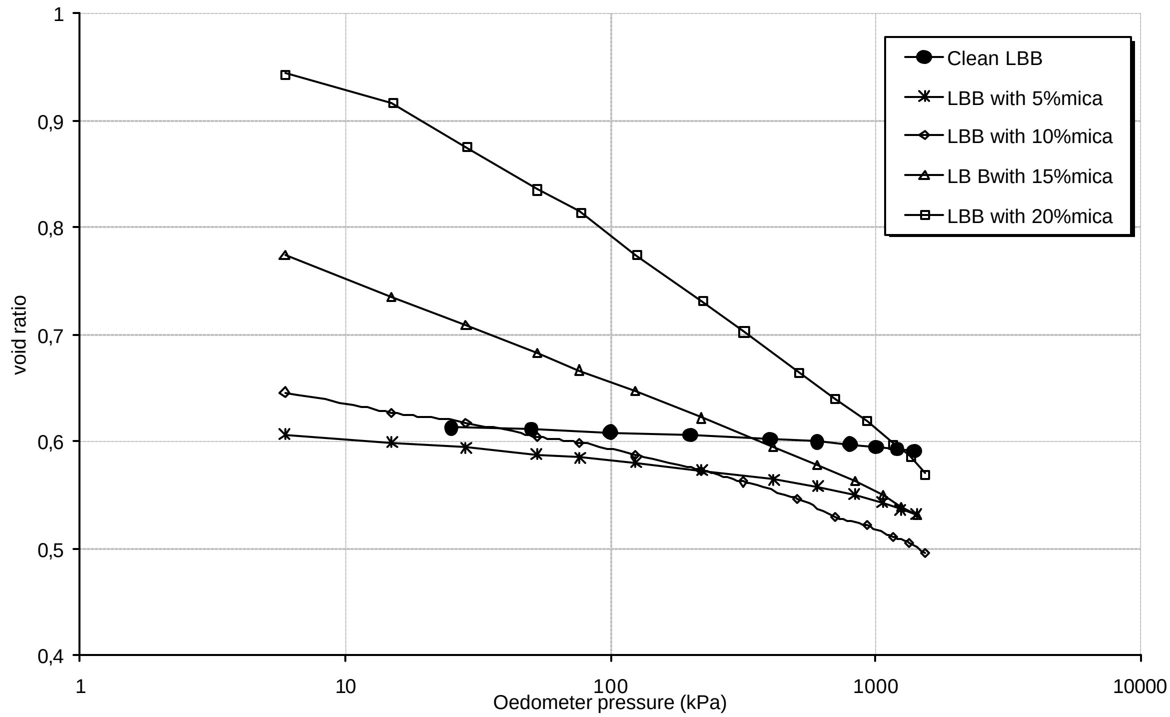


Fig. 3: Variation of void ratio with fines (mica) content and oedometer pressure

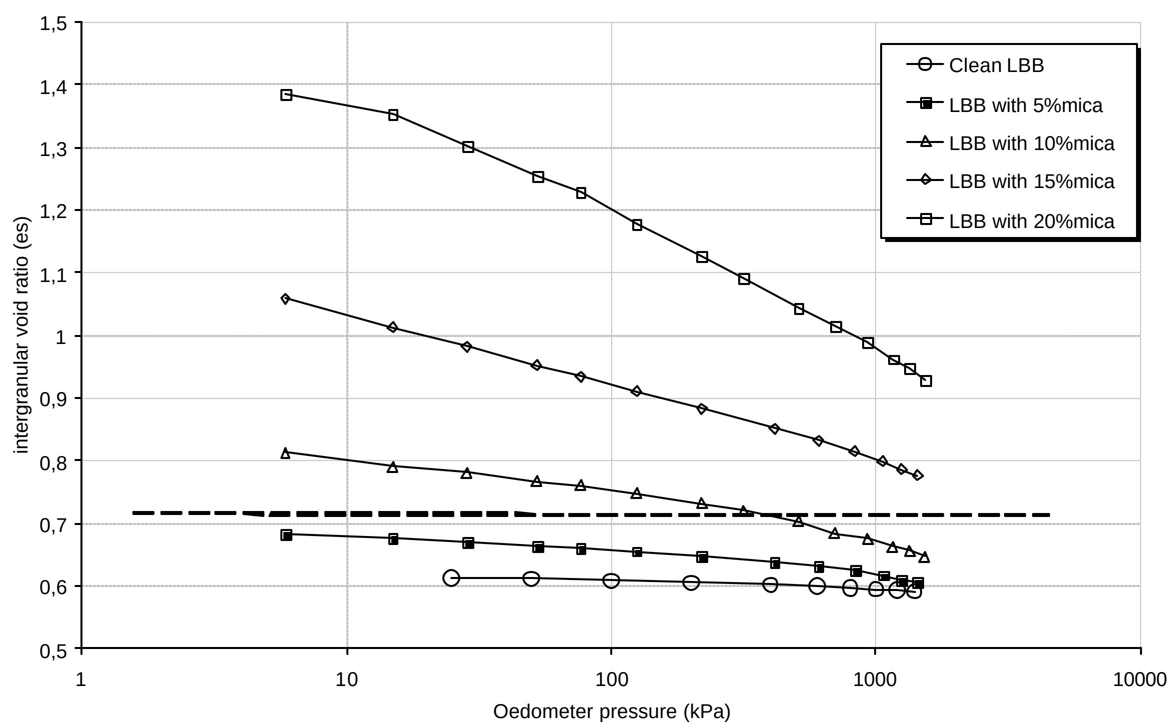


Fig. 4: Variation of intergranular void ratio with fines (mica) content and oedometer pressure

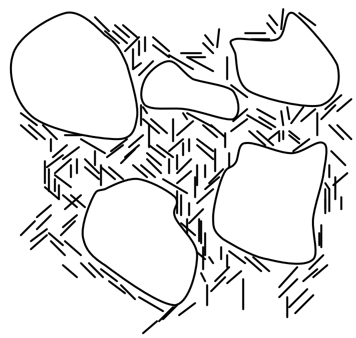


Fig. 5: Different arrangements of matrices under 1-D compression

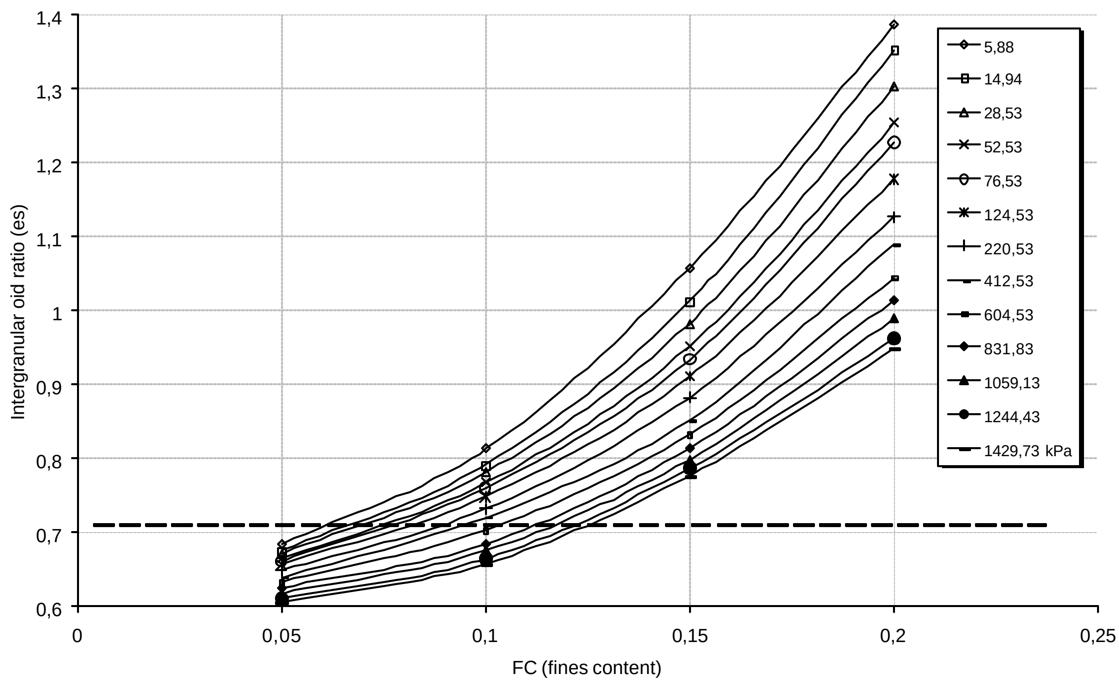


Fig. 6: Variation of intergranular void ratio with fines (mica) content under various oedometer stresses

Surface Plot of es vs EffectiveStress; Mica (%) EC

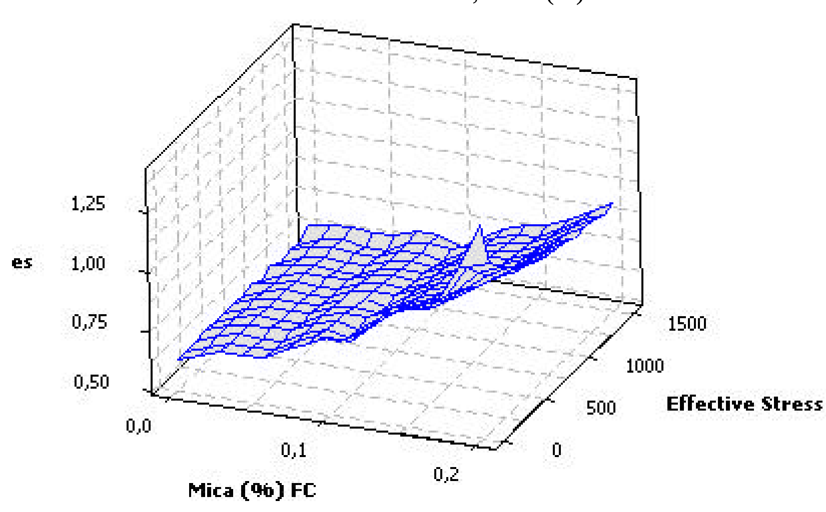


Fig. 7: Variation of intergranular void ratio with effective stress for different fines (mica) contents

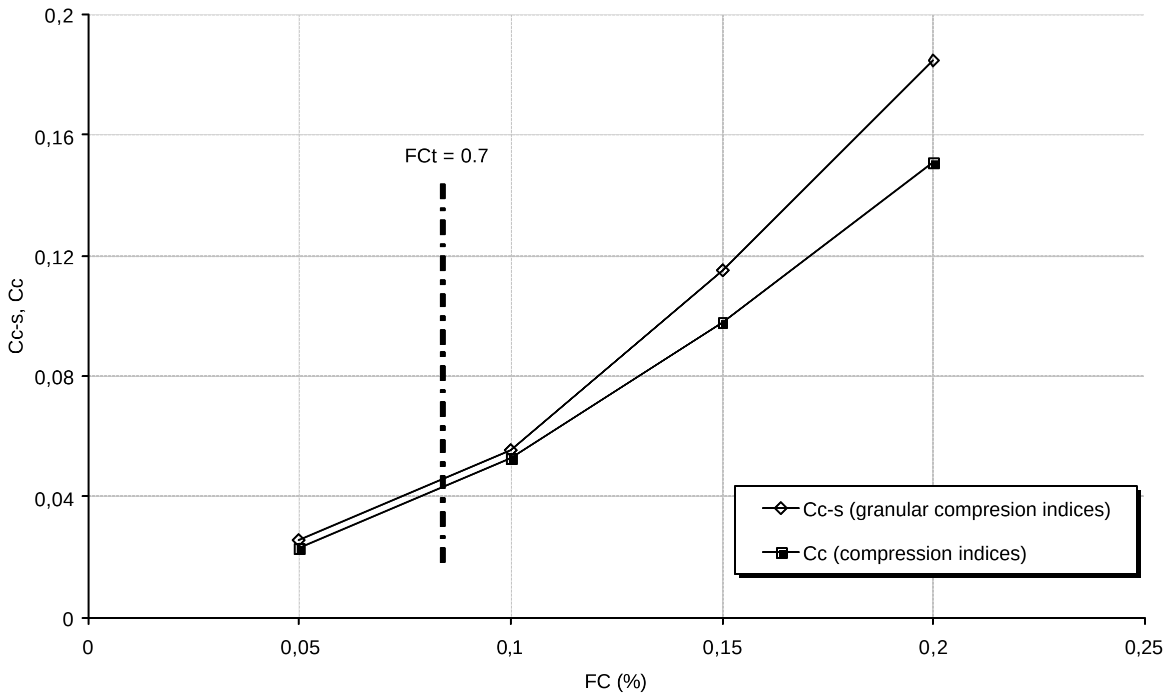


Fig. 8: Variation of compression parameters with fines content under 28 kPa effective stress

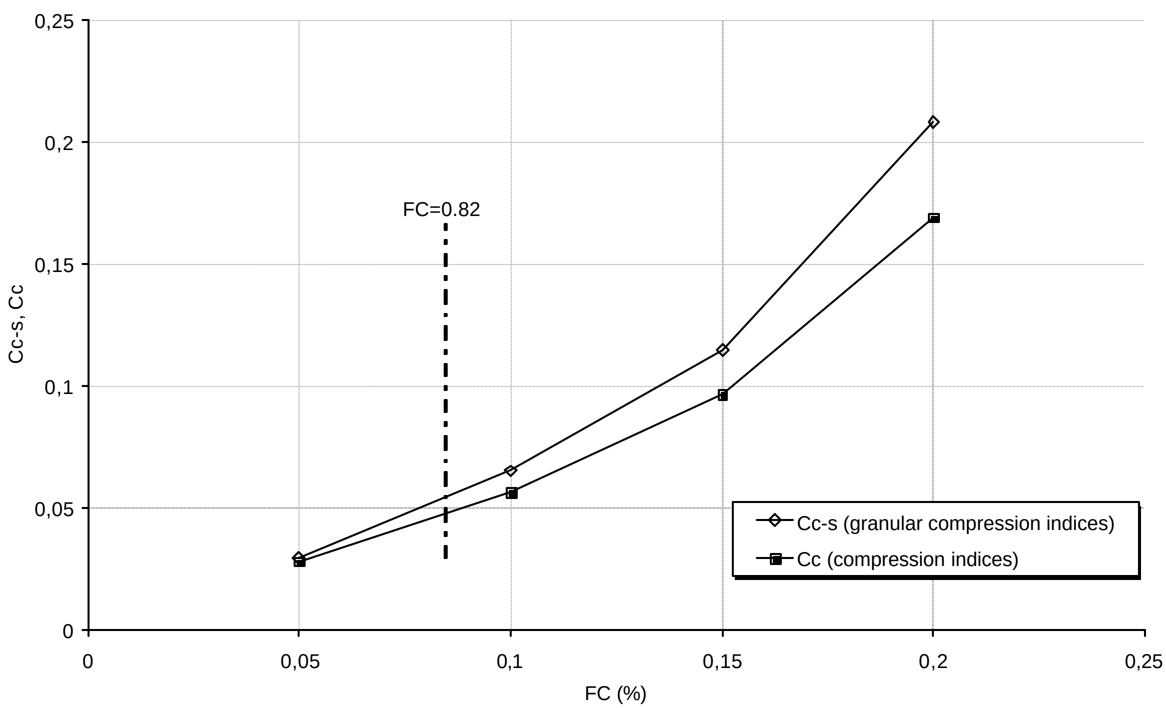


Fig. 9: Variation of compression parameters with fines content under 124 kPa effective stress

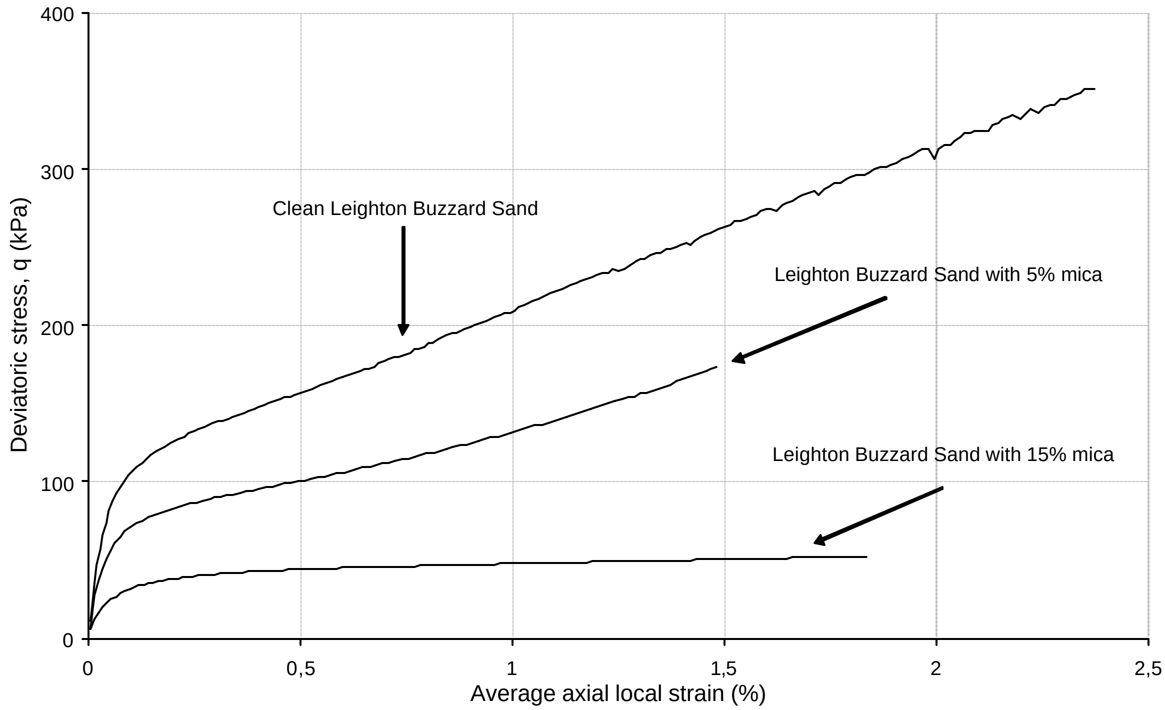


Fig. 10: Stress- strain curve for the loose sand, and sand with different proportions of mica (percentages by dry weight)

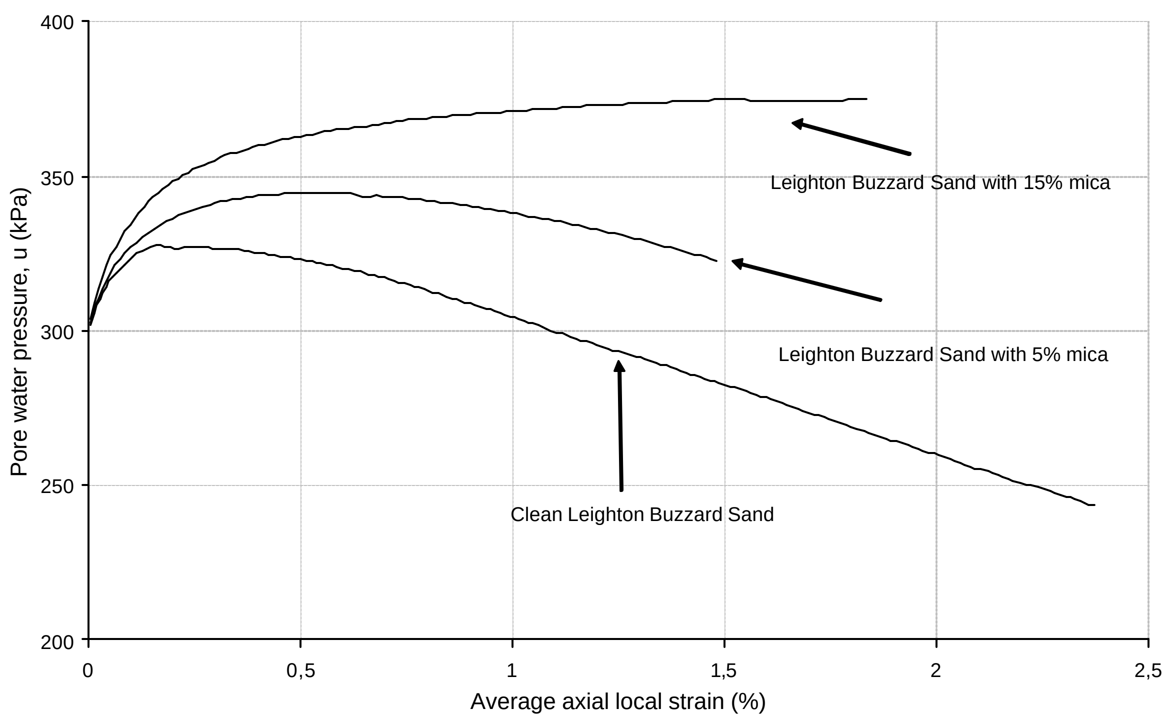


Fig. 11: Pore pressure- strain curve for the loose sand, and sand with different proportions of mica (percentages by dry weight)

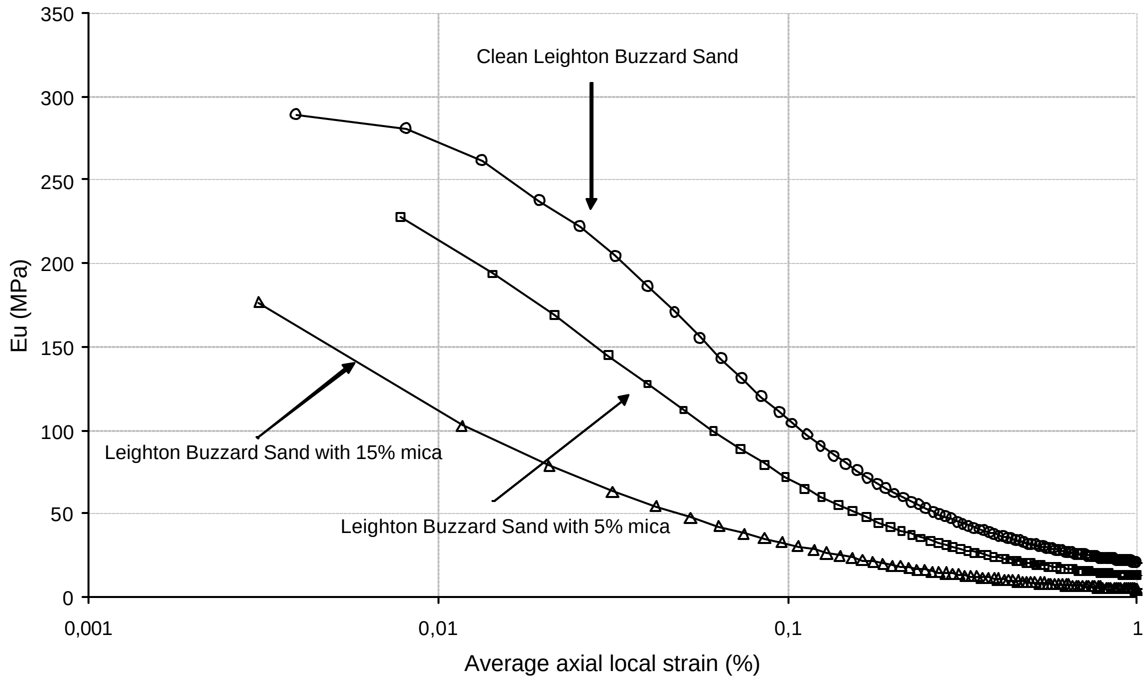


Fig. 12: Undrained Young's modulus as a function of axial local strain

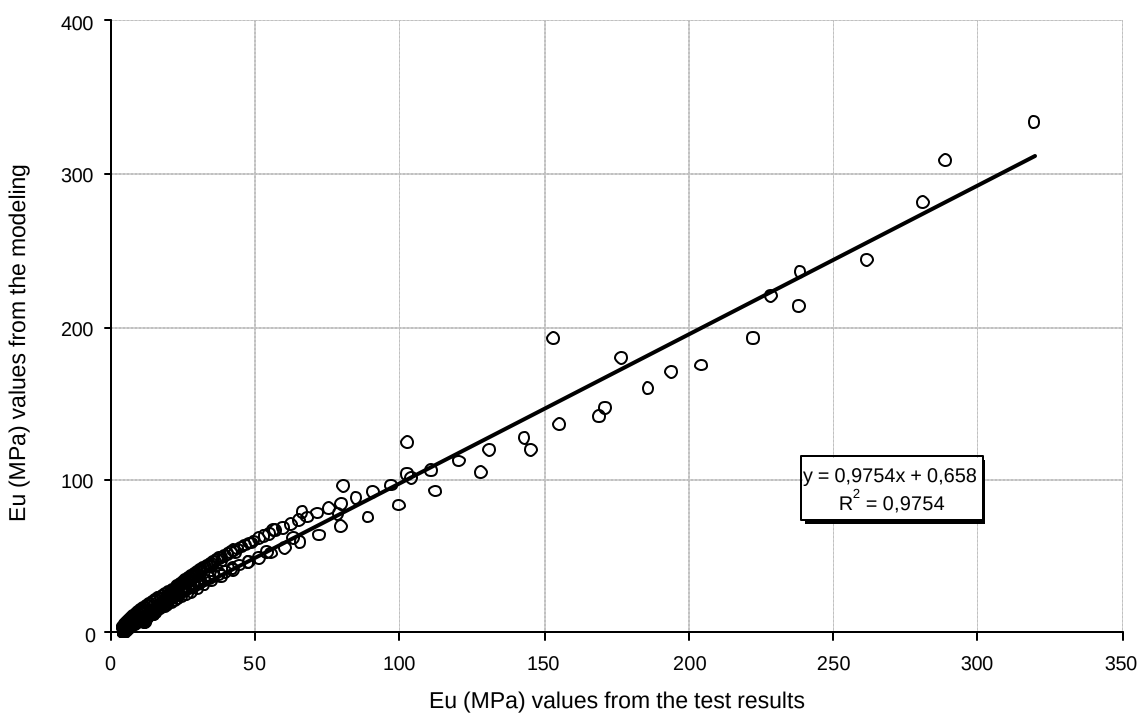


Fig. 13: A comparison between the undrained Young's modulus (Eu) values from the test results and those from the model

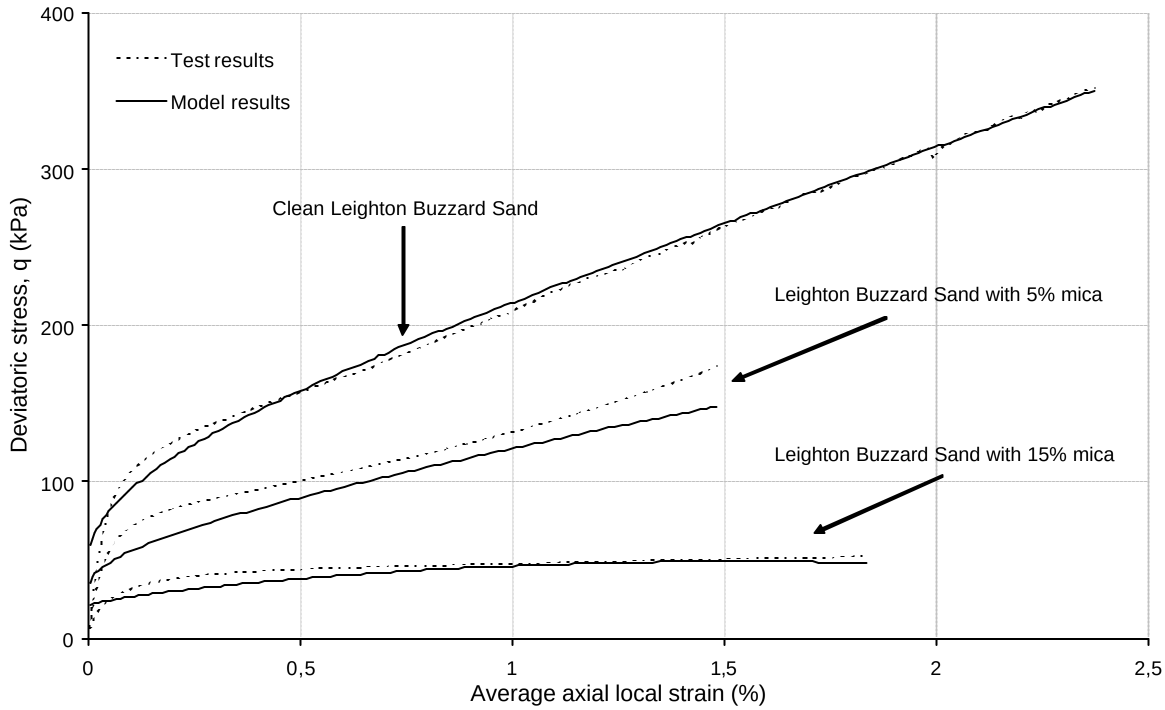


Fig. 14: Comparison of the test and modeling results for deviatoric stress (q)

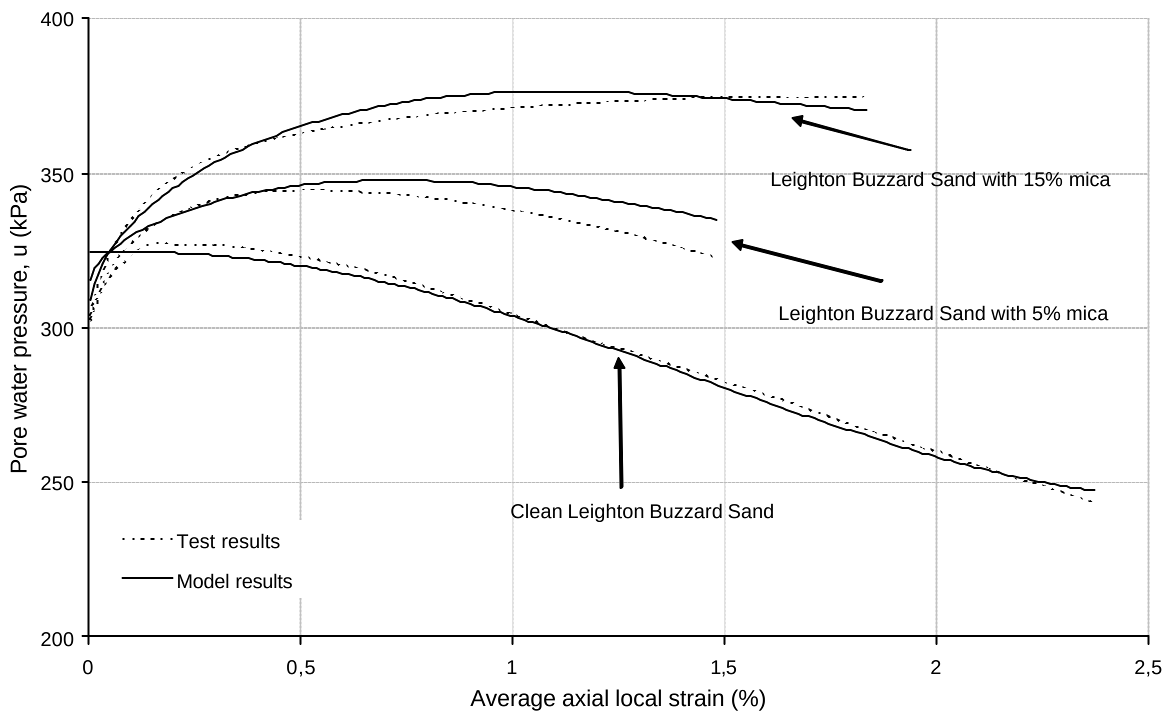


Fig. 15: Comparison of the test and modeling results for pore water pressure (u)

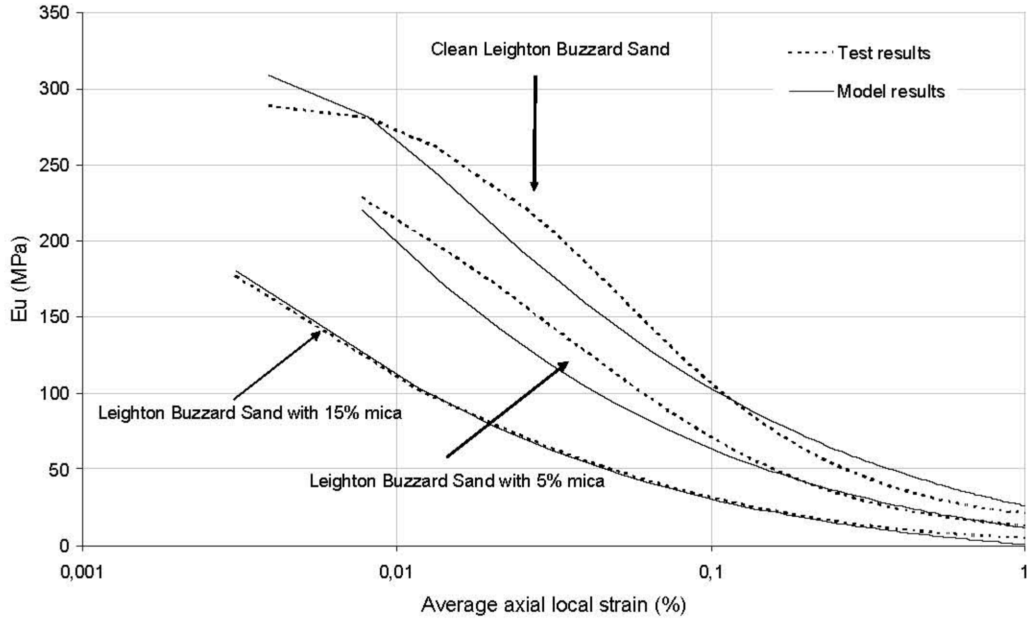


Fig. 16: Comparison of the test and modeling results for Young's modulus (Eu)

is governed by the Leighton Buzzard Sand. As the mica particles fill the pore spaces, the Leighton Buzzard Sand particles are held apart and the platy mica fines start to control the behaviour of the mixes. The contacts between the Leighton Buzzard Sand particles reduce; the behaviour of the samples becomes clay like. With large volume of platy particles, the Leighton Buzzard Sand particles are suspended in a mica matrix which dominates the mechanical behaviour of the mixes. In brief, this shows the significance of the amount and position of the mica particles among the mixes and also shows that the compressibility of Leighton Buzzard Sand increases with platy particles content.

Figure 10 and 11 show the effects of increasing mica content on the stress- strain and pore water pressure-strain behaviour of the material. The clean loose sand specimen behaves as might be expected, but the dilation of 5% and more by weight of mica causes the suppression of any dilation, low undrained shear strengths and high level of pore pressure generation during shear.

The influence of mica on the small strain stiffness was also investigated by considering undrained secant Young's modulus (Fig. 12). Comparing the small strain stiffness behaviour of the mica-Leighton Buzzard Sand mixtures at 100 kPa effective consolidation pressure, it is noted that the addition of mica to the Leighton Buzzard Sand particles resulted in that the Young's modulus of the mixtures tested decreases with increasing platy particle content. Accordingly, it may give insight that any system of analysis which neglects the presence and the effect of the pore fluid characteristics as well as that of the flat-grained constituents will be incomplete.

STEPWISE REGRESSION MODEL

As dealing with large number of independent variables, it is necessary to determine the best combination of these variables to estimate the dependent variable. Modeling by Stepwise Regression (SR) is a robust tool for selection of the best subset models [27]. Subset models' determination is based on deleting or adding the variable(s) with the greatest impact on the residual sum of squares. The selection of variables may be using three ways; forward, backward or a combination of them. In the first one, the subset models are selected by adding one variable at a time to the previously selected subset. In each successive step, the variable in the subset of variables is added to the subset. Without an ending rule, forward selection longs until all variables are included to the model. However, backward stepwise method chooses the subset models by commencing with the full model and then eliminating at each step the one variable whose deletion will cause the residual sum of squares to increase the least and continues until the subset model contains only one variable [28].

In both forward and backward methods, it should be noted that the influence of deleting or adding a variable on the contributions of other variables into the model is not being taken in to account. Hence stepwise regression is a forward selection process that re-evaluates in each step the significance of all previously included variables. If the partial sums of squares for a previously considered variables do not have a minimum requirement to stay in the model, the selection way changes to backward one and variables are dropped one at a time by all remaining variables have the minimum requirement. Stepwise selection of variables needs more computing than forward or backward way but, it has an advantage in potential subset models evaluated before the model for each subset size is fixed. It seems to be reasonable that the stepwise selection have a significant chance of choosing the best subsets in the sample data, however selection of the best subset for each subset size is not under guarantee. Stepwise selection of variables uses both the forward and backward elimination criteria to stop the rule. The variable selection process ends when all variables in the model have the requirements to stay and no variables outside the model have the requirement to enter [28].

This paper aims a single empirical formulation of deviatoric stress (q), pore water pressure (u) and undrained Young's modulus (Eu) of coarse rotund sand-mica mixtures stepwise regression based on experimental results. Therefore, an extensive experimental program has been performed on various coarse rotund sand- mica mixtures. The details of the experimental study including the ranges of parameters have been already given previous sections. Deviatoric stress, pore water pressure and Young's modulus values have been modeled as a function of mica content in percentage and strain and the following equations have been obtained:

$$q = 50 - 7.9 * C_m^{1/2} + 22.3 * \varepsilon^{3/2} - C_m * \varepsilon^2 + 142.4 * \varepsilon^{1/2} - 31.4 * C_m^{1/2} * \varepsilon^{1/2}$$

$$u = 324.8 - 5.4 * C_m^{1/2} + 22.5 * \varepsilon^3 + 24 * C_m^{1/2} * \varepsilon^{1/2} - 46.7 * \varepsilon^{3/2}$$

$$Eu = -14.2 + 41.2 * \varepsilon^{-(1/2)} - 0.002 * C_m^2 * (1/\varepsilon) - 6.81 * C_m^{1/2} * \varepsilon^{-(1/2)} - 1.3 * (1/\varepsilon) + 0.4 * C_m^{1/2} * (1/\varepsilon)$$

Where;
q = deviatoric stress (kPa)
u = pore water pressure (kPa)
Eu = undrained Young's modulus (MPa)
ε = shear strain (%)
C_m = mica content (%)

Figure 13 presents the Eu values, as a typical example, obtained from the tests and SR models for the Leighton Buzzard Sand with mica fines. Comparison between SR and test results are observed to very close as presented in Fig. 14, 15 and 16 for deviatoric stress, pore water pressure, undrained Young's modulus respectively.

CONCLUSIONS

The objective of the study was to determine experimentally the variation of the deviatoric stress, pore water pressure and Young's modulus. It was then aimed to develop empirical stepwise regression (SR) based models for the prediction of deviatoric stress, pore water pressure and Young's modulus of rotund sand- mica mixtures as a function of mica content and strain level. The experimental data presented here in the paper reveals that the high compressibility of the mixes is likely to be a result of particle shape.

Modeling of granular materials is often a complex phenomenon particularly where a mixture of two or more materials exist. In this context, it is showed that alternative methods such as soft computing techniques can be used to overcome this difficulty. This study is a pioneer work that inquires into the capability of SR approach for the empirical modeling of coarse rotund sand- mica mixtures regarding deviatoric stress, pore water pressure and Young's modulus. The predictions of developed SR equations for deviatoric stress (R^2=0.98), pore water pressure (R^2=0.97) and undrained Young's modulus (R^2=0.97) are observed to be quite accurate compared to test results. Researchers can use these three models safely for the prediction of damping ratio and shear modulus of Leighton Buzzard Sand fraction B- mica mixtures. The outcomes of this study are quite satisfactory which may serve SR approach to be widely used in geotechnical engineering applications.

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