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RESEARCH ARTICLE

Effect of Temperature on Triaxial Behavior of a Sand with Disaccharide

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Abstract

Disaccharides are carbohydrates consisting of two monosaccharides, currently introduced as soil improvement additives and an alternative material for identifying the structural behavior of a sand in small-scale model tests. In this experimental study, a type of disaccharide (i.e., sucrose) was used at two different temperatures to investigate the undrained triaxial compression testing of Leighton Buzzard Sand. The materials, specimen preparation and test methods are described, as are the results of a suite of triaxial tests in a temperature controlled cell in which deviatoric stress, pore water pressure and local strain were measured. The results describe unusual behavior involving deviatoric stress and pore water pressure jumps when employing a relatively higher temperature (60°C). However, the results suggest that specimens tested at room temperature (23°C) could suppress dilatancy without any jumps observed in deviatoric stress and pore water pressure.

Keywords

Disaccharide · sand · triaxial · temperature

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1 Introduction

Geotechnical engineering projects are related to both environmental and economic issues. Use of already available construction materials including lime and cement has a deteriorating effect on the environment, and the manufacturing of lime and cement is energy demand. Maintaining a balance between cost and performance, while satisfying environmental regulations has led to use of innovative materials and techniques [1, 2]. Further, such innovative materials and techniques are also employed to the understanding of soil response under various loading conditions by measuring internal deformation non-intrusively [3–5]. For example, a disaccharide solution was identified to find a suitable water-based fluid to visualize conditions within soil models. Disaccharides, which have more favorable properties than other fluids (i.e., mineral oil, calcium bromide brine), are carbohydrates consisting of two monosaccharides, simply referred to as sucrose, linked by a glycosidic bond [6]. Carbohydrates consist of the elements oxygen (O), hydrogen (H) and carbon (C) with a ratio of hydrogen twice that of oxygen and carbon. Depending on the concentration of sucrose in the solution and the temperature, sucrose crystals may grow. Crystals take place when the concentration of a solution is higher than the solubility of the sucrose solids. For example, when one adds sugar to water, the sugar crystals dissolve and the sucrose goes into solution. But one cannot dissolve an infinite amount of sucrose into a given volume of water. When as much sucrose have been dissolved into a solution as possible, the solution is said to be saturated. The saturation level is a function of temperature. The higher temperature, the more sucrose that is able to be held in solution. But when the solution begins to cool, there will be more sucrose solids in solution than is normally possible at the former temperature. Then the solution is said to be supersaturated with sucrose, and crystallization may take place. The sucrose crystals, which precipitates and outgrows, results in binding together the soil grains, hence increase the stability [7].

It has been a long understood that thermal stabilization (heating or cooling a soil matrix) is technically feasible to stabilize soils, in particularly fine-grained soils. Here in the present study, thermal stabilization of a soil matrix fully saturated with disaccharide has been proposed. The sucrose solution employed in the present study was selected due to its simplicity, availability as well as sensitivity to temperature changes in the soil matrix. Accordingly, in this study, effect of temperature on small strain stiffness of Leighton Buzzard Sand with sucrose solution was examined in order to identify an alternative stabilization method, and to have a greater understanding of structural deformation within a soil model. For this purpose, a conventional 100-mm-diameter compression triaxial machine with a 50-kN load capacity was modified to include a temperature control system.

2 Experimental study

2.1 Materials

The experimental work has been directed mainly towards an investigation of the effects of sucrose ($C_6(H_2O)_{11}$) solutions at two different temperatures (i.e., room temperature referring 23^{o}C, and 60^{o}C). Sucrose solutions employed during the experimental study were prepared by using icing sugar solid grains ($C_6(H_2O)_{11}$).

Leighton Buzzard Sand representing equidimensional coarse rotund particles was used, which is a standard material referred in BS 1881-131:1998 [8]. The Leighton Buzzard Sand used in the experiments was fraction B, having minimum and maximum dry densities of 1.48 g/cm^3 and 1.74 g/cm^3 respectively. The procedure defined by BS1377 [9] was used to obtain the maximum and minimum dry density values. More than 90% of the coarse sand particles, which are rounded and quartz, are between (approximately) 0.6 mm and 1.1 mm. The D_{10}, D_{30} and D_{60} sizes were found to be around 0.68, 0.78 and 0.92 respectively. Thus, the coefficient of uniformity (c_u) and the coefficient of curvature (c_c) have been calculated as 1.35 and 0.97 respectively.

2.2 Test set-up

A conventional 100-mm-diameter Wykeham Farrance compression triaxial machine having a 50-kN load capacity was modified to include a temperature control system. Fig. 1 shows a schematic representation of working mechanism of the set up. As can be seen from the figure, the set-up consists of load cell, displacement transducers, pressure transducers, pressure controllers, coil in the cell, thermistors, pump, chiller, water bath, and data acquisition system.

The temperature controlled system is based on a coil in the cell, which circulates water at various temperatures. The temperature difference between the coil and the other components of the apparatus is the driving force for the heat to be exchanged. The wider temperature difference, the greater amount of heat needs to be transferred between the coil and the other components. Accordingly, it was realized that the thermal conductivity of the material and the physical attributes of the coil, including tube size and the distance between the cords, affect the amount of heat to be transferred between the two media. Considering the availability of material, a copper tube having 10 mm outside and 0.7 mm wall thickness, as one of the most effective heat transfer material, was selected to build the coil.

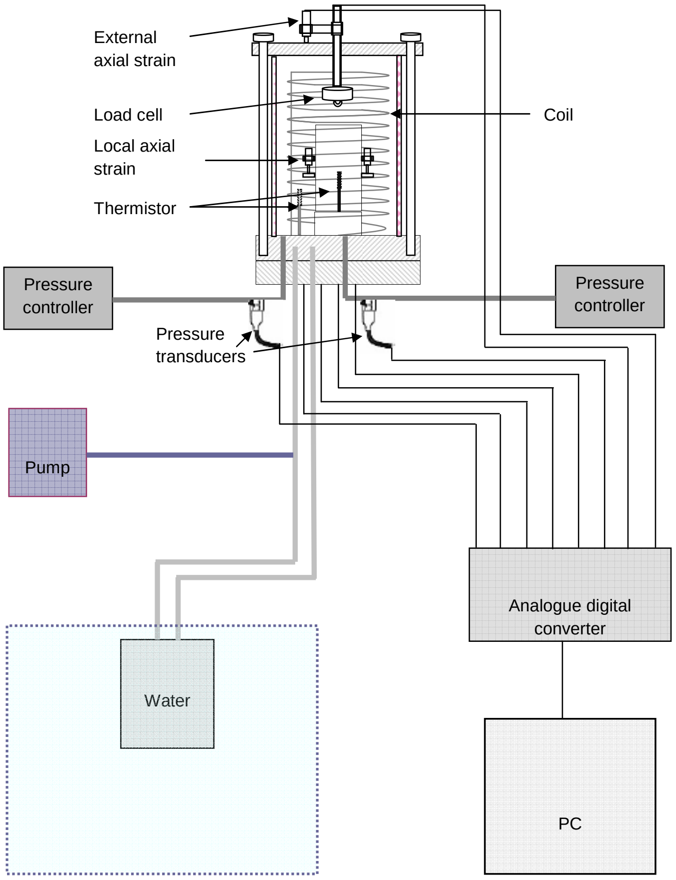


Fig. 1. Schematic diagram of the set-up used during the experimental study

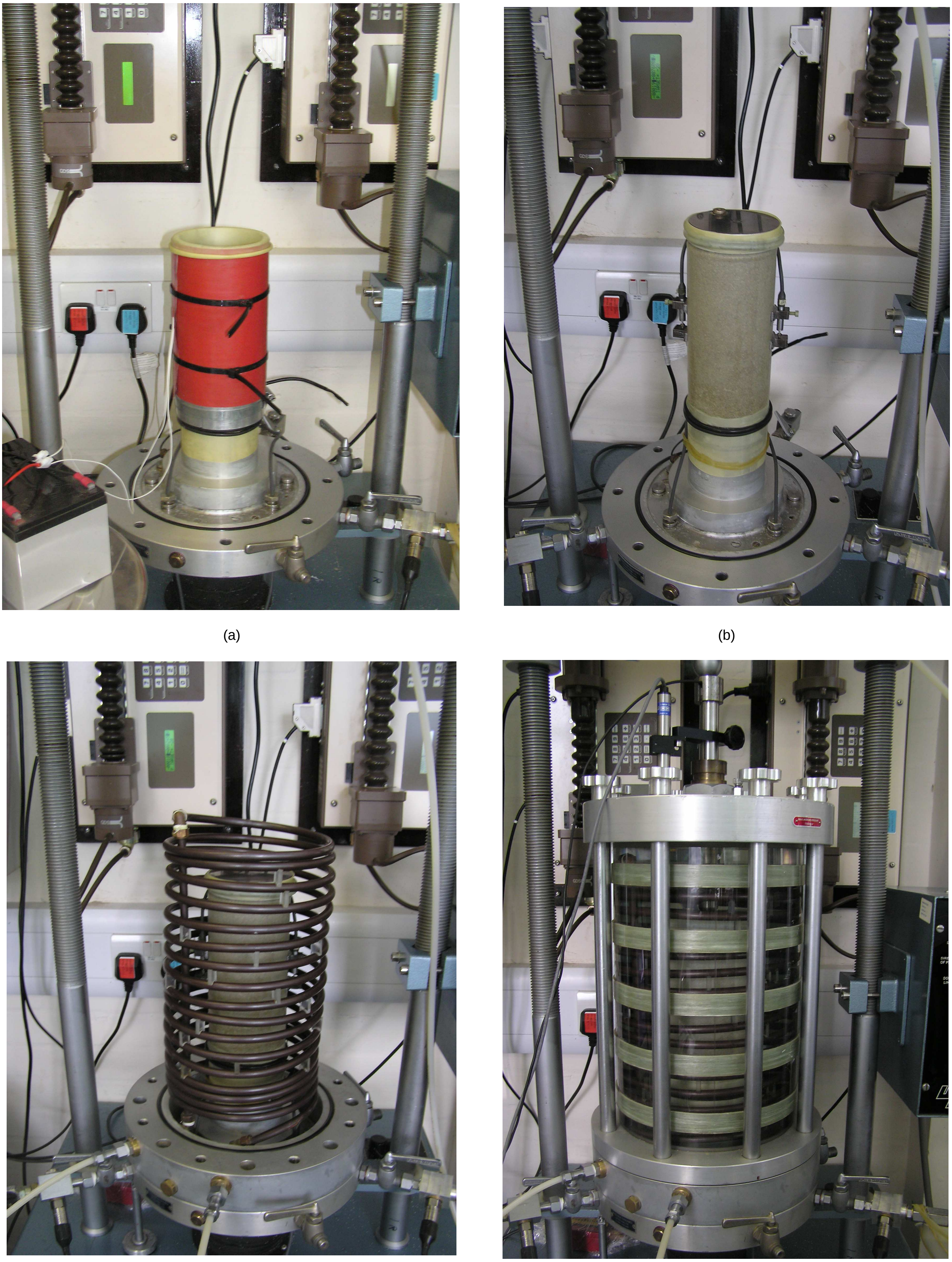
During the testing of a specimen in the apparatus, a peristaltic pump (Watson Marlow 603S-1), a chiller (Tricity 455x455x845) and a heater (Grant type, having 0-80 ^{o}C temperature capacity) were used to ensure that the temperature remained constant in the cell. Great care was taken to manually control the water suppliers (i.e., pump, chiller, heater), which was crucial to maintain the temperature constant in the cell.

For this study, it was realized that local measurements of axial strain were required in order to make more accurate estimates of the soil stiffness. Two submersible linear variable differential transformers (LVDT) were employed to measure the axial displacement in the middle third of the specimen in diametrically opposite positions. They were used over a 27 mm gauge height (clear distance). Two LVDTs with a ± 1 mm linear range was kept in place by means of a plastic screw on brackets, and then they were held in position on the specimen.

A 5-kN Wykeham Farrance STALC 4958 type internal load cell was calibrated using Budenberg dead-weight tester Model 580 L.

2.3 Specimen preparation

The required amount of dry sand was weighed and placed in a conventional oven at a minimum of 70 ^{o}C. It was then kept in the oven at least 24 hours. The required amount of sucrose and de-aired water were also weighed just before preparing of the spec-


(a)

(b)

(c)

(d)

Fig. 2. Four-step-process for the specimen preparation.

imen on the pedestal. Sucrose and water quantities were determined based on the desired temperature value from the solubility chart for the sucrose grains. In this investigation, the mix ratios of sucrose to water was 207/100 g/g to be tested at 60^{o}C. The sucrose grains were mixed with pre-heated water at a minimum of 70^{o}C. The mixture was then stirred by a wire, and kept on a hot plate until the sucrose dissolved entirely. A membrane was attached to the pedestal using an o-ring, and a three-part split mould was placed around the pedestal. The mould was then covered with a heater mat that provides an even distribution of heat to the mould. The heater mat with a 12 V supply voltage, 80 W power rating, 200 mm length and 400 mm width (RS 245-578) is a simple and effective method of applying heat to the specimen on the pedestal. The heater mat was connected to a battery, and around 1-cm-height oil was poured on to the pedestal (to avoid any crystal deposition in the pedestal). The membrane was then filled with the disaccharide solution in layers of approximately 67 mm (1/3 height of the mould). Fig. 2.a illustrates the process followed until this point. The Fig. 2.a presents the mould covered with a heater mat that provides an even distribution of heat to the mould, while the Fig. 2.b presents the specimen with LVDTs to be tested. Region (I) shown in Fig. 3 gives the typical change in temperature and pressure in both the specimen's itself and the triaxial cell. It can be seen that the temperature in the specimen exhibits a sharp increase to 85^{o}C, due to the pouring of sucrose solution into the mould. However, the temperature measurement in the cell was almost constant at approximately room temperature. The sand was removed from the oven and gently spooned in to the mould in thin layers without vibration or any type of method that could lead to compaction. This procedure was repeated until the mould was filled. When the mould was completely filled, the top of the specimen was flattened by gently sliding the sand particles from the centre of the specimen to its side using the tip of a small screwdriver. Excess sand was removed and the weight of the remaining sand was recorded for density measurement. The o-ring stretcher with two o-rings was slipped over the top plate which was placed on top of the specimen. The membrane was slipped over the top plate, ensuring that no sand particles were trapped between the two before using the o-rings. Approximately 20 kPa of vacuum was applied to the specimen. The vacuum was maintained by specifying a target pressure of - 20 kPa to the GDS pressure controller, connected to the pedestal. The region (II) shown in Fig. 3 illustrates the process from the end of the region (I) to this point. It can be seen that the temperature in the specimen gradually decreases to just below 70^{o}C. The thermistor outside the specimen shows values more than room temperature, because the heat of the specimen affects the surrounding devices including the thermistor. Once the pore pressure measured through the pedestal stabilized at this pressure value, the heater mat was removed, and then the three-part-mould was carefully split to prevent disturbance to the specimen. The dimensions of the specimen were measured in mm to two decimal places. The LVDT brackets were glued to the membrane using super glue at the middle third of the specimen. The LVDTs were then inserted in the place with screw on the side of the bracket. The gauge length of the LVDTs was adjusted to ensure the maximum linear range. This was done by adjusting the screw. As shown by region (III) in Fig. 3, the temperature in the specimen decreased around 20^{o}C in a short time. Fig. 2.b shows the specimen at this stage. The coil was assembled (Fig. 2.c), and then the cell was closed and filled with pre-heated water. At the same time, circulation of heated water in the coil was started using a peristaltic pump. The vacuum inside the specimen was reduced while gradually increasing the confining water pressure in small steps until the desired value (400 kPa) was achieved. The process from the end of region (III) to this point is represented by region (IV) in the Fig. 3. The specimen under a constant temperature was left overnight to ensure that the heat evenly distributes through the specimen, and that any air trapped in the specimen would dissolve into the pore fluid, which was 400 kPa cell pressure and 300 kPa back pressure. Fig. 2.d and the region (V) in Fig. 3 represent the details of this step.

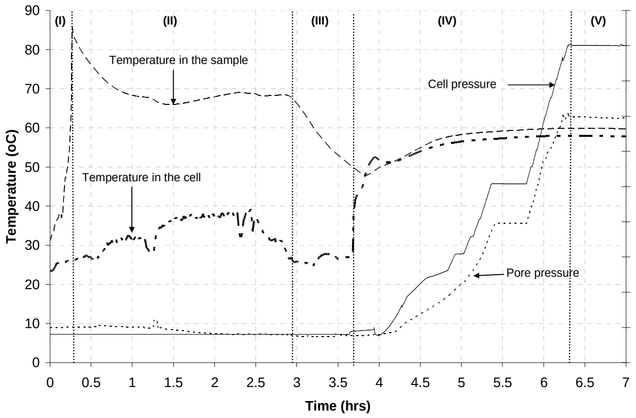


Fig. 3. A plot showing the changes in temperature and pressure with time before testing a specimen in temperature controlled triaxial apparatus.

The technique employed for preparing the loose coarse rotund sand specimens with de-aired water, and the specimens with sucrose solution to be tested at room temperature included all the steps described above except increment in temperature.

2.4 Test procedure

Isotropically consolidated undrained triaxial compression tests were conducted on specimens prepared according to the procedures outlined in the preceding section. Tests in this investigation were applied to fully saturated samples sheared in consolidated-undrained triaxial compression. During the consolidation process, the pore-pressure, cell pressure, volume, strain measurements as well as the temperature reading were closely examined and recorded. Tests were carried out at 100 kPa effective consolidation stress (400 kPa cell pressure and 300 kPa back pressure). Care was taken to ensure that the effective consolidation pressures were achieved by raising the cell pressure in coordination with the back pressure. The load ram is finally brought into just above with the sample using hand and zero of the strain dial is set. Following the consolidation at various temperature values and these last processes, the drainage valve to the specimen were closed, and then compressive load was applied using the load frame. The rate of loading of 0.015 mm/min at which the tests were run was governed by 10 second-logging rates. The test was usually terminated when the maximum deviatoric stress has clearly been reached.

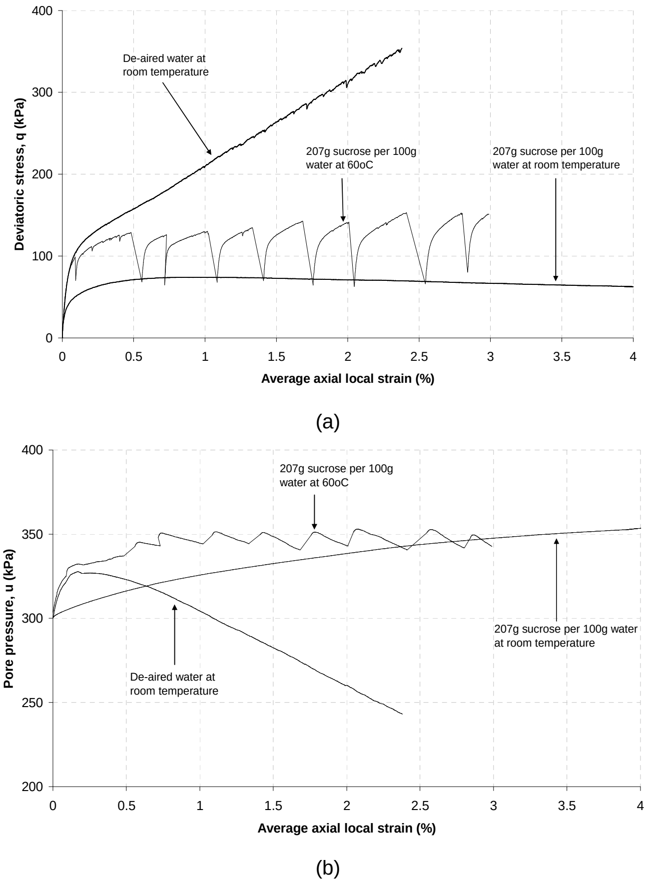
3 Results and discussion

The experimental programme was followed to establish whether changes in temperature influence the behaviour of Leighton Buzzard Sand with sucrose solution. The geomaterial used in the tests was Leighton Buzzard Sand with 207 g sucrose (i.e., icing sugar) per 100 g water. The initial relative density of the specimens tested were kept at around 42%. Each specimen was tested at 60^{o}C, and at room temperature (approximately 23^{o}C).

Fig. 4.a shows the deviatoric stress vs. strain results for three different tests under 100 kPa effective stress. The temperature difference lead to a stick-slip behaviour beginning from the 0.091% strain level to the end of testing on the Leighton Buzzard Sand with sucrose solution tested at 60^{o}C, whilst Leighton Buzzard Sand with sucrose solution tested at room temperature shows a contractive behaviour instead a stick-slip behaviour. The Leighton Buzzard Sand with de-aired water at room temperature gives a higher stress values at almost all the strain levels. Plot for the Leighton Buzzard Sand tested at 60^{o}C with sucrose has a place higher than the Leighton Buzzard Sand with sucrose tested at room temperature, but lower than the Leighton Buzzard Sand with de-aired water tested at room temperature. It is interesting to note that the plot for the Leighton Buzzard Sand with sucrose solution tested at room temperature may be seen as a kind of lower boundary for the specimen tested at 60^{o}C.

Fig. 4.b presents pore water generation corresponding to the deviatoric stress vs. strain plots for three different tests described above. The Leighton Buzzard Sand with de-aired water exhibits a clear dilation process; however, the Leighton Buzzard Sand tested at room temperature with sucrose solution shows a continuous increase from beginning of the test to the end of the test, where the pore pressure generation goes up until above the 350 kPa. As can be seen from the Fig. 4.b, the Leighton Buzzard Sand tested at 60^{o}C with sucrose solution shows a significantly different behaviour from the other two plots. The specimen tested at 60^{o}C shows a mechanism representing a stick-slip mechanism.

It was noted (Fig. 5) that the secant Young's modulus increased with the adding of sucrose solution up until around 0.005% strain level, at both temperature values. Referring to the Fig. 5, it can be seen that the addition of sucrose to the pore fluid resulted in considerably reduced specimen stiffness at room temperature after 0.005% strain level. However, the stiffness of the specimen tested at 60^{o}C with the sucrose solution has higher values up until to approximately 0.044% strain level. The specimen tested at 60^{o}C with the sucrose solution also exhibits sharp drops followed by gradual increase in stiffness.



(a)

(b)

Fig. 4. (a) Stress-strain and, (b) pore water vs. strain curves for clean Leighton Buzzard Sand and that with sucrose solutions at different temperatures at 100 kPa effective consolidation pressure.

The stress paths of the specimens tested in this series are shown in Fig. 6. Comparing all three plots, it can be seen that the shape of the curves are significantly different from each other. The causes of these differences are sucrose constituents as well as the temperature. Similar to the preceding tests, the Leighton Buzzard Sand tested at 60^{o}C with sucrose solution gives an area. On the other hand, the result for the Leighton Buzzard Sand with sucrose solution tested at room temperatures could be attributed to the particle effects of the sucrose solids that were not dissolved.

3.1 Stick slip mechanism

Stick-slip is a complicated phenomenon that can be identified mainly by the stress drop amplitude (Δq) and the deformation ($\Delta\varepsilon$) (or time, Δt) between two successive stress drops. Deviatoric stress oscillations were observed for each sucrose-coarse rotund sand mix ratio, differing in the deviatoric stress amplitude and the strain intervals corresponding to each of the stress drops. The deviatoric stress fluctuations may be attributed to the stick-slip mechanism between the sand grains as they form force chains to support the applied load. Jamming occurs be-

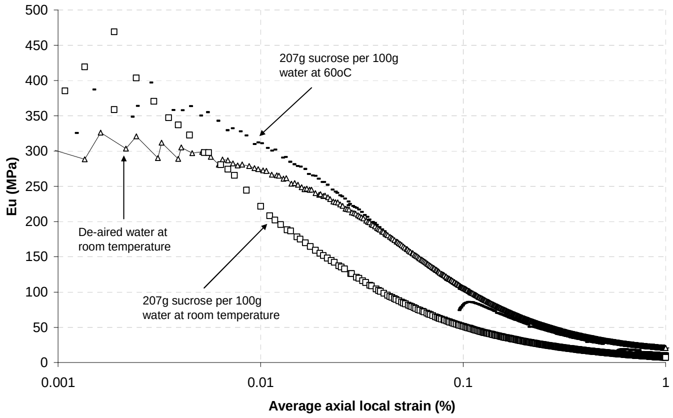


Fig. 5. Young's modulus for Leighton Buzzard Sand with de-aired water and Leighton Buzzard Sand with sucrose solutions at different temperatures at an effective consolidation pressure of 100 kPa.

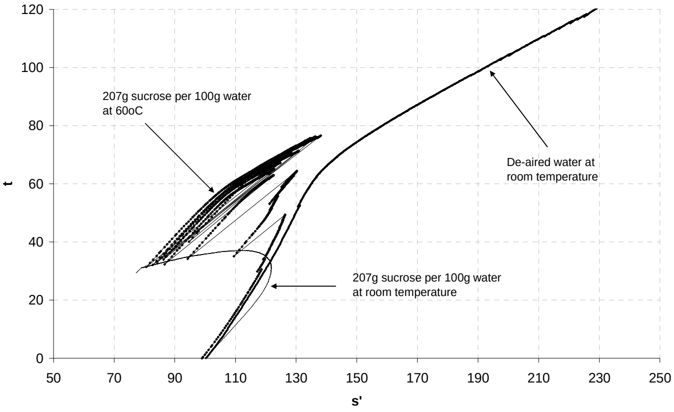


Fig. 6. Stress path results for Leighton Buzzard Sand with de-aired water and Leighton Buzzard Sand with sucrose solutions at different temperatures at an effective consolidation pressure of 100 kPa.

cause the sand particles form the chains (primarily) along the compressional direction. During the sticking, the sand grains are more closely packed and exhibit a gradual increase in deviatoric stress, however; when the force chain becomes relatively unstable, some grains slide out of the column resulting in the deviatoric stress to sharply drop. The deviatoric stress subsequently builds up (self organize) again to form a new chain of columns so as to support an applied stress.

The stick slip behaviour in granular materials has been investigated by numerous researchers in different disciplines, such as; 10 Thompson and Grest [10], Feder and Feder [11], Demirel and Granick [12], Miller, O'Hern and Behringer [13], Nasuno et al. [14], Albert et al. [15], Cain et al. [16], Gourdon and Israelachvili [17]. Materials in granular form are composed of many solid particles that interact through contact forces. The reason of this jamming noted in the specimens tested with sucrose solutions might lie in the fact that the forces may not propagate uniformly through the specimen but are localized along the force chains, and the jammed state is dependent on the properties of the network of these force chains. A similar behaviour was also noted by Alshibli and Roussel [18]. Cates et al. [19] showed that the strain resulting in a simple granular pile from grain weight combines with the randomness in their packing to limit the motion of individual grains, which leads to a jammed state. An applied external stress leads to an internal structure resisting the stress. Then, a jammed state is dependent on the direction and the magnitude of the stress. Vanel et al. [20], and Al Hattamleh et al. [21] described that these force chains form arches shielding the centre from some of the weight, thereby forming the jamming.

From the experimental investigation, comparing the test results obtained using Leighton Buzzard Sand with de-aired water and the Leighton Buzzard Sand with sucrose solutions at various concentrations; it is thought that the difference between these experimental results may be attributed to the force chain mechanism in the specimens tested. A deviatoric stress increment in a specimen tested with sucrose solution causes a stress distribution among the matrix that develops relatively unstable comparing to the other specimens tested with water where the stress distribution occurs gradually. During the loading, stress or force chains distribution in the specimens with sucrose solutions are formed slower than those in the specimens with water, and destroyed suddenly. This takes place mainly in the direction against the applied load. Jensen et al. [22] modeled soil by discrete element model and showed that in two dimensions, each particle brings three degrees of freedom to the model. In that study, each interparticle contact was modeled with a normal-direction spring and dashpot, and a spring-dashpot-slider assembly in the tangential direction. From the investigation by Jensen et al. [22], it seems to be possible that the stress chain in Leighton Buzzard Sand with sucrose may be stronger than that in the Leighton Buzzard Sand with de-aired water in all the aspects in two dimensions.

4 Conclusions

The objective of the study was to develop a greater understanding of the structural behaviour of a sand in small-scale model tests, and to introduce a suitable soil improvement additive under two different temperature values. Influence of temperature on the behaviour of Leighton Buzzard Sand particles was investigated on the Leighton Buzzard Sands with sucrose solutions at both elevated temperature (i.e. 60^{o}C) and room temperature (i.e. 23^{o}C). The effects of temperature on the Leighton Buzzard Sand with sucrose produced a significant difference in mechanical behaviour comparing to the Leighton Buzzard Sand with de-aired water. The test results on the specimens with sucrose at 60^{o}C result in fluctuations in stress and pore water pressure plots, while the specimen with sucrose solution tested at room temperature shows a contractive behaviour. This unusual behaviour gives a stick-slip behaviour nature to the fluctuations, which might be attributed to the temperature value. The results suggest that that any system of analysis which neglects the presence of the temperature will be incomplete.

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