Stiffness and Deformation Characteristics of a Cemented Gravely Sand

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Abstract: *The deformation and stiffness characteristics of a cemented gravely sand was investigated using triaxial equipment. The triaxial tests were conducted in both dry and saturated undrained conditions. Artificially cemented samples are prepared using gypsum plaster as the cementing agent. The plaster was mixed with the base soil at the weight percentages of 1.5, 3, 4.5 and 6. The applied confining pressure varied between 25 to 500 kPa in triaxial tests. The process of yielding of the soil was investigated for the considered soil and the bond and final yield points were identified for the cemented soil with different cement contents. The variations of deformation and stiffness parameters with cement content and confining stress were studied as well. Some of the parameters were determined for both drained and undrained conditions to investigate the effect of drainage condition on the stiffness and yield characteristics of the tested cemented gravely sand. According to the results, the difference between drained and undrained tangent stiffness decreases with increase in confining stress. Finally the effect of cement type was investigated as an important parameter affecting the stiffness at bond yield. The rate of increase in tangent stiffness at bond yield changes with cement content for different cementing agents.*

Keywords: *Stiffness, Deformation, Gravely sand, Triaxial test, Yield, Cementation, Gypsum.*

1. Introduction

There are many regions in the world which are covered with natural cemented or bonded soils. The increasing use of soil treatment in civil engineering has also focused the look of geotechnical engineers to the behavior of cemented soils. The injection techniques that artificially produce cemented soils are widely used in engineering problems to improve the mechanical behavior of undesirable soils. As a result the research on the behavior of cemented soils in the recent decades has increased rapidly.

Saxena and Lastrico [1] were pioneering researchers in this field. According to their studies cementation increases soil stiffness and brittleness. Clough et al. [2,3], Acar and El-Tahir [4], Maccarini [5], O'Rourke and Crespo [6], Lade and Overton [7] continued the study on the behavior of the cemented soils. The fundamental paper of Leroeil and Vaughan [8] was a beginning to the fast increase in the rate of study on the cemented soils. Chang and Woods [9], Airey [10], Coop and Atkinson [11], Gens and Nova [12], Toll and Malandraki [13], Cuccovillo and Coop [14, 15, 16], Das et al. [17], Consoli et al. [18], Malandraki and Toll [19, 20], Schnaid [21] and Rotta et al. [22] have important contributions in this field as well.

The loading on cemented soil is tolerated by two parts i.e. soil skeleton and cemented bonds. Some of the cemented bonds fail due to their lower stiffness and more brittleness. The beginning of yield of weak bonds was named as first yield. More bonds fail with increase in loads until they do not tolerate more loads. At this time a sharp decrease in soil stiffness happens which is named as bond yield.

The yield mechanism of cemented sandy soils has also been studied by a number of researchers. Maccarini [5] defined the first yield as the end of linear part of stress-strain curve and the second yield as the point with the most curvature before failure in this curve. This definition is more useful for loose soils. Bressani [23] defined the first yield as the end of non linear part of stress-strain curve in double logarithmic space and the second yield as the end of next linear part as

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shown in Fig. 1. In this figure "t" is the deviatoric stress in kPa. Airey [10] defined the first yield as the end point of linear part of deviatoric stress-strain curve or volumetric strain-strain curve to be as the end of elastic behavior of the soil. Coop and Atkinson [11] defined an equivalent final yield point as a point that all the cemented bonds fail at that point.

Toll and Malandraki [13] defined the first and second yield of a cemented soil as the two dropping points in tangent stiffness-strain curve in a double logarithmic space as illustrated in Fig. 2. Also the first and second yield envelopes of the soil tested by Toll and Malandraki [13] are shown in Fig. 3. The maximum in the first yield envelope is located in low mean effective stress values; however, the maximum of second yield envelope is not achieved in low stress levels. In this figure the failure envelope of bonded and destructured soils are shown as well. As it can be seen the failure envelope of the bonded soil is curved contrary to the destructured one that is a straight line.

The majority of foregoing studies have been conducted on fine sandy soil. In case of the gravely sands, the following studies can be introduced. Haeri et al. [24] reported experiments on cemented gravely soils using large direct shear tests. They reported an increase in stiffness and brittleness of the cemented soil with increase in cement content up to 6 percent. In continuation of the work of Haeri and his coworkers, Asghari et al. [25] used hydrated lime as the cementing agent. They showed a curved failure envelope for cemented soil and increase in the soil stiffness and brittleness with cement content. Hamidi et al. [26] and Haeri et al. [27] used gypsum as the cementing agent for a gravely sand and investigated the effect of cement content on the behavior of cemented gravely sands.

Haeri et al. [28] continued the research using Portland cement as the cementing agent. They concluded that the texture and structure of the cemented gravely sand can considerably influence the mechanical behavior of cemented soil. Finally in a comprehensive review Haeri et al. [29] studied the effect of cement type on the mechanical behavior of artificially cemented soils.

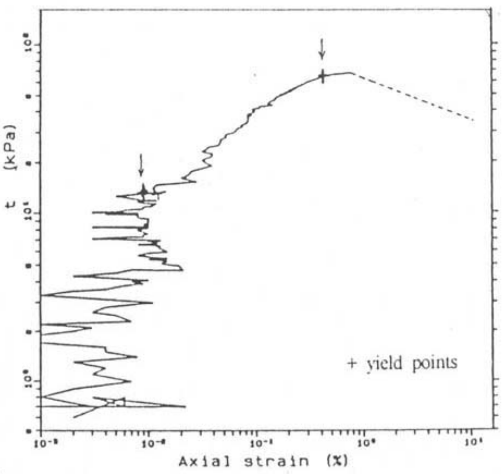

Fig. 1 Definition of first and second yield points in logarithmic stress-strain curve [23]

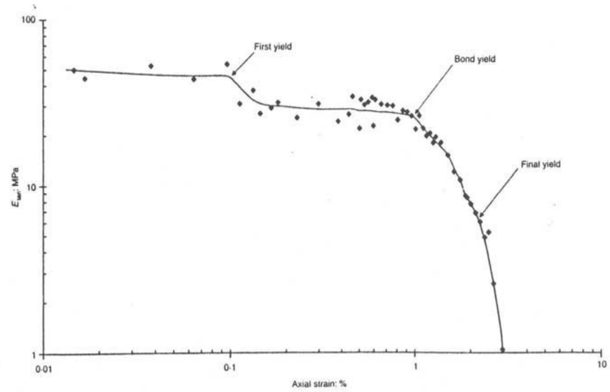

Fig. 2 Definition of first, bond and final yield points in logarithmic stiffness-strain curve [13]

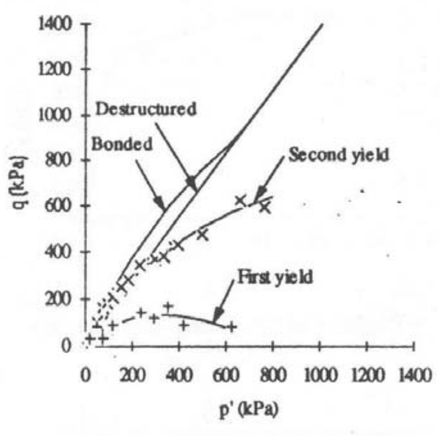

Fig. 3 Definition of first and second yield envelopes [13]

The objective of this paper is to investigate the stiffness and deformation characteristics of the cemented gravely sand especially cemented by gypsum. This is in the line with the experimental studies conducted by Haeri et al. [27]. However, in this paper, more attention is given to the stiffness and yield conditions of the gypsum cemented soil.

2. Physical properties of tested soil

Haeri et al. [24] proposed an equivalent gradation for North Tehran alluvium as the average of gradation curve of the soil specimens obtained from different parts of the North section of the city. By eliminating oversize particles, a gravely sand was selected as the representative soil of North Tehran alluvium that contains 49 percent sand, 45 percent gravel and 6 percent fines according to ASTM and can be named it as SW-SM in Unified System of Soil Classification [30]. However, the soil can be considered as gravel in British system of soil classification. The mineralogy of grains is mostly from silicates. Grains are sub rounded with a nearly rough surface which makes a good bonding to the cemented materials. Fig. 4 shows the gradation curve of tested soil in addition to the gradation curve of the samples taken from the North Tehran alluvial deposit. The maximum particle size is limited to 12.5 mm for triaxial testing of samples with 100 mm diameter to keep the ratio of sample diameter to the maximum particle size as eight. The physical properties of the soil are summarized in Table 1. All the parameters are determined in the laboratory using standard methods. The ASTM D854 and D2049 methods were used to determine the specific gravity and maximum and minimum void ratios of the base soil [30].

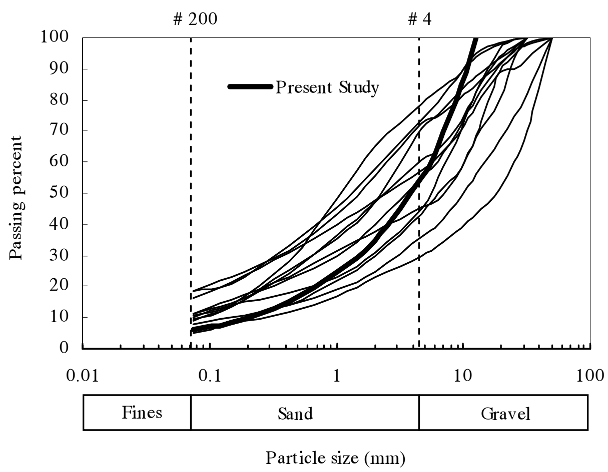

Fig. 4 Gradation curves of North Tehran alluvial deposit and the tested soil in the present study

Table 1 Physical properties of tested soil

Soil name	SW-SM
Specific gravity	2.58
Average particle size (mm)	4
Effective diameter (mm)	0.2
Fine content (%)	6
Sand content (%)	49
Gravel content (%)	45
Minimum unit weight (kN/m^3)	16.00
Maximum unit weight (kN/m^3)	18.74

3. Sample preparation

Three parted split mold with an internal diameter of 100 mm and a height of 200 mm were used in sample preparation. Each sample was prepared in eight layers. For each layer the proper amount of the base soil was mixed with the desired weight of gypsum plaster and 8.5 percent of distilled water. The average setting time for gypsum plaster was 13 minutes. As a result the time for sample preparation should have been kept below 12 minutes. Samples with different gypsum contents of 1.5, 3, 4.5 and 6 percent were prepared. The gypsum content was kept constant for different layers. The mixed material was poured in the mold and compacted using a metal hammer until reached the desired height. The unit weight of soil samples was kept as 18 kN/m^3. This value corresponds to a relative density of about 65 percents [26]. The sample was kept in the mold about one hour for complete hydration. The humidity of the air was low and there was no volume change due to the stiff confinement of the sample in the mold. After sample preparation the mold was opened and the sample was cured in a 50?c oven to reach to a constant weight. The temperature was kept constant in curing time. The samples were kept in a time period of about one week to ensure complete dry condition.

4. Testing Program

Cured sample was set up on the base pedestal of a standard triaxial cell connected to a digital data logger and sensors. At the first step, the outer side of sample was covered with a thin film of clay and fine sand mixture to minimize membrane penetration effects. The top and bottom surfaces of the specimen are also completely leveled and prepared for the test to minimize the bedding errors associated with external deformation measurements. Two overlaying membranes were used with an average thickness of 0.6 mm to prevent membrane puncture by coarse grains

As stated by several researchers, the stress-strain behavior of dry and saturated granular soils is analogous provided that pore fluid can flow freely into or out of pores and no excess pore pressure develops. This was approved by Lambe and whitman [31] as a general rule for granular soils. Although they didn't use cemented soils in their studies, at the present research, dry samples were used as substitution for drained tests.

For dry samples, the volume change was measured via the changes in the volume of the water in triaxial cell. As a result it was measured on the cell pressure line. Head [32] mentioned several factors that affect the movement of water into or out of the cell in the cell pressure line volume change measurement that have been taken into account in this study. When a dry sample is used, the volume change sensor is placed between triaxial cell and cell pressure tank. This sensor measures volume changes indirectly from the water inside triaxial cell. Some corrections are made on the measured value as proposed by Bishop and Henkel [33]. The shear strain rate was controlled at 0.65mm per minute in these tests.

Undrained tests were conducted on samples saturated using a light silicon oil with a low viscosity of 3.2 mm^2/s in 25^o C and a density of 0.782 gr/cm^3. The low viscosity silicon oil has no effect on the rate of generated pore pressure as proved by Ellis et al. [34] and prevents the change in stiffness and strength of gypsum bonds as stated by Coop and Atkinson [11] and Cuccovillo and Coop [14].

Three stages are considered for saturation. First the CO_2 was flushed for an hour through the sample with the minimum available back pressure of 10 kPa and a cell pressure of 20 kPa to push air bubbles out of the pores. Next, the light silicon oil was flushed from the bottom of the sample with a low hydraulic head until the sample is filled and the oil exits from the top. The CO_2 is quite soluble in silicon oil. Finally, in order to ensure sample saturation, the cell pressure and back pressure were ramped simultaneously with a low difference of as low as 10 kPa. The back pressure was increased up to 200 kPa. The process continued to the time that B value exceeded 0.95. The sample was consolidated to the desired confining pressure. The volume change was measured exactly at the end of consolidation. The axial load was then applied with a strain control rate of 0.2mm per minute for the undrained tests. Displacement was recorded using external transducers. A data logger system recorded all data from cell pressure, back pressure, volume changes, pore pressure, displacement and axial load transducers for the analysis. Table 2 shows the testing program used in the present study.

5. Analysis of the test results

The mechanical behavior of the soil cemented with gypsum is presented in Hamidi et al. [26] and Haeri et al. [27]. According to these publications, the brittleness of the cemented soil increases sharply with increase in cement content. Fig. 5-a shows the results of drained and undrained triaxial tests conducted on samples with 3 percent gypsum content. In this figure

Table 2 Testing program in this study

Variable	No. of levels	Description of sample
Type of soil	1	Tehran coarse-grained alluvium
Cementing agent	1	Gypsum
Cement content	4	1.5, 3.0, 4.5 and 6.0 percents
Sample size	1	100 mm diameter and 200 mm height, compacted in 8 layers
Curing condition	1	Cured at 50°C oven until no change in weight was reached
Saturation	2	Dry and Saturated
Drainage condition	2	Drained and Undrained
Confining stress	4	25, 100, 300 and 500 kPa

drained and undrained tests are designated by D and U, respectively, and are followed by a number that shows the amount of confining stress in kPa. All the stress-strain curves show an apparent peak that is associated with the yield point. After that, the slope of the shear stress curve flattens and approaches a constant value for strains of approximately 20%. An increase in confining stress increases the strain associated with the peak strength and results in smaller softening behavior. Comparison of drained and undrained triaxial tests shows that, for a specific confining stress and cement content, the strain associated with the peak stress is more in undrained samples. However, the softening in drained tests is more than that of undrained tests.

Fig. 5-b shows the variation of specific volume with the mean effective stress for cemented samples under consolidated drained triaxial tests. Samples show contractive behavior at the start of shearing followed by a large dilation thereafter. Increasing the confining stress increases the contraction of the cemented soil and reduces the amount of dilation.

For the undrained condition the dilative behavior of cemented soil yields negative pore pressure, as shown in Fig. 5-c. The sample at the beginning of loading shows small positive pore pressures followed by large negative pore pressure. The amount of positive pore pressure increases with increase in confining stress and the negative pore pressure decreases with increase in confining stress.

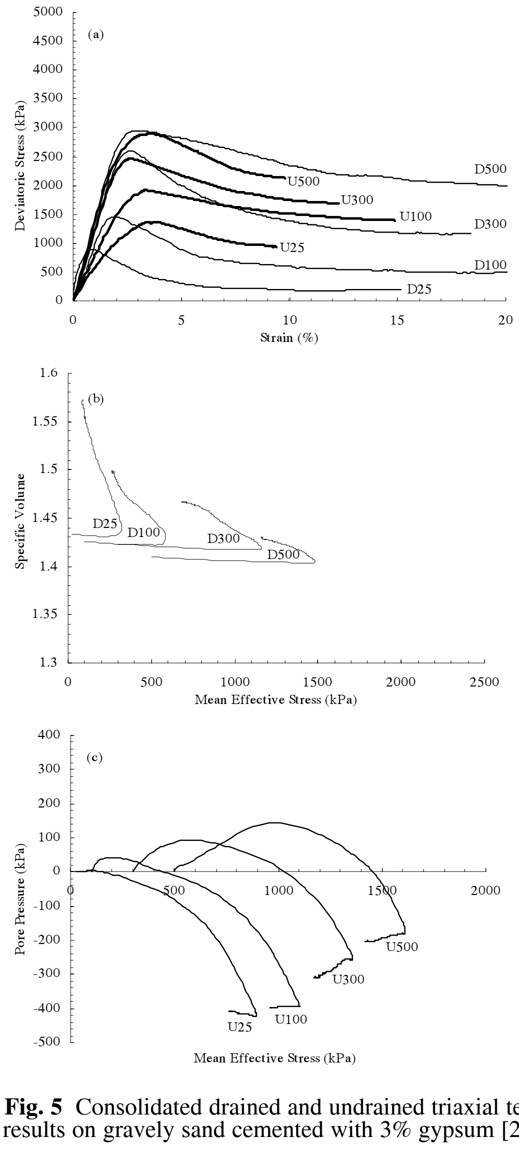

Fig. 5 Consolidated drained and undrained triaxial test results on gravely sand cemented with 3% gypsum [27]

The focus of the present paper is on the stiffness and deformation characteristics of the cemented gravely sand. The criterion suggested by Toll and Malandraki [13], may be used to define the first and second yield points of the studied soil. Fig. 6 shows the variation of tangent stiffness with measured axial strain in semi logarithmic space. The tangent stiffness is determined using the following equation:

$$E_{tan} = \frac{\Delta q}{\Delta \varepsilon_1} \qquad (1)$$

In this equation is the increment of deviatoric stress and is the increment of axial strain.

Fig. 6-a shows the bond yield and failure points for a consolidated drained triaxial test whereas Fig. 6-b shows the similar results for a consolidated undrained triaxial test. The first yield can not be estimated exactly due to the external strain measurement. However, the second yield points are quite visible in this space for drained and undrained triaxial tests. Namely, the second yield or bond point is physically associated with the bond strength. At this point the bonds are not able to withstand more shear stress. As a result the stiffness decreases dramatically. Also the final yield or failure is marked on this figure which is associated with zero tangent stiffness.

Fig. 7 shows the variation of bond yield and failure envelopes with cement content for the studied cemented soil. The failure points in this figure are based on peak deviatoric stress rather than peak stress ratio for both drained and undrained conditions. Based on this figure the position of the yield envelopes moves up with increase in cement content. The results of both drained and undrained tests are used to determine the envelopes. In order to study the effect of drainage condition on the failure mechanism, the bond yield and failure envelopes are separated in Fig. 8 for drained and undrained conditions. The tests and data of Fig. 7 are again used to draw this figure. It can be observed that the drained and undrained envelopes are different for the bond yield and failure envelope. This is an important aspect of the cemented soil behavior which is discussed at the following section.

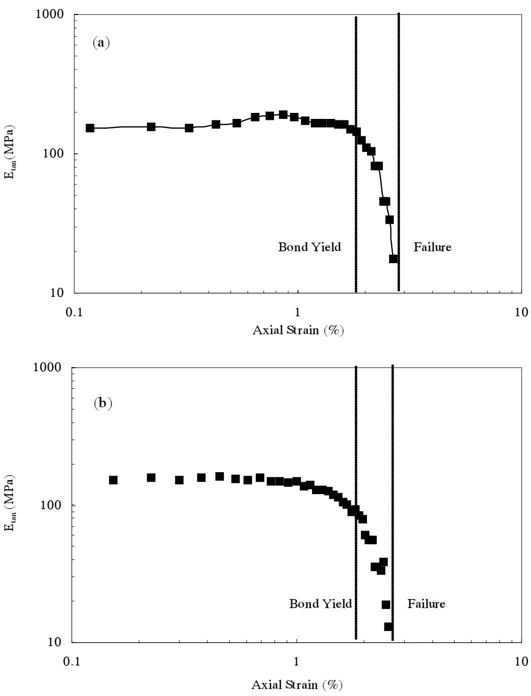

Fig. 6 Bond yield and failure points in two triaxial tests on samples cemented with 3.0% gypsum
(a) Consolidated drained test
(b) Consolidated undrained test

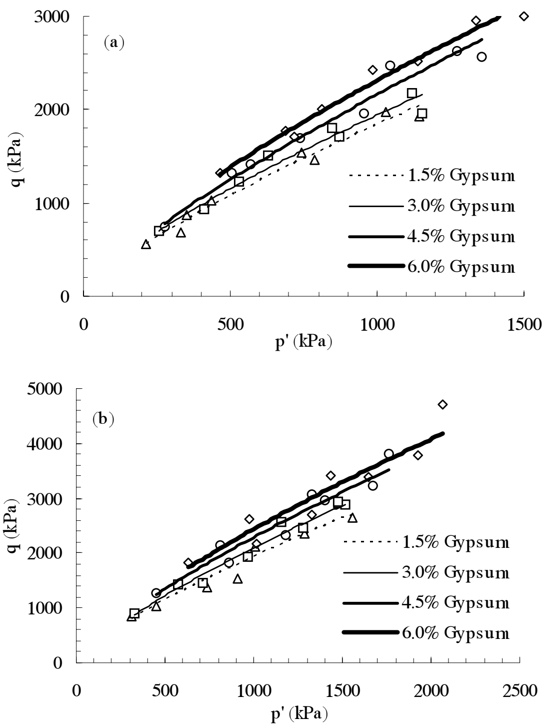

Fig. 7 Variation of bond yield and failure envelopes with the cement content
(a) Bond yield envelope (b) Failure envelope

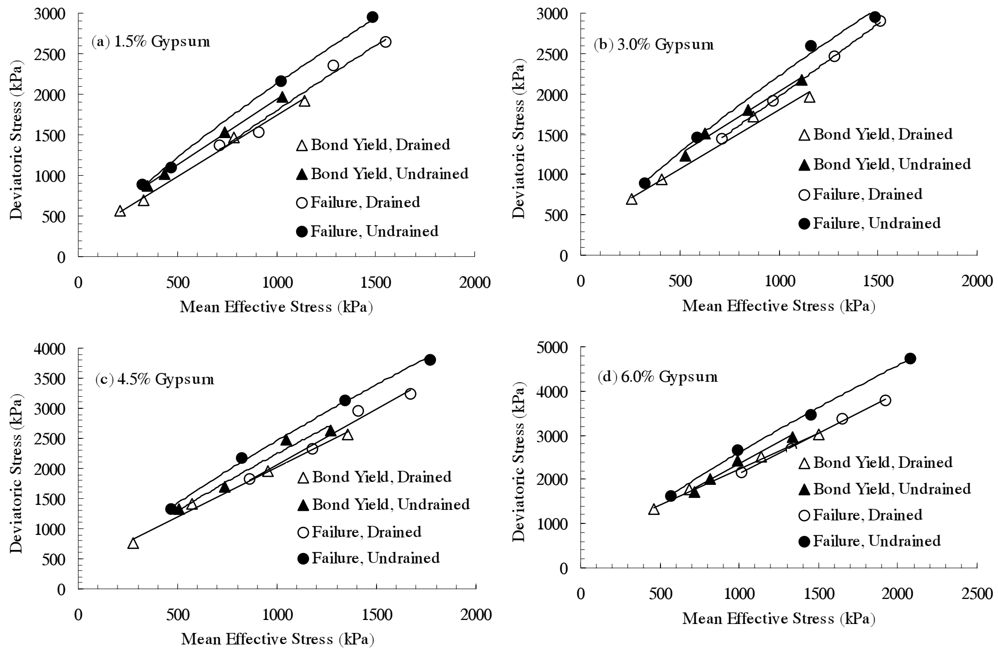

Fig. 8 Bond yield and failure envelopes for drained and undrained conditions (a) 1.5% Gypsum (b) 3.0% Gypsum (c) 4.5% Gypsum (d) 6.0% Gypsum

The deference between drained and undrained failure envelopes of the cemented soil has been reported by Haeri et al. [27]. As they stated the behavior of cemented soil is more brittle in drained condition than in undrained one. This may be observed from different soil stress paths as shown in Fig. 9. In this figure the results of four drained and undrained tests on soil cemented with 4.5 percent cement under confining stresses of 100 and 300 kPa are reported. The undrained stress paths clearly indicate the high negative pore pressures build up in the soil. The peak and ultimate stress points are marked on Fig. 9. It can be observed that after peak drop in strength is more profound in the drained tests compared to those for undrained tests. This is evident in all of the tests with different cement contents (1.5 to 6%) and confining stresses (25 to 500 kPa).

This is in line with the previous studies of Haeri et al. [27] in which it is shown that the brittleness index (I_B) defined in the following equation is higher for drained tests compared to that for undrained tests:

$$I_B = \frac{q_{max}}{q_{ult}} - 1 \tag{2}$$

In this equation q_{max} is the maximum deviatoric stress and q_{ult} is the final deviatoric stress. This is

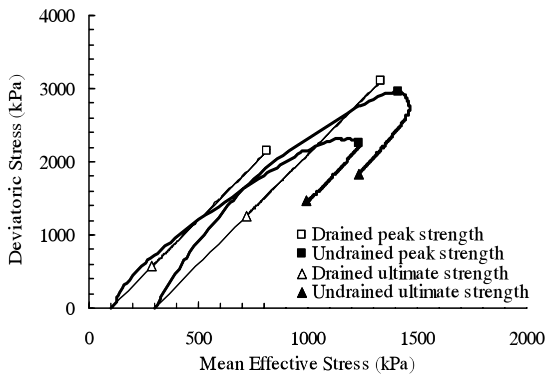

Fig. 9 Stress path of cemented soil in drained and undrained conditions

due to the volume change (dilation) that takes place during shear in drained test on such a cemented gravely soil, and so the bonds can break more freely, whereas in undrained tests, the volume change is restricted and bonds can not break such freely. On the other hand the more brittle behavior of the soil in drained condition results in smaller strain associated with the peak shear stress in comparison to that for undrained tests.

5.1. Stiffness and deformation parameters

There are usually four major parameters to define the stiffness parameters of the soil. These

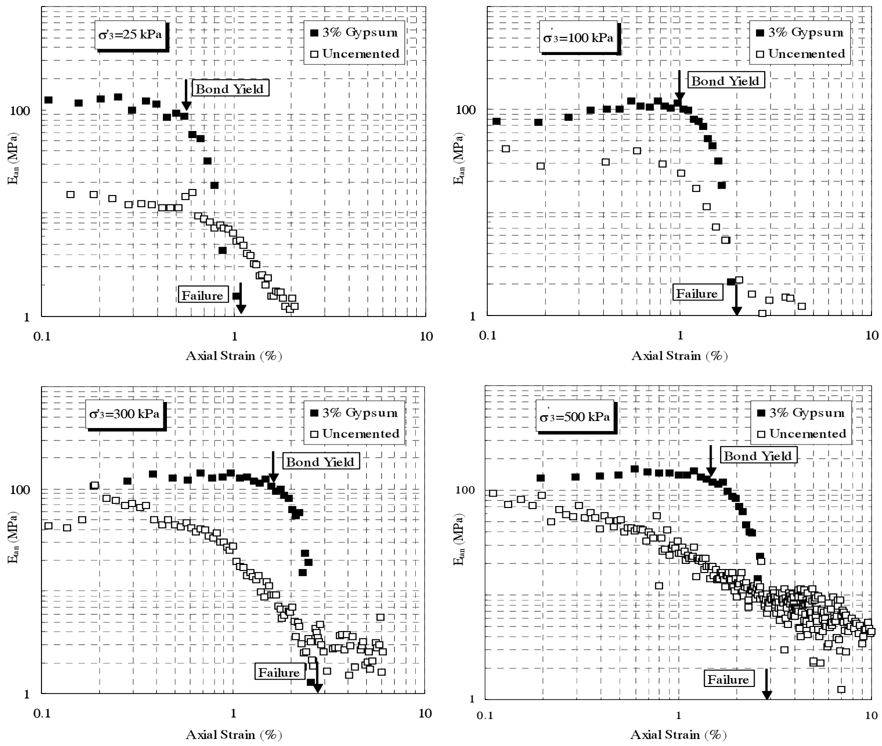

Fig. 10 Variation of the drained tangent stiffness of cemented and uncemented soil with axial strain (a) 25 kPa confining (b) 100 kPa confining (c) 300 kPa confining (d) 500 kPa confining

are Young's stiffness, shear modulus, bulk modulus and Poisson's ratio. Although the definitions of these parameters are different, they are interrelated. In this study two of these parameters are focused. One is Young's modulus in the form of tangent stiffness to determine the deformation parameters under triaxial loading. This can be used for settlement calculations. The second is the bulk modulus to define the volumetric deformations of the cemented gravely sand.

The variations of drained tangent stiffness with axial strain for uncemented and 3% cemented soils are shown in Fig. 10 in logarithmic space for different confining stresses. The tangent stiffness is computed up to the strain associated to the peak shear stress. The figure shows that the tangent stiffness of the cemented soil is always more than that of the uncemented soil. The difference is more in lower confining stresses. Fig. 11 shows the results of isotropic compression tests on samples cemented with different cement contents. In this figure the changes of specific volume is shown against mean effective stress for samples cemented with 1.5, 3, 4.5 and 6 percent gypsum. The figure

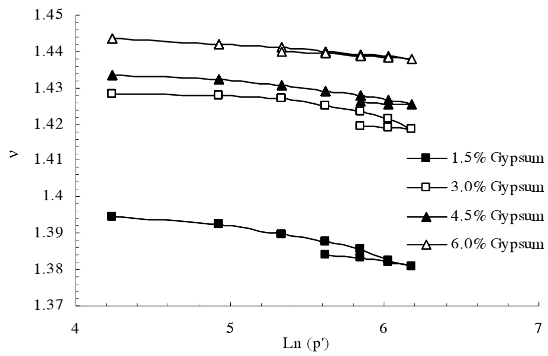

Fig. 11 Isotropic compression test results on samples cemented with different cement contents

shows that the samples do not reach the yield point in the range of confinement used. The previous studies demonstrate that there is a yield point under isotropic stress condition beyond which a sharp reduction occurs in void ratio-mean effective stress curve [11, 14]. It can be concluded that complete bond breakage does not occur. But the volume change of the sample results in some damage to the cemented bonds, development of micro cracks and filling more voids with cement which reduces the confining effects and effectiveness of the cemented bonds on the soil stiffness as stated by Acar and El-Tahir [4]. However, the stiffness of the uncemented soil increases with increase in confinement due to the void ratio reduction and more particle contact. As a result the difference between the cemented and uncemented soil stiffness decreases with increase in confining stress. The rate of reduction in the tangent stiffness is more for the cemented soil compared to that for the uncemented one. In addition there is a sharp reduction in the cemented soil stiffness whereas, the stiffness of the uncemented soil decreases gradually. The strain associated with the beginning of the sharp reduction of the tangent stiffness for cemented soils increases with increase in confining pressure.

A similar behavior can be observed for the undrained condition. Fig. 12 shows the variation of undrained tangent stiffness with axial strain for uncemented and 3% cemented soil. As shown in this figure, the rate of reduction in tangent stiffness is more for cemented soil compared to that for uncemented one. The difference between cemented and uncemented soil stiffness in undrained condition, also decreases with increase in confining stress.

In order to investigate the effect of drainage condition on the deformation parameters, the drained and undrained tangent stiffness of the 3% gypsum cemented soil are illustrated in Fig. 13 at different confining stresses. The figure shows that at the lowest confining stress of the present study i.e. 25 kPa, the drained tangent stiffness is more than the undrained one and the strain associated with the sharp reduction of stiffness is less for drained test than that for the undrained one. Increasing the confining stress to 100 kPa results in smaller differences between the results of drained and undrained tests with respect to tangent stiffness and the strain associated with the bond yield or sharp reduction in stiffness.

Under confining pressure of 300 kPa or more, virtually there is no difference between two curves and they are coincided. This fact shows that the effect of volumetric strain associated with the drained tests on stiffness is more in lower confining stresses due to the more freedom of lateral deformation and less bond breakage. In lower confining pressures the bond breakage and failure mode are more brittle as stated before. In higher confining stresses the bonds break due to

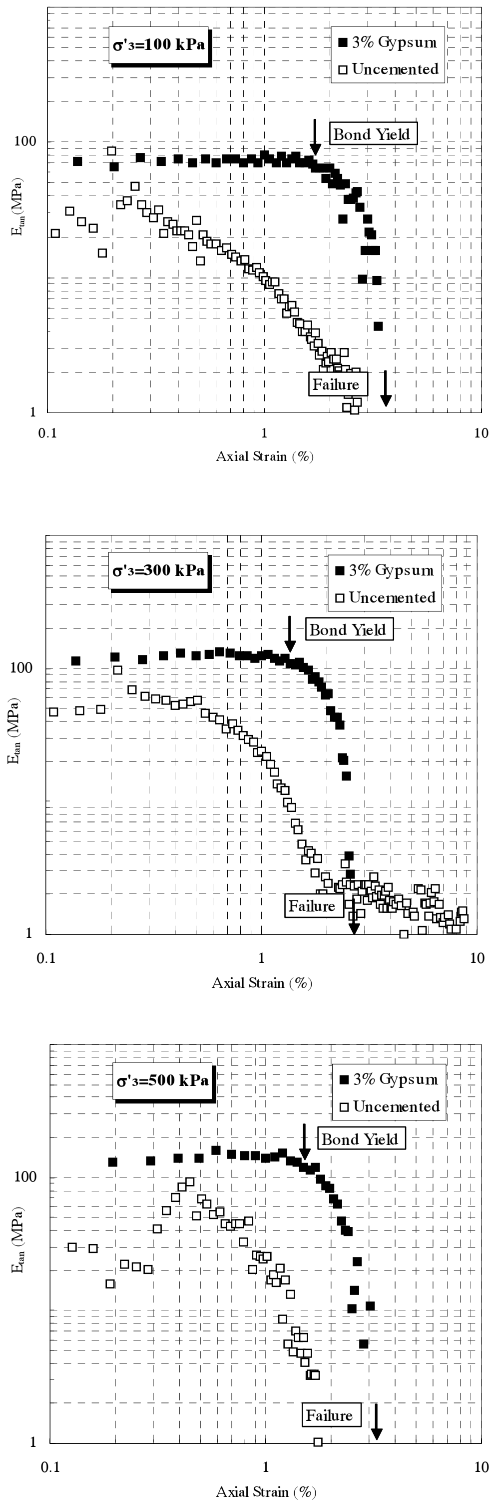

Fig. 12 Variation of the undrained tangent stiffness of cemented and uncemented soil with axial strain
(a) 100 kPa confining
(b) 300 kPa confining
(c) 500 kPa confining

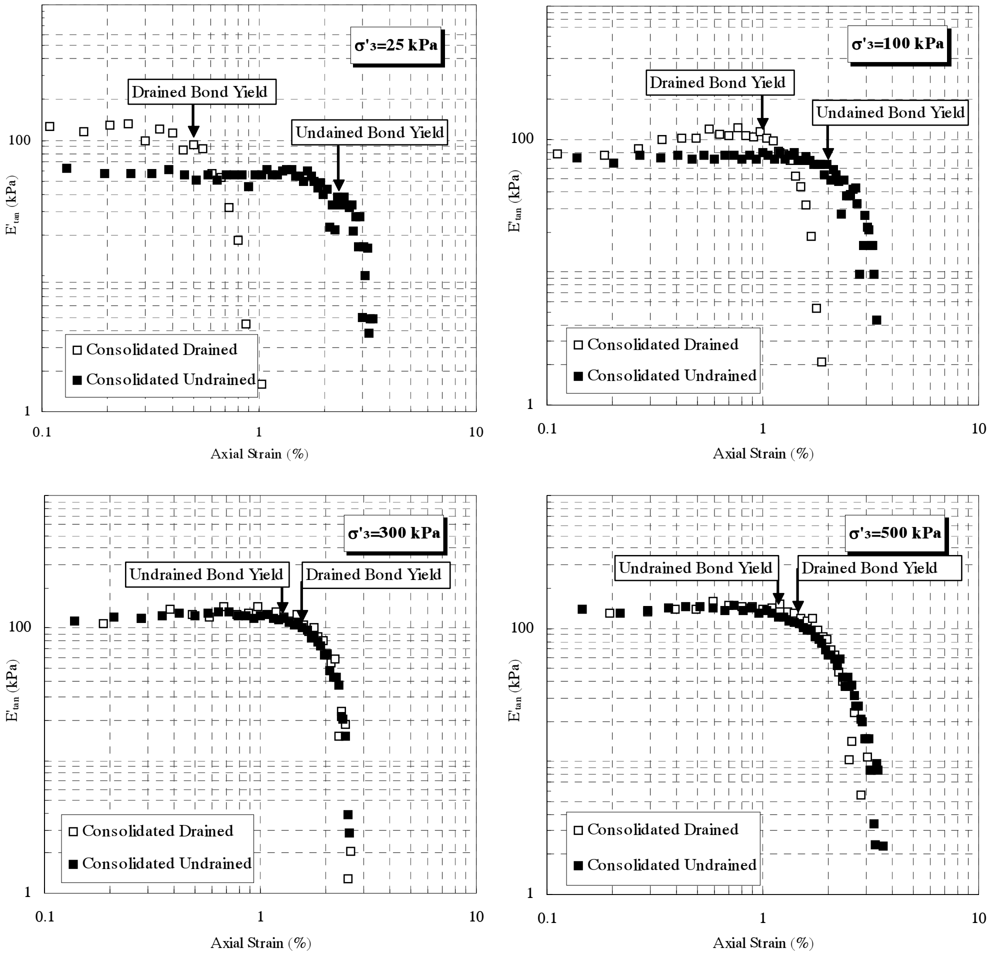

Fig. 13 Variation of the tangent stiffness of cemented soil with axial strain in drained and undrained conditions (a) 25 kPa confining (b) 100 kPa confining (c) 300 kPa confining (d) 500 kPa confining

the combination of confinement and shear stress. As the specimen is more confined the movement and slip of the grains are less dilative which results in less brittle failure and less contribution of the cemented bonds. As a result the stiffness of the cemented soil is similar for drained and undrained conditions in high confining pressures.

Fig. 14 shows the effect of cement content on the variation of the tangent stiffness with axial strain for the studied cemented soil. The results of the drained test with 300 kPa confining pressure are considered. The initial part of the curve associated with small strains is not valid due to the bedding errors. However the rest of the curves with measured strain of more than 0.5% are valid. The figure shows that the tangent stiffness increases with increase in cement content up to 4.5% cement. After that the tangent stiffness of the cemented soil slightly decreases

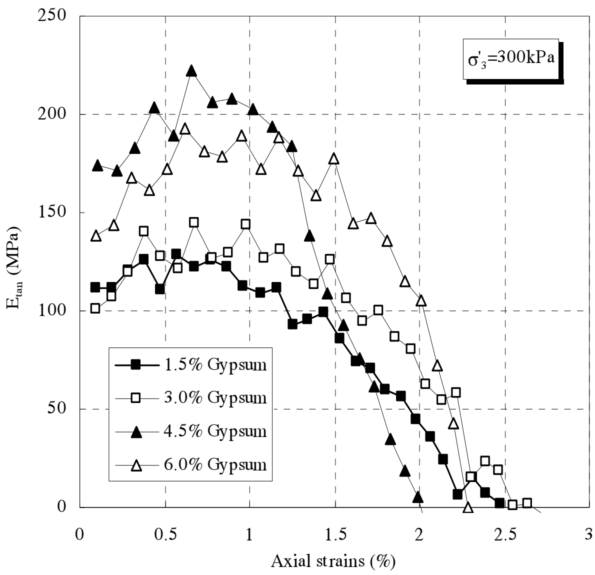

Fig. 14 Variation of the tangent stiffness with cement content

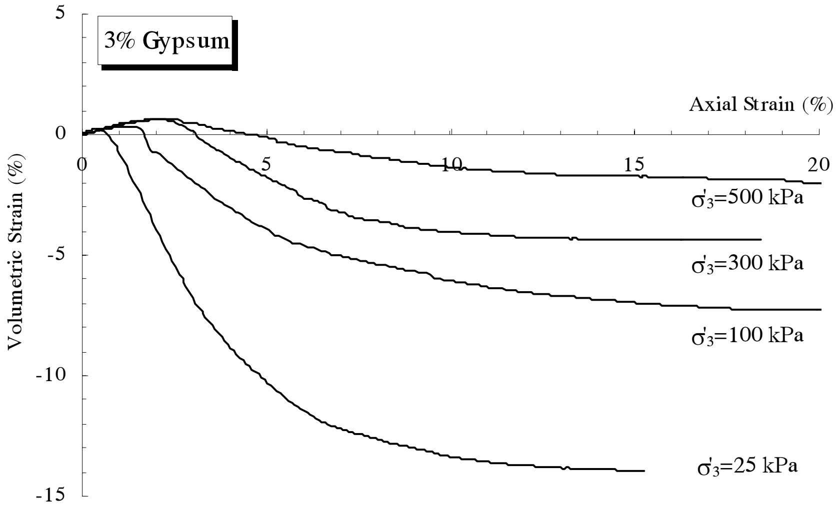

Fig. 15 Axial-volumetric strain curve in triaxial tests on soil cemented with 3% gypsum under different confining stresses

namely when the cement content increases to 6%. This might be due to the gypsum filling of the voids of the soil when the cement content exceeds a threshold value. In high cement contents the cement fills the soil voids that is not structural bond and results in less stiff cemented soil and lower tangent stiffness.

The elastic volumetric deformation of the soil is usually controlled by bulk modulus. Fig. 15 shows the axial-volumetric curves for soil cemented with 3% gypsum under consolidated drained triaxial test with different confining stresses. As indicated in this figure, the soil is contractive in small strains. The soil contraction increases with increase in confining stress. After the small contraction, dilation starts in a rate that decreases with increase in confining stress. The bulk modulus is determined by dividing the increment of mean effective stress to the volumetric strain. The bulk modulus is determined in this study up to the axial strain associated with the maximum contraction. At this point the increment of volumetric strain resigns and there will be a sharp reduction in the curve. From this point onwards, the increment of volume change is negative and as one gets negative incremental volume change associated with incremental volume increase, the bulk modulus becomes negative with increase in mean effective stress. The results of the tests with respect to bulk modulus are shown in Fig. 16

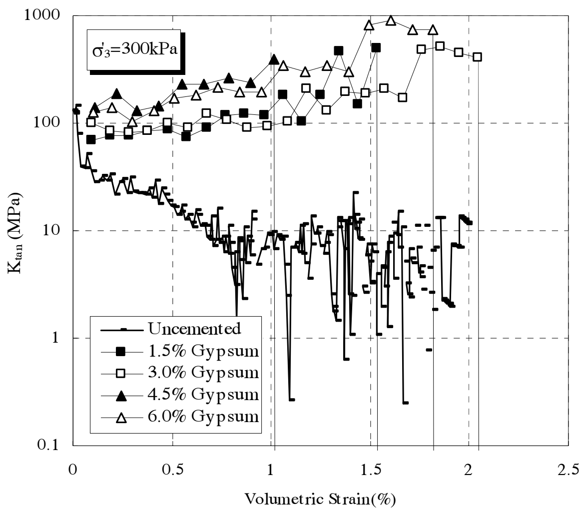

Fig. 16 Variation of the bulk modulus with volumetric strain

which shows the variation of the bulk modulus of the cemented gravely sand with volumetric strain for different cement contents. The bulk modulus is determined using the following equation:

$$K_{tan} = \frac{\Delta p'}{\Delta \varepsilon_v} \tag{3}$$

In this equation is the increment of effective mean effective stress and is the increment of volumetric strain.

The figure shows the increase of the incremental bulk modulus with strain up to 4.5% cement content. Increasing the cement content to 6% reduces the values of bulk modulus value. This is in agreement with Fig. 14 for the variation of tangent stiffness with cement content. As discussed there, this fact can be related to the filling of the cementing agent in the voids rather than the effective bonding between the soil grains for the soil with high cement contents.

5.2. The effect of cement type on the cemented soil stiffness

Fig. 17 shows the variation of tangent stiffness at bond yield with cement content for different cementing agents. Each part of the figure is associated with a special confining stress for drained test. According to this figure the tangent stiffness at bond yield is more for the soil cemented with lime compared to that for all other cementing agents in the range of 1.5 to 3 percent cement content. This indicates that for lower cement contents the lime cement is more effective in increase of soil stiffness. Also the stiffness of the limy cemented soil is more than that for gypsum cemented soil even for 4.5 percent cementing agent, while there is a sharp increase at the stiffness of the soil cemented with Portland cement as the cement content approach to 4.5 percent. It should be noted that the sample preparation method and other parameters like soil gradation and fine content would also be important and effective parameters in the process of hydration of cementing agent and in turn in the mechanical characteristics of the cemented soil.

The increase in tangent stiffness at bond yield with increase in cement content from 1.5% to 3.0% for the soil cemented with Portland cement is consistent with the results of Haeri et al. [29]. It seems that there is a better hydration of cement and more effective bonding in this range of cement for the soil cemented with Portland cement. The same results were reported by Haeri et al. [28] for the strength characteristics of the soil cemented with Portland cement as the cement content approaches to 4.5%.

In all confinements, the tangent stiffness at bond yield increases with the increase in cement content for all cement types. Also the tangent stiffness at bond yield increases with confining stress for all cement contents as well. Although the tangent stiffness at bond yield for the soil cemented with Portland cement is more than that for two other cement types in 4.5% cement

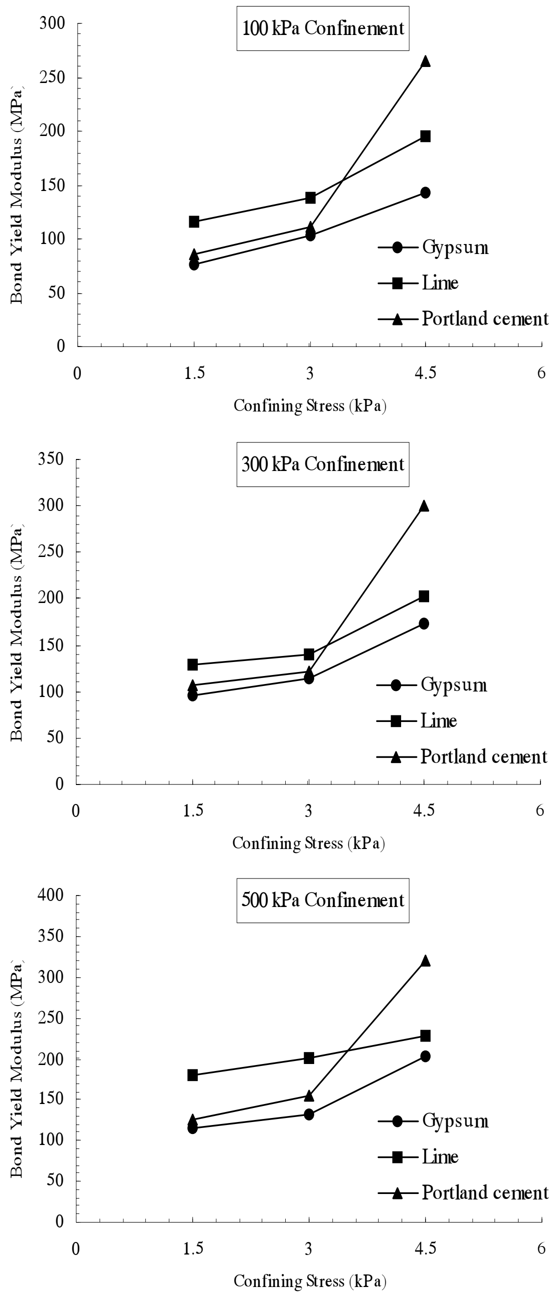

Fig. 17 The effect of cement type on the tangent stiffness at bond yield point
(a) 100 kPa confining stress
(b) 300 kPa confining stress
(c) 500 kPa confining stress

content, the tangent stiffness at bond yield for the soil cemented with gypsum is close to that of the soil cemented with Portland cement when the cement content increases from 1.5 to 3.0%. However, the tangent stiffness at bond yield for the soil cemented with lime is still more than that of soil cemented with two other cement types. As the tangent stiffness at bond yield is the most effective parameter in calculation of soil settlements of the structures under service loads, consideration of the effects of aforementioned parameters should be paid more attention in design, construction and service stages for structures built on cemented soils especially the cemented gravely sands which is the subject of this study.

6. Summary and conclusion

The stiffness and deformation parameters of a cemented gravely sand are studied. Considering the variation of the soil stiffness with axial strain a bond yield is determined before the major failure of the specimen. This finding is in line with previous studies. In the same direction the bond yield and final yield or failure envelopes were determined for the studied soil. The bond and final yield envelopes move up with increase in cement content. The tangent stiffness of the cemented soil is always more than that of the uncemented one. The difference is more in lower confining stresses. This difference decreases when the confining stress increases. Also the strain associated with the beginning of the sharp reduction of the tangent stiffness or bond yield increases with increase in confining stress. This criterion can be observed for both drained and undrained conditions. The difference between drained and undrained tangent stiffness decreases with increase in confining stress and the tangent stiffness increases with the cement content. The cement type is an important parameter in the study of the cemented soil stiffness. The rate of increase in tangent stiffness at bond yield changes with cement contents for different cementing agents. Therefore in settlement studies for the structures built on cemented soils, both the cement content and the cement type should be considered. Portland cement seems to be more suitable cementing agent in higher cement contents (more than 4.0%). However, lime can be used as a better cementing agent in lower cement contents (less than 4.0%).

7. References

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