THE MECHANICAL BEHAVIOR OF A GRAVELY SAND CEMENTED WITH DIFFERENT CEMENT TYPES

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ABSTRACT
Hydrated lime, Portland cement and gypsum were used as the cementing agents to investigate the effect of cement type on the mechanical behavior of a gravely sand. Consolidated drained and undrained triaxial tests performed on dry and saturated samples cemented with 1.5, 3.0 and 4.5 percent of each cementing agents and the confining stresses varied between 25 kPa to 500 kPa in the common tests. According to the test results the cement type effect increases with increase in cement content. Also the influence of cement type on the shear behavior is more in drained condition compared to the undrained one. The gypsum cemented samples showed a more brittle behavior. The peak strength is a function of cement type, cement content and confining pressure. In lower cement contents, gypsum cemented samples showed higher strength. As the cement content increases the samples cemented with Portland cement show higher strength.

RÉSUMÉ
L'influence du type de l'agent de cimentation, à savior le chaux hydraté, le ciment Portland et le gypse, sur le comportement mécanique des graves sableux à été étudié. Les essais triaxiaux consolidé-drainé et consolidé-non drainé ont été effectués sur les éprouvettes sec et saturées, cimenteés par l'appont de 1.5, 3.0 et 4.5 pourcent de l'agent de cimentation, la persion latérale étant de 25 à 500 kPa. Ces essais montrent que dans tous les cas l'effet de cimentation augmente avec le taux de ciment et l'influence de cimentation est plus prononcée pour les essais drainés. Les éprouvettes cimenté à l'aide du gypse ont un comportement plus fragile. La resistance de pic est une fonction du type de ciment du taux de ciment et de la pression de confinement. Pour les taux inférieurs de l'agent de cimentation, les éprouvettes cimentées par le gypse ont plus de résistance et, pour les taux superieurs, c'est le ciment Portland qui donne plus de resistance.

1. INTRODUCTION

Environmental agents often cause structure in the soils. Structure plays an important role in the geotechnical characteristics of the soils. Structure often can be seen as cementation in coarse grained soils, which forms from deposition and compaction of chemical materials between grains. The bonds strongly affect the mechanical behavior of cemented soil. As a result of this process the ductile behavior of uncemented soils often changes to a brittle one.

The effect of cementation on the mechanical behavior of coarse grained soils has been studied by different researchers. Saxena and Lastrico (1978), Clough et al. (1981), Lade and Overton (1989), Leroeil and Vaughan (1990), Gens and Nova (1993), Cuccovillo and Coop (1999) and Schnaid et al. (2001) presented useful contributions in this field.

Ismail et al. (2002) studied the effect of cement type on the mechanical behavior of cemented sand using triaxial tests. The unconfined compressive strength was considered as a measure for indication of the degree of cementation. In this manner samples cemented with Portland cement, calcite and gypsum prepared in a manner to reach an equal unconfined compressive strength. According to the results they introduced the Portland cement as the most ductile cementing agent.

As stated by Clough et al. (1981), gradation has a very important effect on the mechanical behavior of cemented soil. So it is expected that the mechanical behavior of cemented gravely sand differs from cemented fine sand. Investigation of the mechanical behavior of the gravely sands started with a comprehensive plan to define a representative gradation for the North Tehran alluvium by Haeri et al. (2002). They performed some large direct shear tests on limy cemented gravely sand of Tehran alluvium.

Using the same gradation, Asghari et al. (2003) performed some triaxial tests on the soil cemented with lime and reached a curved failure envelope for the cemented soil.

Haeri et al. (2004) performed comprehensive triaxial tests on the soil with the same gradation and cemented with Portland cement. According to the results the uncemented samples and lightly cemented samples showed a contractive behavior at failure while the cemented samples failed with dilation or negative pore pressure in drained or undrained conditions respectively.

Hamidi et al. (2004) studied the mechanical properties of the mentioned soil using gypsum as the cementing agent. They showed that the cement content is an important parameter that controls the mechanical behavior of the

cemented soil. Increase in cement content from a certain value reduces the soil stiffness and dilation or negative pore pressure at failure. Also they reported two different failure envelopes for cemented soil in drained and undrained conditions.
In the present study the results of these three researches are reviewed and compared. As a result the effect of cement type on the mechanical behavior of a gravely sand is investigated.

2. SOIL AND CEMENT

The physical properties of the studied soil are shown in Table 1. Also Figure 1 shows the gradation curve for the tested soil. The maximum grain size is limited to 12.5 mm for triaxial testing of 100 mm diameter specimens. The soil contains 45% gravel, 49% sand and 6% fine and can be named as SW-SM in unified system of soil classification and sandy gravel in BS standard. Coarse-grained particles consist of tuff, shale and volcanic rocks. Particle shapes are usually sub-angular. The degree of cementation varies in Tehran alluvium and is mainly formed from carbonate materials like calcite. However gypsum, hydrated lime and Portland cement were selected as the cementing agents to study the effect of the cement type on this soil.

Table 1: Physical properties of tested soil

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

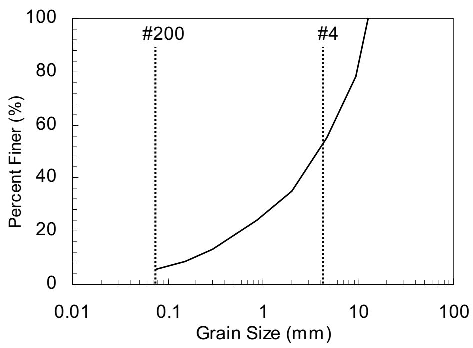

Figure 1: Gradation curve of tested soil

3. PREPARATION OF SAMPLES

The method used for sample preparation with Portland cement and gypsum is nearly the same. However, sample preparation with lime is different in some way. Therefore these are presented in two subsequent parts.

3.1 Samples Prepared with Portland Cement and Gypsum

Each sample was prepared in eight layers. Also the unit weight of the samples was fixed at 1.8 g/cm^3. Using this value the samples reach a relative density of approximately 65 percents. The required weight of the soil for each layer was mixed with the desired cement content and 8.5 percent of distilled water. Each layer was filled in a metalic three part mould and compacted to the desired height. The mould has a diameter of 100 mm and a height of 200 mm.
The process was repeated for other layers. After finishing it for all layers the gypsum cemented samples were cured in an oven under 50°C temperature. The curing was continued until the sample reached a constant weight. Also the samples cemented with Portland cement were cured in a humid room for a period of 28 days.

3.2 Samples Prepared with Lime

Sections of high strength P.V.C. were used as mould to prepare samples with lime. The mould has a diameter of 100 mm and a height of 200 mm. After preparing the base soil and mixing it with the desired amount of lime and water, it was poured in the mould and compacted to the desired height. Each sample was cured in a bag full of distilled water for about six weeks. The sides of the mould were scratched to let the water enter the mould for pozzolanic reaction between lime and fine part of the soil. The temperature was kept constant at 25°C in curing period.

4. TESTING PROGRAM

In order to determine the suitable parameter to indicate the degree of cementation several tests including Brazilian, unconfined compression and triaxial compression tests conducted on the cemented soil. The results of these tests are reported in this part.

4.1 Brazilian Tests

The Brazilian tests were performed on the cylindrical samples with an equal diameter and height of 100 mm. Each sample was loaded vertically until a longitudinal crack appeared in the sample. This shows a tensile mode of failure. The tensile strength was calculated using Equation 1.

$$\sigma_t = 2P / (\pi DL) \quad [1]$$

In this equation "σ_t" is the tensile strength. "P" is maximum vertical load. "D" is the sample diameter and "L" is its height. Figure 2 shows the variation of tensile strength with cement content for three cement types. For each cement type and cement content some tests were carried out and the average was considered as the Tensile strength. The figure shows that the soil cemented with Portland cement gives the highest tensile strength compared to the other soils cemented with other two types of cementing agent. The gypsum cemented samples has more tensile strength than lime and finally lime cemented samples has the least tensile strength.

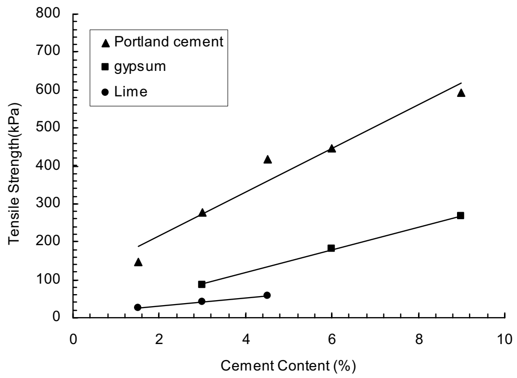

Figure 2: Variation of tensile strength with cement content

4.2 UNCONFINED COMPRESSION TESTS

Unconfined compressive strength tests were conducted on samples with a diameter of 100 mm and a height of 200 mm. The strain applied in a rate of 0.42 percent per minute. A number of tests were conducted for each cement content and each cement type. The averages were selected as the unconfined compressive strength associated with each cement type. Figure 3 shows the variation of unconfined compressive strength with cement content. The Portland cement shows the highest unconfined strength between three cement types while the lime cemented samples show the lowest unconfined compressive strength.

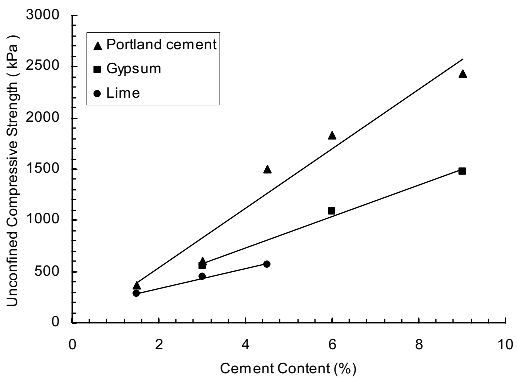

Figure 3: Variation of unconfined compressive strength with cement content

4.3 Triaxial Compression Tests

There are some errors in simple tests like Brazilian and unconfined compressive strength. In order to eliminate this errors some triaxial compression tests under low confining pressure of 25 kPa conducted to determine the relation of cement content with triaxial compression strength. Figure 4 shows the variation of cement content with the triaxial compressive strength for three cement types. According to the figure the soil cemented with Portland cement showed the highest deviatoric strength and the lime cemented samples had the least deviatoric strength.

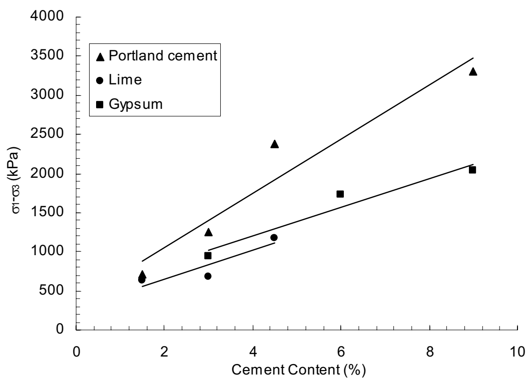

Figure 4: Variation of triaxial compressive strength with cement content

5. THE CRITERIA FOR EFFECTIVE BONDING

Figures 2 to 4 show that different cement contents are needed to reach an identical Brazilian, unconfined compression or triaxial compression strength for different cement types. On the other hand if the samples are prepared in a manner that their Brazilian, unconfined or triaxial strength are the same, there will be a large difference between cement contents for different cement types resulting in different gradation of the cemented soil.
Ismail et al. (2002) prepared specimens with the same unconfined compressive strength to investigate the effect of cement type. In order to achieve this goal they prepared groups of samples cemented with calcite, Portland cement and gypsum. In the first group 3.5% calcite, 8% Portland cement and 10% gypsum were mixed with the base soil. Also in the other group 7% calcite, 15% Portland cement and 20% gypsum were mixed with the base soil. They show that there is a large difference between cement contents for different cement types. The difference between cement contents changes the cemented soil gradation for different cement types and the comparison of soils with different gradations may loosen the basis of comparison. In order to have an identical gradation for soils cemented with different cement types, in this study different cement types are mixed with the base soil in equal cement content.

6. MAIN TRIAXIAL TESTS

Triaxial compression tests performed in different cement contents. The set of experiments on lime cemented soil is reported in Asghari et al. (2003). Also the experiments on soil cemented with Portland cement is presented in Haeri et al. (2004). The triaxial tests on gypsum cemented specimens can be found in Hamidi et al. (2004). Three cement contents of 1.5, 3 and 4.5 percents have been considered from these independent studies to investigate the effect of cement type.

Triaxial tests conducted under a range of confining pressures for each cement type. Four confining pressures of 25, 100, 300 and 500 kPa were selected to investigate the effect of cement type.

Triaxial tests on lime cemented soil were conducted on saturated samples in drained and undrained condition. For the samples cemented with Portland cement, undrained triaxial tests performed on saturated samples. However, the consolidated drained tests performed on wet and saturated samples.

Haeri et al. (2003) made a comparison between failure envelopes of wet and saturated samples of Portland cemented soil in consolidated drained triaxial tests. They showed that the failure envelopes are nearly identical due to the little suction induced for tests on wet samples. As a result the drained tests performed on wet samples can be used the same as the drained tests on saturated samples of these tested soils.

For gypsum cemented samples the consolidated drained tests were conducted on completely dry samples. But the undrained tests were conducted on saturated samples. Due to the extreme reduction in gypsum stiffness and strength with water as the pore fluid, light silicon oil with a viscosity near to that of the water was used to saturate the samples.

7. ANALYSIS OF TEST RESULTS

The results of the tests are analyzed in this part of the paper to investigate the effect of cement type.

7.1 Brittleness Index

Consoli et al. (1998) defined the brittleness index for cemented soil using Equation 2:

$$I_B = (\sigma_1-\sigma_3)_u / (\sigma_1-\sigma_3)_f - 1 \quad [2]$$

In this equation $(\sigma_1-\sigma_3)_u$ is the deviatoric stress at the ultimate state or the end of the test. The failure deviatoric stress is named as $(\sigma_1-\sigma_3)_f$ in this equation. I_B denotes the brittleness index for cemented soil. Figure 5 shows the variation of brittleness index with confining pressure for drained tests on cemented soil with different cement types. According to this figure the brittleness index is larger for gypsum cementation than two other cementing agents. The brittleness index of soil cemented with lime is greater than the corresponding value for 1.5 and 3 percent cement contents of soil cemented with Portland cement. When the cement content increases to 4.5 percent, the brittleness index of cemented soil with Portland cement increases to values more than those of the lime cemented soil and reaches to that of gypsum cemented soil and even more in high confining pressures. This shows a change in stiffness and strength of Portland cement bonds when the cement content increases in the soil from 3 to 4.5 percent.

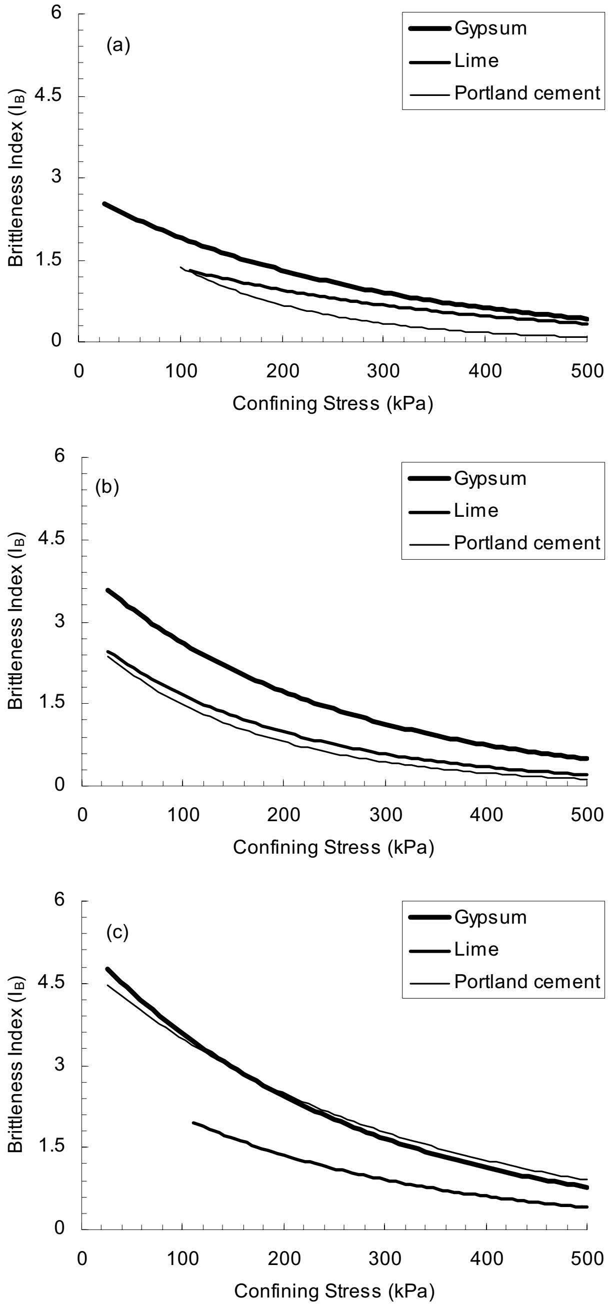

Figure 5: Variation of the brittleness index with confining pressure for drained tests
(a) 1.5% cement (b) 3% cement (c) 4.5% cement

Figure 6 shows the variation of brittleness index with confining pressure for consolidated undrained tests. This figure is drawn in a similar scale of Figure 5. According to this figure there is an extreme reduction of brittleness of cemented soil in undrained condition. Malandraki and Toll (2001) showed that the bonds behave more brittle in drained condition than undrained one. They relate it to the volumetric strains occur during shearing in drained condition. In undrained condition the volumetric strains is prevented. As a result the bond breakage is slow and gradual in undrained condition.

The data presented in this figure are only for 3 percent cement. In this cement content the gypsum cemented soil shows the highest brittleness in undrained condition. It seems that the gypsum cemented soil has the highest brittleness among three considered cement types.

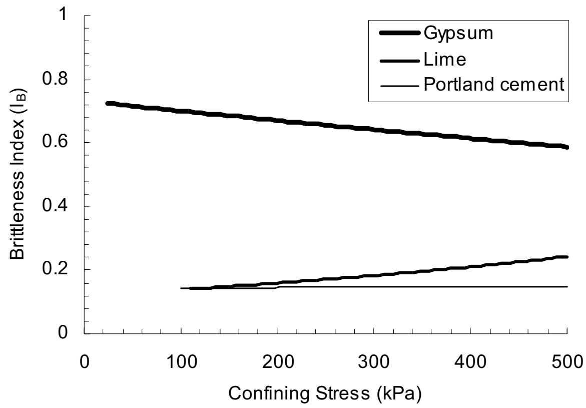

Figure 6: Variation of the brittleness index with confining pressure for undrained test with 3 percent cement

7.2 Shear Strength

Figure 7 shows the variation of the peak deviatoric stress or shear strength with confining stress for different cement contents in consolidated drained tests. According to this figure for cement contents of 1.5 and 3 percent, the shear strength of soil cemented with Portland cement is higher than the shear strength of the soil cemented with two other cementing agents in low confining pressures. As the confining pressure increases, the shear strength of the soil cemented with Portland cement decreases to lower values than gypsum cemented soil strength. In the highest confining pressure of the present study i.e. 500 kPa, the reduction of the shear strength of soil cemented with Portland cement becomes less than that of the lime cemented soil. This shows a reducing rate of change in shear strength of the soil cemented with Portland cement in low cement contents. For 4.5 percent cement content, the Portland cement always shows the highest shear strength compared to the other two cementing agents. This confirms the higher stiffness and strength of Portland cement when the cement content increases to 4.5 percent. The figure shows that the shear strength of the soil cemented with lime is always higher than the shear strength of the soil cemented with lime in drained condition. The soil cemented with gypsum shows higher shear strength compared to that of the soil cemented with lime for all confining pressures. Figure 7 also shows that the difference between peak shear stress envelopes increases with increase in cement content. It can be concluded that the effect of cement type on the shear strength of cemented soil increases with increase in cement content.

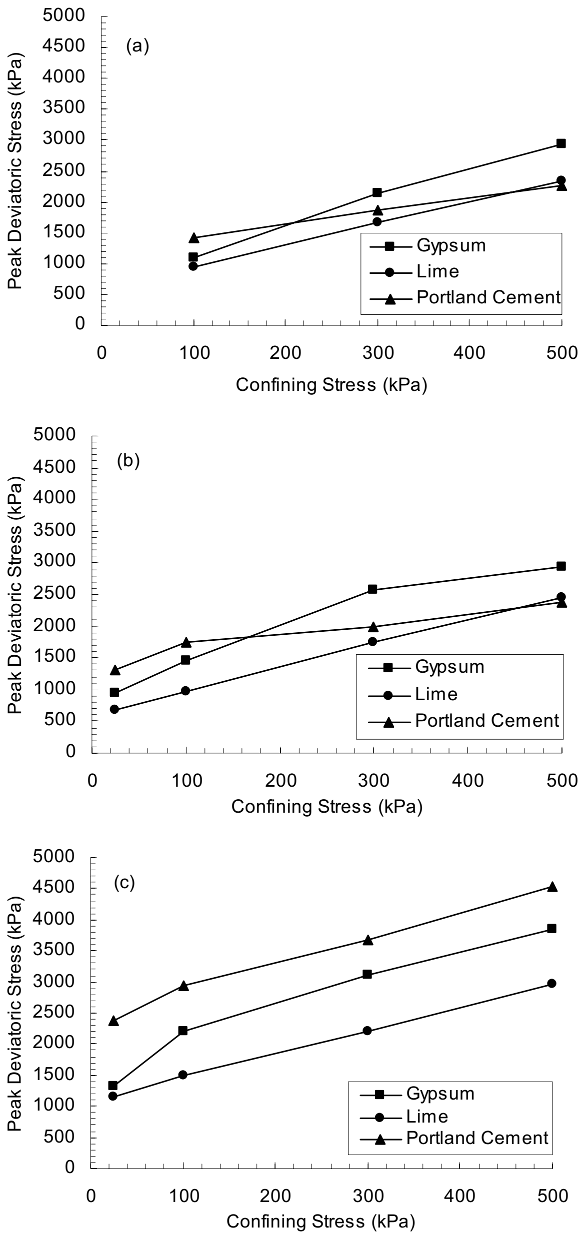

Figure 7: Variation of drained shear strength with confining pressure for different cement contents
(a) 1.5% cement (b) 3% cement (c) 4.5% cement

Figure 8 shows the variation of peak shear strength with confining pressure for soils cemented with 3 percent cement in undrained triaxial test. The figure is drawn in the same scale as Figure 7. It is clear that the differences between curves associated with different cementing agents are lower for undrained tests as shown in Figure 8. It can be concluded that the effect of cement type is lower in undrained condition. This can be related to the gradual breakage of cemented bonds in undrained condition due to prevention of volumetric strains.

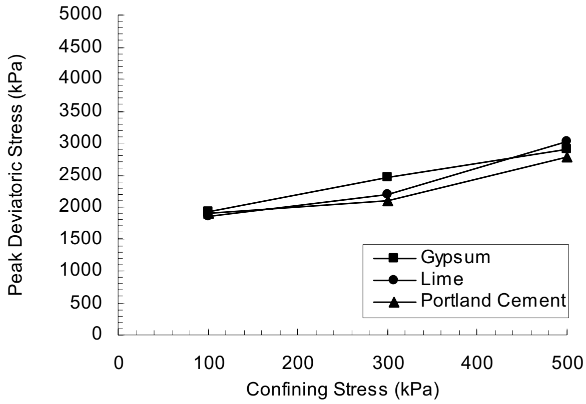

Figure 8: Variation of undrained shear strength with confining pressure for different cement contents

7.3 Volume Change

Figure 9 shows the variation of volumetric strain with axial strain for drained tests under a confining pressure of 500 kPa. According to this figure for cement content of 1.5 percent the sample cemented with gypsum fails with dilation. It can be concluded that gypsum cemented samples fail with dilation even in the lowest cement content and the highest confining pressure. Contrary to the gypsum cemented sample, the sample cemented with 1.5 percent Portland cement fails in a contractive mode. The sample cemented with 1.5 percent lime is in an intermediate state. There is a little volume change for this sample at failure. This trend of behaviour can be seen for the samples cemented with 3 percent cement as shown in Figure 9-b.

When the cement content increases to 4.5 percent, the behaviour of cemented samples at failure is dilative. The dilation of the sample cemented with Portland cement increases more than that of the lime cemented soil, and reaches to that of the gypsum cemented soil.

This trend of behaviour can be observed for other confining pressures as well. The contractive volume changes only occur in soil cemented with Portland cement in a confining pressure of 500 kPa. Dilative behaviour for the samples cemented with Portland cement and lime is observed in other confining pressures.

The volume change for gypsum cemented soil is dilative for cement contents and confining pressures used in this research. It seems that gypsum causes the most dilative behaviour in cemented soil.

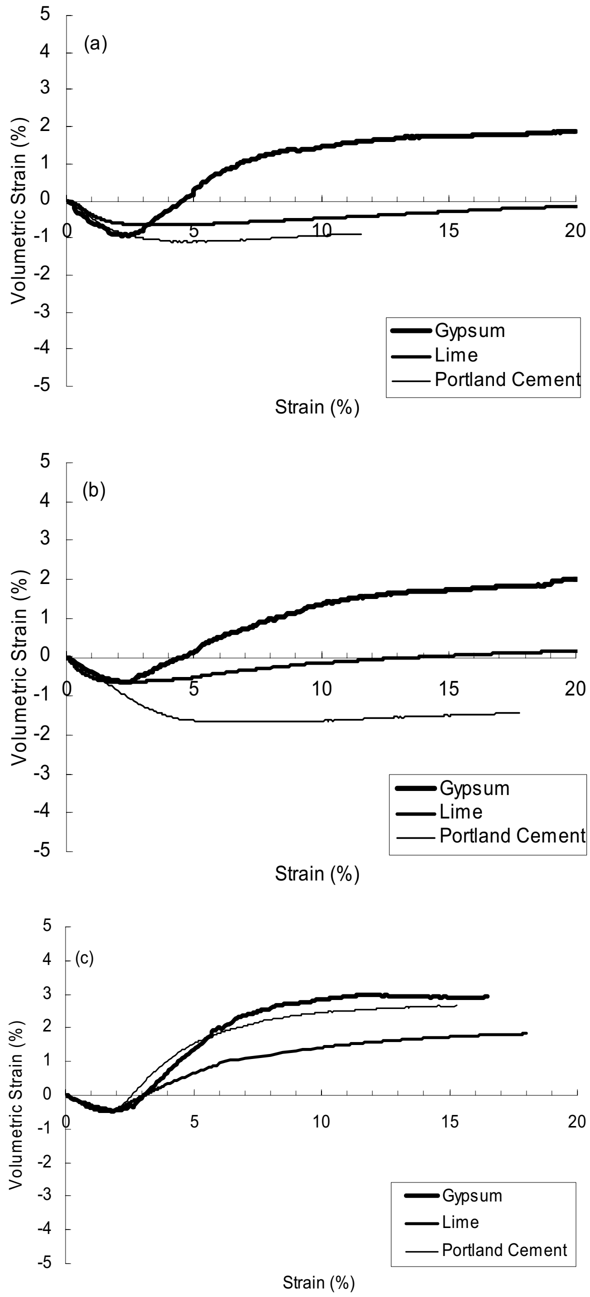

Figure 9: variation of volumetric strains with axial strain for drained tests under 500 kPa confining pressure
(a) 1.5% cement (b) 3% cement (c) 4.5% cement

7.4 Pore Pressure

The variation of pore pressure with mean effective stress for undrained tests is presented in Figure 10 with different confining pressures. According to this figure the negative pore pressure at failure is the highest for gypsum cementation in confining pressures of 100 kPa and 300 kPa. This is in agreement with the results of consolidated drained tests.

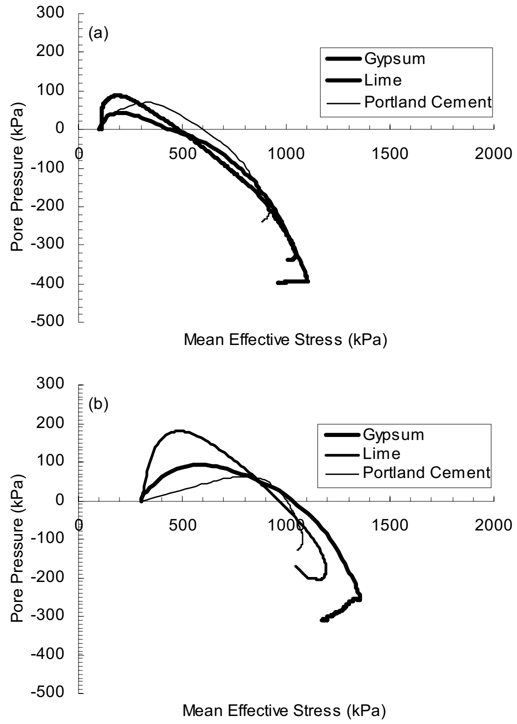

Figure 10: variation of pore pressure with mean effective stress for cemented soil with 3% cement
(a) 100 kPa (b) 300 kPa

7.5 Failure Envelope

Figure 11 shows the failure envelopes for samples cemented with 3 percent of different cement types in drained and undrained conditions. The little difference in failure envelopes of undrained condition confirms the lower effect of cement type for undrained condition. Comparison of failure envelopes for cemented samples with uncemented one in drained condition shows that the gypsum and lime cements increase the friction angle of the soil. However, the cohesion intercept increases more when the soil is cemented with Portland cement.

8. CONCLUSION

The effect of cement type on the mechanical behaviour of a gravely sand was investigated. According to the tests the following results obtained:
-The soil cemented with Portland cement has the highest tensile and unconfined compressive strength in the range of cement contents considered in this research.

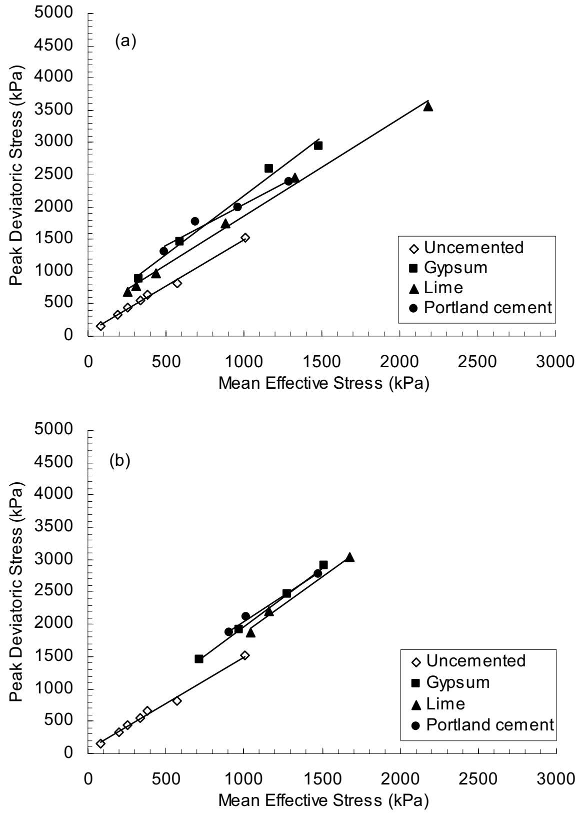

Figure 11: Failure envelopes for samples with 3% cement content
(a) Drained condition (b) Undrained condition

-The cement content is the best indicator for the degree of bonding in cemented soil to investigate the effect of cement type. For other criteria the gradation of soil with different cement types can not be met.
-The brittleness of soil cemented with gypsum is higher than two other ones in lower cement contents. The soil cemented with Portland cement shows an obvious increase in its brittleness when the cement content increases to 4.5 percent.
-The shear strength of soil cemented with Portland cement is higher than the other ones in lower confining pressures of this study. When the confining pressure increases to higher values, the shear strength of soil cemented with Portland cement becomes less than those of the other cementing agents for low cement contents. For a cement content of 4.5 percent, the shear strength of soil cemented with Portland cement is higher than the two other ones in all confining pressures used in this study.
-The effect of cement type on the shear strength of cemented soil increases with increase in cement content.
-The effect of cement type on the shear strength of cemented soil is more for drained condition compared to that of undrained state.
-The ultimate dilation in drained state and ultimate negative pore pressure in undrained condition are higher

in gypsum cemented soil compared to those of the two other ones.
-The increase in drained cohesion intercept is more for cementation with Portland cement.

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