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Proc. 30th Int'l. Geol. Congr., Vol. 23, pp. 449-460
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Engineering Properties of CIPS Cemented Calcareous Sand

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Abstract

An innovative new technology, known as the Calcite Insitu Precipitation System (CIPS), has been developed for improving insitu the geotechnical properties of porous sediments and rocks. CIPS is based on the crystallisation of calcite within the pore fluid and on the surfaces of constituent sand/silt grains so that the grains become strongly cemented but pores essentially remain open. This calcite cement crystallises from a proprietary solution which is permeated into the material. Because it is a non-particulate, low viscosity and water-based solution, multiple permeations are possible. Mechanical strength is significantly increased with each injection but porosity is reduced only slightly. Improvements in the mechanical properties of calcareous sands treated with CIPS have been demonstrated by a variety of laboratory tests including unconfined compressive strength (UCS), direct shear and triaxial tests. Results show that CIPS cemented calcareous sands have similar stress-strain relationships to those of natural calcarenites of similar strengths.

Keywords: calcareous sand, calcite crystal, cementation, direct shear test, grouting, mechanical strength, triaxial test, unconfined compressive strength

INTRODUCTION

Calcareous sediments and some soft porous rocks encountered offshore can pose difficulties in foundation designs for offshore structures. In some areas, such as the NW Shelf of Australia, near seafloor sediments have relatively low densities and consist of uncemented or lightly cemented bioclastic sand or silt particles. These calcareous sediments exhibit high compressibility or “pore collapse compaction” behaviour when subjected to loads which results in low skin friction on piles and large settlements beneath footings.

An obvious method of improving foundation capacity is to increase the degree of cementation within the sediment or rock. An innovative new technology known as Calcite Insitu Precipitation System (CIP System or CIPS), capable of improving insitu the geotechnical properties of these and similar materials, has been developed at CSIRO. CIPS is based on the crystallisation of calcite cement within the pores fluid and on the surfaces of constituent sand/silt grains so that the grains become strongly bonded but the pores essentially remain open. This calcite cement crystallises from a non-particulate, water-based solution of low viscosity that is injected or flushed into the sediment so that repeated

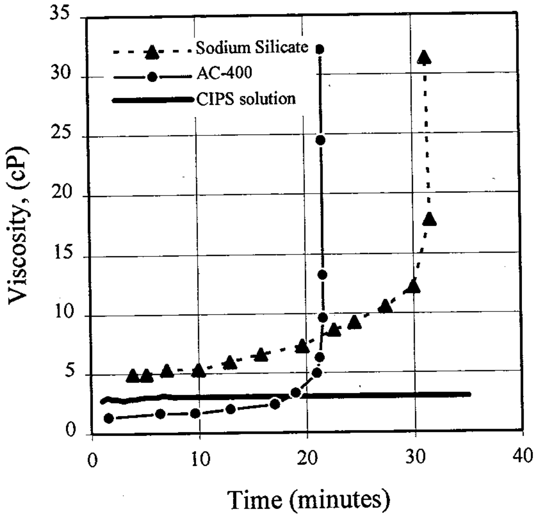

Figure 1. Viscosity versus time relationships for CIPS solution, and two common chemical grouts.

applications incrementally and significantly increase the mechanical strength of the sediment while only gradually reducing porosity.

This paper reports on the effectiveness of the CIP System in improving the mechanical properties of initially uncemented sands. An extensive laboratory testing program, including unconfined compressive strength, direct shear, triaxial and permeability tests, has been carried out on calcareous sand specimens treated with different numbers of injections of CIPS solution.

THE CIP SYSTEM

The CIP System involves injecting, or in some way permeating or flushing, the porous sediment with a specially formulated, water-based solution. The viscosity of this solution is close to that of water so it easily penetrates porous materials and can displace any existing pore fluid. Inside the pores, reactions occur within the solution over a time period which is controllable from 1 to 7 days, causing the formation of many calcite crystallites. The surfaces of the constituent sand/silt grains act as preferred nucleation sites so that the calcite crystallites grow out from those surfaces and form a coating around the pores and between the grains. This calcite coating forms a cement between the grains bonding them together in a manner similar to natural calcite mineral cement. Because the calcite cement coatings are typically thin (5-10 microns) the pores are not filled and pore throats are not blocked. Improvements in mechanical strength originate from the calcite cement which bonds together the constituent sand and silt grains, effectively converting uncemented loose sand or silt into rock.

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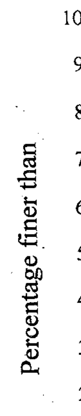

Figure 2. Grading curves for t

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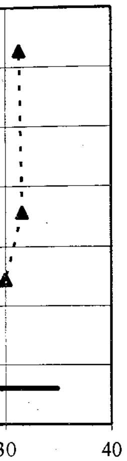

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as AC-400 (epoxy resin) and sodium silicate, have viscosities that increase dramatically with time (Fig. 1). In contrast, the viscosity of the CIPS solution is initially low (3 cP) and decreases slightly with time (down to 1.4 cP). This is due to the removal of calcite crystals from solution by preferential nucleation on grain boundaries. The spent CIPS fluid can be easily displaced from the pores by injections of fresh CIPS solution, thereby allowing the build up of multiple layers of calcite cement and increased bonding between the grains.

EXPERIMENTAL PROCEDURE

Calcareous sand samples with different amounts of CIPS treatment were prepared. From these, essentially reproducible specimens were taken for laboratory testing.

Material

Calcareous sand with two different size distributions in the silt to sand range (Fig. 2, Table 1) were used to prepare the samples. The calcareous sands were obtained from the seabed between Perth and Rottnest Island, Western Australia and contain approximately 96% natural carbonate shell and skeletal fragments.

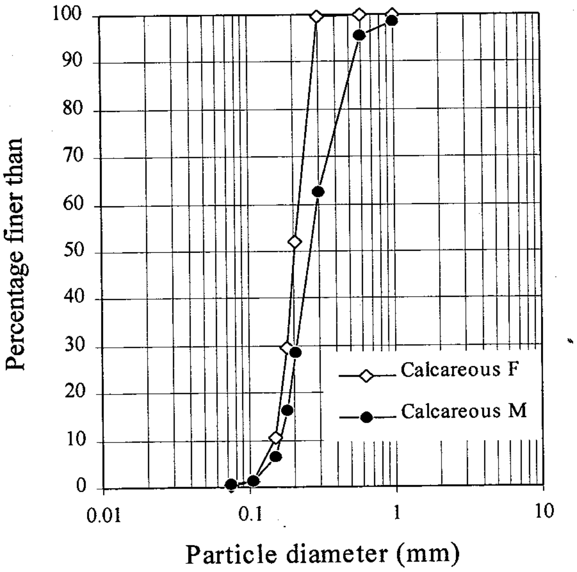

Figure 2. Grading curves for testing sands.

Table 1. Properties of sands before CIP treatment.

Sand	D_{50} (mm)	Uniform coefficient	Dry density (Mg m^{-3})	Void ratio
Calcareous F	0.21	1.43	1.40± 0.016	0.96
Calcareous M	0.27	1.82	1.47± 0.023	0.86

Sample Preparation

Approximately 170 cylindrical samples were prepared by uniformly packing dry sand into 38 mm and 63 mm ID PVC tubes of 300 mm and 425 mm length with layers of coarse clean gravel and filter pads at both ends. Dry densities and void ratios are shown in Table 1. The samples were initially saturated with fresh water and their permeability's measured using the constant head method. CIPS solution was injected (flushed) from the base displacing the fresh water in the pores. The injection system is shown schematically in Figure 3.

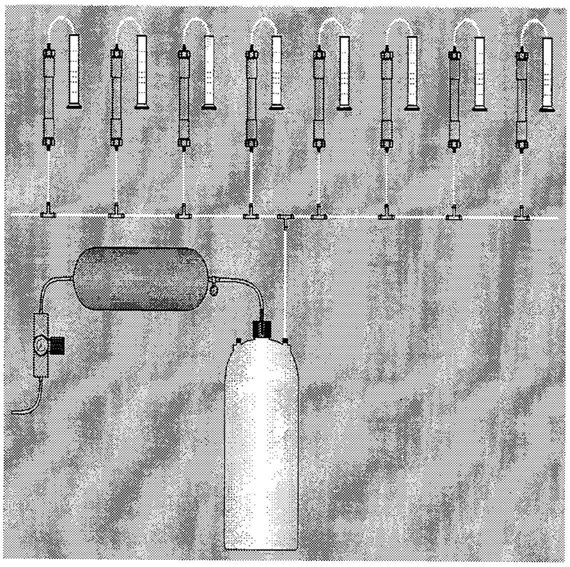

Figure 3. Schematic diagram of injection system.

The CIPS solution was prepared in an 8 litre pressurised tank connected, via control valves, to the sample tubes. The solution was injected under pressures in the range 50-210 kPa until double the pore volume had been displaced or until 10 minutes had elapsed. After injection the CIPS saturated samples were left undisturbed for periods of 1, 3 or 7 days before the next injection was applied. Each subsequent injection flushed out the spent fluid and replaced it with fresh CIPS solution. The maximum number of injections achieved in this study was 8. CIPS treatment was carried out at approximately constant temperature (20±1 °C).

After cementation the middle section (1/3) of each sample tube was cut out with a diamond saw for use as a testing specimen. Constant head permeability tests were conducted in specially constructed permeameters without removing the specimens from the PVC tubes. These tubes were then slit longitudinally to remove the specimens.

Specimen Sizes and Test Conditions

Unconfined compressive strength (UCS) tests were chosen because they are easy to perform, fast and cost effective. More sophisticated tests, such as triaxial, direct shear and

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EXPERIMENTAL RESU

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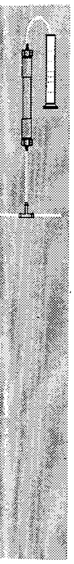

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CPT (not reported here) were chosen to compare behaviour between the CIPS treated specimens and natural materials.

Specimens for UCS tests, which had a diameter of 38 mm and height of 114 mm (height/diameter ratio 3), were capped with high strength dental plaster to ensure uniformity of the ends. They were tested at stress rates of 1.7 MPa per minute for the weaker specimens and 4.2 MPa per minute for the stronger specimens.

To investigate the effect of moisture content on strength, both wet and dry specimens were tested. Wet specimens had been stored under water after capping and re-saturation in a vacuum desiccator. Dry specimens were exposed to air in a constant temperature room for two weeks prior to testing.

Specimens for direct shear tests were 62.5 mm in diameter and 36 mm in height. Normal stresses of 100, 200 and 500 kPa were used and the shearing speed was 0.2 mm per minute.

For the triaxial tests, specimens were isotropically consolidated at one of three effective stress levels (100, 500 or 1000 kPa) with a back pressure of 1000 kPa. They were subsequently sheared under static undrained conditions and constant total cell pressure by applying a constant rate of axial displacement of 0.2 mm per minute. During these tests the axial stress (deviator stress), axial strain and pore water pressure were monitored.

EXPERIMENTAL RESULTS

87 UCS tests, 26 direct shear tests, 6 triaxial tests and approximately 300 permeability tests were performed. Direct shear and triaxial tests were conducted on only one sand type (Calcareous M) with 3-day intervals between CIPS solution injections.

Unconfined Compressive Strength

All specimens failed at axial strains of less than 1%. UCS values ranged from 1 MPa for wet-tested Calcareous M sand with 3 CIPS treatments to 39 MPa for dry-tested Calcareous F sand with 8 CIPS treatments. Specimens with less than 3 CIP treatments were not subjected to UCS testing. Following the International Association of Engineering Geology classification [1], the CIPS treated specimens exhibit a range of strengths characteristic of very stiff soil to moderately strong rock.

Figure 4 shows a classification system developed by Deere and Miller [3] which uses both tangent modulus and unconfined compressive strength. The results of a representative selection of the UCS tests are plotted on Figure 4 together with typical ranges for concrete, limestones, sedimentary rocks and consolidated clays. The CIPS treated sands correlate with fine to coarse grained sedimentary rocks, ie. fully lithified. Presumably sand specimens treated with only 1 or 2 CIPS solutions would have lower unconfined compressive strengths.

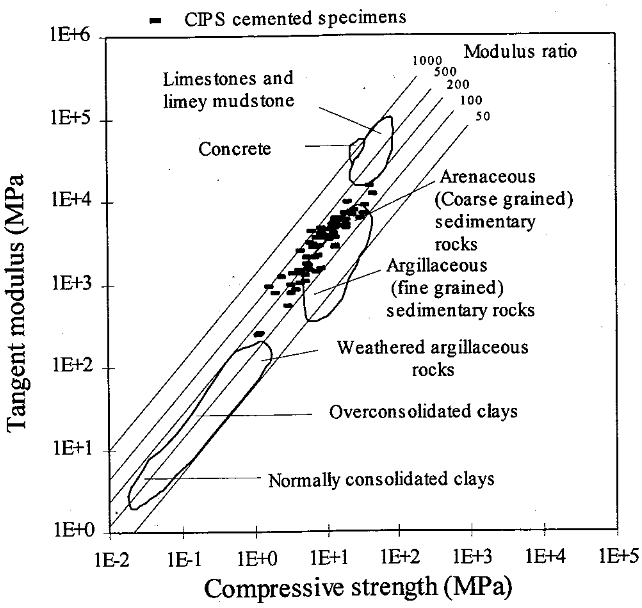

Figure 4. Engineering classification of CIPS cemented calcareous sands.

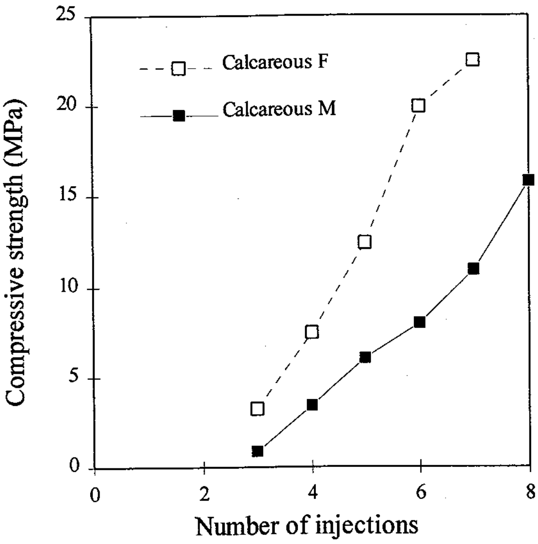

Figure 5. Compressive strength versus number of injections for wet calcareous sands.

The compressive strengths of specimens increases progressively with the number of injections of CIPS solution (Fig. 5). Strengths of over 22 MPa were achieved for CIPS treated Calcareous F sands and 16 MPa Calcareous M sands. Specimens tested after air-

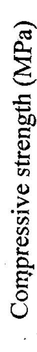

Figure 6. Compressive streng
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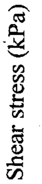

Figure 7. Shear stress versus di

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Direct Shear Test Results

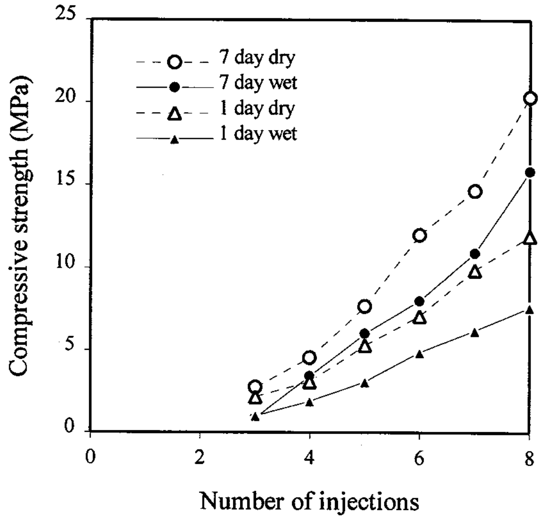

Figure 6. Compressive strengths of dry and wet Calcareous M sand with 1 and 7 day intervals between successive CIPS treatments.

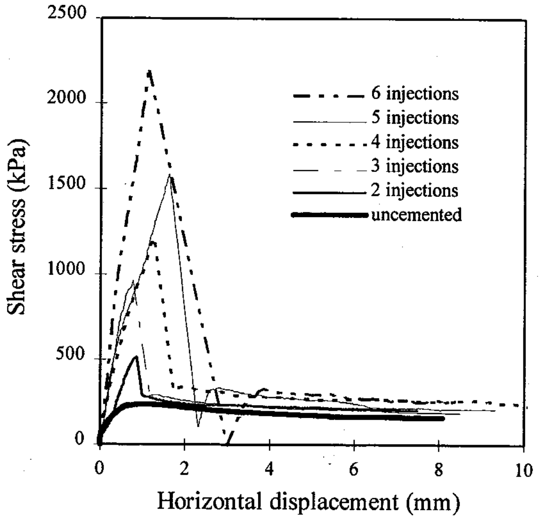

Figure 7. Shear stress versus displacement for CIPS cemented Calcareous M sand.

drying for 2 weeks have higher UCS values than wet tested specimens (Fig. 6). Also, UCS values for specimens with a 7 day interval between injections are higher than those with a 1 day interval between injections. There was no significant difference in UCS values between specimens prepared with a 3 day or 7 day interval between injections.

Direct Shear Test Results

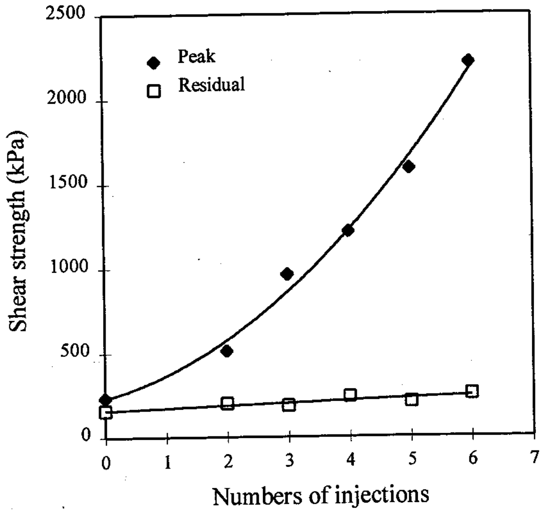

Figure 8. Shear strength (peak and residual) versus number of CIPS injections for Calcareous M sand specimens.

Relationships of shear stress versus horizontal displacement, at a normal stress of 200 kPa, are shown in Figure 7 for Calcareous M sand cemented using different numbers of CIPS injections. It shows that peak stresses develop very rapidly, generally at horizontal displacements of less than 2 mm. Peak stresses progressively increase with increasing numbers of injections. After peak stress, or rupture, shear stresses drop quickly to low residual strengths and thereafter remain constant.

Figure 8 shows the relationships between peak and residual strength for calcareous M sand specimens with different numbers of injections of the CIPS solution. The peak strengths increase with the number of CIPS injections while the residual strengths remain virtually unchanged with the number of injections.

Triaxial Test Results

Typical results of static triaxial testing under undrained conditions at constant total cell pressure are given in Figures 9 through 12. Figure 9 shows the stress-strain relationships at 3 different initial effective confining pressures (σ'_3) for CIPS cemented (2 injections) Calcareous M sand. Similar behaviours are exhibited by the three specimens. The initial deviator stress responses to increasing axial strain were steep and quite linear up to peaks at axial strains of less than 1%. Obvious strength losses occurred immediately after the peaks followed by secondary increases in strength and then large axial strains at deviatoric stresses at or above the yield strengths.

A typical (selected) undrained stress-strain curve for a natural calcarenite [2] is shown in Figure 10 together with results for two CIPS cemented Calcareous M sand specimens, and an uncemented but reconstituted calcareous sand, all at initial σ'_3 of 500 kPa. The CIPS cemented Calcareous M sand specimens have a similar (if slightly stronger) pattern of

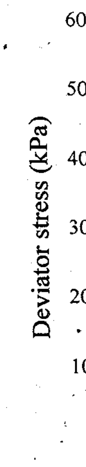

Figure 9. Stress-strain relation
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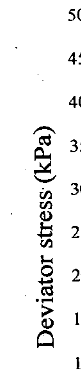

Figure 10. Undrained stress-s
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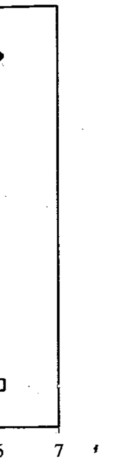

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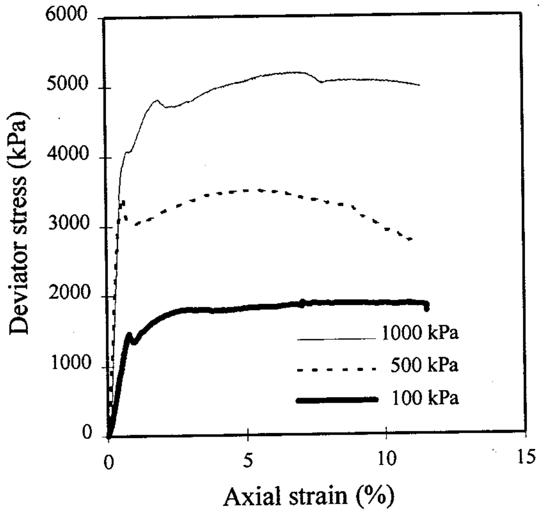

Figure 9. Stress-strain relationships in undrained compression at different initial σ_3 levels for Calcareous M sand with 2 CIPS injections.

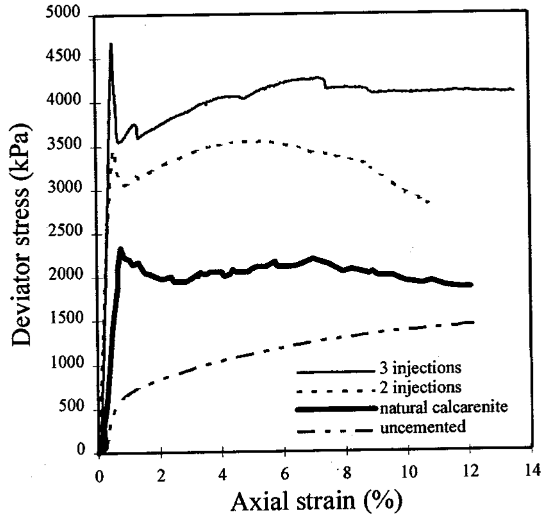

Figure 10. Undrained stress-strain relationships for one uncemented and two CIPS cemented calcareous sands and a natural calcarenite.

stress-strain behaviour to the naturally cemented calcarenite. Initial elastic responses are terminated by abrupt failures and stress drops followed by large displacements at roughly constant stress levels. The uncemented calcareous sand exhibits a much lower yield (around 500 kPa) and an overall softer behaviour.

Figure 11 shows that positive excess pore water pressures were generated early, during elastic deformation and that the magnitude of these pressures depended on the initial effective confining pressure. The higher the initial pressure, the higher the positive excess pore pressure. After yield, excess pore water pressures fell to negative values at high strains.

This pattern of pore pressure response in undrained compression for CIPS cemented calcareous sand is similar to that for natural cemented calcarenites reported by Golightly and Hyde [4] and Carter [2]. However, the fall of pore pressure is larger in the CIPS cemented sands than in the natural calcarenites and the final pore pressure was generally positive. These differences may be due to the smaller void ratio of the CIPS cemented sand specimens.

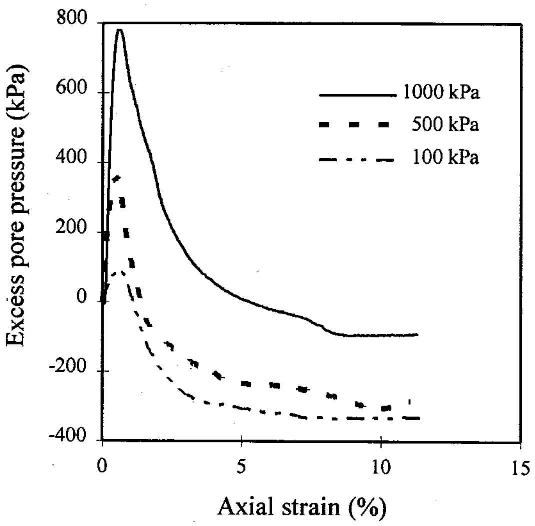

Figure 11. Pore pressure response in undrained compression at different initial σ'_3 levels for calcareous M sand with 2 injections.

Figure 12 shows stress paths in undrained compression at three different initial effective confining pressures for Calcareous M sand specimens treated with 2 injections of CIPS solution. They show a type of behaviour which is characteristic of "overconsolidated" clay soil. Clearly, this "overconsolidation" was due to the cementation of the constituent grains by calcite crystals from the CIPS solution.

The best-fit peak strength line gave an effective cohesion of 133 kPa and an effective internal friction angle of 39.4° with a squared correlation coefficient of 0.995. It is anticipated that specimens with higher numbers of injections of CIPS solution will have higher values of effective cohesion but similar values of effective internal friction angle.

PERMEABILITY

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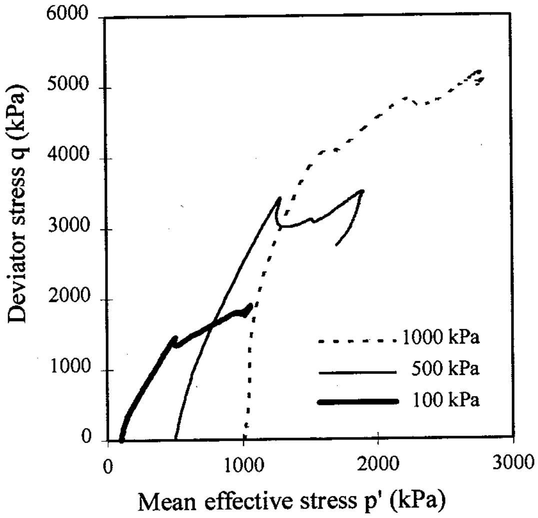

Figure 12. Stress path in undrained compression at different initial σ'_3 levels for calcareous M sand with 2 injections.

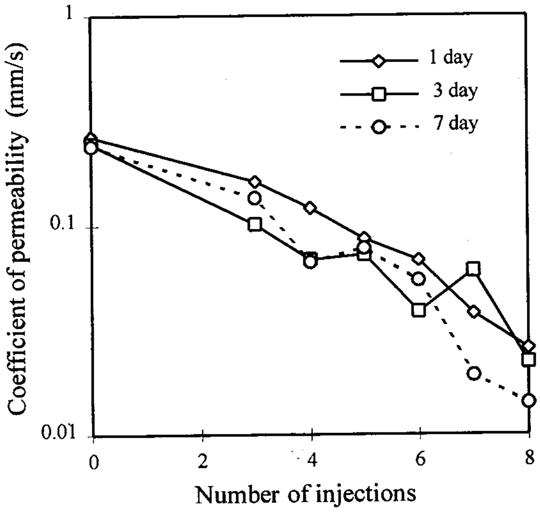

Figure 13. Variation of permeability with number of CIPS injections for Calcareous M sand.

As expected, the permeability of Calcareous M sand decreases with the number of CIPS treatments (Fig. 13). The coefficient of permeability decreases from 0.25 mm/s for uncemented Calcareous M sand to around 0.02 mm/s for specimens cemented with 8 CIPS treatments. It is notable that while permeability reduces slightly, the unconfined compressive strengths increase dramatically from zero for uncemented Calcareous M sand to around 15 MPa for the same material cemented with 8 CIPS treatments.

CONCLUSIONS

The geotechnical properties of CIPS cemented calcareous have been investigated by a series of laboratory tests. The non-particulate and low viscosity CIPS solution allows easy penetration into moderately permeable materials such as calcareous sands. Test results demonstrate dramatic increases in the mechanical strengths of calcareous sands with the number of CIPS treatments. However, permeability is reduced only slowly. The ability to apply multiple injections of the CIPS solution allows almost any desired mechanical strength to be achieved.

The CIP System has great potential for wide application to insitu improvement of the mechanical properties of porous materials such as sands. Although focussed initially on offshore sediments CIPS may be equally effective in many other applications, such as onshore deep and shallow foundations, underpinning, settlement control, slope stability, mine fill, fractured rock masses, etc. These applications are currently under investigation.

Acknowledgments

M.S. Khorshid of Advanced Geomechanics is thanked for his valuable advice on the test program. A.C.T Tan of The University of Western Australia, R. Middleton, J. Magri, D.A. Dabelstein and R. Thompson of CSIRO are thanked for their technical support.

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Proc. 30th Int'l. Geol. Congr.,
Wang Sijing and P. Marinos (
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Some Applications

MAO JIZHEN CHEN QU
Institute of Crustal Dynamics,

Abstract

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of borehole breakouts, size and
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Keywords: Ultrasonic borehol

INTRODUCTION

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