Chapter

Geomechanical Behavior of Bio-Cemented Sand for Foundation Works

Youventharan Duraisamy and David Airey

Abstract

Bio-cementation is an innovative green technology that complements existing ground improvement techniques, but it is yet to be proven for large-scale foundation works. Previously attention has been focused on strategies to inject the bacteria and nutrients to produce the cement in the ground. This study looks at the performance of geomechanical response when the bacteria and nutrients are mixed in sand, an approach that is used in producing cemented soil columns. To explore the mechanical response of bio-cemented soil, results from unconfined compressive strength (UCS) tests and triaxial tests have been analyzed to understand the effects of bio-cementation for sand in contrast to alternative cement, gypsum. The stiffness has also been monitored using bender element techniques in triaxial cell. Both the shear wave signals during the cementation phase and the shearing phase were recorded using this technique. The results show that for a given amount of cement, higher resistances are measured for the bio-cemented samples compared to gypsum. The mixing process is shown to produce homogeneous bio-cemented samples with higher strength and stiffness than the technique of flushing or injection commonly used, provided the amount of calcite is less than 4%. The results show that the bio-cement produces similar mechanical behavior to other artificially cemented sands.

Keywords: bio-cement, calcite precipitation, Sydney sand, strength, stiffness, shear wave velocity, small strain modulus, urea hydrolysis

1. Introduction

The study on the geomechanical behavior of bio-cemented Sydney sand was carried out using unconfined compression strength (UCS) tests and triaxial tests. To date there have been limited numbers of triaxial tests reported on soil cemented by microbes, and owing to differences in soil type and cementation methodology, these have provided variable results on the potential of bio-cementation. Part of the variability in behavior is a result of the widely used method of injecting bacterial solutions into sand to create the cementation. The injection process leads to heterogeneity in the distribution of calcite and hence to variability in the mechanical response and permeability of the bio-cemented soil. The mixing technique was used to create consistent and coherent bio-cemented samples and to overcome the difficulties of interpretation faced by previous researchers [1–3]. It has been suggested that the injection technique targets the contact points between the particles, which is beneficial for cementing, and comparisons are made between mixed samples in this study and other studies where injection has been used to explore this hypothesis. The small strain shear stiffness has been used as an indicator to evaluate the success of bio-cementation [4], and shear wave velocity was monitored in this study to explore the influences of cement level and stress on the data and the ability to predict the success of bio-cementation.

The discussion in this chapter concentrates on:

i. The effect of preparation and curing time on cementation level and corresponding amount of calcite/cement

ii. A comparison of UCS strengths of bio-cemented and gypsum-cemented specimens

iii. The effects of confining stress of soil on the geomechanical behavior of bio-cemented specimens

iv. The influence of calcite content on the strength and stiffness

2. Literature review

Over the past decade, the potential for microbially induced calcite precipitation (MICP), or simply bio-cement, to improve soil and rock responses has been extensively studied by petroleum, geological, and civil engineers [4, 5]. Recently, studies were undertaken to understand the geomechanical parameters of granular soils using microbes in biochemical process, which produce bio-cement in the subsurface [1, 6, 7]. It has been suggested [8] that these reactions simulate the natural geochemical processes that transform sand into sandstone. However, the MICP process is rapid and produces a precipitate with soft and powdery crystals, whereas natural limestone forms slowly and creates a very hard precipitate [6]. Most of this research has focused on the use of ureolytic bacteria, which have been shown to be capable, with the addition of urea and reagents, of producing calcite that binds to soil particles [6–13].

The general trends of cementation effects on granular material are increases in strength and stiffness, which increase with the amount of cementing material, although this may vary greatly depending on the amount of cementing material used. It has been noted that the effectiveness of cement depends on the density, the effect of cement being greater at lower densities [14, 19–21]. Many studies on artificially cemented soils have shown that cementation significantly increases the initial tangent modulus of a soil and monitoring the stiffness can be a useful method of tracking the amount of cementation [22, 37]. A range of cementing agents have been investigated including ordinary Portland cement (OPC), gypsum, sodium silicates, and calcium carbonate [14–22] to understand the influence of cementation and to simulate materials used in ground improvement work. Generally, the geomechanical responses of bio-cemented granular soil are similar to any other artificially cemented granular soil [7].

Although the cementing effect is more significant in loose sand, it is found that more bio-cement is needed to achieve the strength of dense sand when applied in loose sand [13]. It has also been suggested that the growth of calcite crystals at points of contact between sand grains has a significant influence on UCS strength [23]. As bacteria and nutrients are pumped through sand continuing calcite precipitation, it can lead to a large proportion of the voids being filled, and high

UCS can be obtained. For example, strengths of up to 30 MPa [23] were obtained from small-scale experiments, and even at larger-scale (100 m^3) strengths of up to 12 MPa [24] have been reported. Other results show maximum compressive strengths obtained for bio-cemented sand of about 14 MPa [25]. As much as UCS strength increase can be related with individual soil particle strength, factors like roundness, size, and shape too may reduce the strength [23]. An increase in shear strength of 35, 50% and more than 100% is observed for round coarse particles, coarse angular particles, and round fine particles, respectively [26]. According to Al Qabany and Soga [27], for the same amount of precipitated calcite, the greatest UCS strength was obtained when the concentration of the solution was low. These results were obtained over a range of different initial relative densities. Cheng et al. [21] also reported that it is possible to get higher UCS strengths at the initial phase when sample is low or partially saturated. The different soils used and different preparation procedures have resulted in a wide range of parameters to describe the bio-cemented soils. For example, clean Ottawa sand treated with microbes produced calcite in the range of 0–4%. During the treatment, the angle of friction increased from 35.3 to 39.6° and the cohesion from 0 to 93 kPa [34].

A range of applications for bio-cement have been suggested. A recent example is a feasibility study carried using bio-cement for slope stabilization by means of a surficial treatment where a layer of hard stratum was obtained on the subsurface with UCS strength of 420 kPa after 10 days of treatment [7, 35]. However, this method of treatment is not extensively applied in the field of ground engineering.

3. Materials and methods

Microbes, chemical substrate, and reagents have been used to produce bio-cemented specimens. This process uses bacteria to catalyze the urea hydrolysis reaction that precipitates calcite. The ureolytic bacteria known as *B. megaterium* (strain ATCC 14581) were used. To produce sufficient bacteria for the cemented samples, a KWIK-STIK (produced by Microbiologics®) containing the microorganism strain was cultured in batches using liquid medium. The growth medium (refer to **Table 1**) in liquid form was prepared in advance and placed in the incubator at 30°C for 24 hours using a 50 ml beaker. Importantly, this bacterium is nonpathogenic and poses no harm to humans.

Fixed quantity of clean, dried sand was placed in a mixing bowl. Then the required amount of urea powder and calcium chloride powder was added based on a percentage of the sand weight free from moisture. The nutrient masses (urea and calcium chloride) ranged from 5 to 20% of the sand weight free from moisture. Additional water was added to facilitate mixing to give a water mass of about 10% of the mass of the dry ingredients. The ingredients were then thoroughly mixed for

Ingredients (L^{-1})	
Nutrient broth	3 g
Urea	20 g
NH_4Cl	10 g
$NaHCO_3$	2.12 g
$CaCl_2$	2.8 g

Table 1.
Typical liquid medium or broth.

1 min before being placed in cylindrical molds. To prepare uniform and reproducible samples with a consistent density, the mixture was divided into five portions before being filled in the molds and gently tamped each time.

The bio-cemented samples have been compared with gypsum-cemented samples which have been prepared by combining the dry ingredients (sand and unhydrated gypsum) followed by mixing with water and placing in a mold similarly to the bio-cemented samples.

The preparation technique produced cylindrical samples with 55 x 110 mm in dimensions. After extraction and curing, the samples were either placed directly in a compression machine to perform UCS tests or in a fully computerized triaxial testing apparatus to perform geomechanical tests with elevated confining stresses, which was also fitted with bender elements to monitor the secondary (shear) wave pulse. Once the UCS and triaxial shearing tests were completed, bio-cemented samples were extracted and analyzed to determine the amount and distribution of the calcite precipitated. Further details of methods and procedures are provided by Duraisamy [2].

4. Unconfined compressive strength tests

Strength tests have been performed using Sydney sand mixed with two cementing media, gypsum and the bacterial mixture. **Figure 1** shows the responses of the UCS tests of cemented sand performed with gypsum contents in the range of 5–20%. All samples fail at small strains with brittle responses. A clear trend of increasing strength with gypsum content is evident. However, interpretation of these tests requires caution as strength is affected by density, which tends to increase as fines are added; the limited water retention in clean sand, which limits the water available for hydration; and the presence of suctions in the tested samples (dried in laboratory conditions), which tends to increase the strength. All these factors tend to enhance the effectiveness of the cement as more cement is added, at least initially.

Bio-cemented samples of Sydney sand and its UCS strength are shown in **Figure 2**. As expected, as the amount of calcite precipitation increases, the UCS readings also increases. Similarly to the gypsum-cemented samples, the bio-cemented sand samples show generally stiff and brittle behavior, although with more ductility than for the gypsum cement. The results accord with other

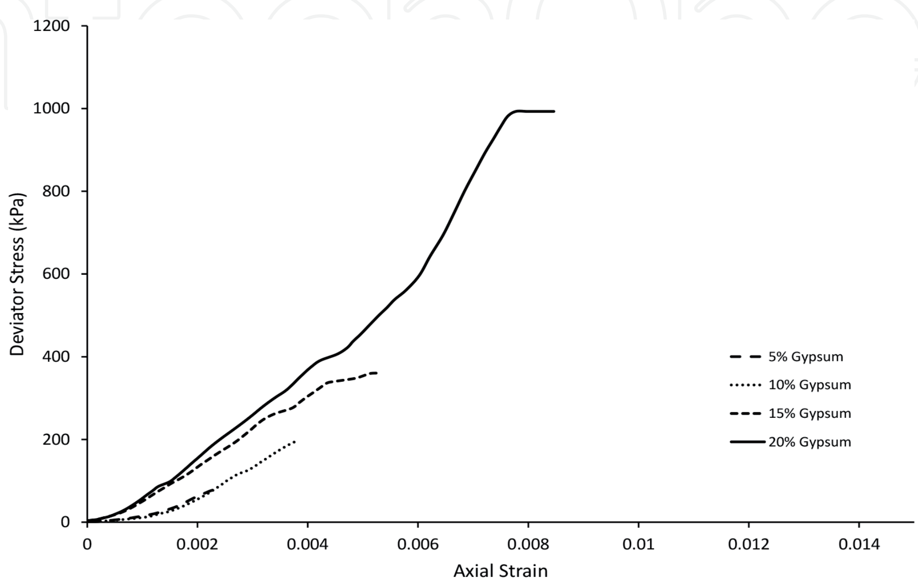


Figure 1.
UCS test responses from gypsum-cemented specimens.

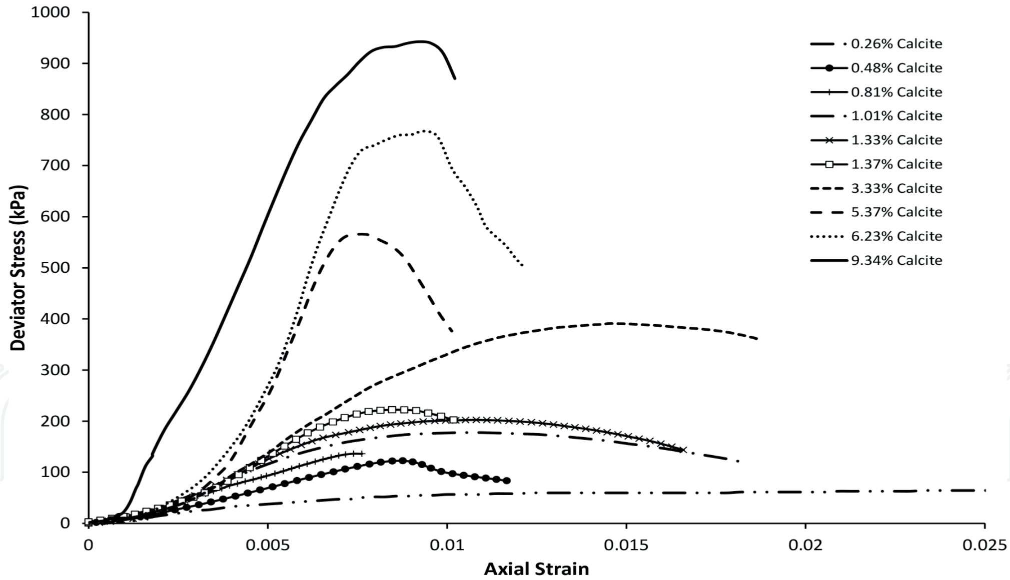


Figure 2.
UCS responses for bio-cemented specimens.

Test No/ID	Test type	Average calcite (%)	Top (%)	Middle (%)	Bottom (%)	Standard variance (±%)	Sample variance (%)
3%B	UCS	1.33	1.52	1.14	1.34	0.19	3.6
B14	Triaxial	1.54	1.49	1.51	1.61	0.10	1.1
5%B	UCS	2.73	2.73	2.91	2.68	0.12	1.5
B10	Triaxial	2.61	2.94	2.79	2.79	0.16	2.7
10%B	UCS	5.33	5.52	5.21	5.26	0.15	2.3
B13	Triaxial	4.26	4.48	4.17	3.62	0.16	2.5
15%B	UCS	6.23	6.13	6.25	6.31	0.15	2.3
B16	Triaxial	6.98	7.09	6.90	6.91	0.11	1.1

Table 2.
Variance of calcite distributions in UCS and triaxial test samples.

studies [4, 7, 37], which have reported bio-cemented sand responds similarly to naturally and artificially cemented sand at low confining pressure. Comparison of **Figures 1** and **2** shows that samples with calcite contents less than 3.33% have lower stiffnesses than gypsum-cemented samples of the same strength. With low calcite contents, it is possible that sample heterogeneity influences the results, as reported in other studies [27] where the bio-solution has been pumped into the samples. However, as shown in **Table 2**, the mixing procedure used in this study has produced uniform calcite distributions through the samples, with less than 5% variance in different sample sections, for all calcite contents. End effects may also have affected the apparent stiffness as the sample ends were not prepared perfectly square and there was a tendency for water and bio-solution to flow out of the samples, because of the low water retention, during sample preparation. Nevertheless, the consistent trend with calcite content suggests that the results reasonably represent bio-cemented sand performance.

Figure 3 shows a comparison between the UCS responses of gypsum-cemented samples and bio-cemented samples of approximately similar strengths. It is evident that based on strength, also shown in **Figure 4**, the calcite produced by MICP is a much more effective cementing agent than gypsum, with about 0.5% of calcite

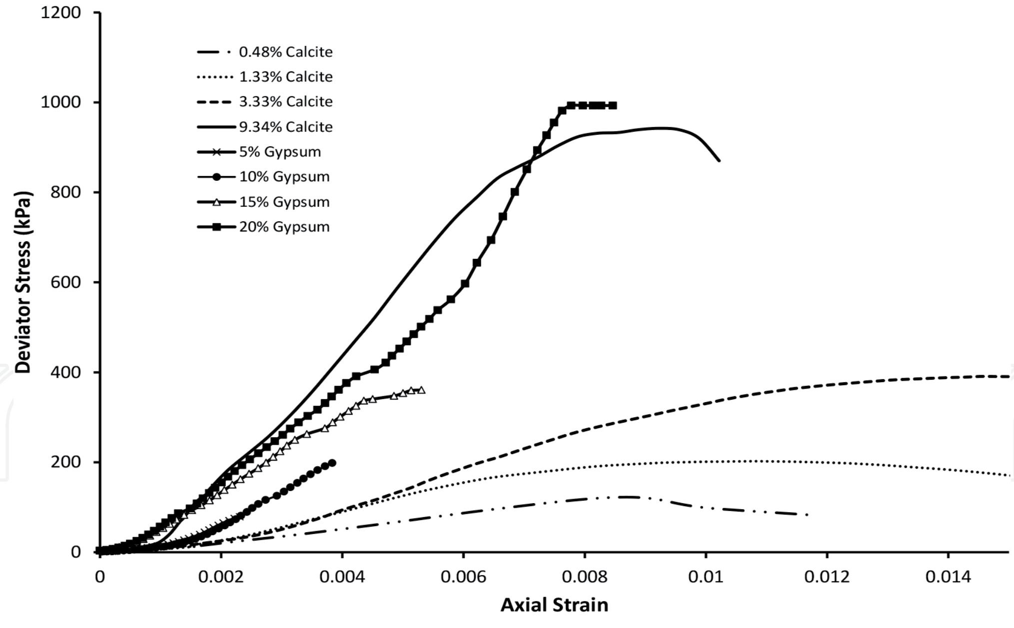


Figure 3.
Comparison of UCS responses of gypsum and bio-cemented specimens.

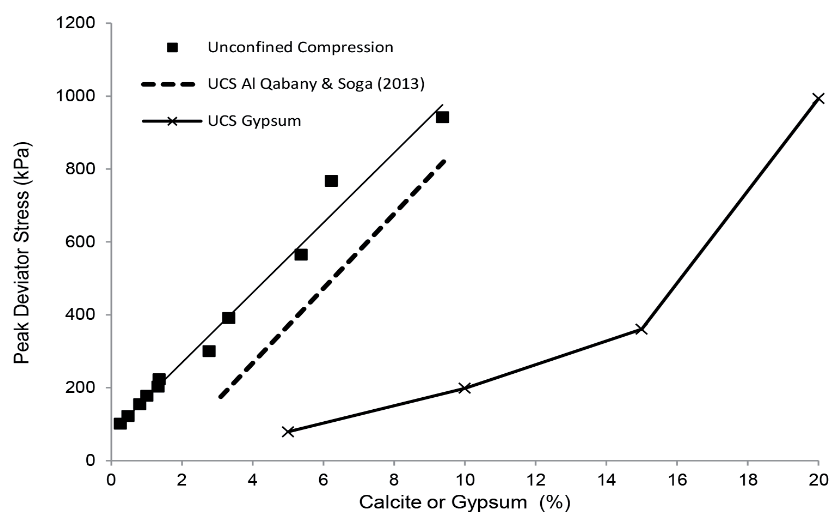


Figure 4.
Effects of cement content on UCS strength.

equivalent to about 5% of gypsum and 9% of calcite equivalent to 20% of gypsum. As noted above the stiffness and ductility of the bio-cemented samples are lower than for gypsum when cement contents are low, and this can in part be explained by the very low amounts of calcite required, and as shown in other studies [13, 28], much of this acts as space filler and does not actively contribute to the strength.

The influence of gypsum and bio-cement content on the strength improvement is shown in **Figure 4**. Previous report [27] also indicates similar UCS and calcite content relationship. However, the results from the current study in which mixing was used all lie above the previous research [27] in which the bio-cement solution was pumped into the samples. It was also reported [27] that preparing samples with low calcite contents by pumping in the solution was problematic as samples tended to have poor homogeneity and these weakly cemented samples tended to deform locally, giving low shear strength, and on occasion to collapse immediately upon loading. In contrast, the low calcite content bio-cemented specimens prepared by mixing in this study all showed significant improvements in resistance. As sands with similar gradings were used and samples were prepared to similar densities in both studies, the different responses point to the sample preparation method as being the key difference. Several studies [13–28] have shown that regardless of the injection process, obtaining uniform calcite precipitation is difficult, and it is also difficult to control, especially for small amounts of cement. The results from the mixing method of preparation show that this can lead to more homogenous cementation at low calcite contents and mixing can achieve calcite contents of nearly 10%. Nevertheless, the process of injecting bio-cement has advantages. It has been shown to be practical at field scale, and by using a series of injection phases, the process is capable of achieving very high strengths [28].

The strength and stiffness produced by the mixing technique varies depending on the soil and cement. Even though gypsum was mixed in with the soil, much more gypsum was required to produce the same strength and stiffness as the calcite cement. Because of its acicular particles, gypsum does not easily bridge between the sand particles, and it tends to fill the void spaces. Many studies have shown that in adding silt-sized fines, such as gypsum, fines fill the voids up to a transition fines content of approximately 25% after which the fines have increasing influence on the behavior. Once enough gypsum is present, it will fill the voids and form a strongly cemented matrix. Gypsum contents >15% appear to be needed to achieve this effect as illustrated in **Figure 4**.

5. Curing process and bender elements

The progress of the cementation process during curing was monitored using bender elements by recording the shear wave velocity change over time. This was achieved during the preparation of samples for triaxial testing. Split mold using PVC material fitted with a rubber membrane inside was designed to produce identical cylindrical samples with length of two times the diameter. Bender elements in the end platens transmitted waves vertically through the samples, and the waveforms and travel times were monitored using a semiautomated procedure [29]. The typical responses in **Figure 5** happen during the curing of gypsum-cemented samples. The hardening process occurs rapidly for gypsum contents above 10% and that curing is essentially complete after 1 h. This is consistent with the setting time reported by the gypsum supplier of 55 minutes. However, for low gypsum contents, there is some variability and longer setting times have been recorded. This is believed to be because

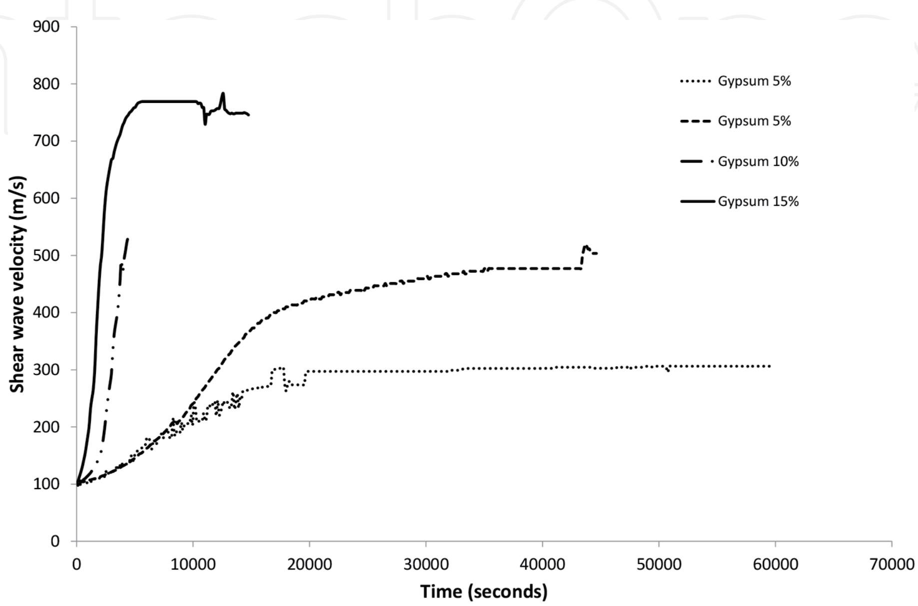


Figure 5.
Shear wave velocity changes during curing of gypsum-cemented specimens.

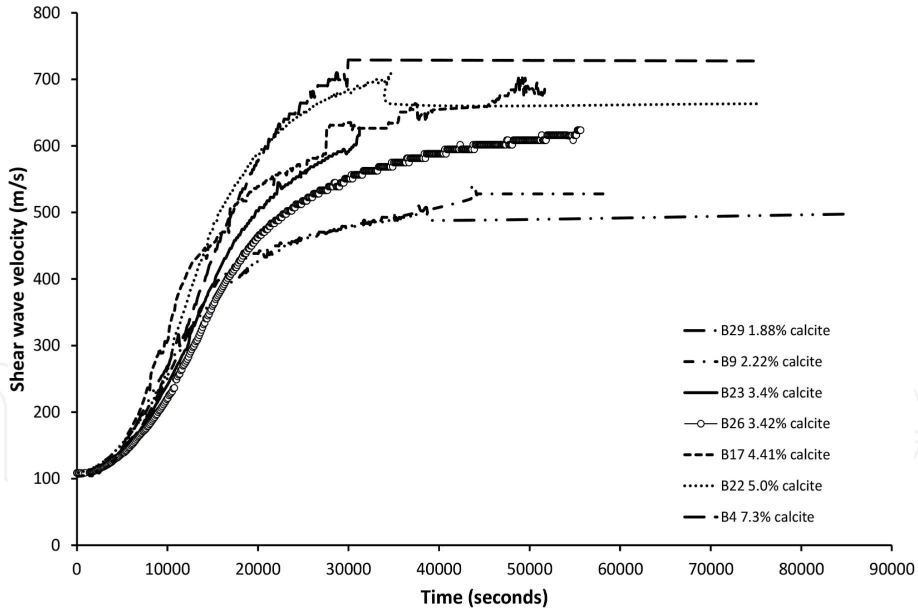


Figure 6.
Shear wave velocity changes during curing of bio-cemented specimens.

the setting of gypsum involves a hydration reaction that can be affected by changes in temperature and humidity. The samples were effectively sealed with limited supply of oxygen during the curing reaction, and with low gypsum contents, temperature rises associated with the exothermic reaction would be limited, hence limiting the reaction rate. After the hardening phase, the samples were left unattended overnight, and during this time no significant change in shear wave velocity was captured.

The variations of shear wave velocity during the calcite precipitation and hardening of the bio-cemented samples are shown in **Figure 6**. Small step changes in the shear wave velocity shown in **Figure 6** are a consequence of manual intervention in the semiautomated interpretation procedure and do not reflect the material response. For the range of final calcite values shown, the reaction time is very similar. In all cases there is a lag of about 1 hour before the cementation process begins, and the process is complete in about 12 hours after which the shear wave velocity remains constant. Samples were left for 24 hours before commencing the triaxial tests, and during this time the stiffness remained essentially constant. **Figure 6** also shows that the initial 100 m/s value increases over time, which is proportional to the stiffness and tends to increase with the calcite content as expected.

The comparative study on shear wave signal responses during curing for selected gypsum-cemented and bio-cemented sand samples is projected in **Figure 7**. The trend in the responses are similar for 5% gypsum and 1.88% calcite, whereas UCS tests have shown that the strength associated with 1.88% calcite is equivalent to about 10% gypsum. However, the rates of the cementation reactions depend on the chemistry of the hydration and MICP processes and are not expected to influence strength and stiffness. Nevertheless, it may be noted that the ratio between strength and stiffness varies with the cement type. The calcite-cemented samples have lower stiffness (shear wave velocity) than gypsum samples with the same strength. A likewise pattern was seen in the UCS tests and was inferred to be a simple consequence of the low amount of calcite cement.

No triaxial tests were performed with calcite contents lower than 1.88%, and thus it is unclear whether with lower calcite contents the reaction time will increase, which occurred for low gypsum contents. In other tests [36–37], when the cementation occurred underwater, the time required for curing was greater than 24 hours, and it is expected that the curing time will depend on the chemical and

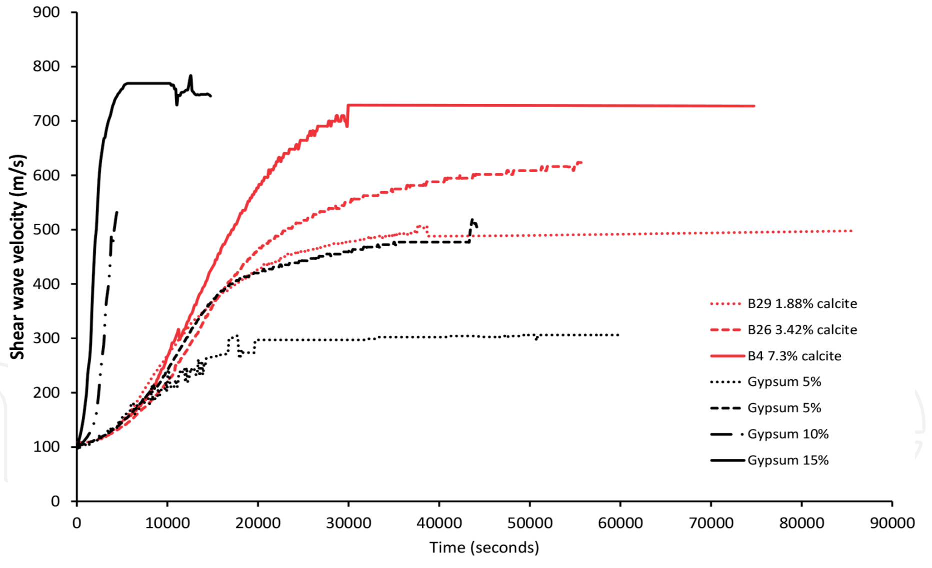


Figure 7.
Comparison of curing for gypsum and bio-cemented specimens.

environmental conditions. It may also be noted that the lag at the start of the cementation process is beneficial for both injection and mixing approaches at field scale.

6. Triaxial stress: strain responses

6.1 Uncemented sand

To enable the influence of the cement to be appreciated, triaxial tests have been performed on loose Sydney sand. Samples with various relative densities have been subjected to standard drained (CID) and undrained (CIU) tests with different confining pressures. Test results as in **Figure 8** are presented in terms of stress ratio (q/p′) against the axial strain. The results indicate that in all tests the stress ratio rises to a peak before gradually reducing toward a critical state value at large strain. Where the stress ratio dropped rapidly post peak, the samples had formed pronounced shear planes. The dotted line in **Figure 8** shows the estimated critical state stress ratio, M = 1.35, which corresponds to a friction angle of 32°.

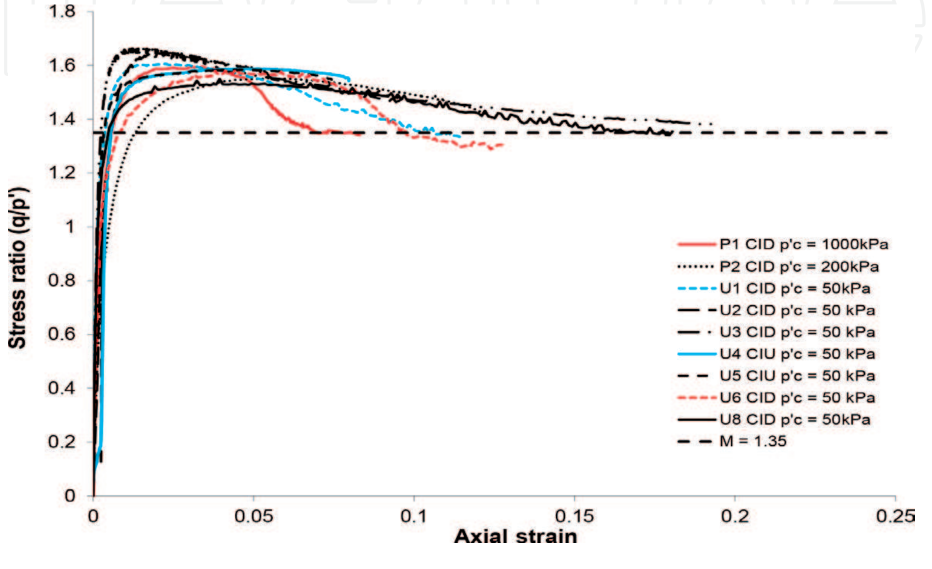


Figure 8.
Response of uncemented Sydney sand.

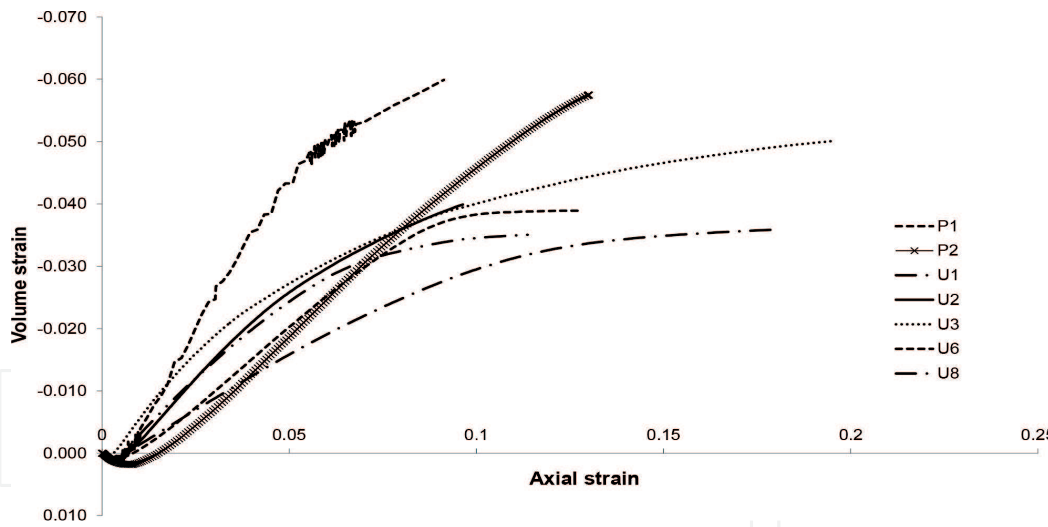


Figure 9.
Volumetric strains for CID tests on uncemented sand.

The volumetric responses from the drained tests reported in **Figure 8** are displayed in **Figure 9**. In all cases the samples expanded on shearing, which is consistent with their mobilizing peak stress ratios greater than the critical state value [30].

The bender element technique was used to obtain the shear wave velocity (V_s) for the uncemented sand. This has also allowed comparison with data on uncemented sand obtained from other studies and hence to demonstrate the reliability of the estimated soil stiffnesses. Knowing the shear wave velocity and bulk density (ρ) of the sand, the small strain shear modulus (G_{max}) can be determined from Eq. (1):

$$G_{max} = \rho\, V_s^{\,2} \tag{1}$$

The parameter functions of G_{max} and the mean effective stress (p') for two typical uncemented sand samples, P1 and P2, are shown in **Figure 10(a)**. During isotropic compression an identical response is obtained, which may be described by Eq. (2):

$$G_{max} = 11.27\, p'^{\,0.475} \tag{2}$$

where G is in MPa and p' is in kPa.

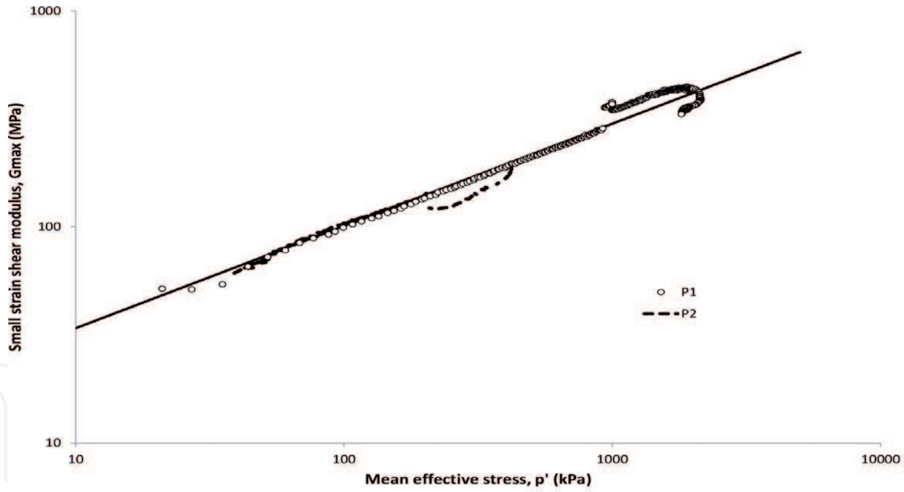
Data on which Eq. (2) is based covers a range of p' from 10 to 3000 kPa, which is greater than incorporated in most published relations. For comparison, the data obtained in this study are plotted in **Figure 10** (b) with another published empirical relation for G_{max} which is given by Eq. (3). This incorporates a function of void ratio $f(e) = (2.17-e)^2/(1 + e)$ and constants A and n which are coefficients that depend on the type of material (**Table 3**).

$$G_{max} = A f(e)\, p'^{\,n} \tag{3}$$

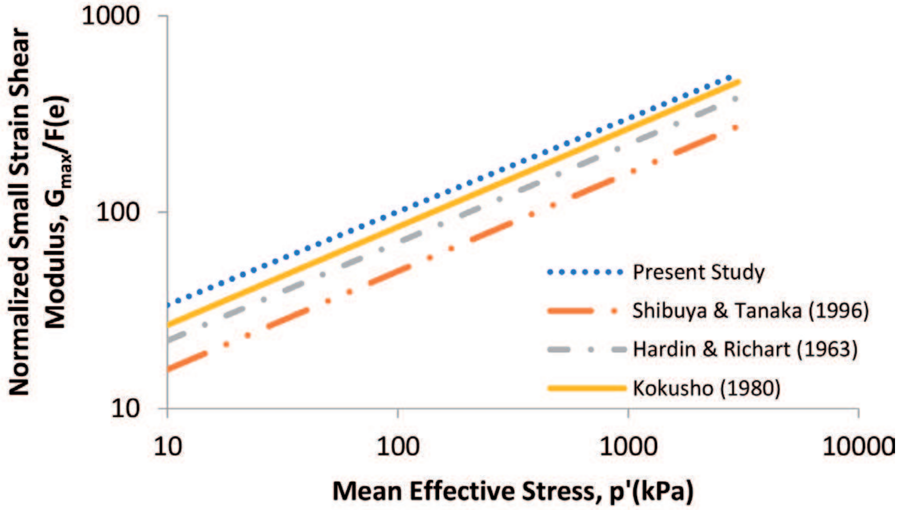
The predicted G_{max} values from [31–32] are similar to the Sydney sand data, and the linear relationship between G_{max} and p' in this study is closest to the equation proposed for Toyoura sand [32] which is to be expected given the similarity of mineralogy, particle size, and shape of the two granular materials.

6.2 Gypsum-cemented sand results

Results from triaxial tests on gypsum-cemented samples are presented in **Figures 11–13**. **Figure 11** shows the stress ratio and axial strain responses of cemented samples with gypsum contents between 5% and 20% and includes undrained and



(a)



(b)

Figure 10.
Variation of G_{max} with p' for uncemented sand (a) dry and saturated Sydney sand (b) validation with published data.

A	*n*	Reference
5000	0.5	Shibuya and Tanaka [31]
8400	0.5	Kokusho [32]
7000	0.5	Hardin and Richart [33]

Table 3.
Constants proposed for empirical equation G_{max}.

drained test results. Comparison with **Figure 8** for the uncemented sand shows the cemented samples developed high peak stress ratios and these are mobilized at lower axial strains than for the uncemented sand. For the drained tests, samples with confining stress of 50 kPa, the peak stress ratio and deviator stress increase with cement content as expected. For the undrained tests, a similar trend with cement content is apparent; however, for the more cemented samples, the stress ratio reaches the limiting value in the triaxial apparatus, which is 3. Once this occurs further loading is equivalent to performing a UCS test and the failure strengths of these samples are between 650 and 1300 kPa, in the range of the UCS strengths of the gypsum-cemented samples shown in **Figure 4**. After the peak the stress ratio reduces

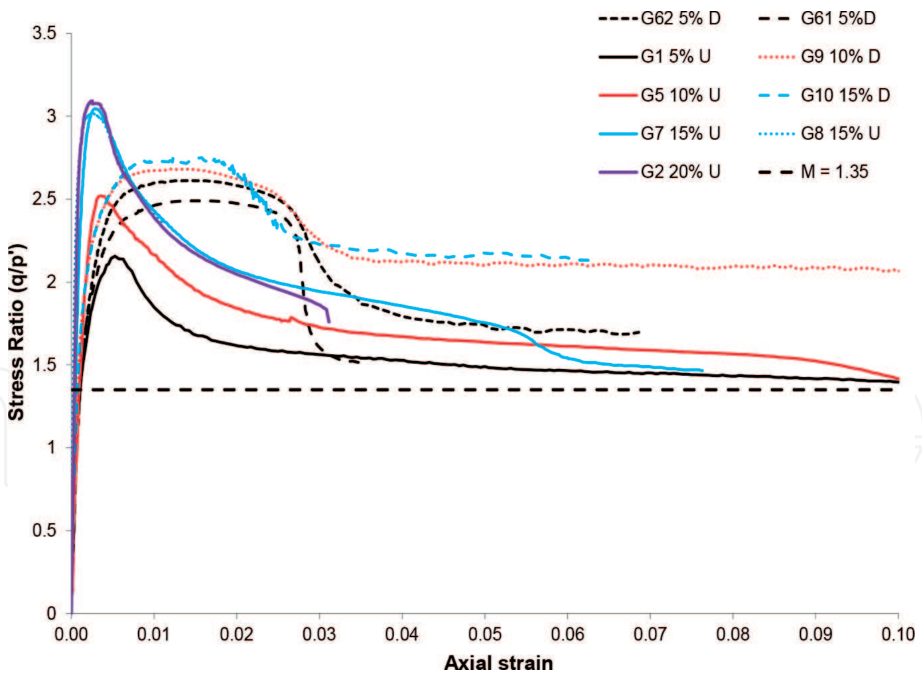


Figure 11.
Stress ratio, axial strain responses for all gypsum-cemented specimens.

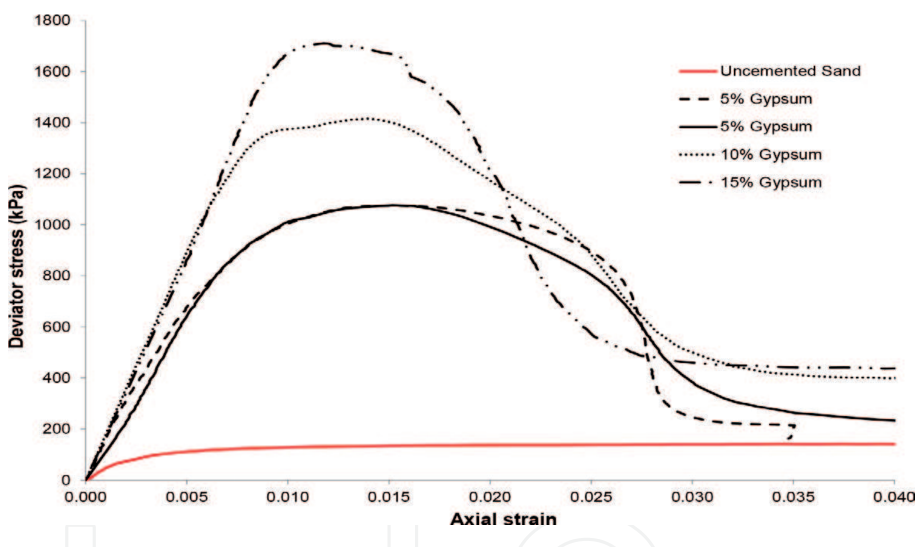


Figure 12.
Deviator stress, axial strain responses from drained tests (p'_c = 50 kPa).

approaching a constant value at large strain, however unlike the uncemented samples, the stress ratio does not appear to approach a unique value. It is believed that this is a consequence of nonhomogeneous deformation and if the samples could be sheared uniformly, they would approach the value of the ultimate critical state, M = 1.35 similar to the uncemented sand. Other studies (e.g., see [14, 15]) in which gypsum-cemented sands were tested showed that the presence of gypsum, up to 20%, did not influence the ultimate frictional resistance.

Figures 12 and **13** show the reactions of gypsum-cemented samples in drained triaxial tests. The gypsum cement leads to significant increases in strength compared with the uncemented sand, and even small amounts of gypsum increase the strength considerably. Further, the comparison with the UCS test responses shown in **Figure 1** indicates that there is a remarkable contribution with even a slight amount of gypsum, which is much greater in the triaxial tests. This is believed to be due to the applied confining stress which prevents the tensile failure mode that occurs in UCS tests. Samples cemented with gypsum reached their maximum strength at axial

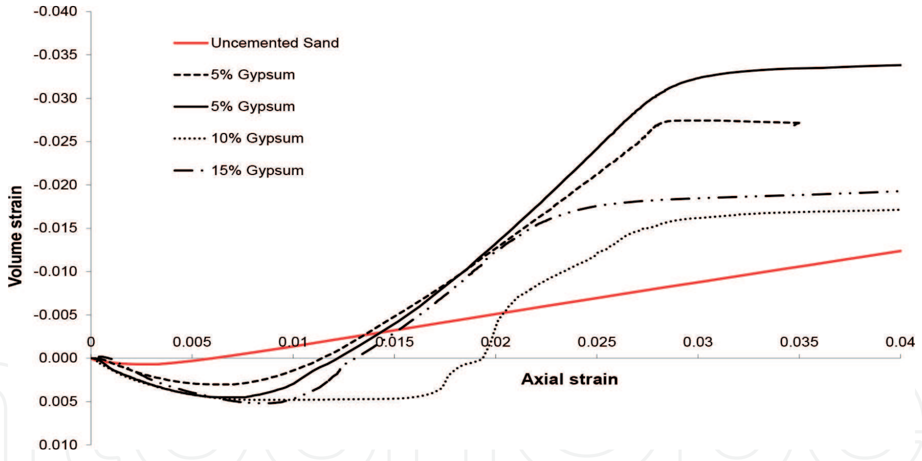


Figure 13.
Volume strain, axial strain responses from drained tests (p'_c = 50 kPa).

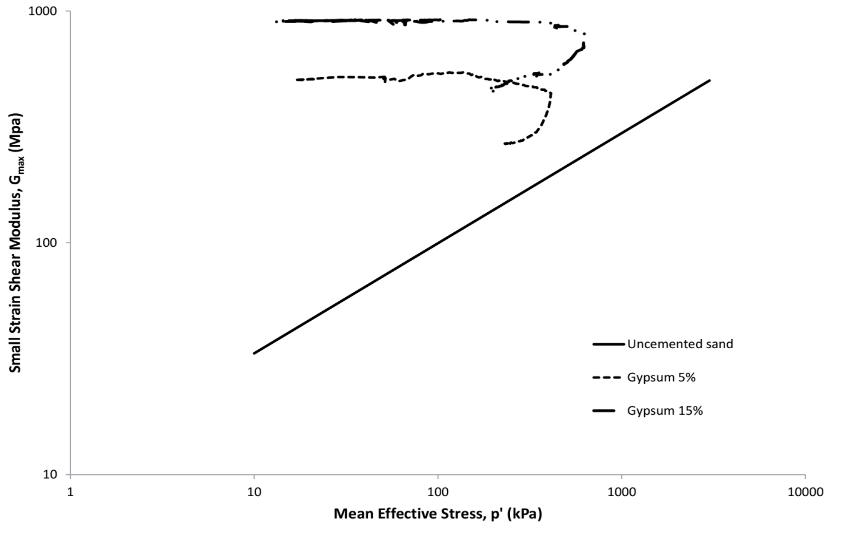


Figure 14.
Variation of G_{max} during compression and shear for gypsum-cemented specimens.

strains <1.5%, while for the uncemented sand, the maximum strength occurred at axial strains of between 2 and 5%. **Figure 13** shows the cementation initially prevents the expansion that occurs almost from the beginning of shear for the uncemented samples. The uncemented samples expand steadily during shear eventually reaching a maximum volume strain of about −0.04 for axial deformations greater than 10%. Even though their densities are similar, the gypsum cemented shows different behavior. The specimens initially compress due to increasing mean stress, but as they approach the peak, they begin to expand at a rapid rate, much more rapidly than the uncemented sand. The rate of expansion then drops as pronounced shear bands develop. In general, these results are typical of the behavior of artificially cemented specimens prepared with a range of cement types [15–22].

Figure 14 shows the response and changes of G_{max} with p′ for typical gypsum-cemented samples and comparison with the response for uncemented sand. The responses include an initial isotropic compression stage to 50 kPa followed by drained shearing to large deformations. The figure shows the cement has a remarkable contribution on the small strain stiffness, with G_{max} nearly constant until reaching the peak strength. However, looking in detail, it is found that G_{max} increases slightly with p′ and then decreases as the cementation begins to break. After the peak, the shear modulus falls significantly and approaches the uncemented response.

6.3 Bio-cemented sand specimens

During the preparation of the UCS and triaxial samples, dry sand was mixed with equal amounts by mass, of powdered calcium chloride and urea, and then with water containing the bacteria (see **Figure 15**). The amounts of calcite precipitated, measured after the mechanical tests, are shown in **Figure 16**. For UCS specimens, there is a clear relationship between the amount of urea added and the amount of calcite. Triaxial samples, on the other hand, show considerable dispersion and variability in the precipitated amount of calcite quantified using acid-wash test. Nevertheless, when the uniformity of calcite precipitation is verified after the test, there is a variability of less than 5% of the amount of calcite in each sample. The calcite concentration in the UCS samples and some typical data were included in **Table 2**.

Figure 16 shows the amount of calcite. However, the amount of calcite in the triaxial specimens has increased. In addition, the variability of the data could be the result of a change of procedure during saturation. In some initial tests, calcite was removed from the samples when pumping water, which could explain some of the lower results. However, in the majority of tests, it is simply a question of pumping water into the samples, and there is no need to lose nutrients or bacteria. The variability of the amount of calcite obtained from the UCS and triaxial tests can be motivated by several reasons. In addition to the hardening time and access to the air causing the drying of the samples, it was the same during triaxial tests; no particular action was taken. Differences in soil temperature and pH during sample preparation may also have contributed to differences in calcite precipitation.

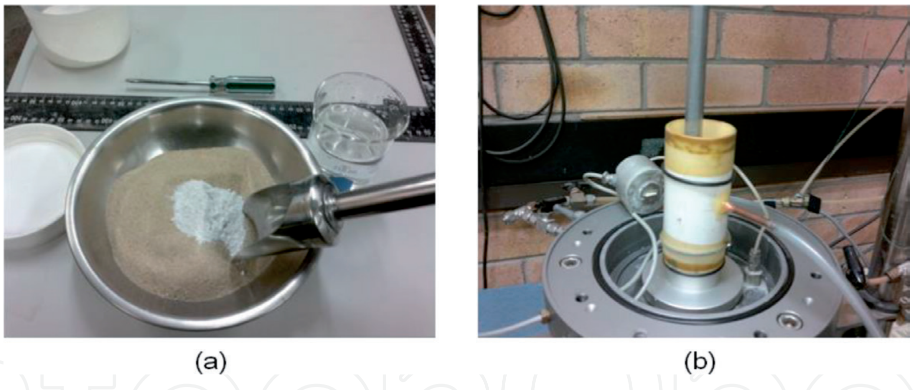


Figure 15.
Procedure of (a) mixing and (b) molding bio-cemented samples for triaxial test.

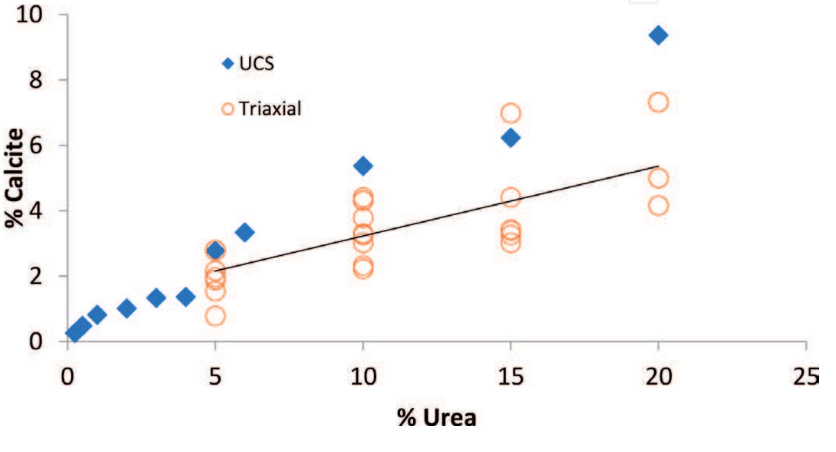


Figure 16.
Relation between amount of urea in mixture and calcite measured posttest.

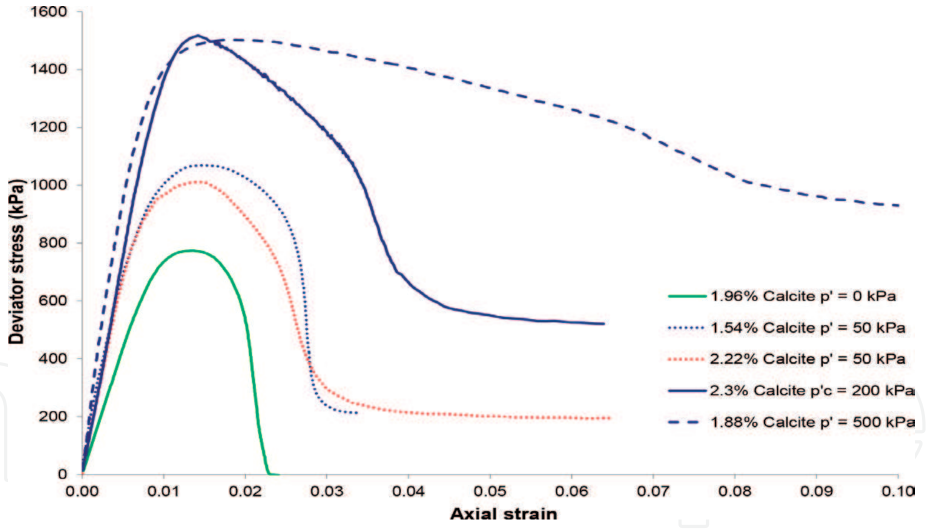


Figure 17.
Deviator stress, axial strain responses for bio-cemented specimens (1.5–2.3% calcite).

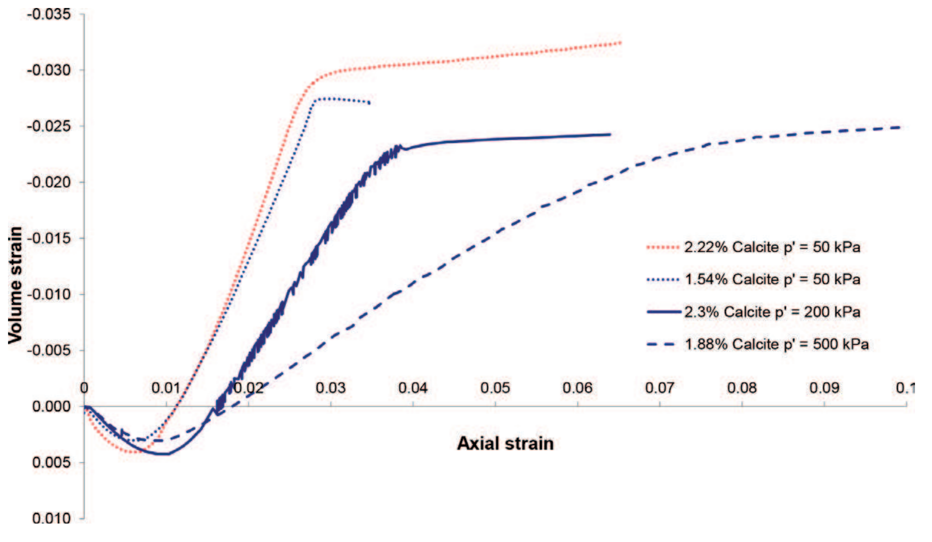


Figure 18.
Volume strain, axial strain responses for bio-cemented specimens (1.5–2.3% calcite).

To study the effects of confining pressure and calcite, different ranges of calcite sample were prepared. In all cases, these differences were prepared in the same way. **Figures 17** and **18** show the stresses, deformations and volume stresses, and axial strains, resulting from a series of CID drained tests with different confinement constraints for the lowest calcite contents, ranging from 1.5 to 2.3%.

The set of tests includes a sample for which the membrane leaks because the cell and the back pressures were equal. This has been done effectively on a totally saturated sample. The UCS tests are shown in **Figure 4**. **Figure 4** suggests a UCS strength of about 300 kPa for a calcite content of 2%. Past research [21] claims that the strength of the UCS in bio-cemented sample is influenced by the level of saturation. However, [21] reported that the degree of saturation causes an increase in UCS, which is the opposite trend of the current study. Previous research [13] has therefore focused on the localization of calcite, with lower degrees of saturation leading to precipitation only at particle contact. In this chapter, all samples have been prepared so that there is no significant saturation effect on the results.

The results shown in **Figures 16** and **17** indicate a general tendency toward strength and stiffness increase with the confining constraint. However, at a

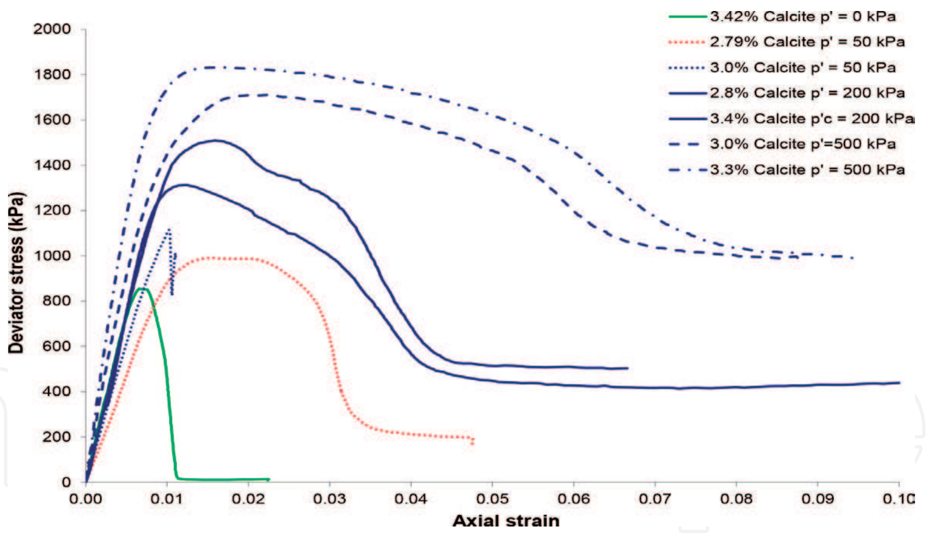


Figure 19.
Deviator stress, axial strain responses for bio-cemented specimens (2.8–3.4% calcite).

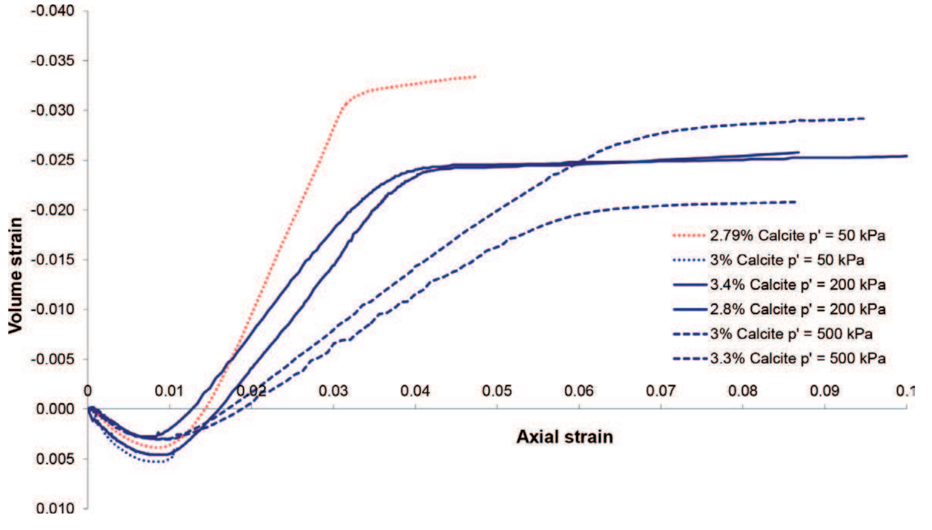


Figure 20.
Volume strain, axial strain responses for bio-cemented specimens (2.8–3.4% calcite).

confining stress of more than 200 kPa, the resistance becomes more obvious. This could be due to the lower calcite content in the more heavily stressed sample. It can also be noted that the cumulative response of the sample subjected to higher stresses shows less compression and more gradual expansion, which corresponds to a lesser effect of cementation. Thus, the calcite content is not only low but also the level of increased stress. Nevertheless, the general behavior patterns correspond to those expected for cemented specimens and are similar to gypsum cement.

Figures 19 and **20** show the effects of confining stress for a series of triaxial CID tests with calcite contents between 2.8 and 3.4%. Another UCS test is available for a saturated test in this cement content range, as previously following the rupture of the membrane. The UCS resistance of 820 kPa is again significantly higher than expected in the UCS tests of **Figure 4**, giving a value of 450 kPa for a calcite content of 3.4%. Reasonably consistent, all bio-cemented specimens showing increased in strength and stiffness as containment stress increases. For lower calcite levels, the rate of expansion tends to decrease as the level of stress increases, although the effect is less pronounced for those more cemented specimens. The trends are generally similar to those of the lower calcite content.

7. Conclusion

The following concluding remarks are made based on the performance and behavior of bio-cemented Sydney sand:

- Bio-cemented samples were prepared by mixing sand, bacteria, and nutrients, as well as samples cemented with gypsum. It has been found that it produces no damage when produced by the sample preparation method. A mixing technique is recommended to study the response of a weakly cemented material. However, there are limits to mixing with the content of the mixture.

- As shown in several other studies, calcite is an extremely effective cementing agent, and, for a given amount of cement, it offers higher strength and stiffness than other cementing agents. The results show that the strength in the UCS tests is similar to, or slightly higher than, the samples treated with injection techniques. At the same time, the problem of injection site obstruction was avoided by using an ex situ mixing technique, and this has been successfully demonstrated as feasible at the laboratory scale.

- The patterns of behavior observed in bio-cemented Sydney sand in triaxial tests are very similar to those of gypsum-related specimens. The results were reasonably consistent throughout the laboratory tests. The results of the triaxial tests were obtained with the amount of calcite produced, and it is difficult to predict the degree of cementation.

- The use of automated shear wave velocity measurement has enabled variations in stiffness, and hence degree of cementation, to be monitored throughout the processes of curing, stress application, and shearing. However, the large changes in shear wave velocity associated with curing have caused some difficulties in obtaining reliable data.

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Author details

Youventharan Duraisamy[1]* and David Airey[2]

1 Department of Civil Engineering, Universiti Malaysia Pahang, Kuantan, Malaysia

2 School of Civil Engineering, The University of Sydney, NSW, Australia

*Address all correspondence to: youventharan@ump.edu.my

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