RESILIENT FOUNDATIONS: BUILDING IN REPAIR CAPABILITY

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ABSTRACT

There is considerable literature on strategies for the repair and self-healing of concrete structures. However, in geotechnical engineering there has been much less interest in the repair of foundation elements. Typical remediation strategies involve provision of extra piles or further ground improvement. One of the approaches which is seen as promising in concrete repair is the use of bio-cements. These are solutions where bacterial actions result in the precipitation of a chemical that can act as a cementing agent. The most widely investigated of these is the use of ureolytic bacteria to precipitate calcium carbonate.

The paper provides a review of repair strategies and techniques used in concrete to encourage self-healing should damage occur. It describes the MICP process, and presents data showing how bio-cement can improve the strength and stiffness of sandy soils. Finally the paper reports results from some preliminary laboratory model tests performed to investigate the ability of bio-cement to repair cemented soil columns.

1 INTRODUCTION

In recent years, there has been increasing interest in self healing concrete materials that have the ability to repair cracks. These have the potential to significantly increase concrete durability by preventing access of corrosive agents to the reinforcement and improve their water tightness, and as a result reduce the need for inspection and maintenance. Research into engineering self healing in concrete was first initiated to reduce the amount of cement needed in concrete mixes (Gerilla et al., 2007; Peris Mora 2007) as part of global efforts to reduce greenhouse gas generation. This is a significant initiative as cement production is currently responsible for about 5% of global CO_2 emissions (IPCC, 2013). The inspiration for the study of self-healing concrete is the ability of living organisms to rapidly detect and repair damage. In concrete, degradation usually begins with micro cracks that lead to corrosion and eventually structural failure. The main form of damage is cracking and thus self-healing concretes must have the ability to repair small cracks and fissures autonomously. The feasibility of self-healing in concrete has been discussed in several studies (Neville, 2002, Reinhardt & Jooss, 2003, Li & Yang, 2007 and Edvardsen, 1999).

Previous research work has demonstrated that concrete repair can be produced by three different processes: natural, chemical and biological. This paper is primarily concerned with biological processes as these are considered to have self-healing potential and they have been shown to be capable of repairing concrete materials. For example, Ghosh et al. 2008, have reported that cement based materials created by biological action exhibited better durability and crack repairing performance than normal concrete. The healing potential of these biological processes are directly related to the amount of calcium carbonate that can be precipitated. Calcium carbonate can be precipitated microbially during urea hydrolysis, denitrification, and iron and sulphate reduction processes (Al-Thawadi 2011). Of these, urea hydrolysis has been the most widely investigated and it has been applied in a range of applications which include bio-remediation, concrete repair (Bang et al., 2010, Ramachandran et al., 2001) and bio-grouting (Paassen, 2009, Paassen et al., 2010). The mechanism of bio-cementation involves the precipitation of calcite, which then bonds to the sand particles. The chemical reactions can be described by Equations 1 and 2. Equation 1 describes the hydrolysis of urea which leads to the production of ammonium and carbonate ions. This reaction is catalysed by the enzyme urease, which is common in a wide range of soil microorganisms. It can be readily induced by adding inexpensive substrates, and is involved in several biotechnological applications (Stocks-Fischer et al., 1999, Hammes et al., 2003). In addition to the reaction requiring bacteria to produce urease, control of temperature and pH is also vital.

$$NH_2 - CO - NH_2 + 2H_2O \leftrightarrow 2NH_4^+ + CO_3^{2-} \quad \textbf{(1)}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad \textbf{(2)}$$

To produce calcium carbonate a calcium source must be provided, which is commonly provided by adding calcium chloride ($CaCl_2$) although a wide range of calcium compounds have been used.

The application of bacteria to assist with repair in the construction industry is not new. Bio-cements have been used to enhance the durability of building structures and the conservation of cultural heritages because of their self-healing potential. Previously, the potential of bacteria to clean concrete surfaces (DeGraef et al., 2005), to improve the strength of cement-sand mortars (Dick et al., 2006, Ghosh et al., 2005), to repair degraded limestone and ornamental stone surfaces (Rodrigues-Navarro et al., 2003) and to repair cracks on the surfaces of concrete structures (Bang et al., 2001, Ramachandran et al. 2003) have been investigated. However, relatively less attention has been given to the possibility of repairing sub-structures and foundations.

In this paper we describe the procedure for creating bio-cemented soil, and demonstrate the ability of the precipitated calcium carbonate to effectively bond a uniform sand. To demonstrate the potential of the bio-cement for ground improvement cemented columns have been created in dry and saturated sand and these have been shown to lead to significant gains in foundation strength and stiffness. During this process it was noticed that the cemented columns broke into two pieces and this has enabled a study of the ability of bio-cement to repair the cemented columns. Three different methods of repair have been investigated.

2 MATERIALS AND METHODS

2.1 SOIL PROPERTIES

The soil used in the triaxial and model tests is Sydney sand, a quartz sand with sub-angular particles. Some of the basic soil properties obtained using Australian standard tests and the particle size distribution are shown in Figure 1.

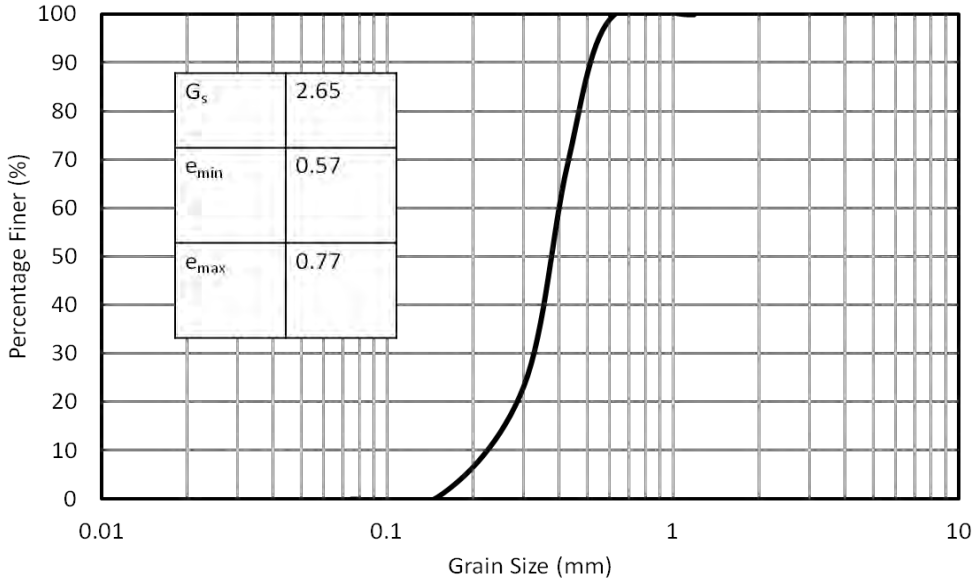

Figure 1: Properties and the particle size distribution of Sydney sand.

2.2 BIO-CEMENTATION

A non-pathogenic microorganism Bacillus megaterium has been used as the urease source to catalyze precipitation of $CaCO_3$. This organism has not received much study, but has been used because previously investigated bacteria were not readily available.

The first step in producing bio-cemented specimens was to culture the bacteria. This involved placing the bacteria (Bacillus megaterium), from American Type Culture Collection (ATCC14581), into a liquid solution comprised of the ingredients shown in Table 1. This mixture was placed in an incubator at a temperature of 30°C for 24 hours.

This produced a highly enriched bacterial solution of 100mL with a bacterial concentration of approximately 9×10^9 cfu/mL. The bacterial solution was then mixed with sand, additional urea, water and calcium chloride and used to create either cylindrical soil specimens or cemented soil columns. The mixture without the sand was also injected into the soil and broken soil columns to enable ground repair. The cultured bacteria continue to multiply in the wet soil mixture, provided sufficient nutrients are available, and facilitate precipitation of calcium carbonate.

Table 1: Liquid medium for bacterial growth

Nutrient Broth	3g	$NaHCO_3$	2g
Urea	15g	Glucose	10g
NH_4Cl	10g	$CaCl_2$	3g

2.3 SAMPLE PREPARATION AND PROCEDURE FOR UCS TESTS

Unconfined compression tests have been used to investigate the effects of the bio-cement on the soil strength and these have been compared with the effects of adding gypsum. To produce bio-cemented samples similar amounts of urea and calcium chloride were used in every mix and the amounts of each were in the range of 0.25% to 20% of the dry weight of the sand. Gypsum cemented samples have been prepared by mixing gypsum, sand and water, with weights of gypsum in the range of 5% to 20 % of the dry weight of the sand.

Specimens were prepared in a split cylindrical mould with lightly greased internal surfaces mounted on a flat base. The sand-cement mixtures were placed loosely in the mould and then lightly tamped to achieve specimens of a uniform dry density, with initial dimensions of 55mm in diameter and 110 mm in height. After 24 hours curing, the split mould was disassembled and samples were left another 6 days to cure. The dimensions of each specimen were checked again before loading. Specimens were then placed on the loading frame and subjected to standard UCS test procedures. An automated loading frame with maximum capacity of 50kN was used to apply a constant displacement rate of 1.14 mm/min.

After completion of the tests on the bio-cemented specimens the amount of calcite precipitated was measured. Sub-samples from parts of the specimens were dried in an oven at 121 °C for 24 hours then weighed. The samples were then flushed with 1M HCL to dissolve the calcite, rinsed with deionized water and then dried for 24 hours. The change in weight of the soil was considered to be the weight of the dissolved calcite.

2.4 PHYSICAL MODEL TEST SET-UP

The objectives of the foundation tests were to demonstrate the ability to create bio-cemented soil columns using ex-situ mixing and to demonstrate the potential of this technique to improve the foundation performance. The procedure for creating the cemented soil columns in this laboratory scale system was designed to be in accordance with deep soil mixing technology. The apparatus shown in Figure 2(a) has been developed for this purpose. It consists of a 600 mm diameter vessel, 500 mm high, which is filled with Sydney sand. The column forming system consists of a vertical frame which enables the lowering and raising of the auger spinning motor, auger and tube holder. In order to maintain experimental consistency and the reproducibility of column formation, a three level travel stop (L1, L2 and L3) mechanism has been used. This enables the column length, the rate of introduction of the cementation liquid and nutrients over the length of the column and the mixing cycles to be controlled accurately and consistently. The speed of the auger spinning motor is adjustable from 5 to 50 rpm. The shaft length of the auger and the blades are 350 mm and 35 mm, respectively.

Cemented soil columns, 38 mm in diameter and extending 200 mm below the surface, have been created in the centre of the confining vessel. To create a cemented column in dry soil, a PVC tube is attached to the fixed frame and placed in the tank to ensure the verticality of the column. While the auger is in the upper L1 position, one third of the dry urea and calcium chloride powders, or gypsum, are carefully poured in using a funnel. The auger is then moved to the middle L2 (position as shown in figure 2(a)) and soil is thoroughly mixed with the additives (gypsum/urea powder) at medium speed. The auger penetration and withdrawal is controlled manually by rotating clockwise at constant speed. After 30 seconds of mixing, the auger is lowered to the bottom L3 position and mixing is continued. This procedure is repeated until the remaining urea and calcium chloride powder (or gypsum) are mixed in. This is followed by pouring in the liquid, either the bacterial solution for the bio-cement or water for the gypsum, before ending with two more cycles (L2 and L3) of mixing at maximum speed. Immediately after finishing mixing the auger is detached from its holder, the column is gently tamped to counter the loosening during auger withdrawal, and the PVC tube is pulled out. The column is then left in the vessel for 24 hours to allow curing to occur before loading. A similar procedure was also used to create cemented columns in wet soil, except that liquid did not need to be added and the bacterial solution was injected using a syringe.

Figure 2(b) shows the experimental setup of the model footing tests. A 90 mm diameter circular footing, 12 mm thick, was placed on the sand surface and the surface was leveled flush with the top of the cemented column. The footings have been vertically loaded to large displacements at a constant deformation rate of 0.076 mm/min. The vertical loads, measured by a 250kg capacity load cell, and displacement, measured by an LVDT transducer, were automatically logged at frequent intervals. A series of tests with bio-cemented columns using different urea amounts, and with gypsum cemented columns with different gypsum amounts have been conducted. Additional tests have been conducted without the cemented columns. Tests have been performed for a range of sand relative densities. To obtain a consistent soil density in the vessel for each test, Sydney sand was poured from a fixed height.

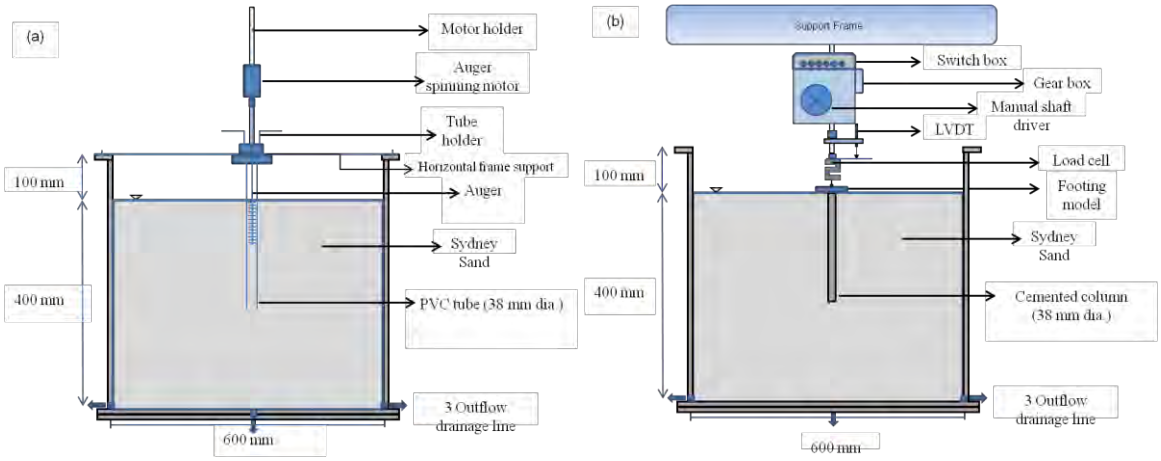

Figure 2: Scematic diagram of (a) column mixing and (b) footing test configuration.

2.5 COLUMN REPAIR METHODS

The physical model tests outlined above were extended to study the potential of bio-cement for repairing damaged pile foundations. As discussed further below, loading of the footing led to all the cemented columns breaking into two, approximately one footing diameter below the surface. Three different strategies were investigated for repairing the damaged columns. In all cases the cemented columns were made by mixing 15% gypsum with the sand. To allow for later repair a glass rod of 8 mm diameter was placed in the centre of the columns after mixing in the gypsum, and this was removed after 2 hours when the gypsum had set leaving behind a hole down the centre of the column for the full length of the cemented column. The column was then left to cure for at least 24 hours before loading the footing. The footings were loaded until a sudden drop in load indicated the breaking of the column. At

this point load was removed and the column repaired. The first repair technique involved injection of the bacterial solution (bacteria and nutrients) around the cemented column in the vicinity of the break as shown in Figure 3a. Five points, equi-spaced around the column were injected with 2 mL of the bio-solution, with each point at a distance of about 40 mm from the centre of the column. The second repair technique involved simply pouring 10 mL of the bio-cement forming solution into the hole in the centre of the column using a funnel as shown in Fig 3(b). The third repair technique also involved pouring 10 mL of nutrients (urea + $CaCl_2$) into the central hole, but in this case no bacteria were added. The third approach was used on columns that had already been repaired using the second method and had been reloaded to failure. The third technique was designed to assess whether residual bacteria from the previous repair could be reactivated by providing additional nutrients. Tests have been performed with the sand surrounding the cemented columns in both dry and saturated states.

(a) (b)

Figure 3: Foundation repair using (a) injection into surrounding sand and (b) pouring solution into the hole in the centre of the column.

3 RESULTS

3.1 UNCONFINED COMPRESSIVE STRENGTH

The variations of the unconfined compressive strength of gypsum and bio-cemented specimens with unit weight are shown in Figure 4(a). This figure shows that the strength increases with dry unit weight, and that a similar trend is observed for both the bio-cemented and gypsum cemented specimens. Interpretation of Figure 4(a) is not straightforward as the increases of unit weight are also associated with increases in the amount of calcite in the bio-cemented specimens, and increases in the gypsum content in the gypsum cemented specimens, and it is well established that the strength of artificially cemented soils increases with both cement content and unit weight. The similarity of the behaviour of soils cemented with gypsum and calcite has been noted in other studies (Ismail et al., 2002), and this is why comparative tests using gypsum are included here. Furthermore, the similar strengths of calcite and gypsum cemented specimens suggest that the method of calcite precipitation is not that important.

Figure 4(b) shows the relations between the amount of urea, which is the same as the amount of calcium chloride, in the bio-cement mixtures and the amounts of calcite precipitated and the UCS. Figure 4 also shows that the amounts of calcite precipitated in each specimen at three locations (top, middle, and bottom) are similar without any consistent pattern. There was less than 5% variance in the calcite distribution which compares favorably to other

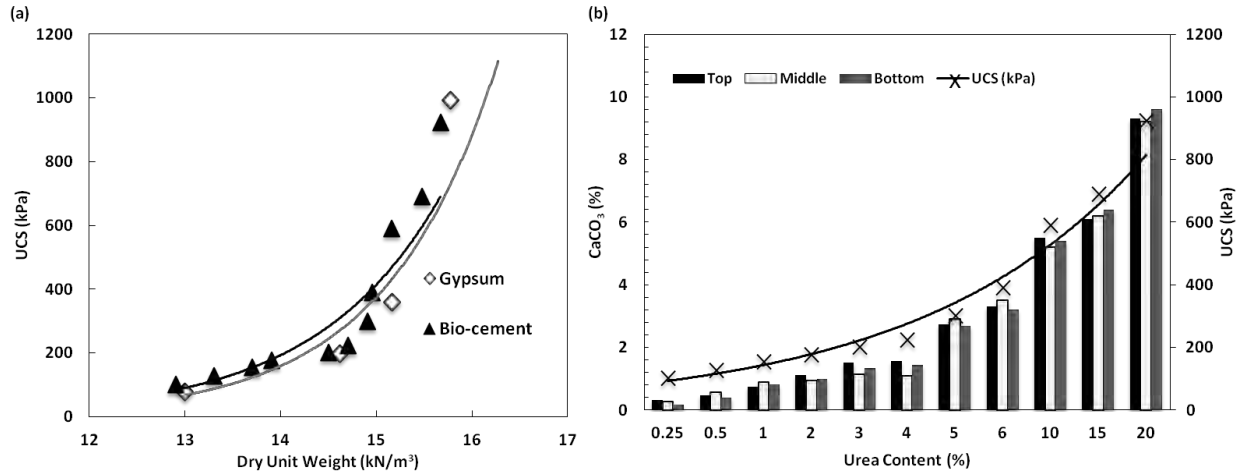

Figure 4: Variations of UCS strength with (a) dry unit weight (b) urea content of bio-cemented sample.

methods used in the past to create bio-cemented specimens (Martinez et al., 2011; van Paassen et al., 2009; Whiffin et al., 2007).

The amount of calcite precipitated is generally reported as the amount of bio-cement and this can be correlated with the UCS strength. This provides a strong linear correlation (R^2= 0.97) which can be described by Equation 3, where C is percentage of calcite precipitated. The trend of linearly increasing strength with increasing calcite content is similar to that previously reported (Al Qabany et al., 2011). Alternatively, the amount of urea required to precipitate the calcite, can be used as a means to estimate and monitor the degree of cementation in this study.

$$UCS(kPa) = 89.9C + 83.7 \quad \textbf{(3)}$$

Analysis of the data shows that the calcite cement is twice as effective as the gypsum, that is the UCS strength with 10% gypsum is similar to the UCS strength with 5% calcite. For example, Figure 4b shows that approximately 5% calcite is produced by adding 10% urea and 10% calcium chloride to the bacterial solution.

3.2 MODEL TESTS

Figure 5 shows the evolution of the average vertical pressure (load divided by area of the footing) with vertical displacement for the model footing tests. Results are shown for surface footings, footings on gypsum cemented columns, and footings on bio-cemented columns. The soil surrounding the columns was Sydney sand with a relative density of about 60% in both dry and wet conditions. As expected, the cemented columns significantly increased the stiffness of the foundation response compared to the tests with no columns, and increasing amounts of both gypsum and bio-cement increased the stiffness and load carrying capacity of the footings. All footings on the dry sand failed in a general shear mode, with a shear plane forming and breaking the column about one diameter below the footing. Failure was associated with a sudden loss in load and tests were terminated when this occurred. In the saturated sand the columns also failed in a similar manner, however this was not evident in the load, deformation responses (Figure 5b) which generally showed a monotonic increase in resistance. The tests in saturated sand also appeared to show a smaller difference than for dry sand between the footings with and without the cemented columns.

In UCS tests it was found that the strength and stiffness of specimens cemented with either gypsum or calcite were similar when the percentage of calcite was half that of gypsum. However, in the footing tests the gypsum cemented columns were superior to the bio-cemented columns with equivalent UCS strengths, providing higher strengths and stiffnesses. This difference was more pronounced in columns mixed in saturated soil where gypsum cemented columns gave almost double the resistance of the bio-cemented columns. These differences are believed to be

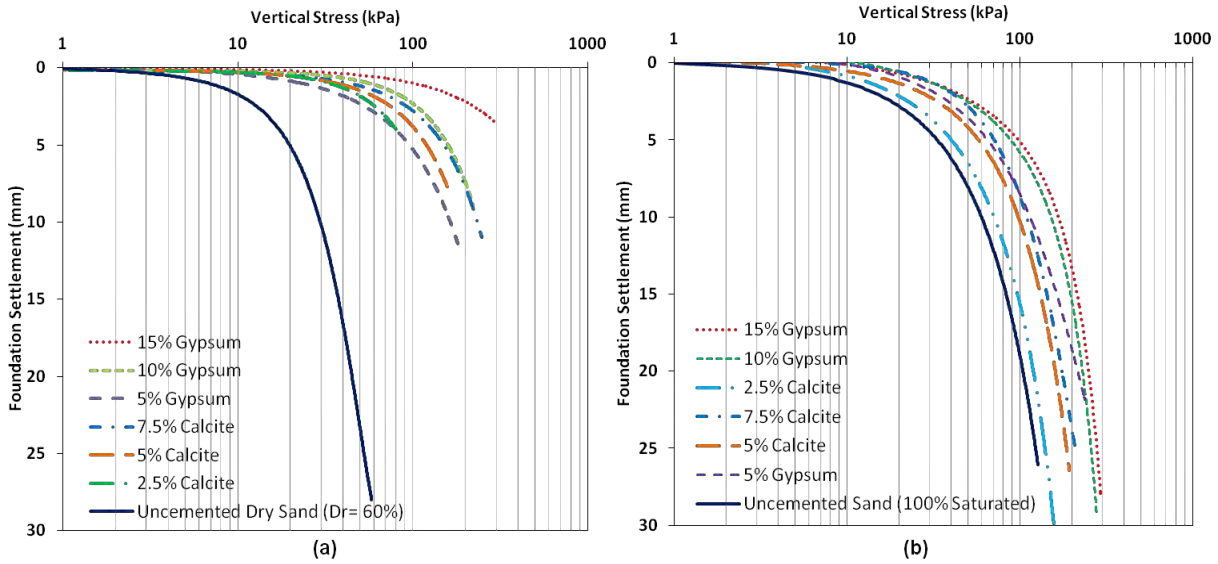

Figure 5: Stress, displacement responses from model foundation tests in (a) dry sand (b) saturated sand.

related to insufficient curing of the bio-cemented columns. By monitoring the shear wave velocity it has been found that about 24 hours is needed for completion of the bio-cementation reaction in UCS specimens (Duraisamy, 2015), but the extra 6 days curing time of the UCS specimens may have resulted in some additional slight strength increase. Under saturated conditions the curing process of the bio-cemented specimens could be affected by the surrounding water. This is possible because dilution by the water may limit changes in pH which are necessary for calcite precipitation. During microbial activity in soil the pore fluid pH increases and calcite typically precipitates when the pH is 8.5 to 9.0 (Stocks-Fisher et al. 1999).

In practice cemented columns are used to control settlements and in these model tests settlement reductions of 50% in dry sand and 32% in saturated sand were observed using bio-cemented columns (7.5% calcite). Similar trends were also observed in other footing tests when the sand surrounding the columns had relative densities of 40% and 50%. Similar settlement reductions have been reported in other model tests using bio-cementation (Martinez and Dejong, 2009). These tests have shown the potential of bio-cementation to create cemented columns of sand, however uncertainty remains regarding the influence of the ambient temperature, which can affect the calcite precipitation; the speed of the mixing auger which can affect the bacterial activity and influence the amount and distribution of calcite; and the curing time required on site.

3.3 COLUMN REPAIR

As noted above all the columns broke about one footing diameter below the tops of the columns. Figure 6 shows the response of the footings on initial loading and in both dry and saturated sand a distinct peak in the stress, deformation response is observed. After unloading, two of the footings were reloaded to show the response without any repair. In each case the stress increased to the value before unloading and then decreased with further deformation. Three methods of repair were then investigated using the bacterial solution to precipitate calcite and restore the columns. In repair method 1 in which the bio-cement is precipitated around the column the foundation stiffness is similar or less than for the failed reloaded column. This suggests that the cement has not been effective in repairing the column, however, the effect of the cement is evident at large settlements where the repaired column shows a higher resistance. In the second repair method where the bacterial solution is poured into a central hole in the column the solution can flow through the region of the break and calcite precipitated there can weld the two parts of the column back together. Evidence that this has successfully occurred can be inferred from the high stiffness and the higher resistance than the reloaded footing seen in Figure 6a for the footing on repaired column 2. The effect of this repair approach does not appear to be so successful in saturated sand (Figure 6b), although even in

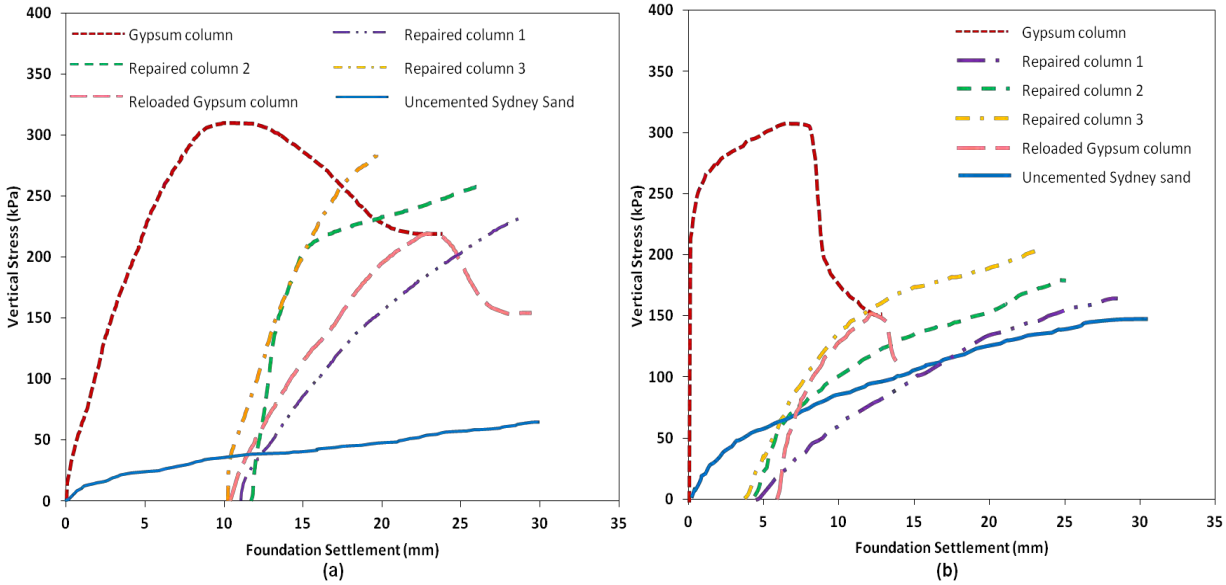

Figure 6: Stress, displacement responses from repaired model foundation tests in (a) dry sand (b) saturated sand.

this case there does appear to be some benefit of the repair at large settlements. In the third repair method the previously repaired column 2, which had been loaded to its breaking point, was repaired again by adding nutrients without any bacteria. The responses in Figures 6a and 6b shows that after this repair (Repaired column 3) the best foundation response was obtained, which suggests that additional calcite has been precipitated. This indicates the potential for self healing exists provided the column has bacteria present at the time of construction and nutrients for the bacteria can be provided as and when required to heal and cracks.

4 DISCUSSION

The challenges of producing uniform and strong bio-cementation have been noted in many studies, and to date none of the methods proposed has proven to be suitable in field application. It has been shown in this study that simply mixing the bacteria, nutrients and soil can produce uniformly cemented specimens suggesting that ex-situ mixing combined with dry soil mixing technologies may provide a viable method for application of bio-cementation. However, it has been noted that obtaining effective bio-cementation in saturated sand is more difficult than in dry sand and further study is needed to investigate whether longer curing periods will result in the same strength for the same amount of precipitated calcite. It was also observed that more nutrients were required to produce a given amount of calcite in saturated sand than in dry sand.

The effects of the repair techniques could also be investigated by extracting the columns from the sand after the loading tests. Two repair mechanisms could be identified. First, in the tests where the bacterial solution was injected around the pile evidence of calcite precipitation on the surface of the column was evident as can be seen in Figure 7a. This precipitation appeared to be primarily filling in cracks in the column surface created during the first loading. There was no evidence of cemented sand surrounding the column, but this may have been because this cementation was broken down during the loading of the repaired column. These observations suggest that injection of bacterial solution in the vicinity of cracks may be effective in sealing them and be able to prevent damage from water entry. Second, when the bacterial solution was poured through the central hole it was able to weld the two parts of the damaged column together as shown in Figure 7b. This observation suggests that there is potential for pile repair providing provision is made for tubes that can enable the bacterial solution to be directed to regions needing repair.

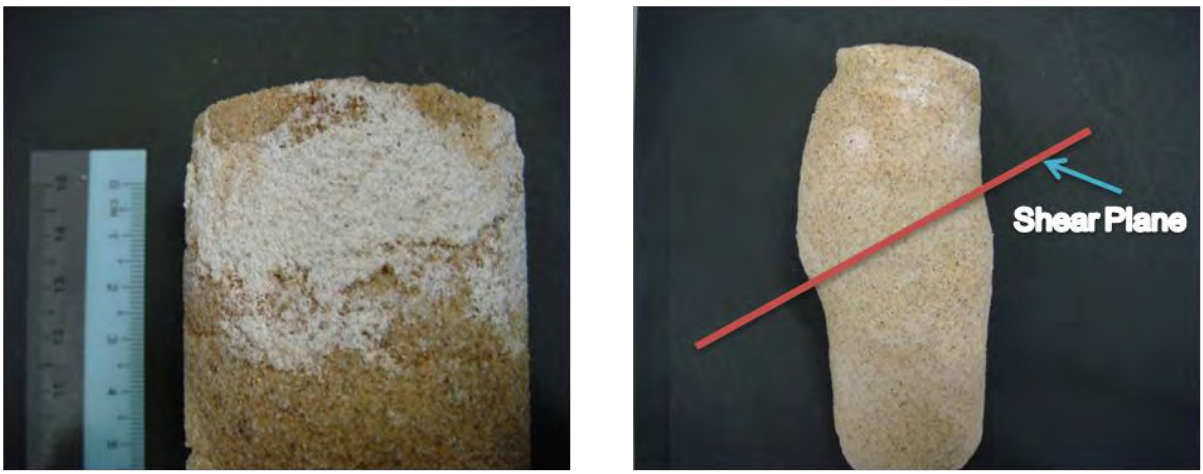

Figure 7: Samples retrieved from model test showing (a) sealing (b) welding effects.

Self-healing strategies generally rely on the bacteria and nutrients being available when repair is required. This can be achieved by encapsulating cells of bacteria and nutrients which are released if cracks occur. The third repair strategy involved simply adding further nutrients and reactivating bacteria from an earlier repair. The success of this approach suggests that incorporation of bacteria in the original soil column may be beneficial for future repair and would require only the release of nutrients to enable self-healing.

Although these tests have shown the ability of bio-cementation to form and repair soil columns the applicability of this approach to real foundations needs further study. In particular, the resilience of the bacteria when subjected to stress and construction handling needs to be demonstrated. Even for cementing agents that are well understood it has been reported (Terashi, 2003) that strength parameters obtained from laboratory treatability studies are usually five times higher than those obtained in the field from deep soil mixing applications.

5 CONCLUSIONS

The patterns of behaviour observed in bio-cemented Sydney sand are very similar to those in specimens bound with gypsum and have been reasonably consistent throughout all the laboratory tests conducted. The laboratory tests have identified the quantities of nutrients required to produce a range of calcite contents and hence soil columns with a range of strength and stiffness. It has also been demonstrated that mixing of soil, bacteria and nutrients can produce specimens with a uniform distribution of cement. Small scale footing tests have been performed on sand improved by bio-cemented columns, where the column creation has modeled the deep soil mixing process. These tests show that bio-cement could be an alternative to existing cementing agents.

The ability of bio-cement to repair broken soil columns, either by injection around the periphery of the column or by injection into a hole in the centre of the column, has been demonstrated. The presence of bacteria can stimulate calcite precipitation when nutrients are provided, and this offers the potential for self-healing foundations.

6 ACKNOWLEDGEMENT

The authors would like to acknowledge the technical support from Mr. Ross Baker and Mr. Sergio de Carvalho.

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