General Report of TC101: Session III
Laboratory Stress Strain Strength Testing of Geomaterials: Soil Reinforcement

Rapport Général du TC101 : Session III
Expérimentation en Laboratoire des Géomatériaux : Sols Renforcés

Erdin Ibraim
Civil Engineering Department, University of Bristol, UK

ABSTRACT: This paper presents a General Report of 29 written contributions submitted for one of the parallel sessions, Soil reinforcement, of the Technical Committee 101: Laboratory Stress Strain Strength Testing of Geomaterials. The origin of the authors shows a wide geographical distribution. The General Report reviews these contributions and presents the current research directions mainly in relation to the experimental behaviour as well as the key outcome results. The topics covered by the written contributions have been grouped within the following thematic strands: mechanical stabilisation and chemical stabilisation by microbial induced cementation and by artificial cementation through the addition of various cementation agents.

RÉSUMÉ : Ce document présente un rapport général de 29 contributions écrites pour l'une des sessions parallèles, Sols renforcés, soumis au Comité Technique 101 : Expérimentation en laboratoire des géomatériaux. L'origine des auteurs montre une large répartition géographique. Le rapport général examine ces contributions et présente les axes de recherche actuels principalement en ce qui concerne le comportement expérimental ainsi que les principaux résultats. Les sujets couverts par les contributions écrites ont été regroupées dans les volets thématiques suivants : stabilisation mécanique des sols, stabilisation chimique par précipitation de la calcite induite par des microbes at par l'addition des agents de cémentation.

KEYWORDS: laboratory testing, fine soil, granular soil, soil stabilisation, soil reinforcement

1 INTRODUCTION

This paper presents a summary in the form of a General Report of the topics, current research directions and main results of the written research contributions submitted to the Technical Committee 101 (TC101): Laboratory Stress Strain Strength Testing of Geomaterials, Session III: Soil Reinforcement. TC101 promotes and actively encourages co-operation and exchange of information concerning research and developments in advanced laboratory geotechnical testing, including apparatus, techniques and interpretation, and their use in practical geotechnical engineering, site characterisation studies and ground modelling approaches.

TC101 sessions contain a total of 60 written research contributions. Their presentation is organised in four parallel sessions organised around the following themes: Thermo-Hydro-Chemo-Mechanical (THCM) behaviour, Soil improvement, Dynamic testing, and Sample handling, storage and characterization. This General Report particularly refers to 14 papers selected for the Session III: Soil improvement.

The origin of the authors of the papers selected for the Soil improvement session shows a wide geographical distribution with 4 contributions from North America, 3 from South America, 2 from Europe, 2 from Asia, 2 from Australia and one from Africa. USA and Brazil are particularly active in this research area and leading in terms of number of contributions with 3 papers each. 7 papers have been selected for oral presentation, while 7 papers are presented in the poster sessions.

Although the papers in this session explore the experimental aspects of the behaviour of stabilised/reinforced fine and granular soils using a large variaty of techniques and procedures, the analysis and interpretation of the results are enhanced by the complementary use of numerical, and analytical modelling approaches. In general, there is also a trend to correlate results along scales, from micro-structure to small scale element testing and model scale.

The quality of the soils involved in civil engineering, structural and infrastructural projects cannot be chosen. In most majority of the cases, their quality is not adequate and solutions for in situ improvement of their properties are necessary. In addition, the societal needs for reducing the demand for raw materials, enhanced design capabilities and long-term resilience performance including vulnerability resistance of geotechnical structures also require advanced solutions for soil improvement. The concept of enhancing the soil properties using reinforcing techniques is widely accepted in geotechnical engineering practice. Soil improvement solutions include: partially or complete replacement; preloading; soil compaction; mechanical stabilization using either tension-resisting elements such as strips, fabrics, geotextiles, discrete fibres, or using lightweight particulate inclusions like polymers or tire waste crumbs/chips derivatives; particle bonding through chemical cementation by addition of cement, lime, fly ash or other compounds or through microbial induced calcite precipitation (DeJong et al. 2010).

The research topics covered by the written contributions in this session can be grouped within the following thematic strands: (i) mechanical stabilisation (six research contributions) and (ii) chemical stabilisation by microbial induced particle calcite precipitation (three papers) and by artificial cementation through the addition of various cementation agents (five papers). The following sections report the results under these thematic strands.

2 MECHANICAL STABILISATION

Soil mechanical stabilisation is based on the use of a range of inclusions and relies on the mechanical interaction that develops between these inclusions and the host soil material. Depending on the practical applications, needs and other design considerations, the choice of the inclusions used for the soil reinforcement is normally based on their mechanical and geometrical properties. In this session, the research work considered several inclusions types from nano-silica particles (Garcia et al. 2017) to crumb rubber tires (Ajmera et al. 2017), synthetic coarse aggregates (Campos et al. 2017), and low density polyethylene pellets and flakes (Nolutshungu and Kalumba 2017), as well as discrete fibre elements (Senez and Casagrande 2017) and planar inclusions (Morsy et al. 2017). Nan-osilica and crumb tyres are mixed with fine grained soils of low mechanical properties, synthetic coarse aggregates are used in asphalt mixtures for roads, while the pellets, flaxes, fibres and planar inclusions are used to improve the response of granular soils.

Garcia et al. (2017) were studying the stabilisation of a lacustrine soft clay of high plasticity from a site in the Texcoco ex-lake (Mexico) with nano-silica (nano-SiO_2) particles. Nanoparticles have a high surface-area-to-volume ratio and although no details of their actual size and type are given, provide a specific area of 600 to 785 m^2/g. Three different soil materials (different liquid and plastic limits) sampled from this site were mixed in laboratory with different nano-silica contents from 0.5% to 3% by soil dry weight. The influence of nano-silica on the mechanical strength development was assessed through unconfined compression tests (UCS). The addition of nano-silica to the lacustrine soft clays was found to systematically increase the unconfined compressive strength nano-silica content dependent. Typical UCS stress-strain responses of the Soil No. 2 (LL 205%, LP 68%, w 90%, γ_m= 1.2 t/m^3) are shown in Figure 1. While it was found that the liquid and plasticity limits, and plasticity indexes of the treated soils are not affected by the presence of the nano-particles, the clays become less compressible with the increasing of SiO_2 content. A change on the way that failure occurs is also observed when nanoparticles are present with no tensile cracks developing. Scanning electron microscope (SEM) images of soil samples reveal some interesting observations and can provide some insight on the reinforcement and interaction mechanisms at the materials micro-scale: while the natural samples show a dispersed structure (Figure 2(top)) with clay particles and clay clusters prone to sliding if clay sheared, an increase of nano-SiO_2 content promotes the packing of clay particles, decreasing the volume and distances between as well as the amount of water that develops a double-layer (Figure 2(bottom)). The nanoparticles of SiO_2 to may act as a nano-filler, improving the clay particle contact properties.

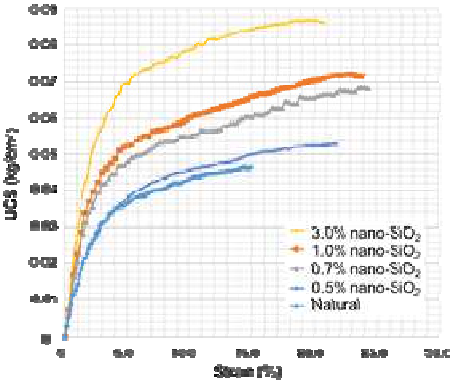


Figure 1. Stress-strain curves of clay stabilized with nano-SiO_2 obtained from unconfined compression test, Soil No.2 (Garcia et al. 2017)

The number of scrap tyres is increasing rapidly in both developed and developing countries due to the steady rise in the number of vehicles. Although there is an increased use of recycled tyres (e.g., replacement for some conventional materials in civil engineering industry, road construction), large quantities are still disposed in landfills, stockpiled or abandoned in the nature, thus generating ground pollution as they are not biodegradable. In this context, the possibility for further recycling options and use of rubber crumb derivatives in mixtures with granular soil particles, sand, can be a solution for some geotechnical applications like backfilling for retaining structures, slope and highway embankment or soil erosion prevention (Humphrey and Manion 1992, Garga and O'Shaughnessy 2000, Lee et al. 1999, Bosscher et al. 1997, Poh and Broms 1995, among others). However, one area that has not been fully explored is the use of waist rubber tires for stabilisation of weak clay soils.

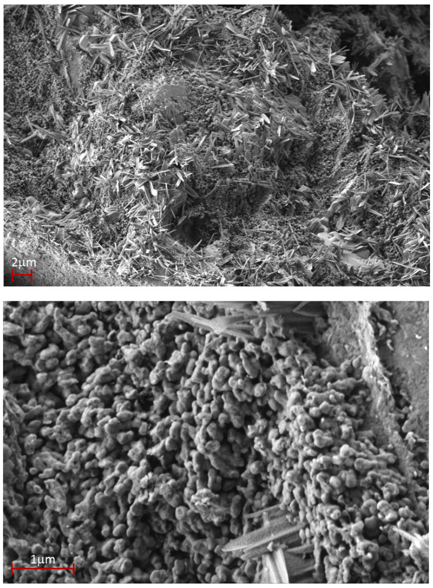


Figure 2. SEM images of Soil No.1: (top) natural specimen, (bottom) clay+3% nano-SiO_2 (Garcia et al. 2017)

The work presented by Ajmera et al. (2017) in this TC101 session explores this possibility and studies the response of five different types of fine-grained soils (kaolinite, granular kaolin, montmorillonite, 50% montmorillonite and 50% granular kaolin, and 50% montmorillonite and 50% quartz) when mixed with five different sizes of crumb rubber (passing through 4-16 mesh, 10-30 mesh, 30-50 mesh, 50-80 mesh and 80-200 mesh) at several proportions (0%, 2%, 4%, 6%, 8% and 10% by volume). The resulting mixtures were used to assess the the compaction characteristics, optimum moisture contents, unconfined compressive strengths, coefficients of permeability, drained shear strengths, and one-dimensional compressibility. The paper concentrates more on the kaolin soil, while full data can be found elsewhere (Obaid 2016 and Koirala 2015). Figure 3 presents compaction results for kaolin/rubber mixtures and it is show that the maximum dry unit weight is reached for about 4% crumb rubber of any size, while the maximum dry density decreases as the size of the crumb rubber increases. However, in mixtures with montmorillonite, a reduction in the maximum dry unit weight with an increase in the size of the crumb rubber was observed. It is also interesting to note that the maximum unconfined compressive strength was found for the same 4% crumb rubber proportion irrespective of the size of the crumb rubber used (Figure 4). A peak of the compression index was also observed for the kaolin mixture with 4% rubber content.

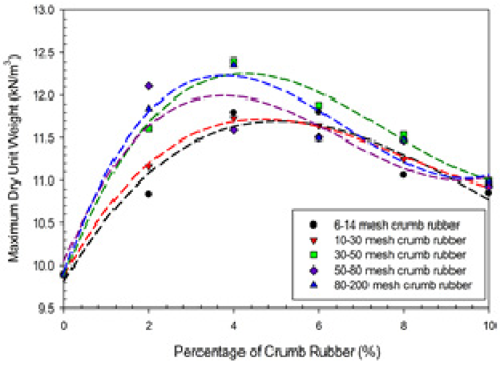


Figure 3. Variation in maximum dry unit weight with size and percentage of crumb rubber for kaolinite (Ajmera et al. 2017)

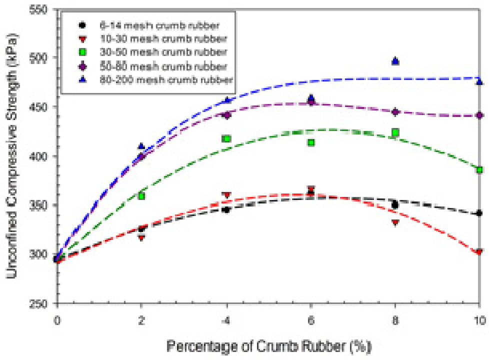


Figure 4. Variation of the maximum unconfined compressive strength with size and percentage of crumb rubber for kaolinite (Ajmera et al. 2017)

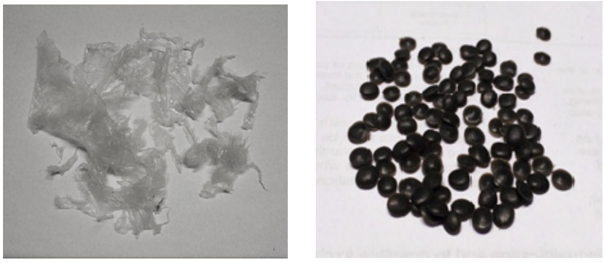
Higher rubber percentages than 2% did not result in any substantial additional changes in the coefficient of permeability of the kaolin. However, higher increases of the coefficient of permeability were observed for montmorillonite. Direct shear test conducted in drained conditions showed that both the angle of friction and the cohesion intercept increase with the addition of rubber but these values remain unaffected for the range of rubber proportions used in this study.

An interesting study driven by particular local soil conditions in the Brazilian Amazon region and economic considerations related to roads and pavement surface, was conducted by Campos et al. (2017). The acute shortage of coarse aggregate - pebble or crushed stone – used in asphalt led to a new technical, more efficient and environmental alternative by developing an unconventional replacing material based on the use of local natural clay. The production process adopted by the pottery industry was replicated for the production of Synthetic Coarse Aggregate of Calcined Clay (SCACC) (Figure 5). The temperature of calcination is also a variable in this study. A comparative analysis based on Marshall Stability and flow value, indirect tensile strength and resilient modulus tests between conventional hot mixed asphalt – using pebble as coarse aggregate - and that employing synthetic aggregate was made. In a general way, hot mixed asphalt using synthetic aggregate showed improved mechanical properties in comparison to the conventional mixture, mainly at higher temperature of aggregate calcination and reached better values of the asphaltic parameters, suggesting a better mechanical interaction at the particle level of constituents.

(a) (b)

Figure 5. Production process of SCACC: (a) natural clayey soil, and (b) after burnt at 850 ºC (Campos et al. 2017)

The viability of using recycled LLDPE plastic (linear low density polyethylene) waste material as soil reinforcement for ground improvement purposes was explored by the work presented by Nolutshungu and Kalumba (2017). The effect of the inclusion of two recycling process products, polyethylene flakes (fibre like) and pellets (granular like) as shown in Figure 6, on the shear strength of a sub-angular sand (Cape Flat sand: D_{50}=0.32mm, C_u=1.8, C_c=1.176) was conducted under drained triaxial testing conditions. Five flake percentages from 0.1% to 1% and five pellet percentages from 1% to 7.5% were mixed with the sand and tested in drained conditions under three confining pressures, 75kPa, 150kPa and 300kPa. Shear strength parameters obtained from the Mohr's circles for both inclusions are shown in Figure 7. While an increase in pellet contents induces an increase of the angle of friction due to a better sand/pellets interlocking mechanism, an increase of the flake contents shows a reduction of the angle of friction of the composite due to the plastic punctures which may reduce the flake/sand bonding mechanism. The cohesion increases and it peaks for 0.5% content of flakes, while a minimum is obtained for 3% pellet concentration.



(a) (b)

Figure 6. Recycled LLDPE plastic: (a) flakes and (b) pellets (Nolutshungu and Kalumba 2017)

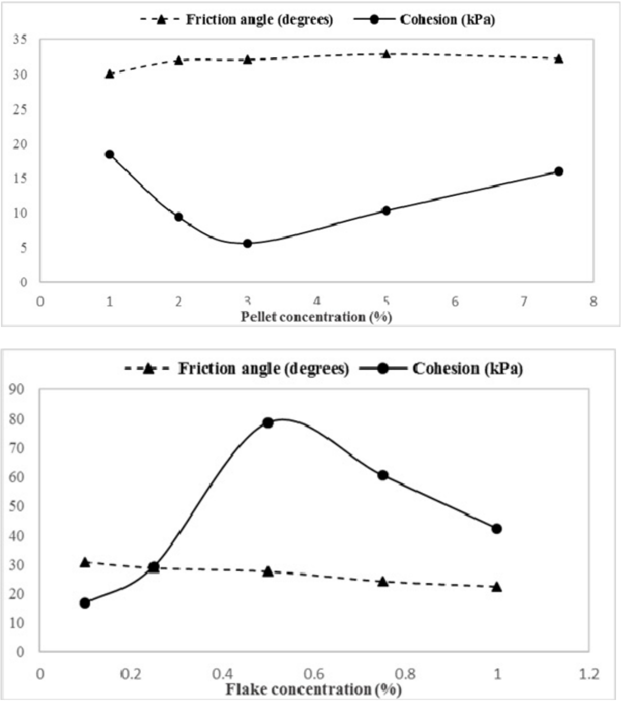


Figure 7. Friction angle and cohesion strength parameters at various: (top) pellet and (bottom) flakes concentrations (Nolutshungu and Kalumba 2017)

In a similar goal of using waste materials as soil reinforcement, Senez and Casagrande (2017) proposes to study the slope response improvement under loads transmitted by individual pad foundations. For this purpose, a small scale slope model test was designed and constructed in a box (80cm long x 60cm wide x 45cm deep) using a fine poorly graded sand on both unreinforced and fibre reinforced conditions and tested under a plate loading as schematically shown in Figure 8. As reinforcement, polymeric fibre type inclusion obtained from recycled materials of Ethylene Terephthalate, commonly known as PET, with a diameter of 0.0098mm and a length of 38mm, was used at a fibre content of 0.5% by dry weight of soil. The fibre/sand mixture was done at a 10% moisture content and at a dry unit weight of 14.4kN/m^3 (equivalent to a relative density of 50%). The fibre reinforced sand material showed a higher bearing capacity and reduced settlements when compared with the unreinforced soil. The failure mechanism under the plate loading is also affected by the fibre inclusions: the classical circular wedge failure is changing into a localised and much more constrained zone around foundation. The horizontal displacements of the slope for the composite soil was also observed to reduce considerably.

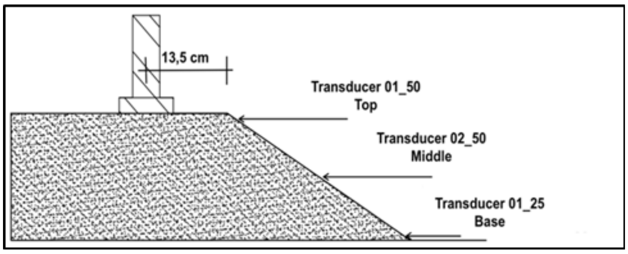


Figure 8. Schematic presentation of the small scale model of the slope and plate load test, including the position of the displacement transducers for lateral slope measurements (Senez and Casagrande 2017)

Traditional methods of earth reinforcement also use a large variety of continuous planar synthetic inclusions such as strips, fabrics or geotextiles (Koerner and Welsh, 1980). These inclusions are normally oriented in a preferred direction and the degree of strengthening and interaction between the reinforcement layer and surrounding soil are strongly dependent on the spacing between reinforcement layers. The spacing between reinforcement layers equally affects the degree of interaction between the soil-reinforcement interfaces of neighbouring reinforcement layers. Reinforcement spacing has also been reported to have a greater effect on the reinforced soil composite strength than that of the reinforcement tensile strength. Although research progress has been made in characterizing the soil-reinforcement interaction of individual reinforcement layers, further studies are still needed for the understanding of the mechanisms and extent of such effects. In this context, the work presented by Morsy et al. (2017) is timely and provides valuable insight into these complex interactions mechanisms, especially if the reinforcement spacing is comparatively small. For this purpose, a new large-scale pull-out geosynthetic-reinforced soil apparatus that can accommodate specimens up to 120cm deep, 150cm long and 75cm wide was developed and validated (Figure 9).

The apparatus was particularly designed to quantify the thickness of the soil shear band that develops in the vicinity of the soil-reinforcement interface by including a transparent side wall and it has the ability to vary the thickness of the soil layer above and below the main reinforcement, as well as the characteristics of the materials used as top and bottom boundaries that represent the presence of contiguous reinforcements. Additional technical developments include the assessment of soil dilatancy and the control of a zero-volume-change condition. Typical results for one of the tests are also presented and the new apparatus was found to provide high quality measurements of reinforcement straining in all geosynthetic reinforcements as well as measurement of soil deformation field via a digital image analysis, including determination of the evolution of the shear bands with the increases in the soil-reinforcement interface load. The equipment was also able to successfully monitor the dilative/compressive behaviour of the reinforced soil mass during the pull-out test.

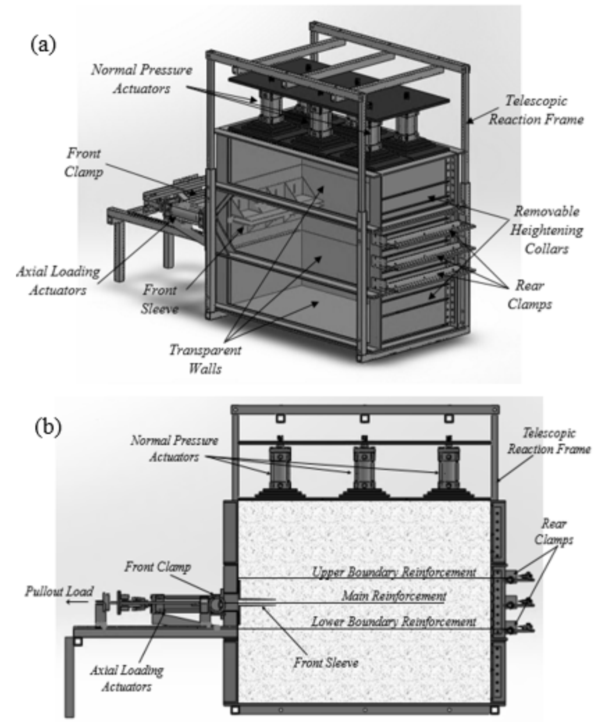


Figure 9. General view of the new large-scale pull-out equipment: (a) 3D perspective; (b) sectional side view (Morsy et al. 2017)

3 CHEMICAL STABILISATION

3 .1 *Microbial induced calcite precipitation (MICP)*

Three research contributions presented in this Soil reinforcement session refer to the microbial induced calcite precipitation (MICP) soil stabilisation technique: Do et al. (2017), Hata and Kaneda (2017), and Rahman and Hora (2017). While MICP has gained wide interest in recent years (Lin et al. 2015), this technique provides, in comparison to mechanical, chemical, and other reinforcement approaches, the advantage of an eco-friendly alternative (DeJong et al. 2010). As explained by Do et al. (2017), during the MICP process the bacteria in the presence of calcium ions hydrolyse urea to induce calcium carbonate ($CaCO_3$) precipitation at the soil particle contacts, which eventually leads to an increase in the strength and stiffness of the medium. Alkalophillic soil bacteria such as *Sporosarcina pasteurii* with high active urease enzyme is normally used for urea hydrolysis. In practice, two different approaches - bioaugmentation and biostimulation – are considered. In bioaugmentation, external microbes are either injected or percolated into the soil along with nutrient medium to help in their growth and calcite precipitation. In biostimulation indigenous microbes of the soil are stimulated with external nutrient medium thereby inducing growth and calcite precipitation.

The study of Do et al. (2017) focuses on the effect of the MICP on the strength and hydraulic conductivity properties of loose sand under low level of confining stress conditions. Triaxial and permeability tests were conducted on cemented and uncemented sand (D_{50}=0.49, C_u=2.48, C_c=0.99) specimens, while the stiffness evolution was assessed through shear wave velocity measurements with bender elements. To facilitate comparison between different specimens, the bio-treatment was conducted through multiple injections of the cementation solution until a target shear wave velocity of about 650m/s was achieved (Figure 10), in which case a moderately cemented specimen was obtained. The treatment was done under the constant low confining stresses of 10kPa, 30kPa and 50kPa.

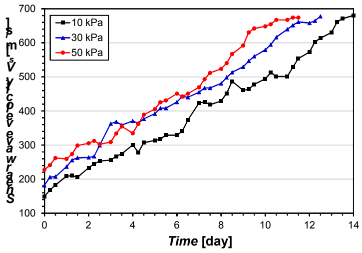
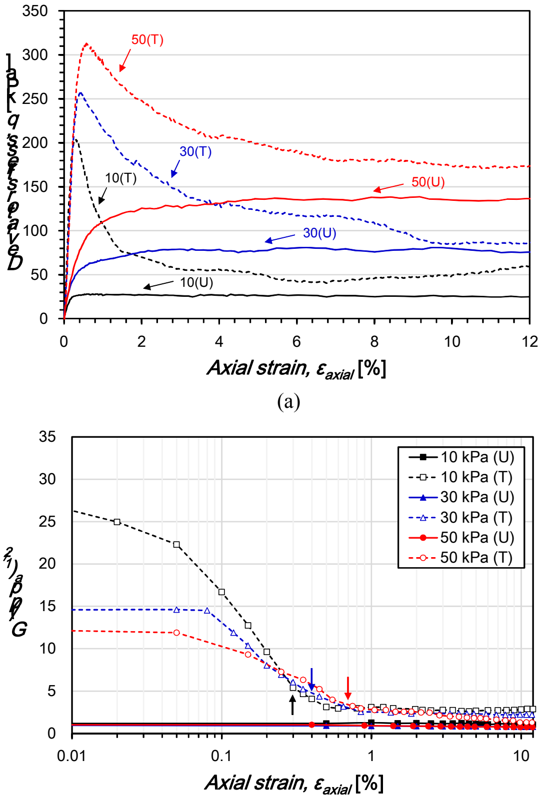


Figure 10. Variation of shear wave velocity during bio-treatment (Do et al. 2017)



(a)

(b)

Figure 11. Triaxial compression tests of untreated and treated specimens during shearing: (a) Stress-strain response; (b) the variation of the normalized shear wave velocity (Do et al. 2017)

Triaxial compression strain-stress responses for all tested specimens are shown in Figure 11a. While all of the untreated specimens show clear loose type hardening response, the treated ones present rapid and higher increase in deviator stress at small strains followed by post-peak strain softening. The variation of the normalized shear modulus with respect to the confining stress during the triaxial tests for the untreated and treated specimens is shown in Figure 11b. The normalized shear modulus for the untreated specimens remained nearly constant over the entire strain range, while for the treated specimens the normalized shear modulus showed a sudden decreases at a low level of strain of 0.05%, which may signify the starting of the crystal cementation breakage, until a strain level which corresponds to the peak strength. The bio-treated specimens, however, exhibit an increase of the cohesion, while no changes of the angle of friction are observed if compared with untreated specimens.

An attempt to correlate the unconfined compressive strength (UCS) of MICP treated soil specimens with the total amount of calcite precipitation ($CaCO_3$) was made in the work of Rahman and Hora (2017). However, the analysis of UCS data compiled from published literature results do not show a clear correlation between the two parameters. Considering that the size of the pores is related to the particle size corresponding to 10% passing in a sieve analysis, it was further hypothesised that soil grading properties such as D_{10} and C_c could give a better correlation with the UCS and $CaCO_3$ content. Based on the available experimental data, a regression model was developed and a function between the normalised UCS by the UCS value at 10%$CaCo_3$, the total calcite precipitation and D_{10} was proposed as shown in Figure 12. UCS increases with the cementation content and with the reduction of the particle size.

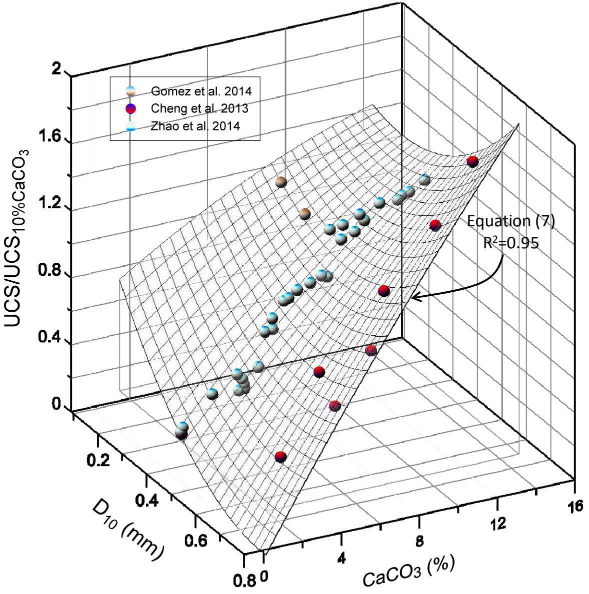


Figure 12. 3D plot of D10, UCS and $CaCO_3$ data points and the function defined by the regression process (Rahman and Hora 2017)

Hata and Kaneda (2017) explored the use of the MICP for soil liquefaction mitigation. Both bioaugmentation and bio stimulation techniques were used on Toyoura sand. Cyclic triaxial tests have been performed on untreated and treated specimens. Initial triaxial compression tests on bioaugmented specimens showed an increase of the cohesion for the treated material and unchanged angle of friction, in a similar way as shown by Do et al. (2017). The initial stiffness of the treated sand is also increased. The biostimulation method used in situ urease-positive microorganisms taken from the bottom of Toyama Bay and it the result shown that this urease producing bacteria can also survive high salinity conditions of difficult environments. Figure 13 presents the undrained cyclic test results on the untreated Toyoura sand and those of the treated samples containing microorganism isolated from Toyama Bay bottom sediments. As can be seen in the figure, the treated sand shows higher cyclic stress amplitude ratios (CSR) at low cycle numbers, but tended to approach the sand's CSR at higher cycle numbers. Numerical FE analyses of an embankment under seismic action and having the superficial layer reinforced with MICP show clear increase in the behaviour with improved strength both in the surface superficial layer but also in the core of the embankment, avoiding the liquefaction failure.

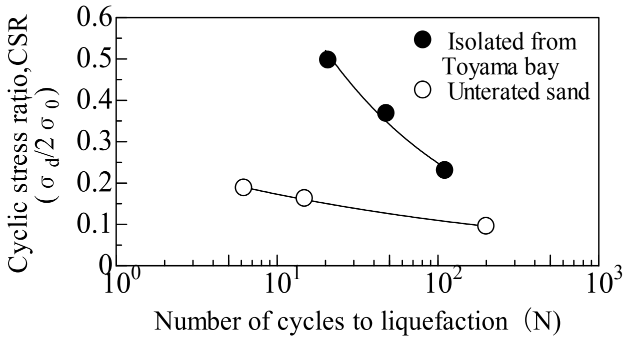


Figure 13. Undrained cyclic triaxial tests on untreated and MICP t reated Toyoura sand.

3 .2 *Artificial cementation*

The addition of cement to soil has become an increasingly popular method for ground improvement, but there are some environmental concerns in the production and use of cement, including also the costs. As a consequence, the attention of many recent research studies has been directed to the use of more sustainable materials, some of them being waste products.

The study of Le and Airey (2017) on the suitability of gypsum (calcium sulphate dihydrate) and bassanite (calcium sulphate hemihydrate) as ground improvement agents fully aligns within this trend. The use of the latter also provides environmental benefits associated with the reduction in the quantity of waste plasterboards sent to landfills from demolition in the construction industry. Gypsum cemented sands and soft rocks (Huang and Airey, 1998, Ismail et al, 2002) behave similarly to other artificially cemented sands, however, they have been found to demonstrate higher creep rates than other natural and artificial weak rocks. When plaster is mixed with clays, samples with significant strength and stiffness are also created (Le, 2017). However, as reported by the authors, there is limited knowledge regarding the physiochemical and mechanical properties of gypsum, as well as their long term durability. Both hemihydrate and dihydrate are soluble in water, and the dissolution of gypsiferous minerals was observed to cause subsidence, voids and caverns in natural geological formations. Areas that experienced frequent temperature fluctuations also showed heaving due to the hydration and dehydration of gypsiferous compounds (Yılmaz 2001). Plaster (hemihydrate) samples mixed with water by Lewry and Williamson (1994) also indicated that excess water has a critical role in the strength of gypsum after comparing the results of the dry strength test (samples allowed to dry after casting), with that observed in “wet” test specimens (samples kept under polyethylene film to prevent moisture loss), Figure 14. An overall reduction of unconfined compression strength (UCS) values with wetting-drying cycles for lime-stabilized gypseous soils was also reported by Aldaood et al. (2014). While gypsum has potential for use in ground improvement, it was concluded by Le and Airey (2017) that further site specific studies are required to ensure it will produce the intended benefit.

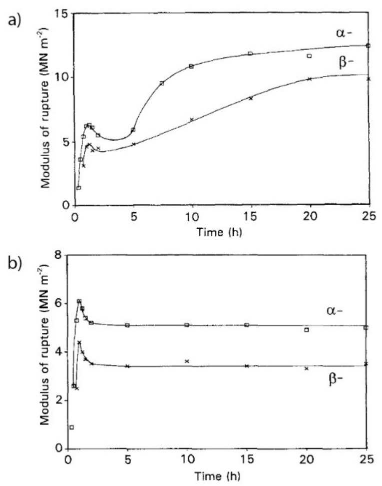
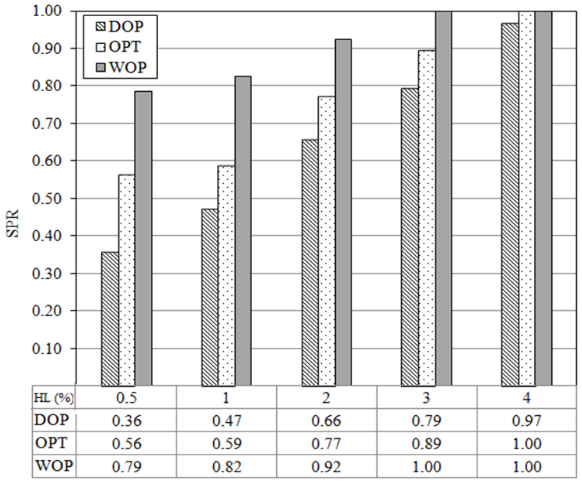


Figure 14. The development of (a) “dry” strength and (b) “wet” strength of two different gypsum products as the paste hardens (Lewry & Williamson, 1994)

Expansive soils undergo considerable volumetric changes, in terms of swelling or shrinkage, due to changes in moisture content and these have been responsible for significant damages on transportation infrastructure, shallow foundations and lightweight constructions. As a solution to mitigate these effects, the work presented by Martinez Belchior et al. (2017) investigates the use of lime treatment for swelling potential reduction. The effect of lime treatment on an expansive soil, Eagle Ford clay, was studied using the new geotechnical centrifuge developed by The University of Texas at Austin. While the expansive soil was treated with different percentages of lime, the focus of the research was the assessment of the effect of moisture content and density variables on the efficiency of the treatment. The efficiency of the lime treatment was assessed through the use of Swelling Potential Reduction Ratio (SPR) parameter with SPR=0 for untreated soil and SPR=1 if the lime treatment completely reduces the swelling potential compared with the untreated clay. The influence of the moisture content was studied on samples formed at different moisture content between dry of optimum (DOP, 21% moisture content), optimum (OPT, 24% moisture content) and wet of optimum (WOP, 27% of moisture content). The variation of the SPR at different compaction moisture conditions and hydrated lime percentages is shown in Figure 15.



HL (%)	0.5	1	2	3	4
DOP	0.36	0.47	0.66	0.79	0.97
OPT	0.56	0.59	0.77	0.89	1.00
WOP	0.79	0.82	0.92	1.00	1.00

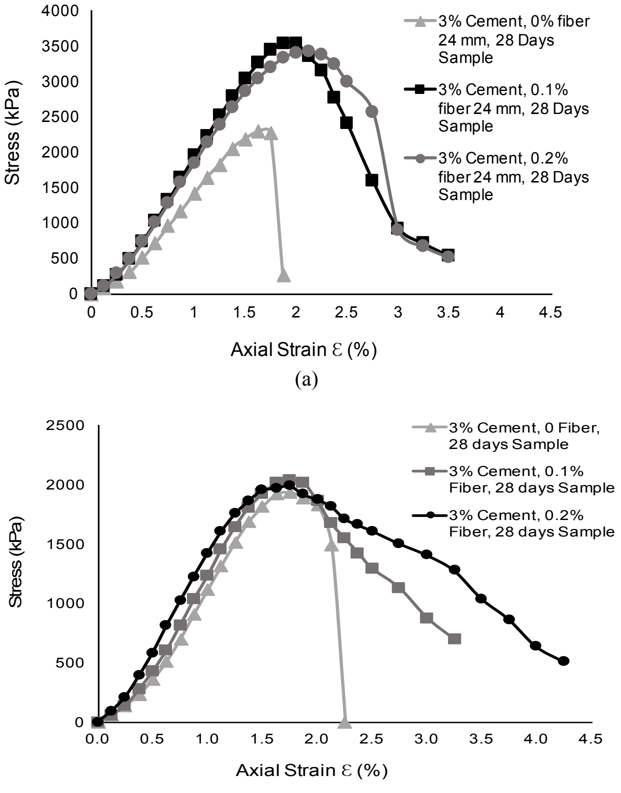
Figure 15. Swelling potential reduction ratio (SPR) at different compaction moisture conditions and hydrated lime content.

The WOP condition produced the highest SPR values for all percentages of hydrated lime considered. However, the difference between the SPR at the three compaction moisture conditions DOP, OPT and WOP seems to be reduced with the increase of the hydrated lime percentage. The effect of the compaction density was examined for samples fabricated at 94% and 100% of the maximum dry density at the optimum moisture content (24% moisture content). The SPR for all hydrated lime percentages used was greater in specimens compacted at 94% than those compacted at 100%, while the reduction in dry density leads to increase of lime addition efficiency on swelling reduction.

Stabilisation of typical forest road structure by treatment with wood fly ash (WFA), a by-product of electricity and heat plants production, was studied by Skels (2017). Conventionally, in Latvia, forest road construction uses either compacted crushed gravel or fractioned dolomite breakstone. Specific laboratory tests, standard Proctor compaction, California bearing ratio (CBR), and unconfined compression strength (UCS) were therefore conducted on crushed gravel and fractioned dolomite breakstone mixed with 10%, 20% and 30% WFA. Tests were also conducted at different curing times, 7 and 28 days. While immediate bearing index (IBI) from CBR tests on fresh mixtures showed for both materials an optimum WFA of 10%, (UCS) results indicated that the maximum values are obtained for 30% WFA mixtures. Modulus of elasticity determined from UCS test showed similar results and emphasise the importance of the curing time.

Published research and experimental laboratory test results on granular soils treated with cement show increased initial stiffness and peak strength compared with the untreated soils but the failure of the material is brittle and may occur at lower levels of strain (Consoli et al. 2003, among others). One way of taking advantage of the benefits of cementation and particle bonging but avoiding the brittle behaviour is to add into the mixture uniformly distributed discrete short fibre inclusions. An improvement of the material ductility is expected to result. The work presented by Erken et al. (2017) focuses on this research area and studies the effect of short fibres on the shear strength and tensile strength of cemented sands. Two different sands were used in the study: one, Yellow sand, containing a large fraction (31%) of plastic fines (classified as clayey sand), and one, Gray sand, having 13% of non-plastic fines (classified as silty sand). Both sands were mixed with 3% cement and poliamid fibre with 0%, 0.1% and 0.2% by dry weight of sand. Unconfined compression strength (UCS) and flexural tensile tests were conducted on cemented sand specimens with and without fibres prepared by the modified proctor test. The effect of curing time (at 7 days and 28 days) on the strength and deformation behaviour was investigated as well as the effect specimen saturation. Both sets of tests, UCS and flexural tensile tests confirm the expected responses with brittle collapse of sand-cement mixtures and more ductile post peak response for the sample reinforced with additional fibres. While the UCS for the cemented clayed sand is also improved by the presence of fibres, no changes are detected for the cemented silty sand, as can be observed in Figure 16. However, the effect of the fibre content is apparent in the post peak loading regime. The flexural tensile tests presented similar behavioural trends especially in the post peak stages.

Xiao et al. (2017) focused on the small strain shear stiffness (of unconfined specimens) and unconfined compression strength of high cement (Ordinary Portland Cement (OPC))-Singapore marine clay (plastic and liquid limit of the clay of 31% and 74%, respectively) mixtures with and without fibre inclusions. The assessment of the shear stiffness is based on the wave propagation velocity measurements made by bender elements. The laboratory cylindrical specimens contained 50% to 100% cement (Aw) by mass of soil solid, 100% to 133% water (Cw) by mass of total solids, 0% to 3.04% fibres by total volume of the mixture, and the testing considered specimens with 7 to 28 days of curing time.



(a)

(b)

Figure 16. Unconfined compression tests on artificially cemented soils with or without fibres: (a) clayey sand (Yellow sand); (b) silty sand (Gray sand) (Erken et al. 2017)

Two different 6 mm cut fibre length types, polypropylene (PP6), and polyvinyl alcohol (PVA6), were used but no noticeable differences between the responses were observed. The results showed that G_{max} of fibre-reinforced cement-admixed marine clay (FRCMC) specimens increases with the increase in cement content and curing period, and decreases with increasing water content. To investigate the fibre effect on G_{max}, the small strain shear modulus of FRCMC was normalized with the shear stiffness, G_{max1}, of the cement-admixed marine clay (CMC, 0% fibre). Figure 17 shows the variation of the normalized stiffness (G_{max}/G_{max1}) with fibre content for FRCMC specimen with high (Aw=100%) cement content. The normalized stiffness does not change significantly with the fibre content and almost stabilises at 2.28% of fibre content, while the effect of curing time is also apparent. Furthermore, it was observed that G_{max} can be linearly related to the unconfined compressive strength q_u (Figure 18). However, the effect of the fibre inclusion is to reduce the slope of this linear relation compared to cement-admixed clay without fibres.

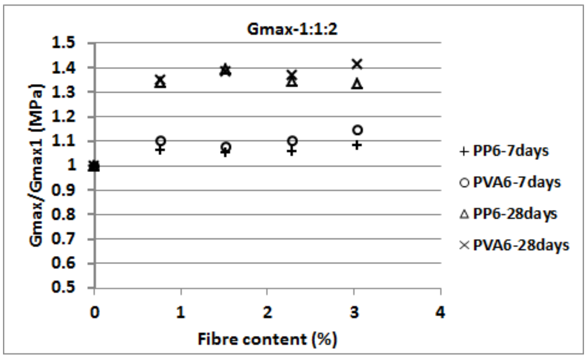


Figure 17. Fiber effect on G_{max} for specimens with 100% cement and with 100% of water content (Xiao et al. 2017)

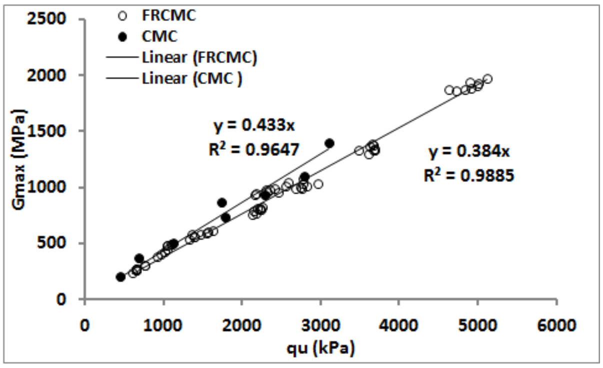


Figure 18. Relationship between small strain shear modulus G_{max} and unconfined compressive strength q_u (Xiao et al. 2017)

4 CONCLUSION

This paper presents a General Report of 14 written contributions from authors representing eight countries submitted for one of the parallel sessions, Soil reinforcement*,* of the Technical Committee 101: Laboratory Stress Strength Testing of Geomaterials. The General Report reviews these contributions and presents the current research directions mainly in relation to the experimental behaviour as well as the key outcome results. The topics covered by the written contributions have been grouped within the following thematic strands: mechanical reinforcement, chemical stabilisation through microbial induced cementation and artificially induced cementation.

Some residual challenges could be listed: solutions for mixing of constituents at the real scale of geotechnical structures; large number of test parameters and test configurations; conduct studies along several length scales and consideration of modelling tool developments; development of design recommendations and guidelines; long term behaviour of the mixtures of any type and durability.

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