CASE STUDIES AND RESEARCH: ISSMGE SYMPOSIUM

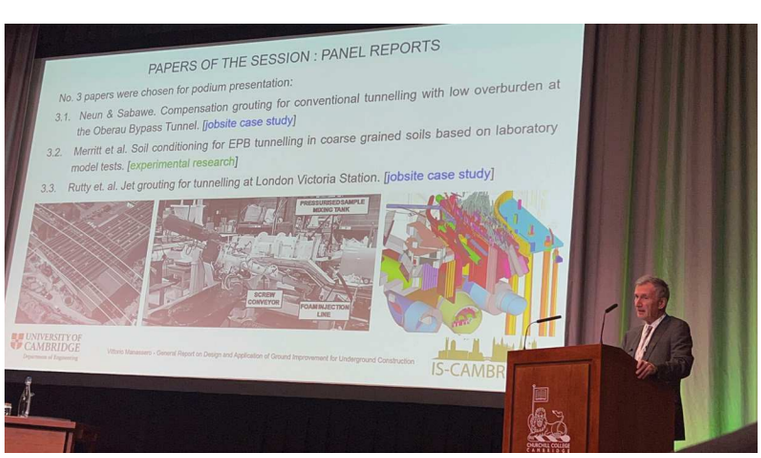
Ground improvement and conditioning case studies and research were discussed earlier this year at ISSMGE's TC204 symposium, in Cambridge, UK

A number of papers on the theme of design and application of ground improvement were presented at the 10th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, held in Cambridge, UK, in June this year.

The symposium was organised by the Geotechnical Research Group of the University of Cambridge, under the auspices of the International Society for Soil Mechanics and Geotechnical Engineering's (ISSMGE) Technical Committee TC204. It had been delayed and rescheduled by the covid pandemic.

A total of 14 papers were submitted and accepted to look at various aspect of the ISSMGE symposium theme of ground improvement. Artificial ground freezing methods were also discussed in the theme session but not presented in papers.

Almost two-thirds of the papers focused on laboratory research, leaving five looking at project case studies: compensation grouting as part of the Oberau Bypass road tunnel in Germany; jet grouting as part of the Victoria tube station upgrade, in London; a grouted bottom plug for a deep excavation on a metro station in Taiwan; checking various design code predictions against site data of deflections of diaphragm walls at a shaft; and, the Northern Landfall, in Hong Kong's Tuen Mun Chek Lap Kok subsea tunnel.



Above: presented paper listed ALL IMAGES: PATRICK REYNOLDS

The papers that focused on lab research covered: self-healing for cement stabilised clays; biopolymer hydrogel for control of ground hydraulic conductivity under pressurised conditions; injected with non-conventional grouts into sand with fines; tests to improve Singapore soft marine clay with alternatives to Ordinary Portland Cement (OPC), such as carbide slag (CS) and ground granulated blast-furnace slag (GGBS); examination of pore water pressure development with foam infiltrating saturated sand as simulation of soft ground tunnelling by earth pressure balance (EPB) shields; test on increasing strength and stiffness of sandy soil using bio-cementation, while aiming no minimise disturbance and checking how porosity is affected; tests of a model EPB screw conveyor on coarse grained soil samples with a range of gradings and conditioning methods; experiments on mineral or polymeric modification of bentonite conditioning for a lab simulation of mechanised tunnelling; investigation of hydraulic conductivity through a range of permeability tests on foam-conditioned coarse-grained soils of varying grades.

In summary, four papers looked at permeation/penetration grouting, three at foam conditioning for EPB tunnel boring machines, three at deep soil mixing, and one on each of bentonite conditioning for mechanised tunnelling, jet grouting, and surcharge and drains.

The various papers were reviewed and then a summarised overview was verbally delivered to the symposium by Italian geotechnical consultant Vittorio Manassero, of Underground Consulting S.a.s, acting as General Reporter. *T&T* attended the symposium and presentations of the summarised key points of the ground improvement papers.

GROUND CONDITIONING

The following are summaries of papers on project case studies that were selected as key presentations by authors to delegates.

Port of Miami tunnel

Merritt et al – tests of a model EPB screw conveyor on coarse grained soil samples with a range of gradings and conditioning methods, in preparation for TBM boring of the Port of Miami tunnel, in Florida.

The paper presented to delegates discussed laboratory tests undertaken ahead of tunnelling for the 12.9m twin bores, as ground conditions were toward the limits of experience of EPB applications. The test programme was, therefore, important to assess feasibility of excavation by EPB method as well as establishing appropriate soil conditioning for the expected ground conditions.

Geology at the Port of Miami site was layered carbonate sedimentary formations with a variable sequence of limestone, cemented sand/shell and sand layers, and including a highly porous variable cemented coralline limestone layer.

The authors note that with standard foam and polymer conditioning treatment, formation of a homogenous soil paste for controlled EPB operations is challenging for saturated soils with more than 50% gravel and less than 10% fines, particularly with groundwater pressures.

Super water-absorbent polymers can help condition soil and extend the range of geology to tunnel in using EPB machines, and would do so by absorbing large amounts of water and increasing the viscosity/cohesion of the soil.

The lab modelled the EPB excavation process to investigate and assess the performance of different ground conditioning treatments in samples of soil prepared with different gradings in ranges of gravel, sand and fine particle sizes.

The tests were performed at Bouygues' Pole Ingenierie Materiaux laboratory using the OBYONE apparatus, and comprised a pressurised sample tank with mixing rotors, connected to a model screw conveyor (1.2m long, 100mm dia). Test samples of approx 60l volume were prepared by conditioning soil.

The conditioning treatments included different combinations and quantities of standard foam, two polymers and thick mortar for the addition of fines.

The work showed that laboratory model tests can provide experimental support for published guidance on typical ground conditioning for EPB boring in a range of coarse grained soils under pressurised conditions.

The findings also showed there is potential to expand the application range, such as up to 80% gravel and less than 10% fines, by use of the specialised water-absorbent polymer treatments.

The performance of the polymers, though, is sensitive to the salinity of water. They also need enough swelling time to develop their properties in the soil mix and, therefore, consideration needs given to where they are injected from the TBM and the advance rate of the machine.

The authors note that conditioning can be done inside the TBM chamber and screw conveyor, while the TBM is stationary, to restore spoil plasticity in difficult ground prior to continuing the advance.

While the laboratory findings are relevant for those materials and combinations tested (soils, water, polymer) for the Port of Miami, the authors say that appropriate site specific tests could be performed to design treatments suited to ground conditions on other projects. The dosage approach is set out in the paper with test procedures based on the water absorption capacity, rate and rate viscosity of the polymers.

The co-authors are from Pells Sullivan Meynink, Environmental Geotechnics and Bouygues Construction.

GROUTING AND JET GROUTING

The following two summaries were also selected for presentation to delegates, although only the second occurred on the day.

Oberau Bypass road tunnel, Germany

Neun & Sabew – the presented paper looked at compensation grouting as part of the construction works for the 3km-long, twin tube Oberau Bypass road tunnel project, in southern Germany.

The 11.8m wide bypass tunnels run under some industrial buildings and the alignment only has 10m of cover. Ground improvement was required to limit settlement before conventional excavation could be undertaken. The challenge for compensation grouting over an area of 7700m^2 was increased with geology that included highly permeable gravels.

The paper describes the design concept for tunnelling and compensation, based on finite element method, the impact on surface settlements, and interaction between tunnelling and compensation grouting, and the effectiveness of the ground improvement.

Geology in the area is around 50m of alluvial gravel deposits over ground glacial moraine. The tunnel alignment rests in upper gravel layer, which extends to 15m-22m below the ground surface. The upper layer has a comparatively higher stone and fines content and is interspersed with stones and blocks up to 50cm wide.

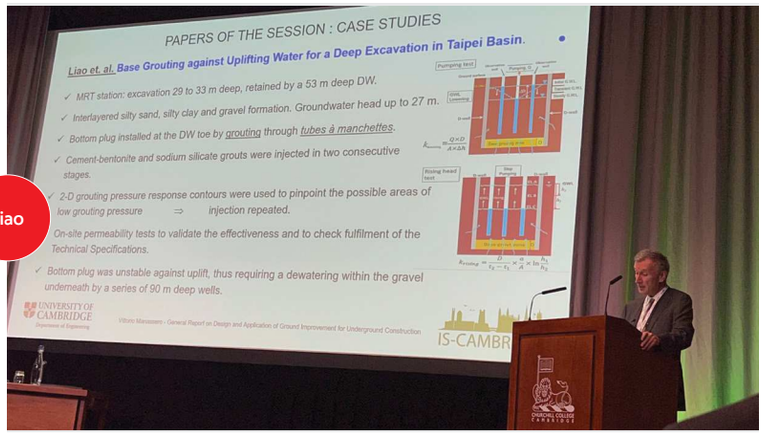
In some locations, the tunnel bench/invert touches the lower gravel layer which consists of sandy, slightly stony gravel. Groundwater level is in the valley is typically slightly below the vertical alignment of the tunnel invert, though can rise due to heavy rainfall.

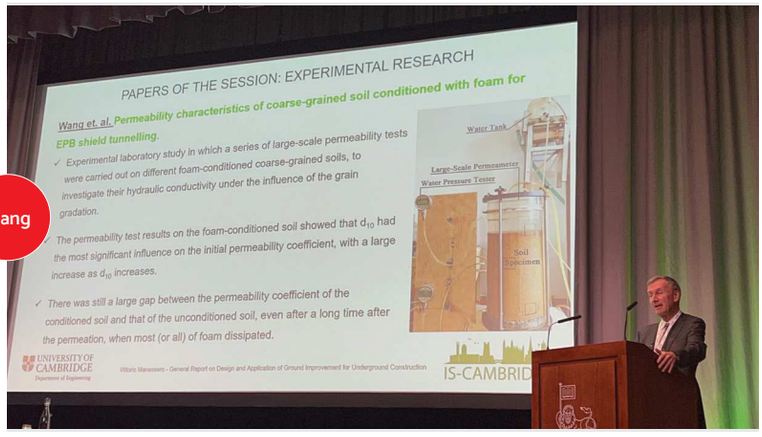
Boreholes showed the upper and lower gravel layers to have medium to dense bedding, the former classed as highly permeable.

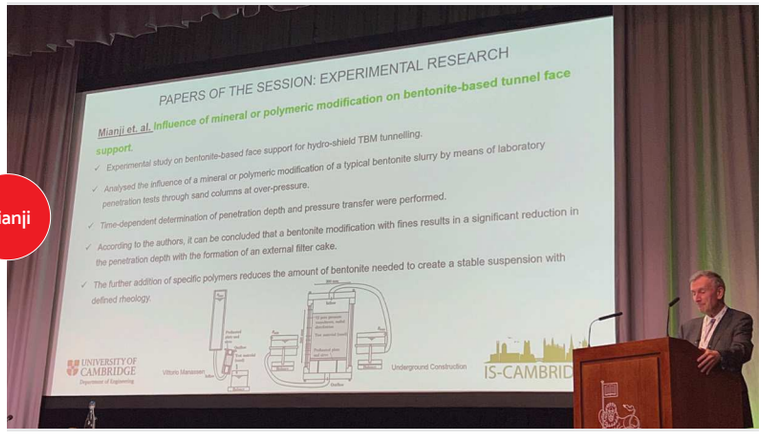
With the tunnel route passing under buildings, there was concern over the potential for differential settlement of its pillar foundations.

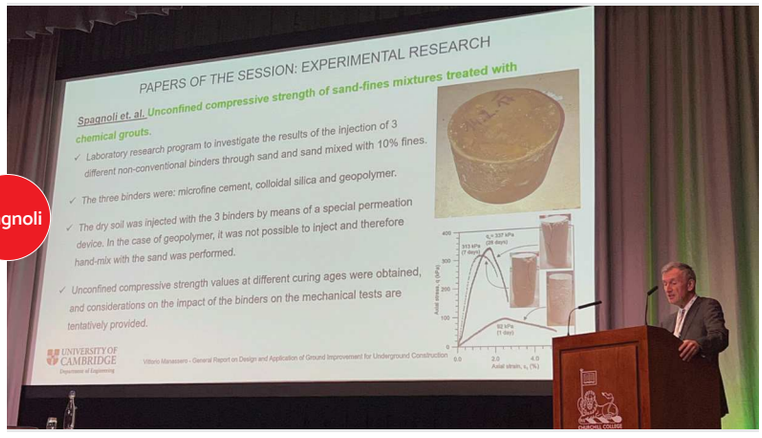
Initial plans for the conventional tunnelling proposed a pilot bore within the top heading, and excavations would widen the tunnel and then the bench/invert sections would be dug out. But works at the north portal, plus 2D and 3D numerical analyses indicated no pronounced benefit. The pilot tunnel was dropped and usual conventional tunnelling proceeded.

The tunnelling used self-drilling spiles and radial anchors to help limit risk of differential settlement at the ground surface. But drilling of holes for arrays of spiles brought slight instability of their holes and some settlement risk, and bentonite dropping out of the inclined holes in the crown. This resulted in a









switchover to tube spiles – with less overcut and using the inside of the tubes to transport spoil, unlike the surrounding void used by self-drilling spiles.

Compensation grouting was examined for use.

However, it could not be undertaken close to the tunnel face during excavations for reasons of potential risk to stability as well as possibly reducing the efficiency of the process. With more than allowable differential settlement calculated, it was decided, therefore, before excavation to lift the building by about half the predicted settlement. This lift, or 'heave', or 'uplift' also had the allowable tolerances of differential settlement applied.

The compensation grouting would then be performed to provide support in stages to the tunnelling works, depending on real onsite data from the excavations and site, automatically collected every minute and compared with allowable differential movements.

The amount of grouting needed before and after the excavation steps was modelled, although the 3D finite element method (FEM) model, used to verify assumptions in the 2D model, did not account for possible ground loss due to the self-drilling spiles and so the maximum credible settlement from the lower bound 2D analysis was taken.

Drilling for the compensation grouting was performed using a shaft drilling rig specifically designed for the project. Analysis of drilling showed the majority of drilling endpoints to have been less than 3m apart. Overall, the median drilling deviations were 0.8% for drillings of less than 30m depth, 1.2% (30m–50m) and 3.6% (50m–53.2m).

The grout batching plant was enclosed due to cold winter conditions over the periods of the works, 2016–2017, conducted over a total of 228 days. The grouting steps were completed without need for the last step of extra grouting needed after the bench/invert excavation. The efficiency of the grouting differed in the central and peripheral areas – approx 15% to 7%, respectively.

After conventional tunnelling, the observed total settlements were less than heave lift executed in advance of the excavations. No longer-term, further, settlements were measured in the area over the twin tunnels.

The authors said more than 36,500 injections with many per shift would not have been possible without digitalised monitoring, controlling, documentation, visualisation and data transfer. The data management system was accessible to all on the project, which was a key factor in the success outcome.

The co-authors are from EDR GmbH and Renesco GmbH, respectively.

Victoria Station Upgrade

Rutty et al – jet grouting as part of the Victoria station upgrade, in London.

Limited overburden was again a theme in excavations required to construct a complex layout of new ticket halls and related tunnels to upgrade the London Underground (LU) metro station in the busy heart of the

UK capital. But geology of water-bearing granular soils of River Terrace Deposits added to the challenge for most of the excavation as only the tunnel inverts were in stiff London Clay.

The design was developed collaboratively throughout, starting with the client, LU, with its designer Mott MacDonald, then the main contractor Taylor Woodrow BAM Nuttall JV working with Motts and ground treatment subcontractor Keller. For the project, building information modelling (BIM) was used extensively.

The approach taken for ground improvement was jet grouting with a trial of 27 columns ahead of eventually having more than 2500 columns for the works. The jet grouting with double-fluid construction and mostly 1.6m-diameter columns were installed, their layout and required locations pinpointed with a 3D model in the BIM environment holding data on ground conditions as well as existing infrastructure above and below ground.

After the jet grouting, the 3D model was populated with 'as-built' grout column data to help risk management of any gaps before tunnel excavation. Column diameters were checked using the thermal degradation method developed by Porr. The assurance process revealed only a single defective column, enabling tunnelling to be performed with minimal disruption to stakeholders as the metro continued operations.

CASE STUDY PAPERS

Summaries follow of case study papers to the symposium, where the Pittaro et al paper got opportunity to also be presented.

Tapei metro station, Taiwan

Liao et al – presented a case study of base grouting to form a bottom plug against uplift groundwater pressure for a deep metro station in Taipei Basin, in Taiwan.

Geology at the site is interlayered silty sand and silty clay, and gravel formation deeper down. The groundwater level is high. The metro station is a 160m (L) x 26m-34 (W) structure, and the excavation depth was 29m-33m, generally in the silty sand and silty clay.

The structure was to be constructed with diaphragm walls of 53m depth, cut through the silty sand and silty clay layers for their bottom to be embedded in the highly permeable gravel layer. Grouting would be performed above and below the bottom of the walls to cut-off the vertical upward seepage of groundwater.

With the plug also unable itself provide sufficient gravity stability to counter risk of hydrostatic uplift during excavation, dewatering would also be required within the station site during the excavations. A total of 22 wells of 90m depth were installed to lower the groundwater table as the excavation proceeded deeper.

The base was constructed at the toe of the diaphragm wall using tube-a-manchettes in a two-step process with a suspension cement-bentonite (CB) grout and then a solution type sodium silicate (SL) grout injected in consecutive stages. The aim was to use the CB and SL grouts in a 1:3 ratio over the two steps to reduce the 45% porosity of the silty sand (fines content 10%-25%) almost entirely, as has been common practice in Tapei metro.

The plug thickness was generally 5m (where grout hole spacing was 2m) but increased to 8m adjacent to the walls (grout hole spacing reduced to 1m), following past experience of seepage in such zones. Any need for supplementary grout in local spots was identified by 2D mapping of grouting pressures, at given depths, measured from the injection ports.

Once completed, the permeability of the grouted bottom zone was measured by both a pumping test and rising head test to ensure the plug acted as an effective barrier to upward leakage of groundwater. Permeability of the plug was found to have satisfied requirements by being less than the threshold of 5 x 10-5 cm/s set by the project owner. The plug's permeability level was two orders of magnitude lower than that of the silty sand layer before grouting.

With in-situ transmissivity and the storage coefficient both low for the underlying conglomerate gravel layer, once the excavation reached the final depth only six wells were needed to sufficiently draw down the groundwater table structure. This helped to keep the factor of safety against base uplift at more than 1.2.

The co-authors are from National Taiwan University of Science and Technology and SanShin Construction Corp.

Codes -v- site data for diaphragm walls

Pittaro et al – lessons from checking data from an instrumented shaft sites against numerical analysis by various design codes to examine deflections of deep diaphragm walls. The aim was to explore design parameter selection.

Data from site were obtained from both core samples of soil improved by deep mixing together with inclinometers to measure wall deflections.

The site data from the core samples were then compared to various predictions that could be made via different design codes – in this case codes in Europe (Eurocode – EC7), Japan and US. Using FEM, the researchers, undertook back analysis on the shaft excavation according to the different design codes.

Predictions of deflections from the back analysis were compared to data from the field inclinometer measurements. The closest match of prediction to field data from the diaphragm wall came from EC7.

However, the researchers also found that the result wasn't so conclusive, and global stability of an excavation could be significantly affected, due to spatial variability in the improved soil zone.

This finding was obtained after undertaking random FEM analyses, and by looking at both probabilistic and deterministic analysis. The researchers said that deterministic FEM analysis may potentially result in un-conservative design.

The co-authors are from Mott MacDonald and National University of Singapore

North tunnel portal at Tuen Mun Chek Lap Kok, Hong Kong

Lockhart – the case study looked preparations to bore large diameter tunnels bored in freshly consolidated soft soil, at the Northern Landfall of the Tuen Mun Chek Lap Kok subsea tunnel in Hong Kong.

The tunnels were constructed in land reclaimed using very soft marine deposits and alluvium, where soft soil consolidation was achieved under surcharge and installation of vertical drainage.

The area holds the road tunnel portal and subsea access ramp, comprising a combination of cut-and-cover tunnel and two parallel bored tunnels, the Northbound of which had an excavation diameter of 17.73m (15.60m i.d.), to hold three traffic lanes. The southbound tunnel (14.0m i.d.) has two lanes.

With the soil far too weak for both the tunnelling and concrete-lined operational stages of its life, the paper focuses on the design and monitoring activities of the consolidation work to prepare the ground for tunnel boring, and the relationship to tunnel lining design. Adjacent seawall stability was also a consideration.

The classical approach of consolidation by surcharge was elected for the works. With plenty of data available from developing reclaimed land in Hong Kong, the necessary height of the surcharge to increase the effective vertical stress of the soil and gain adequate shear strength for the tunneling activities, could be calculated. Provision in the surcharge was also made for future settlements. Plastic band drains were placed by barge.

The effectiveness of the consolidation preparations was checked by cone penetration tests (CPT) and, where necessary, jet grouting was performed as local improvements.

It should be noted that the tunnel lining design proceeded in parallel with the reclamation works. It included the in-situ conditions resulting from the consolidation process.

The author is with Bouygues Travaux Publics

RESEARCH PAPERS

Summaries follow of experimental research papers to the symposium but not presented by authors to delegates.

Permeability of coarse conditioned soil for EPB bores

Wang et al – The researchers looked at the permeability characteristics of coarse-grained soil conditioned with foam for EPB shield tunnelling, as low permeability coefficient is required when boring below the water table.

The researchers said there are limited research findings on permeability characteristics of foam-conditioned soil, especially considering the effect of grain gradation.

Their research, therefore, investigated hydraulic conductivity with respect to three grades of grain sizes (d_{10}, C_u, C_c), prepared with collected and sieved natural sand. The findings shows the d10 to have most effect on the initial permeability coefficient, the two other grades having relatively little effect. Increased d10 led to higher initial permeability coefficient.

The finding were also that, with the structure and saturation state of soil altered by the addition of foam conditioning, there was still a gap between the permeability coefficient of soil before and after conditioning. This was so even a long time after dissipation of the conditioning foam.

The researchers say this has significance for guiding how to undertake post-treatment handling of such soil.

The co-authors are from Central South University, Changsha, China

Modifications for bentonite-based TBM tunnelling

Mianji et al – the researchers looked at the influence of mineral or polymeric modification on typical bentonite-based face support for TBM tunnelling.

The study analysed the influence of the modification treatment by penetration tests through sand columns at over-pressure, with sand type chosen to avoid formation of external filter cake.

The laboratory tests collected measurements of pore water pressure up the column height, and also inflow and outflow of water using electronic balances. The data enabled study of how penetration depth and pressure transfer varied with time.

The researchers found that a bentonite modification with fines results in a significant reduction in penetration depth with the formation of an external filter cake.

Further addition of specific polymers reduces the amount of bentonite needed to create a stable suspension with defined rheology.

The co-authors are from Ruhr-University Bochum and University of Wuppertal, in Germany.

Pore pressure and foam infiltration

Zheng et al – the researchers looked pore water pressure development in soil when foam infiltrates into saturated sand to help simulate soft ground conditions of EPB tunnelling.

As a starting point, the researchers reviewed the pressure transfer mechanism of a slurry driven shield. This was to help establish the pressure transfer mechanisms to be expected during EPB boring.

They studied development of pore water pressure into saturated sand during foam infiltration tests. The aim was to examine how pressures could change during tunnelling.

The research indicated that pressure drop can be induced through the foam infiltration area, and so supporting pressure can be applied on soil in front of the face.

Further pressure development reveals that the foam infiltration area functions similarly as an internal cake in slurry shield tunnelling.

The co-authors are from Ghent University and Ruhr-University Bochum

Non-conventional chemical grout

Spagnoli et al – research on the effect to unconfined compressive strength (UCS) of clean dry sand, with varying fines content, when injected with non-conventional chemical grouts

In tests with dry sand and sand with 10% fines, respectively, the permeability and pore-size distribution were measured in separate samples and then three chemical grouts injected – microfine cement; colloidal silica; and geopolymer. The first two binders were injected with a special permeation device while the geopolymer was hand-mixed into the sand samples.

Measurements of UCS were obtained from the treated sand samples at different curing ages.

In their paper, with the aim of providing useful information to consultants and contractors when designing such non-conventional grout injection, the researchers provide tentative views on considerations on the impact of such grouting on the mechanical tests.

The co-authors are from MBCC Group and Universitat Politecnica de Catalunya

Singapore soft clay stabilisation

Yu et al – stabilisation of Singapore soft marine clay using a novel sustainable binder for underground construction

With Singapore typically having soil with poor engineering properties (low shear strength and stiffness, and high compressibility), say researchers, they wanted to look at possibilities to improve the mechanical characteristics of soft marine clay by using a combination of two alternatives to Ordinary Portland Cement (OPC) – carbide slag (CS) and ground granulated blast-furnace slag (GGBS).

They add that using such industrial byproducts as CS and GGBS to form a novel binder could also significantly reduce their associated environmental impacts.

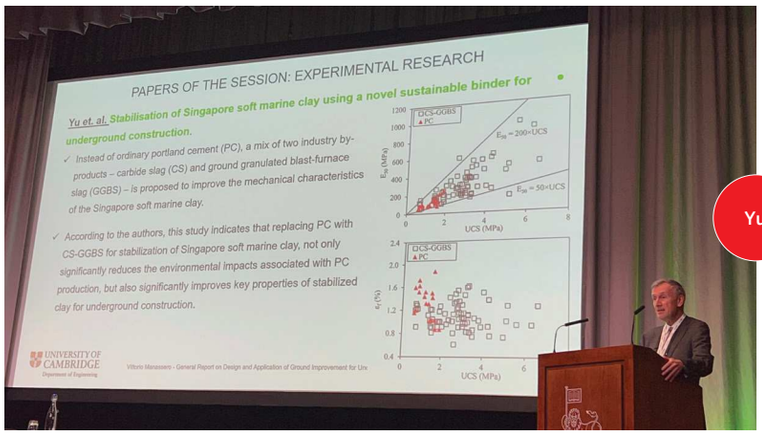
Tests took specimens of soft clay (air-dried, ground, sieved and then oven-dried) to stabilise with the combination of CS and GGBS, the relative ratios of which used and also the curing times involved for the stabilised clay samples were recorded to help establish engineering properties.

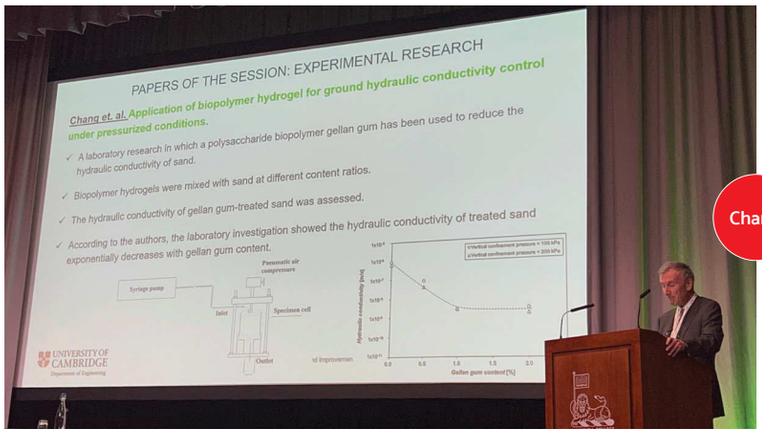
Key engineering properties sought for the stabilised clay included UCS, elastic modulus and permeability. The findings indicated that the novel CS-GGBS combination helped to achieve better strength and stiffness, and lower permeability, than Singapore soft clay stabilised with OPC.

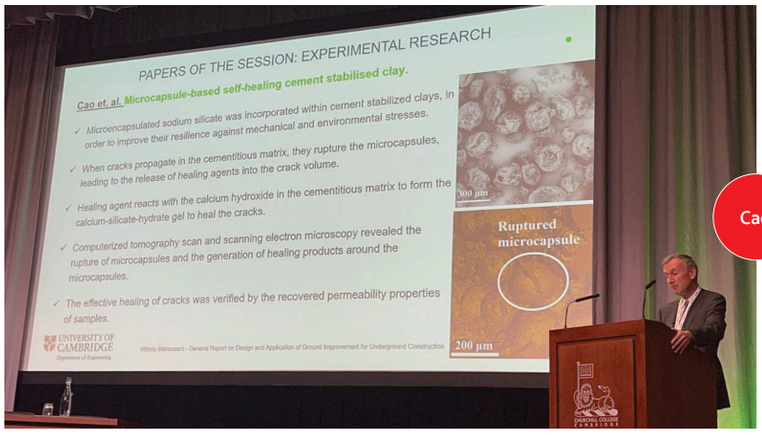
The co-authors are from Nanyang Technological University, Singapore; Tianjin University, China; University of Hawai'i at Manoa

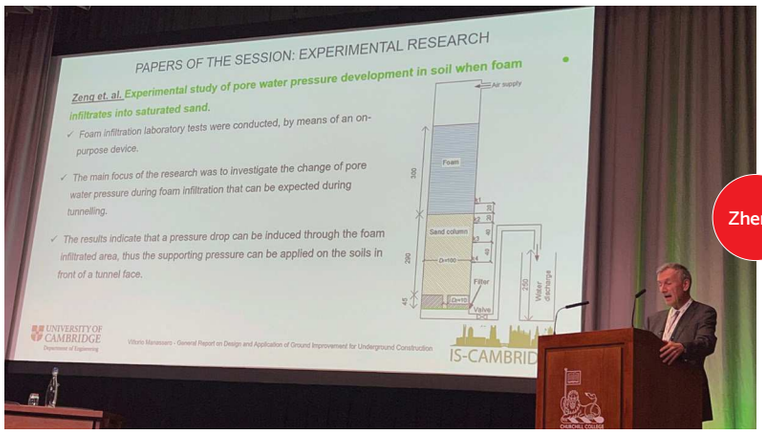
Biopolymer hydrogel to reduce hydraulic conductivity

Chang et al – studied the potential for creating a hydraulic barrier or grout for groundwater control by examining the application of biopolymer hydrogel to modify hydraulic conductivity under pressurised conditions









The researchers examined how a polysaccharide biopolymer gellan gum, used at different content rations, was able to reduce hydraulic conductivity of sand. The assessment of the gum-treated sand took place with vertical confinement conditions as water pressure was increased.

The tests found that higher hydrogel content exponentially reduced hydraulic conductivity of the treated sand.

The co-authors are from University of New South Wales, Korea Advanced Institute of Science and Technology, and Hue University of Sciences

Soil improvement with bio-cementation

Konstantinou & Biscontin – their research examined soil enhancement via microbially-induced calcite precipitation to increase the strength and stiffness of sandy soil.

The aim of the bio-cementation research was to improve the soil without causing too much disturbance to other properties, while also assessing how porosity was reduced.

The research had calcite precipitation induced microbially, enabling granular material to be bound with a carbonate-based agent. As it is a naturally occurring process, it is considered to be an environmentally friendly technique.

The findings of the research show improvements in soil strength and stiffness. Tomography and scanning electron microscopy showed permeability was reduced with heavy cementation.

The researchers say the method has been used in the field where low amounts of cementation were needed and soil permeability was to be maintained, such as for soil stabilisation.

The co-authors are from University of Cambridge

Self-healing capsules for cement stabilised clay

Cao et al – the researchers examined the use of micro-capsules of sodium silicate for studies into the potential to support 'self-healing' of cement stabilised clay where cracks develop.

The aim of the researchers was to examine the method of micro-encapsulation to help improve the resilience of cement matrix in such stabilised clays against mechanical and environmental stresses, respectively.

For the research, micro-encapsulated sodium silicate was incorporated in samples of cement stabilised kaolin clay. Crack propagation through the cementitious matrix leads to rupture of the micro-capsules and the release of sodium silicate, which reacts with the calcium hydroxide present in the cement. The product of the chemical reaction is a calcium-silicate-hydrate gel that fills the cracks.

The parameters of the system studied include the distribution of the micro-capsules as well as the lease of sodium silicate; the micro structure and permeability of the stabilised clay samples.

Tests proved that inclusion of the sodium silicate micro-capsules helped to keep down the permeability of the cement stabilised clay. The rupture mechanism and presence of chemical reaction products were confirmed by computerised tomography scan scanning electron microscopy.

The co-authors are from University of Cambridge

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ISSMGE's proceedings from the symposium are due to be published soon as a 2nd edition, with eds Elshafie, Viggiani and Mair. From Routledge.