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PERMEATION GROUTING USING ALKALI-ACTIVATED GROUT FOR LIQUEFACTION CONTROL

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ABSTRACT: Earthquakes worldwide raise significant concerns, particularly in densely populated areas. In the field of geotechnical engineering, the persistent challenge of liquefaction demands attention. Soil liquefaction is an event where the surrounding soil loses its strength and behaves like a liquid when shear stress is experienced. Permeation grouting is a method of ground improvement that is compact and not destructive. It achieves densification and solidification of the ground by permeating grout solution at low pressure. Conventionally, solution-type grouts or cement-type grouts are used. However, the study proposes the use of alternative materials to help reduce waste and carbon footprint of the grout. The mixture used in the study was a suspension-type grout composed of blast furnace slag and calcium carbonate powder, activated by sodium hydroxide. To quantify the feasibility of the grout formula for permeation grouting, several preliminary analysis and permeation tests were done. The results demonstrated that the grout mixture effectively developed sufficient strength for liquefaction control while maintaining low permeation pressure. Although clogging can occur with suspension-type grouts, adjusting variables such as injection rate and implementation of two-stage permeation mitigated negative effects. Optimization allowed the grout mixture to achieve a permeation radius of 0.8 meters during the one-dimensional test, slightly exceeding the ideal range of 0.75 meters. Subsequent two-dimensional and preliminary centrifuge modeling tests confirmed that filtration of grout particles in the soil occurred, and that alkali-activated grout could serve as a viable alternative for permeation grouting.

Keywords: Permeation grouting, Alkali-activated material, Clogging mechanism, Liquefaction control

1. INTRODUCTION

Constant seismic activity results in a considerable number of earthquakes. Soil liquefaction is a phenomenon in which the strength and stiffness of a soil are reduced to the point where the soil can no longer support loads. Effective stress in soil means a summation of granular contact forces, when total stress from soil and pore water pressure reaches equilibrium, liquefaction happens [1]. Fine sandy soil profiles with low cohesion strength are the most susceptible soil types. There are several ways to deal with liquefaction, physical ways like compacting or through chemical solidification. Cement has caught a lot of attention to be used as a reinforcement material for its versatility and ease of use. Though being a very good material, it emits harmful emissions through its production. The Intergovernmental Panel on Climate Change (IPCC) estimated that emissions must be reduced by 60% to prevent substantial climate change [2]. Constant effort must be made to reduce emissions.

Ground improvement is a branch of geotechnical engineering that deals with altering the properties of a soil to meet the required parameters. Regarding liquefaction, the topsoil layer is the most treated portion of the ground as this is where most liquefaction occurs. A technique that combines both physical and chemical improvement is permeation grouting.

1.1 Permeation Grouting

One of the greatest features of permeation grouting lies in its simplicity. The concept of this method is to permeate grout solution into the ground using a pump and a nozzle that is inserted underground as shown in Fig.1. Along with this, administration of the grout solution uses relatively low pressure that limits noise and impact to the ground. This means that the initial bearing capacity of the soil will not be affected during the permeation process, allowing improvement of ground even with structures built above. As a non-destructive soil improvement technique which only utilizes simple and compact machinery, it is beneficial in urban areas where infrastructures are abundant, and space is not readily available.

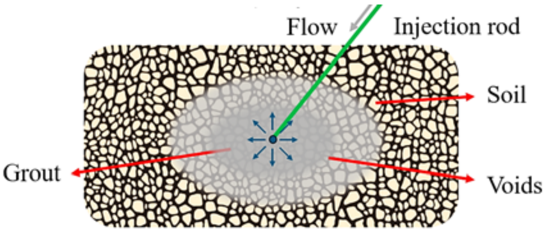


Fig. 1 Permeation grouting concept

Typically, permeation grouting uses two types of grout solutions, solution-type and suspension-type. Solution-types use water glass as its main ingredient for gelation, thus, is more expensive and requires extensive understanding of the reaction between an acid and a base. However, being a solution, it easily permeates the ground with little resistance [3]. The other type, on which this study focuses, is the suspension-type grout formula. Suspension-types use fine powders, typically cement or pozzolans, suspended in water. Being not limited to solutions, it offers a higher versatility to suit different ground conditions. Moreover, it generally develops a higher strength. This can be attributed to the additional densification of the ground resulting from the permeation of fine particles. The main disadvantage, however, is that clogging of the particles within the voids of the soil is a prominent problem which limits the range and increases injection pressure.

Cement is currently being used as material for grouting. To improve the groutability, past studies tackled micro-cement that was finer than ordinary cement, at about 2µm to 30µm. Using finer particles and increasing the water content were found to increase the performance of the grout mixture when permeated into the ground [4][5]. Considering these, similar physical properties of alternative materials were sought and discussed in the following chapters.

1.2 Objective and Scope

The main objective is to formulate an alternative suspension grout formula using by-products to improve the soil properties enough to mitigate the risk of liquefaction. The grout is aimed to be administered into the top layers of soil with the goal of maximizing permeation radius while minimizing injection pressure. The study investigates the performance of the grout, particularly the injection pressure and range, permeation shape and the developed strength using various permeation tests and centrifuge modeling. The soil type used throughout the study was sand with non-reactive components and all samples were saturated prior to permeation.

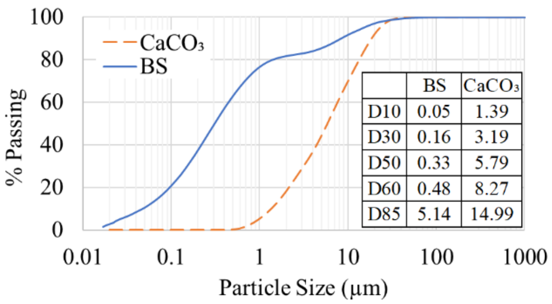
2. RESEARCH SIGNIFICANCE

Permeation grouting has been around for quite some time but continuously uses conventional materials that release harmful emissions. Modifying the composition of the grout solution to eco-friendlier alternative helps reduce the carbon footprint while maintaining or even exceeding the performance of conventional materials. Application of geopolymers into permeation grouting is a relatively new topic that has a high potential for mass application due to its simplicity and efficiency. Repurposing wastes to lower the carbon footprint of soil improvement contributes to the sustainability of our environment.

3. MATERIALS

Silica sand #6 was the sand chosen to be used for the experiments because of its size that was not too fine yet not too coarse. This type exhibits a balance between permeability and grain size that also simulates liquefiable soil. It is also resistant to changes in soil pH, which minimizes its influence on the performance of the grout formula.

Blast furnace slag (BS), calcium carbonate ($CaCO_3$), and sodium hydroxide (NaOH) were tested for its potential to be used in permeation grouting. Physical properties are shown in Fig. 2 while chemical properties were analyzed through XRF. It was found that BS was composed of 48.8% calcium oxide (CaO), 31.1% silicon dioxide (SiO_2), and 13.2% aluminum oxide (Al_2O_3). In soil improvement, the presence of high amount of lime may potentially improve properties of soil when mixed [6]. Observing the spectrum from XRD analysis, it was determined that BS was amorphous in nature. This means that it tends to break down easier when exposed to an alkaline environment, aiding polymer formation. With the other materials, both $CaCO_3$ and NaOH used were standard laboratory reagents.



	BS	$CaCO_3$
D10	0.05	1.39
D30	0.16	3.19
D50	0.33	5.79
D60	0.48	8.27
D85	5.14	14.99

Fig. 2 Grain size distribution of BS and $CaCO_3$

To assess the grout materials for groutability, groutability ratio (G_R) and sphericity ($Ø_S$) of the material were analyzed. G_R is the ratio of D_{15} of the soil to D_{85} of the grout, and this estimates the feasibility of a material to be used for permeation. A G_R value of less than 11 is not advised to be used for grouting [7][8]. BS and $CaCO_3$ had a ratio of 38.91 and 13.31, respectively, showing its potential for grouting. Comparing the materials with conventional micro-cement, BS and $CaCO_3$ had a finer particle distribution and this aids in grouting performance. Apart from the particle size, shape also plays a factor. A round shape offers lower friction and flow more freely compared to jagged shapes which interlock and restrict movement. Sphericity assesses the roundness of a particle by how close it resembles a perfect sphere. A value of 1 means perfect sphere and near 0 means very angular. Using microscope images of the material and Powers chart [9], it can be deduced that BS and $CaCO_3$ scored approximately 0.17 to 0.35, and 0.25 to 0.49, respectively.

4. METHODOLOGY AND RESULTS

4.1 Unconfined Compression Test

The standard size used for testing is a sample with a height of 10cm and a diameter of 5cm. The soil samples were made with silica sand #6 at a relative density of 60%. For the grout mixture, 1:1 ratio of BS:$CaCO_3$, by weight, was used and formulated to a concentration of 20% grout particles to void volume. This meant that 20% of the void volume was meant to be filled with grout particles, by weight. Different molarities of NaOH were used to check for optimal molarity. Samples were cured at ambient temperature with high humidity for 28 days before being subjected to compression tests. A speed of 1% strain per minute was adopted and continued until failure or 15% strain, whichever came first.

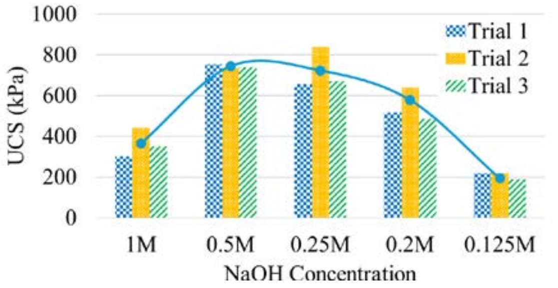


Fig. 3 UCS of BS mixes after 28 days

From Fig. 3, it can be observed that a lower concentration of 0.5M resulted in better strength development. The initial assumption was that higher concentration of alkaline solutions provides better activation of the materials and therefore should develop greater strength. Assessing the results, however, states the opposite. It was assumed that the occurrence of the bell-shaped curve was due to setting time and excess unreacted alkaline molecules. Since higher molarity hastens the reaction of the precursors, it may have contributed to incomplete or suboptimal formation of the polymer chains. While excess alkaline molecules may trigger redissolution of the already formed polymers, leading to a weaker structure. Apart from the strength differences, the developed strength of the samples can be attributed to the formation of C-A-S-H and C-S-H gels and densification that was confirmed with the microscope images of the solidified sample in Fig. 4.

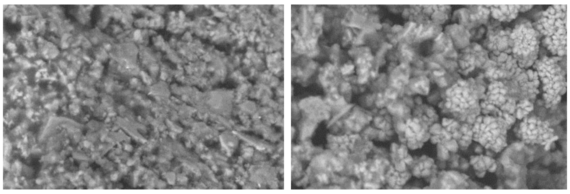


Fig. 4 1000x magnification of cured samples

4.2 Short-type Permeation Test

Permeation grouting is a very simple procedure, but understanding how each material interacts with the soil and the relationship between injection volume and pressure is a complex process. A lot of factors influence the efficiency of permeation of the grout to the soil, such as particle size, grout concentration, injection pressure, and many other factors. To understand the behavior of grouting, one-dimensional permeation tests were performed. The short-type permeation apparatus was used to model 20cm length of soil. The grout injection flow was from the bottom-up, against gravity. This simulates the hardest path the grout will travel through when injected into the ground. To maintain uniformity, the sand and density used for the test was the same as the UCT test. Filter layers were placed as shown in Fig. 5 to assist with distribution of grout throughout the cross section upon permeation. It also served to prevent sand flowing backwards and from getting pushed out by the pressure towards the output located in the top-end.

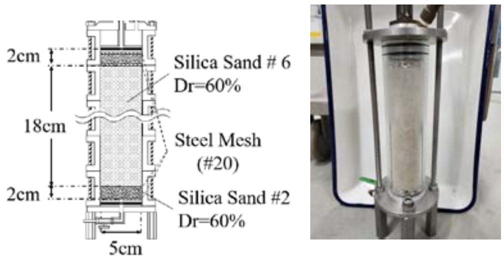


Fig. 5 Short-type permeation apparatus

Injection pressure is crucial in permeation grouting, so a 1MPa water pressure sensor was installed between the apparatus and the pump that continuously monitors the injection pressure as the permeation commences. An upper limit of 400kPa injection pressure was imposed to prevent disturbance and fracturing of the soil layer that may create path of lesser resistance which leads to uneven distribution of grout particles. The pump utilized in this study was a mono pump, or a helical rotor pump, which operates by trapping a fixed volume of fluid and then forcing it into the discharge pipe.

The grout mixture was 1:1 ratio of BS:$CaCO_3$. Using the weight of the de-aired water used for saturation, 20% of which was used as basis for the mass of dry materials. The grout mixture was formulated at a concentration of 3%, meaning 97% was water and 3% were solid particles, by weight. Different flow rates of 25, 50, 100, and 150mL/min were done, resulting in flow velocities (upward direction) inside the apparatus of 1.3, 2.6, 5.1, and 7.6cm/min, respectively. For the alkaline activator, 1M and 0.5M concentration of NaOH were used to check whether a bell-shaped curve in compression strength can also be observed in this experiment.

A two-stage permeation process was performed in the permeation experiment. The first stage consisted of only BS and $CaCO_3$, and the second stage was the alkaline solution. The pozzolans and the activator were split into two different permeation phases to prevent any premature activation of the material during the duration of permeation. Another benefit of having a separate alkaline solution permeation is the ability to properly compute for the minimum required amount of alkaline solution. This lessens the overuse of alkaline solutions that may be detrimental to the environment.

The result of the injection pressure to the grout volume injected can be observed in Fig. 6. The sudden drop of pressure around 2 liters marked the end of the first stage and the start of the second stage. Low flow rates showed erratic pressure profile while higher flow rates showed lower and smoother pressure profile.

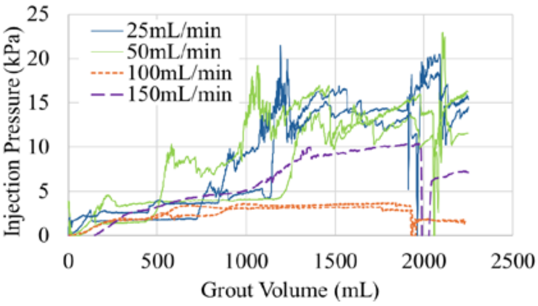


Fig. 6 Pressure profile of different flow rates

The behavior of the grout mixture under different flowrates can be better understood using Fig. 7. Low flow rates tend to clog the materials due to the lack of pushing force which can lead to continuous clogging and unclogging as reflected with the frequent sudden rise and drop of pressure in Fig. 6. On the other hand, high flow rates tend to flow more freely due to the increased pushing force. This distributes the grout materials deeper in the soil matrix, leading to less clogging. However, having too high of a flow rate prevents the materials from settling at all, causing reduced overall grout concentration retained within the soil voids.

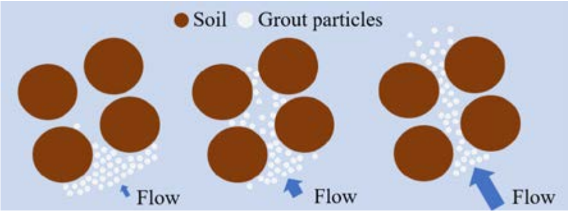


Fig. 7 Effect of flow rate to the grout particles

As mentioned, the short-type sample consists of 20cm solidified soil sample. This was divided into two-10cm cylinders as upper part and lower part, then subjected to compression tests. Results demonstrated that low flowrates tend to have increased strength in the area near the injection port and less further up the soil, while higher flows tend to have lower strength in the bottom portion but higher in the upper portion. This indicated that higher flowrates had a higher penetration that resulted in better permeation radius. Some samples broke upon demolding, making it unsuitable for testing.

In permeation grouting, a balance between injection pressure, grout retained, and strength developed is needed. Considering the variables, 100mL/min was deemed to be the optimal flowrate as this offered the best pressure profile and considerable developed strength. Apart from the flowrate, Fig. 8 shows a similar pattern of 0.5M solution developing a higher strength was observed.

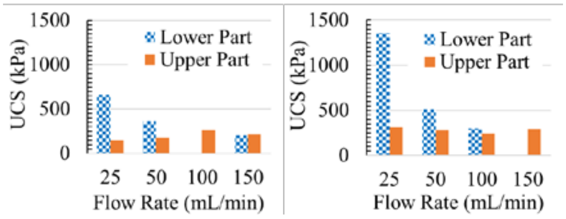


Fig. 8 UCS of 1M (left) and 0.5M (right) samples

4.3 Long-type Permeation Test

This test had the same properties as the short-type but scaled to a longer soil column designed to simulate the ideal permeation radius of suspension grouts of 0.75m. Shown in Fig. 9, the apparatus was made with 11-10cm acrylic molds that were bolted together to form a 1m long soil column.

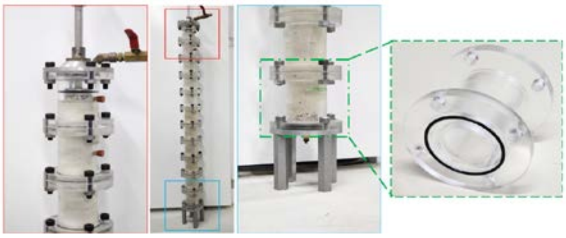


Fig. 9 Long-type permeation apparatus

From the results of the short-type permeation tests, 100mL/min flow rate was adopted in this test and 0.5M NaOH solution was used. In Fig 10, the grout injection pressure gradually rose as the permeation commenced as more particles situate in the voids. Fluctuations were noticed just after the 4L injection volume, this can be related to frequent clogging and unclogging of the particles, resulting in spikes and downs in pressure. Achieving the desired 20% grout concentration retained in the soil, second stage permeation started at the 6L mark. Since the 0.5M NaOH was a solution, the flow rate was adjusted to 150mL/min to increase distribution and efficiency. It was assumed that it did not contribute to clogging and the increased flow provided better distribution of the grout particles.

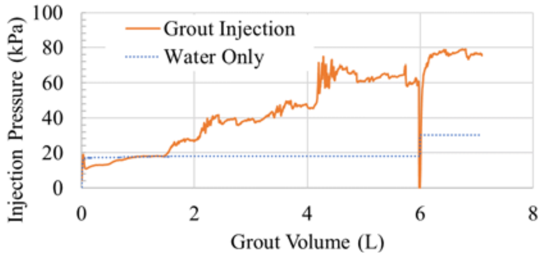


Fig. 10 Long-type permeation pressure profile

After curing inside the apparatus for 7 days, the samples were carefully de-molded and cured with an additional 21 days in ambient temperature with high humidity, shown in Fig. 11. After a total of 28 days of curing, the samples were subjected to unconfined compression tests and results tallied in Fig. 12. Based on the strength developed, the grout was able to penetrate about 90cm from the injection port. With up to 80cm part developing strength enough for liquefaction control, which is above 100kPa. This meant that the grout mixture successfully permeated up to 0.8m, slightly exceeding the ideal permeation range of 0.75m.

Fig. 11 Demolded samples

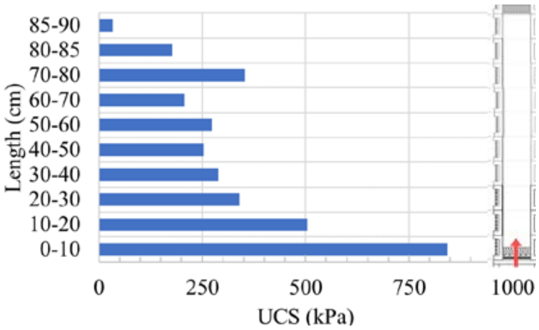


Fig. 12 UCS of long-type samples

4.4 Two-dimensional Permeation Test

The one-dimensional permeation test developed understanding regarding the permeation radius of the formulated grout formula. The next step towards the feasibility of the grout solution for permeation grouting is the two-dimensional permeation test which injects grout omnidirectionally. This gives insight into how the grout flows within the soil strata and how this affects the surrounding ground.

For the two-dimensional permeation test, a flat-box type aluminum apparatus was used. The inner box dimensions were 36cm wide by 41cm deep with a thickness of 5cm. Inside the box was an acrylic mold that had a circular form with a diameter of 30cm to contain the soil sample for permeation grouting. The reason for the circular form as opposed to the typical rectangular shape was for the ease of drainage. Essentially, having a circular dimension simulates an infinite drainage dimension with minimal influence of the boundaries. Differentiating from normal rectangular shape, having a circular form means that the thickness of soil is equal from the port to the drainage area. Drainage holes, for expelling liquid outside the container, were located at the top-portion of the container. By allowing water to drain from the container, the water level can be maintained.

The nozzle for permeation was installed in the center of the circular soil sample seen in Fig. 13-14. It had several openings to enable permeation in all directions. In the acrylic inner box, silica sand #6 was used which had the same relative density of 60%. Surrounding the sand was a steel mesh that helps separate the sand from the gravel layer. A water pressure sensor was installed between the injection port and the pump.

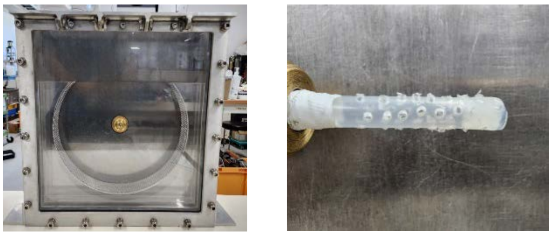


Fig. 13 Aluminum box apparatus and nozzle

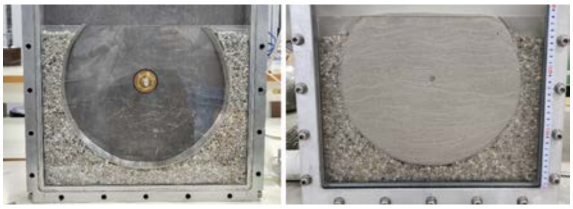


Fig. 14 Completed 2D sample

Prior to permeation, the sample was vacuum-saturated, meaning saturated under vacuum. By doing this, trapped air can be minimized to obtain a fully saturated condition of the soil. The grout was prepared to permeate a radius of 5cm from the injection port with the aim of achieving 20% concentration. Using the same grout mixture, permeation commenced. Due to the shape of the nozzle and the minimal grout amount, permeation pressure was relatively low, only reaching about

8kPa. Though pressure is an important factor, the main objective of the two-dimensional permeation test was to see how the grout spreads throughout the sand sample, and how the fine particles situate in the voids. Similar to the one-dimensional test, two-stage permeation was also performed. To aid with visualization of the permeation, coloring was added. Red for the first stage and blue for the second stage. The green marker in the container showed the desired 10cm diameter circle. This can be observed in Fig. 15. During permeation, water (red) was detected to flow freely leaving the grout (white) particles situated in the voids. Calculating the required amount of activator, exact solution can be permeated to activate the grout materials. While it did not permeate as a circular shape as predicted, this provided good insight into the permeation behavior of the grout.

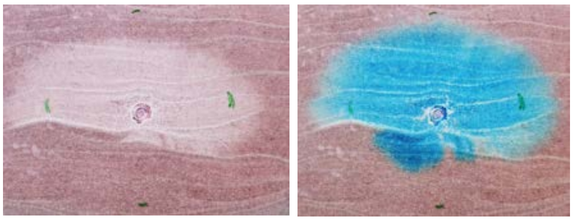


Fig. 15 Grout after 1st stage (left) & 2nd stage (right)

With a separate second stage, the amount of alkaline solution needed for the treated area can be estimated depending on the targeted volume. Upon completion of the grouting process, the alkaline solution (blue) was observed to cover almost the same volume as the volume occupied by the grout particles (white). This way, excess alkaline can be minimized, saving on costs and preventing alkaline pollution or leakage to the surrounding ground. Checking for alkaline pollution resulting from permeation, pH tests within and around the treated area were done after 7 days of curing. From Fig. 16, it can be concluded that minimal alkaline pollution happened after permeation grouting, showing little to no change of pH outside the treated area. Sand is naturally slightly alkaline in nature, so it was expected that the pH level of the untreated zone to be around 8 to 9.

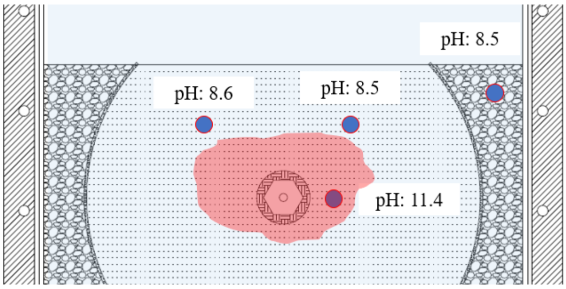


Fig. 16 pH test results around the treated area

5. CENTRIFUGE MODELING

Geotechnical centrifuge is a complex piece of equipment utilized in the field of geotechnical engineering. Its main function is to enable conducting tests of various real-scale structural and geotechnical systems in a controlled laboratory scale model. It works by adjusting the gravitational acceleration of a sample to achieve a similar stress condition to a real-scale structure in a small-scale model. By enabling small-scale modeling of big structures, the cost can be minimized, and variables can be easily adjusted. Apart from the size, timescale can also be modified depending on various conditions. To accurately model a real-scale structure in a small model, various scaling laws are being followed.

Fig. 17 Tokyo City University Mark III Centrifuge

5.1 20G Permeation Test

For accurate testing of grout permeation in actual stress conditions, centrifuge modeling was performed. However, permeation grouting under centrifuge field has yet to be evaluated whether it is feasible or not. To check for the feasibility of permeation grouting under a higher gravitational acceleration, preliminary testing was done, substituting the grout formula with water only. Similar to the 1G test, this aims to observe the permeation shape of injected fluid to the soil sample. Along with visual analysis, various mini water pressure sensors labelled as 1, 2, 3.1, 3.2, and 3.3 were also installed around the injection port as shown in the diagram in Fig. 18. Data obtained from the sensors helps understand the pressure changes happening during permeation.

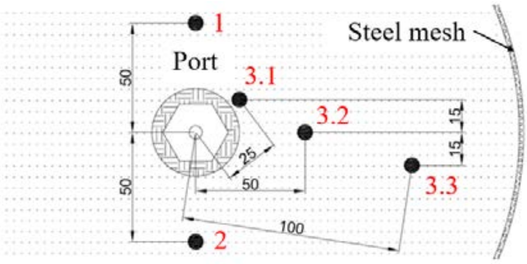


Fig. 18 Water pressure sensors setup

Similar soil conditions were used for the setup of the apparatus. During the saturation phase however, blue water was used to saturate the sample. The reason why blue water was used for saturation and not for permeation was because only clear water was permitted to enter the centrifuge device to prevent any future difficulties arising from using colored water. Using colored water for saturation and clear water for permeation gave the same visual result as the 1G test. The acceleration set for the test was 20 times the gravitational force, 20G. The estimated maximum bulb diameter of an improved area in a real-world scale was 3 meters. Using the scaling law of linear dimensions (1/*n*), *n* being the gravitational acceleration, a prototype of 3 m diameter can be scaled to just 15 cm diameter in the scale model [10].

The centrifuge platform gradually spun and raised sideways until 20G was reached. Confirming everything was stable, permeation commenced. The permeation continued until the desired 15cm diameter was achieved. The resulting permeated area is highlighted in Fig. 19. The egg-shaped permeated area can mean that in increased acceleration environment, the uncovered top-portion of the soil sample played a significant role. The small variation in soil thickness was multiplied by the increased acceleration, leading to a noticeable difference in the effective flow resistance of the soil layer. With a lower resistance on the top portion, the permeated liquid flowed towards it. This was not as apparent during the 1G test, and confirming this phenomenon under centrifuge conditions contributed to better understanding of the flow characteristics.

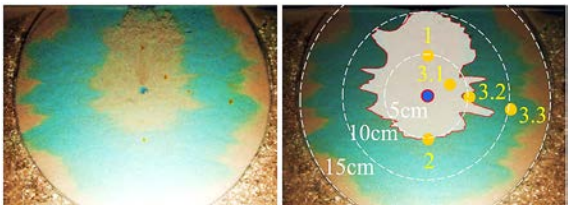


Fig. 19 20G Permeation test and highlight

The pressure profile obtained from the sensors is plotted in Fig. 20, and data tallied in Table 1. The gradual rise of the pressure was the acceleration of the centrifuge equipment. Upon reaching 20G, each sensor had a different value because of the positioning of the sensors within the soil. A shift in flow due to the commencement of permeation, at around 1000s, was detected by the sensors, registering a rise in pressure. Looking at Table 1, the largest value recorded was from the water sensor located above the injection port. This varied from the anticipated pressure readings as sensors 1, 2, and 3.2 were expected to have the same pressure readings. The difference may be caused by the variation in flow since most of the permeated water flowed upwards towards sensor 1. In contrast, the bottom one, sensor 2, recorded less water pressure. Comparing sensors 3.1, 3.2, and 3.3, sensor 3.1 recorded the highest value among the three and was attributed to its proximity to the injection port. As the distance increases, the pressure also dissipates. This meant that the permeation pressure is inversely related to the distance and affected by grout flow.

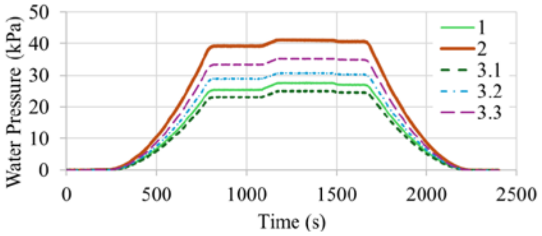


Fig. 20 Water pressure under centrifuge field

Table 1 Water pressure during permeation (kPa)

Sensor	1	2	3.1	3.2	3.3	Port
Before	25.4	39.1	23.0	28.7	33.3	27.5
During	27.4	41.0	25.0	30.7	35.1	29.4
Change	2.09	1.84	1.95	1.90	1.80	1.92

6. CARBON STORAGE

One of the problems towards sustainability is the continuous increase in carbon emissions. To aid the health of the environment, alternative materials were investigated for their potential. In terms of permeation grouting, substituting conventional use of cement to slag and calcium carbonate, a greener grout formula can be formulated. Using the proposed ratio and concentration, an approximate quantity of carbon emission can be made. Calcium carbonate contains a carbon dioxide molecule, by incorporating into the ground, a carbon storage system can be realized. From the calculations made in Table 2, a net emission of 1.1kg was expected in improving 1 cubic meter of soil. Comparatively, cement usage emits about 50kg to 180kg of CO_2, depending on the amount used.

Table 2 Carbon emissions per $1m^3$ calculation

Parameter	Amount (kg)	Emission (kg CO_2/kg)	Total (kg CO_2)
BS	44.13	0.040	1.765
NaOH	8.830	0.625	5.516
$CaCO_3$ (P)	44.13	0.300	13.239
$CaCO_3$ (S)	44.13	-0.440	-19.417
-	Net emission per $1m^3$		1.103

Note: in $CaCO_3$, P – Production; S – Storage

7. DISCUSSION

The proposed grout mixture was able to achieve satisfactory performance as per the permeation tests. As several factors influence the overall strength and permeation radius in grouting, exact comparison between two kinds of mixtures can be difficult. Compared to micro-cement, BS used in this study were finer in particle size and this increases its groutability [5]. Along with this, increasing the water content aids performance. With the filtration effect of soil confirmed by the 2D test, using a low concentration grout mixture can be feasible as particles get trapped within the voids and the excess water dispersed. The problem arising from using low concentration is in the lengthened permeation duration. But the utilization of two-stage injection process eliminates the possibility for premature activation, meaning that permeation time is not a factor in developing strength. A separate alkaline solution permeation enabled the computation of the required amount of alkaline activator to reduce the impact of alkaline pollution. Another benefit was minimal diffusion of the solution upon permeation, resulting in near-optimal activation of the pozzolans.

With flexible water-grout ratio, performance of grouting can be improved [5]. Although tested feasible for homogenous sandy soil, performance under different soil profiles and conditions are currently unknown and there is a need to perform permeation with heterogeneous soil layers.

8. CONCLUSION

One-dimensional tests revealed that the grout made with blast furnace slag and calcium carbonate was capable of permeating with low pressures of around 80 kPa and was able to develop liquefaction control strength up to a permeation radius of 80 cm.

In the two-dimensional and centrifuge modeling, the filtration effect of the soil was observed, leaving particles situated in the voids and dispersing excess water from the grout solution. Permeation was also found to be plausible under centrifuge field and from the data obtained from the various water pressure sensors, pressure experienced by the soil was inversely proportional to the distance from the injection port and influenced by flow.

The implementation of the two-stage permeation process eliminated the possibility of premature activation and enabled the proper calculation of the required alkaline activator, minimizing pollution.

In terms of carbon footprint, the proposed grout solution approximately emits 1.1 kg CO_2 for improving 1 m^3 of soil under the same experimental conditions, which was significantly lower compared to conventional use of cement as the main material.

From the various permeation tests which yielded satisfactory values in terms of permeation radius, unconfined compressive strength, and minimal carbon footprint, it was deemed that the grout mixture, made with slag and calcium carbonate and activated by sodium hydroxide, has a potential to be a viable alternative as a grout formula for permeation grouting for liquefaction control.

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