Pilot Use of Alternative Compliance Criterion for Cement-soil in a Slope Upgrading Works Project

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ABSTRACT

Currently the General Specifications for Civil Engineering Works stipulates the use of in-situ density tests as compliance criterion for both compacted fill and cement-soil. However, the latter derives its strength from cementation between particles and could exhibit very high strength as opposed to the former whose strength closely relates to its density. Hence, the use of strength as a compliance criterion for cement-soil seems more direct and appropriate. This paper describes the pilot application of unconfined compressive strength as the compliance criterion for cement-soil in a slope upgrading works project. It details the field trial conducted prior to the production run to work out the mixing and placement procedures, the cement content to be adopted and identification of appropriate field control measure to augment the compliance criterion. It also covers the experience gained, the potential benefits of such application and areas where further optimisation could be achieved.

Keywords: Cement-Soil, Compliance Criterion

1 Introduction

Replacement of loose fill with suitable material is one of the engineering solutions to enhance the slope stability in Hong Kong. Fill replacement construction standard and compliance criterion are stipulated in the General Specification of Civil Engineering Works (GS). The compacted fill materials are required to achieve at least 95% relative compaction of compacted mixture and the moisture content to be within ± 3% of the optimum moisture content.

Mixing fill material with cement has sometimes been used to improve the existing fill engineering properties in slope upgrading works under the Landslip Preventive Measures (LPM) Programme (BBVL, 2002; Fugro 2009). Unlike compacted fill with strength closely related to its density and moisture content, the strength of a cement-soil mixture is due to cementation between soil particles resulting from the chemical reaction between soil and cement. The cement-soil could achieve relatively high strength and is generally designed to withstand the design load. Hence it will not contract resulting in an increase of pore water pressure during shearing and saturation, and liquefaction is generally not a concern in cement-soil. The behaviour of cement-soil is more akin to weak rock or soft soil treated with deep cement mixing which gains strength with time. As cement-soil behaves differently from compacted soil fill, it seems that in-situ density tests may not be appropriate for cement-soil. Furthermore, the relatively high strength of cement-soil also renders the in-situ density tests difficult to perform in the field.

In light of the foregoing, it seems more appropriate and direct to adopt strength tests as a compliance criterion for cement-soil. As cement-soil is similar to soft soil treated with deep cement mixing, unconfined compressive strength (UCS) was proposed as an alternative to in-situ density test as a compliance criterion for cement-soil at a fill slope at Pok Fu Lam Road. Prior to the production run, a field trial was carried out to:

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a. work out the mixing and placement procedures,
b. determine the required cement content, and
c. identify other appropriate tests as field control measures to augment the compliance criterion.

This paper describes the findings of the field trial and the experience gained in the production run. It also covers the potential benefits of the application of the alternative compliance criterion and areas where further optimisation could be achieved.

1.1 Background

This field trial was carried out at a large fill slope at the downslope side of Pok Fu Lam Road (see Plate 1). The fill slope was to be upgraded under the Landslip Prevention and Mitigation (LPMit) Programme managed by the Geotechnical Engineering Office, Civil Engineering and Development Department (CEDD) of the Hong Kong SAR. The maximum height of the fill slope is about 30 m, with an average slope angle of 30° and a length of 220 m along the crest.

Ground investigation records revealed that the slope comprised a thick layer of fill with a maximum thickness of 30 m. In-situ density tests indicated that the relative compaction of some of the fill samples at the slope was less than 75%. This precluded the use of soil nailing. Fill replacement with cement-soil at the top 3 m was proposed as a slope upgrading measure. Design assessment indicated that the cement-soil needed to exhibit a UCS of at least 0.07 MPa in order to have the upgraded slope meeting the prevailing standard.

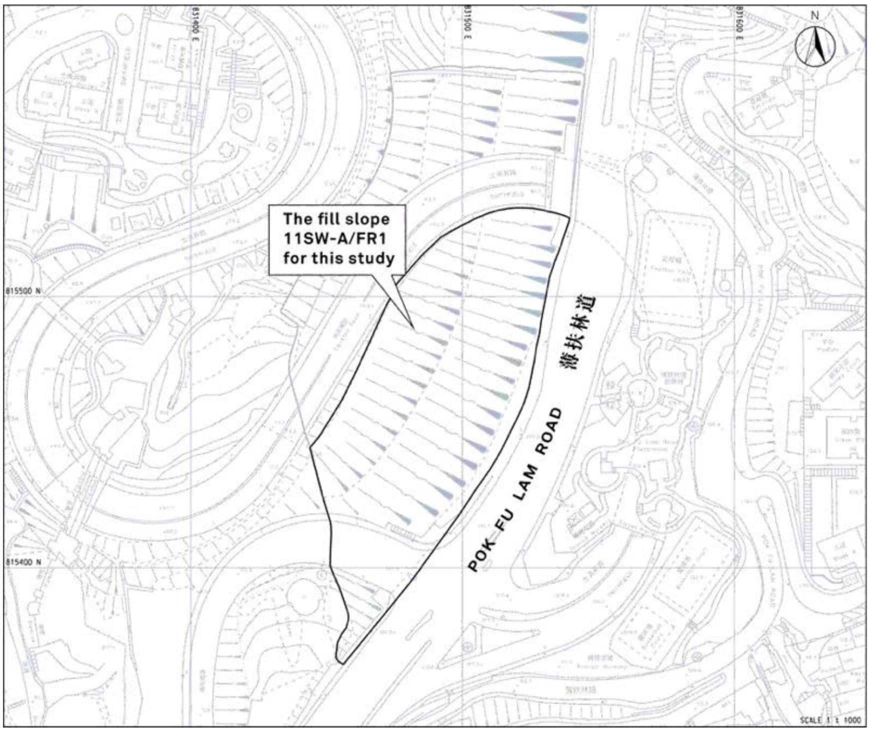

Plate 1: Location plan of the slope where the cement-soil study was conducted

2 Cement-Soil Material Components

2.1 Cement-soil Composition

The GS stipulates that the cement-soil mixture shall comprise Portland cement, sand and inorganic soil. Soil material that is suitable for cement-soil mixture shall be free of organic matter and contains not more than 30% of soil particles passing a 63 μm British Standard test sieve. Portland cement and sand shall comply with BS EN 197-1 and BS 1200 respectively. The constituents of the cement-soil used in this project conformed with these requirements.

2.2 Mixing and Placement Method

Following the GS requirements, excavated fill material at the site was sieved to remove unwanted materials, including fallen foliage, roots, organic soil, construction debris and gravels with size larger than 20 mm before mixing with cement, sand and water.

The cement-soil mixture was prepared by first adding appropriate proportion of sieved fill material and sand to a pugmill mixer, then measured quantities of cement and water were added to the mixture and further mixing was performed until it was homogeneous in appearance. In view of the limited working space in most LPMit slope works sites, small plants and equipment were used. The pugmill mixer used was electric-powered with a 200 kg maximum loading capacity and consisted of a U-shaped trough in which a shaft fitted with pitched paddles to pulverise the cement-soil mixture (see Plate 2).

Plate 2: Mixing equipment

The cement-soil was placed in layers to the excavated pits/trenches within 30 minutes of mixing and compacted in lift thickness of 300 mm. Each layer was systematically tamped with a minimum of 8 passes by a mechanical rammer/tamper with a force output per 100 mm width in a range of 3.5 kN to 4.9 kN. Tamping operation was found necessary in order to ensure that the samples when extracted from the sampler would not disintegrate as discussed in Section 2.3.

2.3 Cement Content

The cement content of cement-soil used in previous LPM projects ranged from 3% to 6%. In the field trial, the screened soil was mixed with cement content of 3% to 6% by weight of the soil. Samples were taken using open tube sampler for the determination of UCS.

Core samples of the cement-soil were delivered to the Public Works Central Laboratory (PWCL) of the CEDD for the determination of their UCS following the guidelines published by HKIE (2017).

After delivery to the PWCL, it was noted that some of the samples treated with 3% cement disintegrated when extracted from the sampler and could not be tested. Furthermore, some samples with 3% cement did not have uniform cross-sections or even surfaces (as shown in Plate 3) as required by HKIE (2017). Re-coring of samples was attempted in some cases to obtain better quality cement-soil samples for testing. Sometimes, this was not possible or not successful and no results were obtained for that particular batch.

Plate 3: Poor quality of core sample with 3% cement content

Figure 1 shows the average UCS obtained from about 200 samples with different cement contents. The compressive strength of the cement-soil increases with the cement content in the mixture. All individual samples met the project requirements of achieving a UCS of at least 0.07 MPa. It was noted that soil treated with 3% cement content yielded more varied UCS and exhibited lower consistency in sample quality. The uncertainty in the quality of samples with 3% cement content for laboratory testing described earlier renders it highly undesirable from a compliance testing perspective. Consequently, cement content of 3% was ruled out from further consideration.

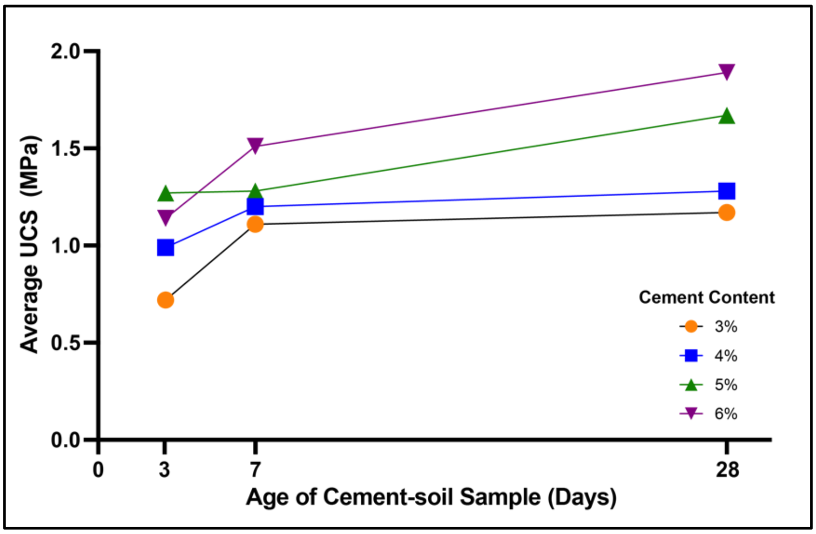

Figure 1: Average UCS of samples with different cement contents

Apart from the integrity of core samples, the opportunity for future landscaping of the cement-soil slope surface was taken into consideration in deciding on the cement content to be used. While high cement content in the mixture could yield higher strength and exhibit high reliability in meeting the compliance criterion, it also renders high pH value in the cement-soil which is less favourable to slope greening. To strike a balance amongst other things, the acceptable strength of cement-soil, the confidence level of core sample quality and the possibility of future slope greening, a cement content of 4% by weight of soil was selected for this project.

2.4 Sampling Tools

Having an effective and practical means to recover good quality samples for testing was a challenging task and is critical to the practical application of the UCS as a compliance criterion. In principle, core samples should preferably be taken using ground investigation (GI) tools such as a double-tube or a triple-tube sampler driven by conventional GI drilling rig to minimise disturbance. In view of the limited working space in most LPMit slope works sites, mobilising such drilling rigs all over the slope could cause complications on site management and poses significant time and cost issues for sampling within the cement-soil. A portable sampler may be a viable option for this task. Due to the limited construction time, the LPMit contractor was unable to source a portable sampler and opted to devise a tailor-made sampling device. After several attempts of trying out different tailor-made core sampling methods in the field trial, a hand-held rotary coring machine using a 100 mm diameter core barrel was considered to be a viable means for procuring samples from the ground. It was noted that the friction developed between the core barrel and the surrounding cement-soil during coring could critically affect the quality of the core sample. The use of water as a flushing medium during the coring operation would damage the cement-soil structure and ruin the samples. As such, additional bits at the core barrel opening and additional auger-like blades were welded on the core barrel surface together with low pressure compressed air as a flushing medium (as shown in Plate 4) were used to improve the core recovery. The quality of a recovered sample is shown in Plate 5. This sampling method will no doubt inflict higher sample disturbance compared to that of sampling tools commonly used in geotechnical works. Given the relatively low UCS requirement in this project and the agility of such sampling method, it deemed to have met the project needs.

Electric hand-held coring machine connected with low pressure of compressed air

Additional welded bits and auger-like blades on core barrel

Plate 4: Tools for collecting UCS samples

Plate 5: Samples recovered using the tailor-made core sampling method

2.5 Field Control

While 28-day UCS was used as compliance criterion, it is imperative to have some kind of early assurance that the cement-soil would meet the project strength requirement. Knowing that the strength of the cement-soil would increase with time, if its earlier UCS meets the project requirement, so will the 28-day strength (as shown in Figure 2). Hence, 3-day UCS and 7-day UCS of the samples were also determined in the field trial as possible early assurance indicators.

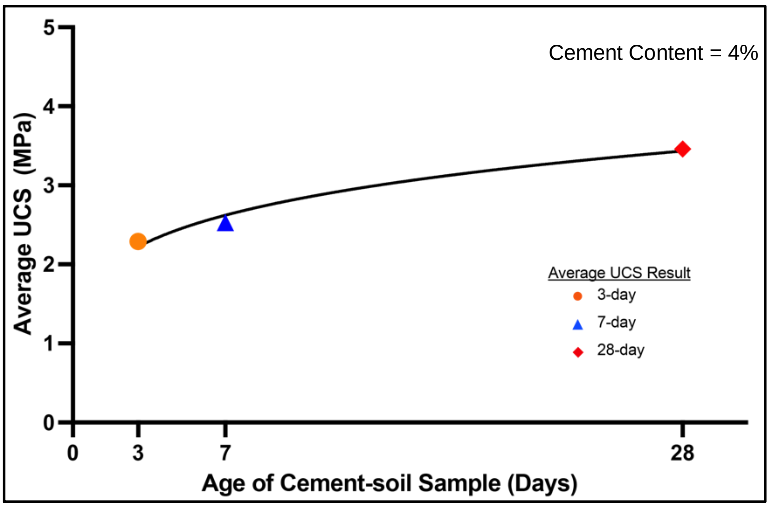

Figure 2: Correlation between average UCS and age of cement-soil samples

As the 3-day and 7-day UCS test results will only be available days after the placement of cement-soil, it is desirable to have a quicker means to give some indication on whether the in-place cement-soil meets the project requirement in order to expedite the works flow and minimise the need to carry out remedial works should the samples fail to meet the project requirement.

GCO probing was identified as a possible quick field control measure. During the field trial, it was conducted on cement-soil with different contents at hourly intervals for the first 4 hours after placement and then daily for the next 3 consecutive days to find out the optimum time to conduct such test. Figure 3 shows that GCO probe blow count increased gradually in the early stages and exceeded 40 at four hours after placement, thereafter there was a drastic increase.

To accommodate site workflow, GCO probe tests were conducted within 4 hours after the placement of a lift of 300 mm thick cement-soil. Following the practice of conducting a GCO probing for backfilling using pit by pit method, three GCO probe tests were conducted at each lift. Figure 4 shows that the 3-day UCS plotted against the minimum GCO blow count for the same lift in the field trial. All 3-day UCS exceeded 0.07 MPa and the minimum GCO blow count was 40.

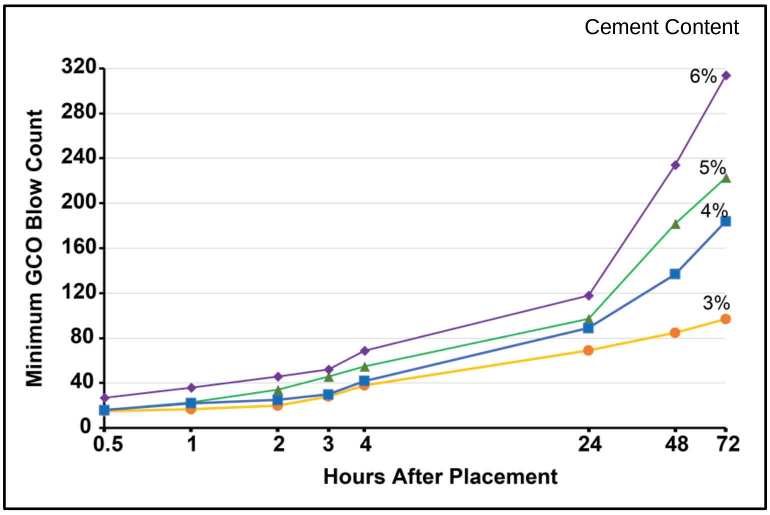

Figure 3: Field trial - GCO probe test results with different cement contents

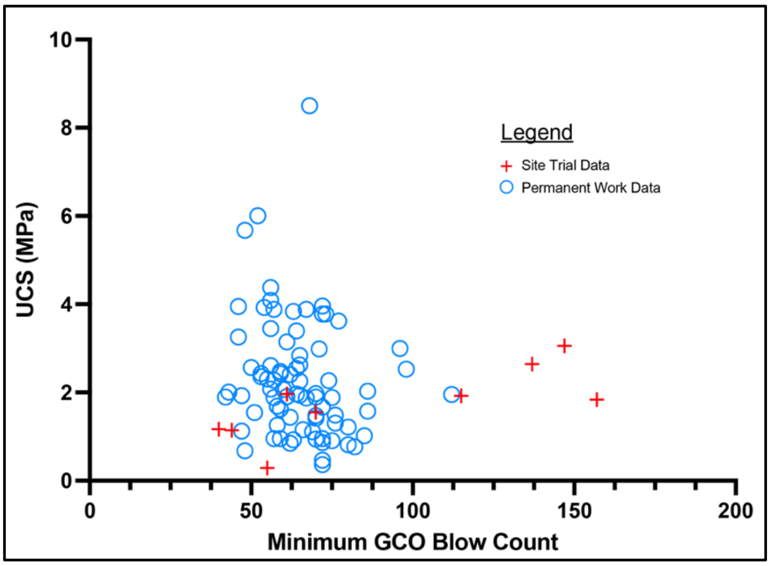

Figure 4: 3-day UCS vs GCO blow count

3 Permanent Cement-Soil Construction

Upon the completion of the field trial, results of UCS tests and GCO probe tests substantiated the postulation of adopting alternative testing method for cement-soil. Consequently, these testing methods were implemented in the production run of placement of 4,200 m^3 of cement-soil at the study works site.

3.1 Mixing and Placement

Following the GS requirements, excavated fill material was sieved as detailed in Section 2.2 in the field trial. To maintain the uniformity of the cement-soil fill and facilitate subsequent GCO probe tests, the excavated materials were further screened using 10 mm and 5 mm test sieves before adding into the pugmill for mixing.

In this study, cement content of 4% by weight of soil was adopted. The mixture consisted of Portland cement, sand and sieved fill material in the proportions of 1:4:20 by weight. Mixing and placement of the cement-soil followed the procedures outlined in Sections 2.2 and 2.3. Mixed cement-soil was backfilled in layers to the excavated trenches of 6 m long by 2 m wide within 30 minutes of mixing and compacted in lift thickness of 300 mm thick. As a common workmanship control on site, each layer was systematically tamped and the surface of the compacted cement-soil was then visually checked for any defects such as any cracks and dusting surface. If such circumstance occurred, water would be sprayed onto the compacted surface and the tamping procedure was repeated.

3.2 Field Control and Sampling Frequency

To streamline the workflow in the production run, it was decided that GCO probe would be conducted within 4 hours after placement of three lifts of 300 mm thick cement-soil. Placement of cement-soil could be continued when the minimum GCO blow count for the previous 900 mm thick cement-soil exceeded 40. Figure 4 shows that such approach could speed up the production without compromising the reliability of the field control measure.

As the behaviour of cement-soil is akin to soft soil treated with deep cement method, the sampling frequency of cement-soil mixture in this study was devised with reference to that adopted in a recent CEDD reclamation project at Lantau Island using deep cement mixing. One continuous core sample would be taken at each 900 mm completed layer from a 3 m depth trench for every 50 m^2 of slope area treated with cement-soil for the compliance testing, i.e., determination of 28-day UCS. In this study, each 900 mm continuous core sample was split into three 300 mm core samples for 3-day, 7-day and 28-day UCS tests to furnish information on the early strength after placement. To allow for sufficient time for the cement-soil to gain some strength and for the contractor to cope with site workflow, sampling of cement-soil for UCS tests was conducted 24 hours after its placement. This arrangement took due account of the site works activities and also enabled sampling to be conducted after placement of every 3 lifts of cement-soil.

3.3 Optimised Construction Time

According to the GS, three in-situ density tests would be conducted for each batch of compacted fill. Table 1 shows the number of compliance tests required following the prevailing practice and the alternative proposed in this paper at the study work site. The proposed field control and compliance requirements, apart from entailing fewer tests, the time in relation to testing activities on site was also found to be shorter. As demonstrated in the production run, the time required for the excavation and placement of cement-soil and relevant field testing following the proposed field control and compliance requirements for a trench of 6 m long by 2 m wide by 3 m deep was completed in about 2 days. This considerably shortened the construction time and the works cycle was more effective and less affected by inclement weather. This is beneficial to site operation as it could reduce the risk of temporary slope instability and better utilise the limited storage area for mixing and storage of spoils.

Table 1: Number of in-situ tests for different compliance requirements at the study slope

	Compliance Criterion in GS for Soil-cement	**Tests for Field Control and Proposed Compliance Criterion for Cement-soil**	
	In-situ Density Test	UCS Test	GCO Probe Test
No. of test	1,650 approx.	348*	1,044

* 3-day, 7-day and 28-day UCS were determined for each 900 mm core sample

3.4 Experience Gained

Adopting the alternative compliance criterion and field control for cement-soil permanent slope work would allow the contractor to have an early indication of the cement-soil strength condition in a short period of time. The time input for completing a 3 m depth trench of cement-soil backfilling was significantly reduced comparing with the use of the traditional in-situ density test for compacted fill. This allowed the backfilling operation to be carried out more efficiently and less affected by the weather conditions.

During the permanent works, attempts to further expedite the workflow was continued to be examined. For example, an attempt was made to increase the lift thickness to 500 mm while keeping the same number of passes of the tamper. However, it was found the quality of the samples deteriorated significantly when extracted for testing and was not pursued further. As the contractor gained more experience in the cement-soil backfilling operation and the use of the sampler in the latter phase of the permanent works, the core sampling depth for a 2.7 m deep cement-soil trench (excluding top 300 mm thickness for soft landscaping work) was relaxed from every 900 mm compacted thickness to a 2-phase coring of compacted thickness in 1.2 m and 1.5 m. This arrangement further improved the progress of work without sacrificing the quality of core samples.

The trial showed that both 3-day and 7-day UCS could be used as an early assurance indicator. However, as 3-day UCS was available sooner, it was preferred. Hence, the actual number of tests required to fulfil the proposed field control and compliance criterion would be less than that shown in Table 1. GCO probe seems to be a useful and agile field control tool giving early assurance once a correlation between the blow count and 3-day UCS was established.

A tailor-made sampler was used in this study because the contractor had difficulties in sourcing a portable sampler due to time constraints. While the tailor-made sampler seems to have served its purpose in this project partly because of the relatively low strength requirement of the cement-soil, it may not be adequate or efficient when higher cement content is adopted. Hence, the use of a portable sampler should be explored in future application in hope of standardising and making the sampling operation more efficient.

As this is a pilot application of the use of UCS as a compliance criterion, a conservative approach was adopted requiring all samples to meet the compliance criterion. While in principle, remedial works could be implemented if a specific layer failed to meet the compliance criterion, this would in reality pose much difficulty in doing so as that specific layer might already be covered by considerable thickness of cement-soil and would have a significant impact on the works programme. This may be circumvented with the choice of a more conservative GCO blow count as field control to minimise such occurrence or it is worth exploring the possibility of accepting a small percentage of samples not complying with the criterion. As the slope stability is governed by the strength of the soil mass, the impact of having discrete locations of slightly lower strength can be assessed by means of slope stability assessment to see if this can be accommodated or whether appropriate remedial measures are needed.

The requirement of adding sand to the cement-soil mixture as stipulated in GS is worthy of further examination. If the sand is substituted by the original sieved soil, this could, in some cases, minimise the transport of surplus excavated soil offsite and better utilise the in-situ material.

4 Conclusion

The GS adopts the same compliance criterion for both compacted fill and cement-soil. The strength of cement-soil derives from cementation resulting from chemical reaction between cement and the soil while that of the compacted fill closely relates to its density. Hence, the use of strength rather than density seems to be a more direct and appropriate parameter for compliance criterion of cement-soil. This paper describes the pilot use of UCS as an alternative compliance criterion for cement-soil used in a slope upgrading works project. It details the findings of a field trial prior to the production run to work out the mixing and placement procedure. It identifies that GCO probing could be a useful field control measure to augment the use of UCS as compliance criterion.

Furthermore, in the prevailing practice, in-situ density tests are generally performed on cement-soil at least 24 hours after its placement. Figure 3 shows that 24 hours after its placement, the cement-soil could have gained significant strength as reflected by the high GCO blow counts. It can be easily envisaged that use of conventional hand tools to excavate the cement-soil for in-situ density tests could be a daunting task.

The pilot application indicated that the adoption of the proposed alternative compliance criterion could lead to optimisation of the work flow in placement and sampling of cement-soil. This allows more efficient site operation resulting in potential time and cost saving. The filling operation would also be less affected by inclement weather.

As this is a pilot application, the work procedure had been concocted in a cautious manner. There is room for further improvement/optimisation, some of which are outlined in this paper for consideration.

5 Declarations

5.1 Acknowledgements

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