

QA/QC PLAN AND EVALUATION OF FIELD STRENGTH AND PERMEABILITY VALUE FOR DEEP CEMENT MIXING

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ABSTRACT: Deep Cement Mixing (DCM) is widely used to improve the strength and stiffness of soil by mixing it with cement. When DCM is used as a low permeability barrier for water cut off, permeability must be tested in addition to the usual strength values. One concern in DCM construction is the quality assurance and quality control (QA/QC) of this technique to ensure uniformity along the DCM column. It is even more crucial when low permeability is required for the DCM column to be used as a seepage cut-off in an earth bund, in addition to its strength requirement. In this application, the DCM columns require low permeability and adequate strength. In this paper, two QA/QC aspects will be evaluated: the operational control and the evaluation of the treated DCM column. The operational control in terms of mixing time, cement content, rotation speed and mixing energy will be studied to gain an understanding of how strength and permeability changes with the variability of the soil with depth. A rational QA/QC plan will be briefly proposed to ensure a consistent and rational method is developed for the evaluation of the strength and permeability variation of the treated soils over the area and the depth. These will help in the development of acceptable characteristic value for the geotechnical parameters of soils treated with DCM (in line with Eurocode 7).

Keywords: Deep Cement Mixing, Soil Improvement, Permeability, Quality, Eurocode 7

1. INTRODUCTION

DCM is widely used to improve the strength and stiffness of soil by mixing it with cement, and its application has gained popularity over the years in Singapore [1]. When installed in an earth bund, the DCM not only improves the stability of the slope but also act as a low permeability barrier for water cut-off if the earth bund is used to retain water, for example in a reservoir, dam, disposal basin and offshore barrier [2-4]. When DCM is used as a low permeability barrier for water cut-off, permeability must be tested in addition to the usual strength values.

When used to increase stability, there is usually no limit in strength requirements for the DCM column. However, a higher strength implies a more brittle behaviour and the likelihood of crack formation when the DCM column is subjected to higher loads. This is not acceptable if the DCM columns are used as a seepage cut-off. Hence, the strength of the DCM columns needs to be capped.

One concern in DCM construction is the quality assurance and quality control (QA/QC) of this technique to ensure uniformity along the DCM column [5-6]. It is even more crucial when low permeability is required for the DCM column to be used as a seepage cut-off in an earth bund, in addition to its strength requirement. In this application, the DCM columns require low permeability and adequate strength [7-8].

In this paper, two QA/QC aspects will be

evaluated: the operational control and the evaluation of the treated DCM column. The operational control in terms of mixing time, cement content, rotation speed and mixing energy will be studied to gain an understanding of how strength and permeability changes with the variability of the soil with depth. A rational QA/QC plan will be briefly proposed to ensure a consistent and rational method is developed for the evaluation of the strength and permeability variation of the treated soils over the area and the depth. These will help in the development of acceptable characteristic value for the geotechnical parameters of soils treated with DCM (in line with Eurocode 7).

The results, values, and parameters presented and suggested in this paper are only indicative and are intended to illustrate principles. They do not refer to any specific project and should not be used contractually.

2. PROPOSED QA/QC CONTROL FOR ACTUAL WORKS

Two QA/QC aspects will be evaluated: the operational control and the evaluation of the treated DCM column strength and permeability.

2.1 Operational QA/QC Control

The operational control in terms of mixing time, cement content, rotation speed and mixing energy is to be studied to gain an understanding of how

strength and permeability changes with the variability of the soil with depth.

To ensure the installation of good quality DCM columns, stringent operational controls are to be set up. For every column installation, a digitized record of the mixing efficiency, in terms of mixing time, cement content and mixing energy is to be recorded. Contractors will be required to submit records of the DCM column installation and compare that with the designed operation curves. These operation curves must be established with a site trial. An example of a design operation curve is shown in Fig.1a, b and c. The values in this figure are only indicative.

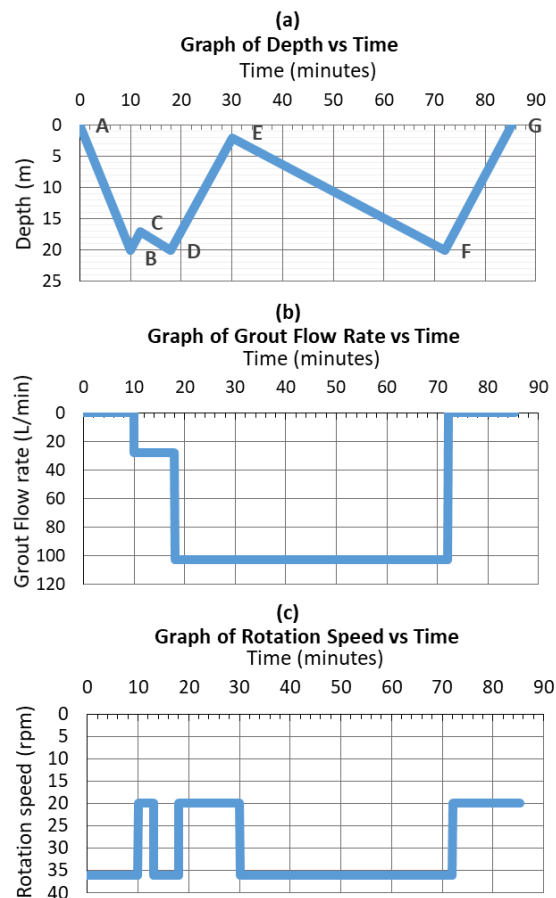


Fig.1 Example of a design operation curve.

In Fig.1(a), the vertical axis is the depth of penetration, while the horizontal axis is the time. Fig.1(b) and (c) are the grout flow rate with time and the mixing blade rotation speed with time respectively.

Based on this information, the amount of cement mixed with the soil at a depth of interest can be evaluated based on the grout flow rate at that depth. The calculated rate of mixing and cement used must be consistent with the design value. Any variation will suggest that the column was not properly installed, and remedial action could be necessary.

2.2 End Result Evaluation

The properties of Singapore Marine Clay treated with cement mixing has been well studied [9-10]. However, due to the changes in soil profile with depth in the ground and differences in operation parameters, the quality, and properties of the DCM columns can vary greatly from laboratory studies.

To understand the long-term characteristics of the DCM columns, the qualities of the DCM columns were inspected by coring the completed columns after 91 days. The conventional method of using only absolute average strength values often indicate highly varied and inconsistent results and will result in difficulty to access the overall performance of the DSM columns. Besides, permeability is usually not tested or specified. Hence, an improvement to the QA/QC criteria is needed.

To provide consistent and representative quality sampling, the DCM treated area will be divided into sections of 100m along the cut-off wall.

2.2.1 Coring tests

The quality of DCM columns is to be inspected by coring the completed columns throughout the depth. The coring shall consist of at least two cored locations per section of 100m along the cut-off wall.

2.2.2 Representative zones along DCM columns

Sampling at 1.5m intervals will be conducted along each cored location of the selected DCM column. Unconfined compressive strength tests will then be carried out for all cored samples, while permeability tests will be carried out on five selected samples per cored location.

2.2.3 Acceptance criteria for DCM column

The acceptance criteria for the cored sampled obtained from the selected DCM column are as follows:

- (1) The minimum Unconfined Compressive Strength (UCS) for all the samples must be greater than 200 kPa, while the maximum UCS for all the samples must be less than 450 kPa;
- (2) At least 70% of the total number of cored samples have to attain a UCS between 250 kPa and 350 kPa;
- (3) Lower bound limit: not more than 15% of the total number of cored samples are to attain a UCS between 200 kPa and 250 kPa;
- (4) Upper bound limit: not more than 15% of the total number of cored samples are to attain a UCS between 350 and 450 kPa;
- (5) For the five samples per cored location tested for permeability, the average permeability for all five samples must be less than 10^{-9} m/s. No single permeability value should be more than 10^{-7} m/s.

3. PRELIMINARY DCM SITE TRIAL DESIGN

Before implementation of the actual works, a site trial was conducted to determine the optimal cement

dosage and operation parameters in order to achieve the stringent strength and permeability requirements. Too high a cement dosage will likely lead to a higher strength but more brittle behavior

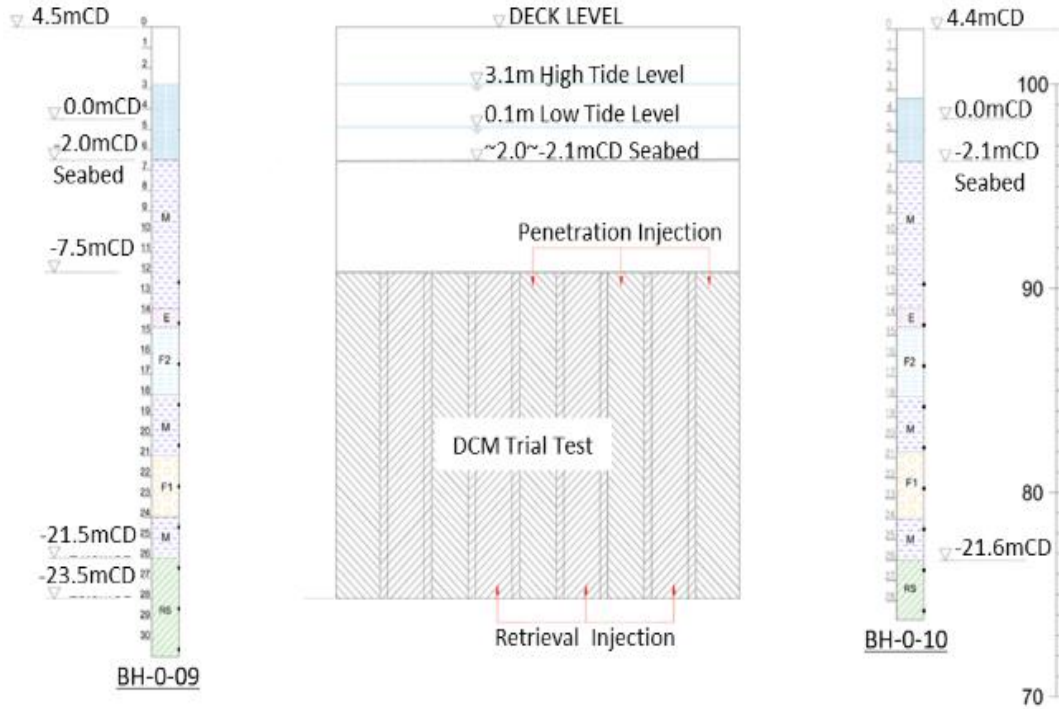


Fig.2 Reference borelogs for site trial.

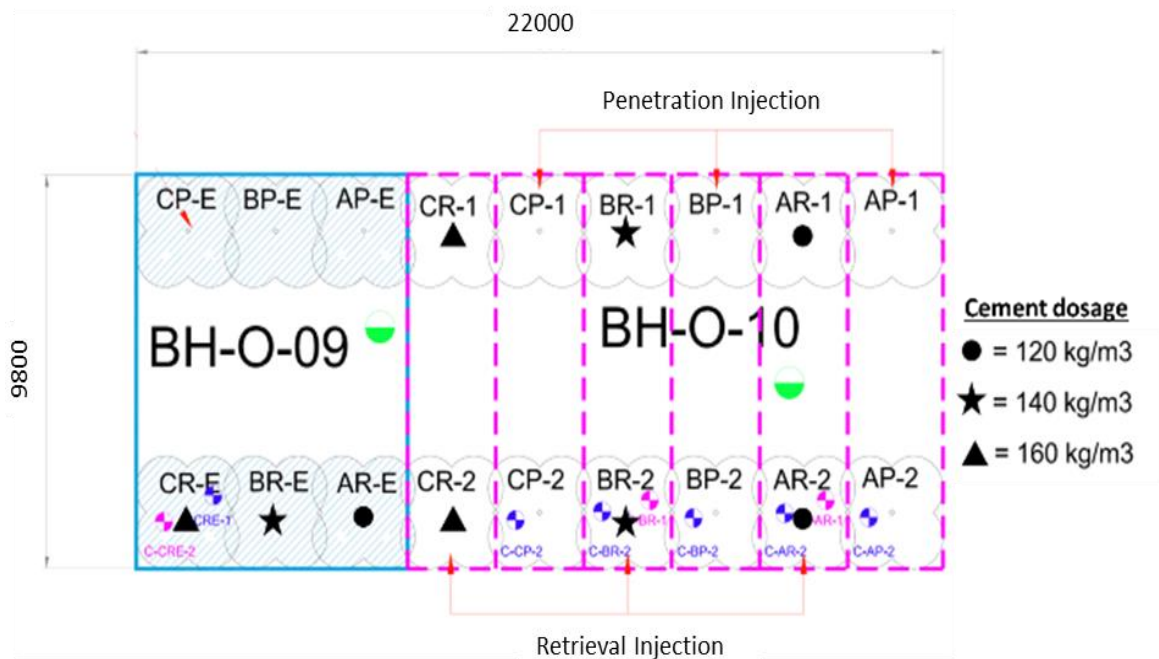


Fig.3 DCM site trial plan.

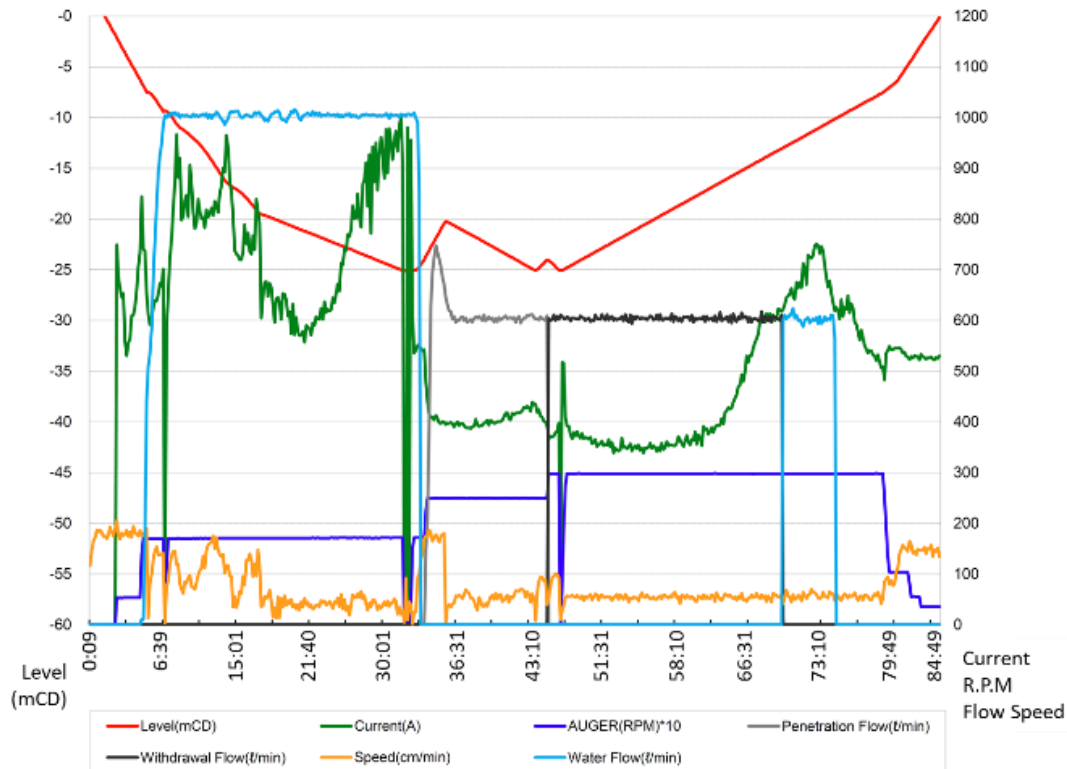


Fig.4 Actual DCM site trial operation curve.

of the DCM; which is not acceptable in this case. The site trial, as compared to laboratory tests mix results, is also more representative of the actual DCM construction as it considers the variability in the actual DCM behaviour due to installation methods.

The DCM columns for the site trial were installed beneath the site's existing seabed, with the top level of the columns at -7.5 mCD and the toe level at -23.5 mCD, resulting in a design column length of 16m. The ground consists of soft marine CLAY (M) overlaying fluvial CLAY/SILT (F2) and fluvial SAND (F1) and underlined by the original formation of sandy SILT residual soils (RS). Fig.2 shows two reference borelogs with respect to the DCM columns installed in the site trial.

The DCM columns were constructed using four mixing blades, resulting in four overlapping columns that form a 2.8m by 2.8m block. A total of 18 DCM blocks with varying cement dosage and installation method (penetration/retrieval injection of cement) were installed for the site trial, as shown in Fig. 3. All blocks were installed within a week. As shown in Fig.3, the DCM blocks labelled with circles represent the DCM columns constructed with a cement dosage of 120 kg/m³ of treated soil volume. Similarly, the DCM blocks labelled with stars and triangles represent cement dosages of 140 kg/m³ and 160 kg/m³, respectively. All mentioned above are for the retrieval injection installation method. The other DCM blocks that were not

labelled were constructed using the penetration injection method and will not be discussed in this paper.

The operational QA/QC control will be closely monitored during the construction of these blocks, and the cored samples obtained from the completed DCM columns after 28 and 91 days will be tested for strength and permeability.

4. SITE TRIAL RESULTS

Two QA/QC aspects will be evaluated: the operational and end result. However, this paper will only summarize the 28 and 91-day results.

4.1 Operational QA/QC Control

The operation parameters of every DCM block constructed were recorded and monitored. One of the actual operational curves is shown in Fig.4.

For the site trial, the preliminary set of key operational parameters adopted were as follows:

- (1) The maximum main penetration and withdrawal rate should not be more than 0.5 m/min.
- (2) The grout flow rate should not be less than 100 l/min for the main penetration and withdrawal steps.
- (3) The blade rotation speed should not be faster than 40 rpm for the penetration step and 30 rpm

for the withdrawal step.

- (4) The current supplied to the four blades must be more than 300A and less than 1200A for all effective penetration and withdrawal steps.

Every DCM block was found to satisfy and/or are close to the limiting operational parameter values stated above. Hence, if the core strength and permeability results satisfy the minimal specification requirement, the above operational parameter values will indicate the minimum requirement needed to achieve a good quality DCM block. Otherwise, if the core strength and permeability results do not satisfy the requirements, the above operational parameters must be adjusted accordingly.

4.2 End Result Evaluation

The recovered cored samples comprised of cement mixed with the different types of in-situ soils occurred through the depth of the DCM columns. This ranged from M (clay) to F1 (sand) and RS (residual soils). Different strengths and permeability values were obtained for the different soil mixes even when the cement dosage is kept constant throughout the depth.

4.2.1 Unconfined compressive strength (UCS)

For ease of comparison, the 28-day and 91-day UCS results have been plotted with depth for the cement dosages of 120, 140 and 160 kg/m³ and are shown in Figs.5, 6 and 7, respectively. In general, the 91-day results show an increase in UCS as compared to the 28-day result. However, the increase in strength resulted in a more brittle behaviour in DCM column as observed from the increase in stiffness and reduction in elastic strain limit and failure strain. Besides, all the samples had exhibited a UCS higher than the maximum allowable limit of 450 kPa. This implies that cracks may develop in the DCM columns due to shrinkage. This could affect the overall permeability of the DCM columns, leading to its inability to function as a seepage cut-off wall.

By comparing the UCS result with depth for a constant cement dosage, it can be observed that the UCS varies significantly in the different soil types, and the DCM column does not have a uniform strength throughout its depth. In addition, for the same soil type treated with a constant cement dosage, the UCS results obtained also significantly varied as shown in the clay (M) layers treated with a cement dosage of 140 kg/m³ shown in Fig.6. This indicates that the operational QA/QC control is not adequate, and further refinement is necessary.

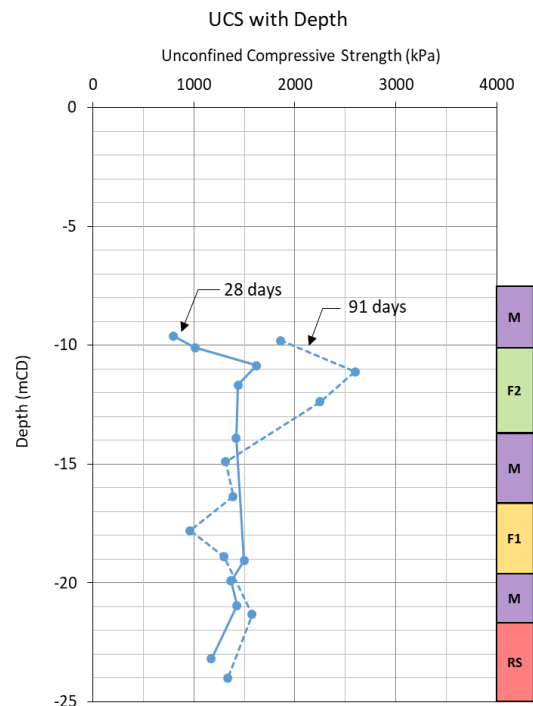


Fig.5 UCS with depth for the cement dosage of 120 kg/m³ of treated soil.

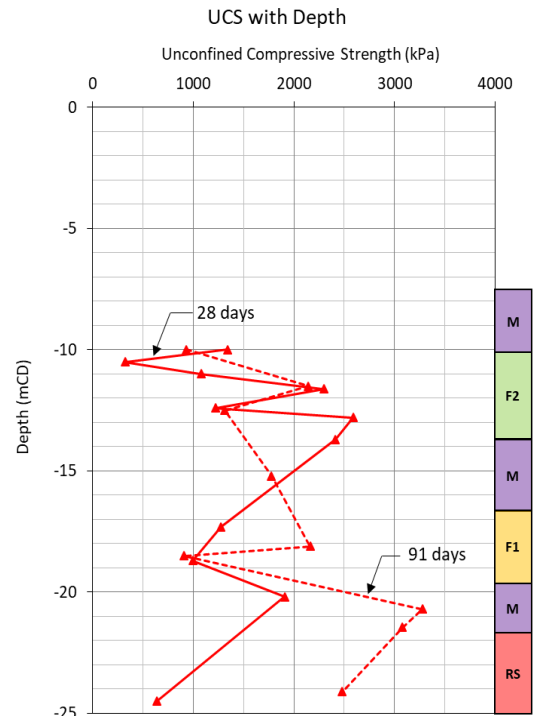


Fig.6 UCS with depth for the cement dosage of 140 kg/m³ of treated soil.

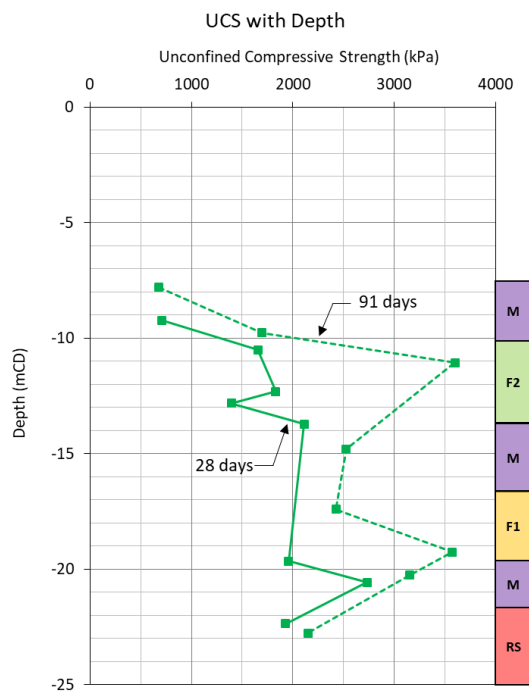


Fig.7 UCS with depth for the cement dosage of 160 kg/m³ of treated soil.

4.2.2 Permeability

Triaxial permeability tests were carried out for some of the cored samples. The permeability results at the various depths of the DCM columns have been plotted in Fig. 8.

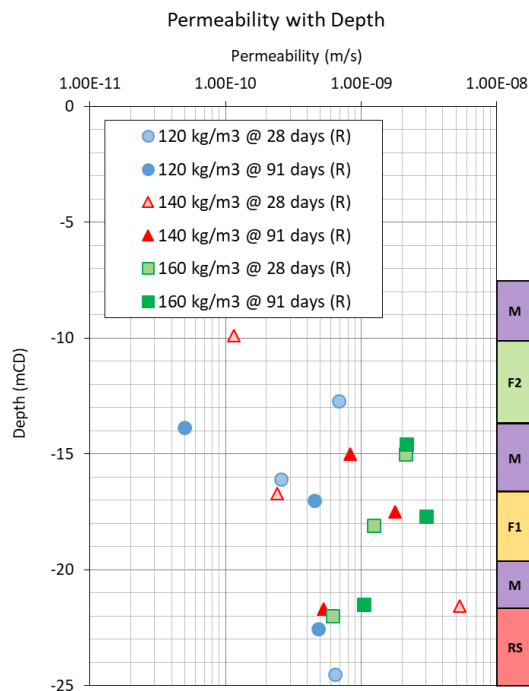


Fig.8 Triaxial permeability tests result.

The permeability test results show that the core samples obtained from the DCM columns constructed with a cement dosage of 120 kg/m³ were able to meet the permeability requirements of less than 10⁻⁹ m/s after 28 days and 91 days of curing. The permeability test results obtained from the DCM columns constructed with a cement dosage of 160 kg/m³ was not satisfactory as it had obtained higher permeability values than the required. Besides, it was also observed that the sand (F1) layer tended to have higher permeability results. This result is due to a lot of more granular particles present in this layer.

A summary table of the UCS and permeability tests result obtained from the three different cement dosage of DCM core samples is shown in Table 1.

Table 1 Summary of UCS and permeability tests result.

Cement Dosage	Remarks	
	Unconfined Compressive Strength	Permeability
120 kg/m ³	Almost all samples obtained	All samples lower than 10 ⁻⁹ m/s
140 kg/m ³	higher than the upper limit of 450 kPa	Average at 2.5 ⁻⁹
160 kg/m ³		Average at 1.7 ⁻⁹

5. CONCLUSION

A quality assurance and quality control (QA/QC) plan for the construction of a DCM cut-off wall was proposed and consisted of two components: the operational mixing control the end result check.

To ensure the adequacy of the QA/QC plan, a site trial was conducted before the actual site works. Another objective of the site trial is to determine the optimal cement dosage and operation parameters in order to achieve the stringent strength and permeability requirements.

It was found that the DCM design implemented for the site trial did not fulfil the DCM strength and permeability requirements. As observed from the non-uniform UCS results obtained through the DCM depth, different cement dosage may be required for the different soil types.

As such, the proposed QA/QC plan is not suitable. Additional site trials should be carried out to refine further the operation process such that good quality DCM columns with adequate strengths and low permeabilities can be constructed. This will enable the satisfactory performance of the DCM columns to improve slope stability and function as a seepage cut-off wall.

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