Effects of Curing Temperature and Stress on the Mechanical Behaviour of Cemented Hong Kong Marine Clay

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ABSTRACT

Deep cement mixing (DCM) is an important method for treating soft clay. In the field, cemented soils are usually subjected to various temperatures and stresses during the curing process. The influence of curing conditions, including the curing temperature and stress, on the mechanical behaviour of cemented soil has not been well understood. In this study, the effects of cement content, curing temperature and curing stress on the strength of cemented soil were studied by unconfined compression tests. Hong Kong marine clay with an initial water content of 65% was used. Cemented specimens were prepared at different temperatures (20 °C, 30 °C, 40 °C), vertical stresses (0 kPa, 300 kPa) and with various cement contents (15%, 25%, 35%). Specimens were tested after 28 days of curing under constant temperature and pressure conditions. This paper will present and analyses the influence of cement content, curing temperature and stress on the unconfined compressive strength (UCS) and secant Young's modulus E_{50}.

Keywords: Cemented soil; Curing temperature; Curing stress

1 Introduction

DCM is considered an environmentally friendly and fast construction method for land reclamation (Chung *et al.*, 2022). This technique generally has less disturbance to the marine ecological system than conventional reclamation methods. Moreover, it can form DCM columns in a shorter time to support the seawall and filling materials, reducing the construction time.

Cemented soils are usually subjected to various temperatures and stresses during curing in the field. According to the field data from Japan (Van Nguyen *et al.*, 2021), Singapore (Lu *et al.*, 2012) and Norway (Bache *et al.*, 2021), the temperature inside DCM columns can be as high as 40 degrees and last for a month, which is around 20°C higher than that of laboratory conditions. Furthermore, the length of DCM columns is generally above 10 meters, and the effective confining pressure can reach several hundred kPa. Therefore, it is important to understand the influence of curing temperature and stress on the properties of cement-treated soils.

So far, some studies in the literature have investigated the effects of curing temperature (Bache *et al.*, 2021; Ju, 2019; KIDO *et al.*, 2009) and curing stress (Fernandez & Santamarina, 2001; Rabbi *et al.*, 2011) on the mechanical behaviour of cemented soils, but they mainly focus on the cement contents lower than that of DCM practices. Furthermore, the previous studies mostly focus on UCS but not soil stiffness. E_{50} is a commonly used stiffness parameter in engineering, which is often estimated from the value of UCS. In the U.S. design guideline (Kitazume & Terashi, 2013), the ratio of E_{50} and UCS is 300 and 150 for the wet and dry mixing methods, respectively. So far, the effects of curing temperature and curing stress on E_{50} have not been investigated.

This study conducted unconfined compression tests to investigate the mechanical behaviour of cemented Hong Kong marine clays, including the stress-strain relation, UCS and E_{50}. Particular

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attention was paid to the effects of cement content, curing temperature and curing stress. A new temperature and stress-controlled curing equipment for cemented soil was developed.

2 Test Program and Materials

A series of unconfined compression tests were carried out to study the effects of cement content, curing temperature and curing stress on the mechanical behaviour of cemented Hong Kong marine clay. Three cement contents were used: 15%, 25%, and 35%, which refer to the mass ratio of the dry cement and dry soil. Three curing temperature levels were used based on the results of field monitoring (Bache *et al.*, 2021; Lu *et al.*, 2012), namely 20°C, 30°C, and 40°C. The curing vertical stresses at the 1D condition are 0, 150 and 300 kPa. Details of the test programme are summarized in Table 1.

Table 1: *Testing programme*

Test ID	Cement content (%)	Curing stress (kPa)	Curing temperature (°C)
1	15		
2	25	0	20
3	35		
4	25	0	30
5	25	300	
6	15		
7	25	0	40
8	35		
9	25	300	

The materials used are Hong Kong marine clay and ordinary Portland cement. The initial moisture content of Hong Kong marine clay is 65%, and its engineering properties are summarized in Table 2. The wet mixing method was simulated in which the cement is mixed with water before mixing with marine clay. Referring to the test methods of Wang *et al.* (2019), the water/cement ratio of the cement slurry was kept at 1:1. This study considered three different cement contents (15%, 25% and 35%), which is defined as the ratio of cement to the mass of dry of Hong Kong marine clay. Given each cement content, specimens were cured at different temperatures (20 °C, 30 °C, 40 °C) and vertical stresses (0 kPa, 300 kPa). Unconfined compression tests were conducted after 28 days of curing.

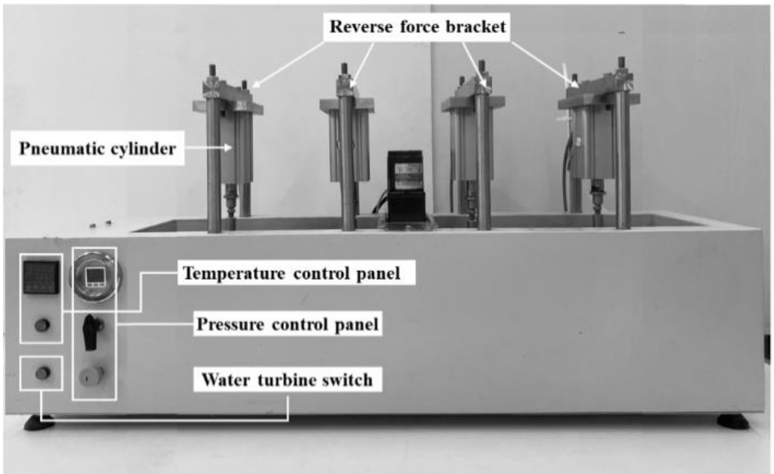
Table 2: *Basic properties of Hong Kong marine clay*

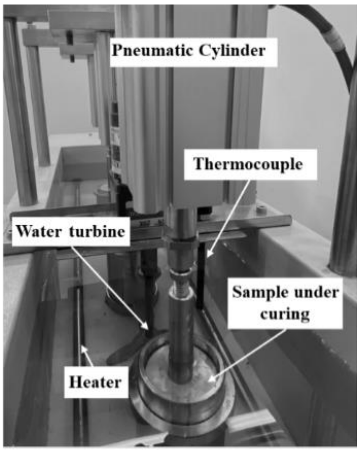
	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Particle Size Distribution (%)		
					Sand content	Silt content	Clay content
HKMD	2.62	63.9	28.2	35.7	63.69	18.62	17.69

3 Test apparatuses

Figure 1 shows a newly developed system for curing cemented specimens at different stress and temperature conditions. It has two main modifications: the overburden pressure application system and the heating system. The curing stress application method used in this study is K_0 loading, which is applied by the cylinder above the specimens. Some studies show that curing stress is applied in a triaxial chamber via isotropic stress. The shortage is the cemented soil has a large compressibility before the initial setting time of the cement, which may lead to a large volume change. The experimental results may be affected by the size effects. Two kinds of moulds were used for curing, that is, 50 mm in diameter and 100 mm in height for zero stress curing and 50 mm in diameter and 150 mm in height for stress curing. The mould used in stress curing is higher to ensure a specimen length larger than 100 mm after curing. The excess length was cut by a cutting machine.

Figure 2 shows the experimental setup for unconfined compression tests. To well capture the stress-strain relationship of cemented soil in the whole process of compression, three kinds of sensors are used to measure the specimen strain, including two vertical strain gauges, two local LVDTs and one global LVDT. After 28 days of curing, the specimens are cut to a standard size using a cutting machine with a diameter of 50±0.5 mm and a length of 100±1 mm. The stress and strain are determined according to ASTM (2017) standard D2166.





(a) external structure (b) internal structure

Figure 1: *Specimen curing equipment*

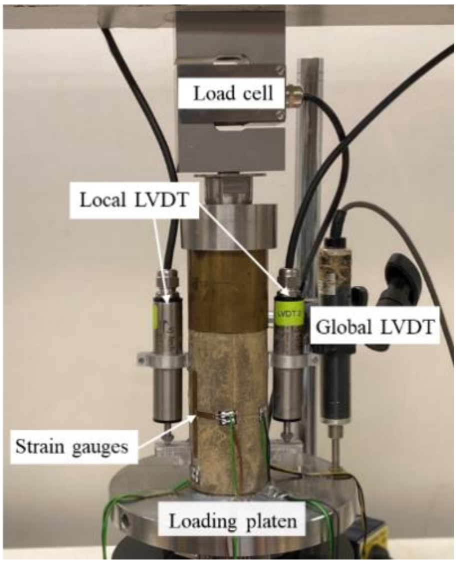


Figure 2: *Photos of unconfined compression test setup*

4 Interpretations of Experimental Results

4.1 Effects of cement content

Figure 3 shows the stress-strain curves of the specimens with different cement contents. The results at two different curing temperatures (20°C and 40°C) are presented. All specimens show similar stress-strain relations at a qualitative level. The specimen usually reaches its peak strength at 1-2% strains, followed by a significant softening.

Consistent with the results of previous studies (Chang & Woods, 1992; Ho *et al.*, 2021; Nafisi *et al.*, 2020; Yin, 2001), the strength of cemented soil increases significantly with an increase in cement content. The peak strength doubles as the cement content increases from 15% to 35% because the hydration of cement increases the cohesion between soil particles. The chemical mechanism of cement hydration and its influence on soil behaviour were discussed in detail by some previous researchers (e.g. Huawen, 2009).

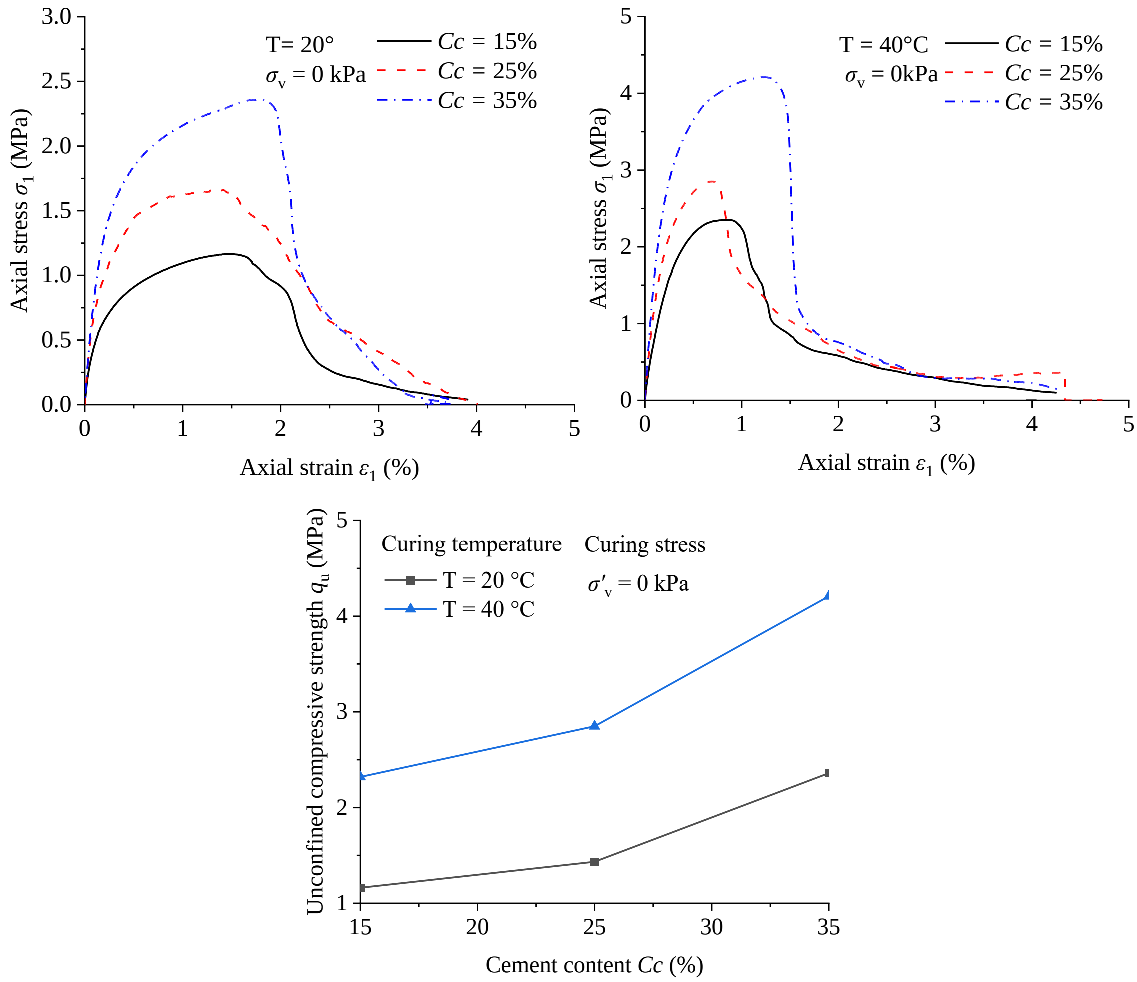


Figure 3: *Effects of curing temperature on cemented soil*

4.2 Effects of curing temperature

Figure 4 shows the unconfined compression behaviour of the specimens at different curing temperatures of 20°C and 40°C. When the curing temperature increases from 20 to 40 degrees, the UCS increases by about 75%. The increase is at least partially because, with increased curing temperature, the cement hydration rate is higher, producing more hydration products and enhancing the bonding between soil particles. Figure 5 shows the scanning electron microscope photomicrographs of the specimens under different curing temperatures. Soil pores are more effectively filled with cementation products at a higher curing temperature.

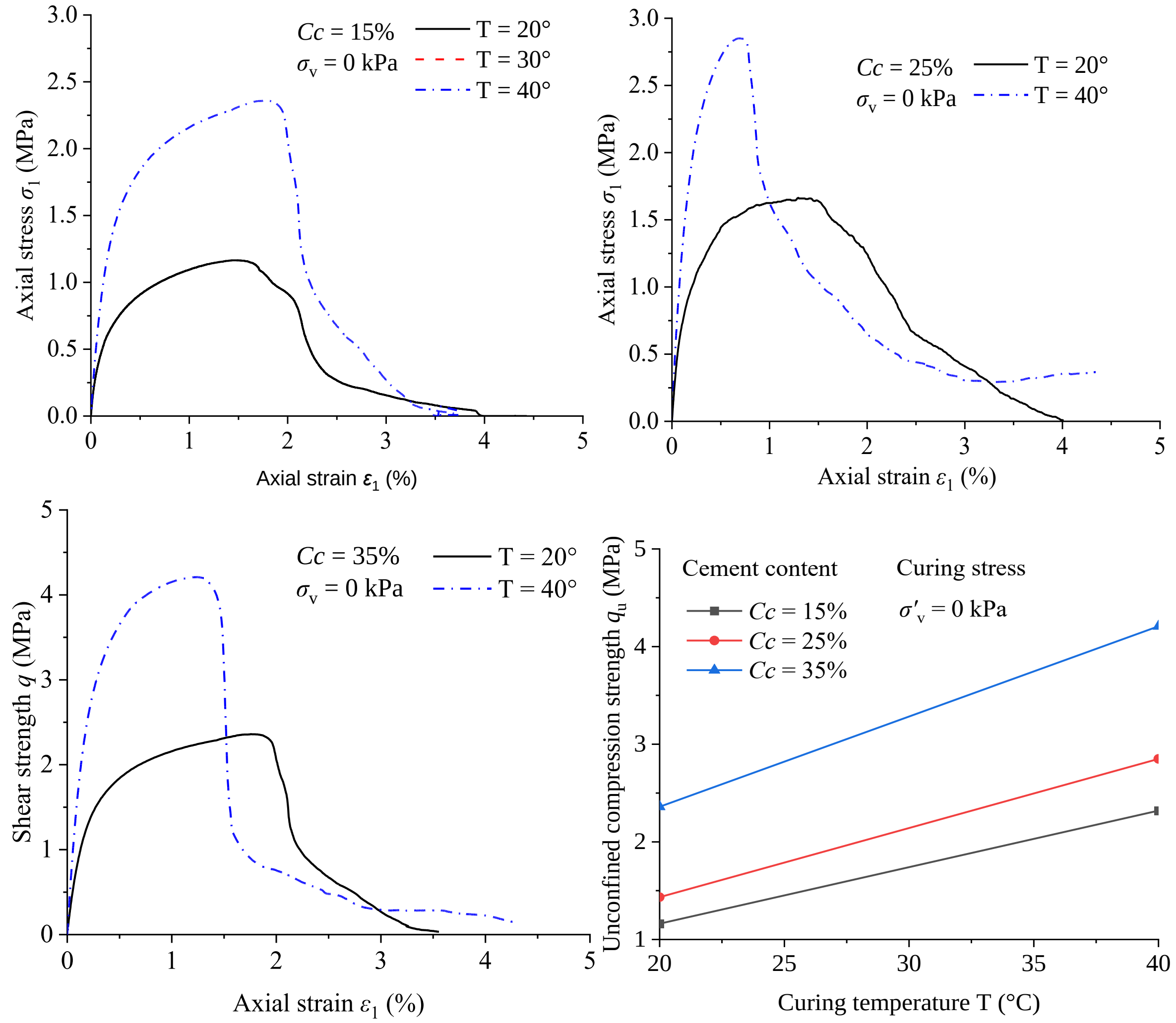


Figure 4: *Effect of curing temperature on strength*

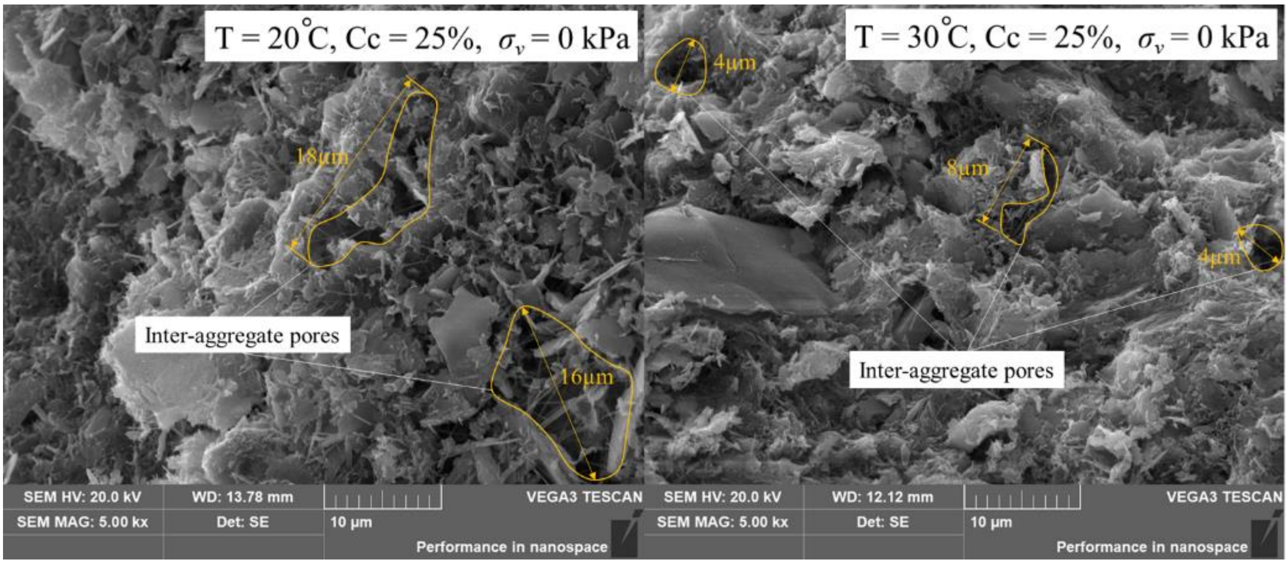


Figure 5: *SEM photomicrographs of specimens with different curing temperatures*

4.3 Effects of curing stress on cemented soil

Figure 6 shows the effects of curing stress on UCS. As the curing stress increases from 0 to 300 kPa, UCS increases by about 2 times. This is likely because a denser cemented structure is formed when the curing stress increases. For example, the void ratio decreases from 1.73 to 1.24 when the curing increases from 0 to 300 kPa at 30°C. SEM photomicrographs under different curing stresses provide better evidence. Scanning electron microscopy photomicrographs in Figure 7 shows that the specimen exhibits a denser structure under stress curing. The pore size in the specimen under stress curing is smaller than the specimen without curing stress. The stress-strain curves of cemented soil exhibited a similar pattern with increased strain. For all the specimens, the strain softening ends at 3% strain.

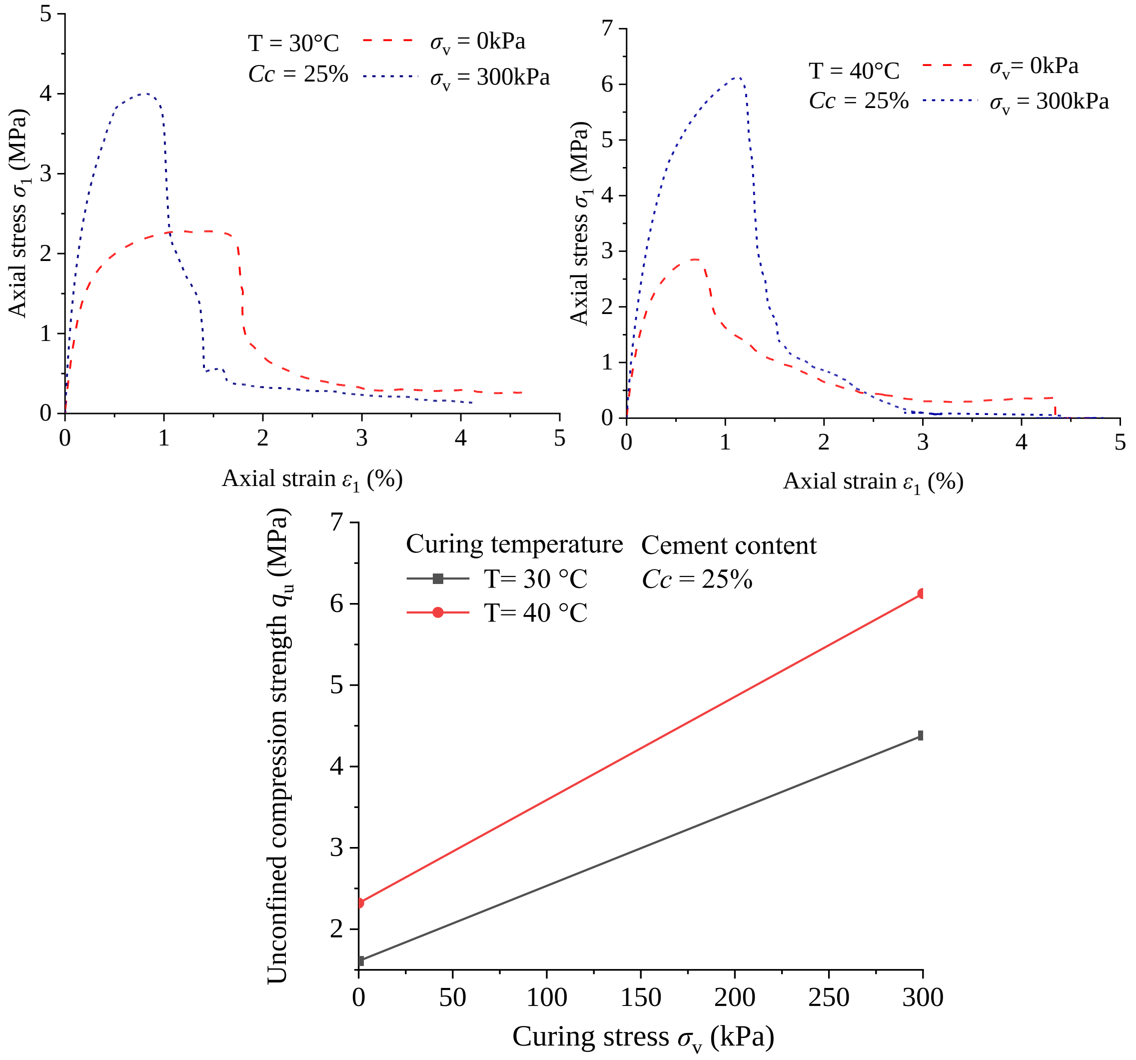


Figure 6: *Effects of curing stress on strength*

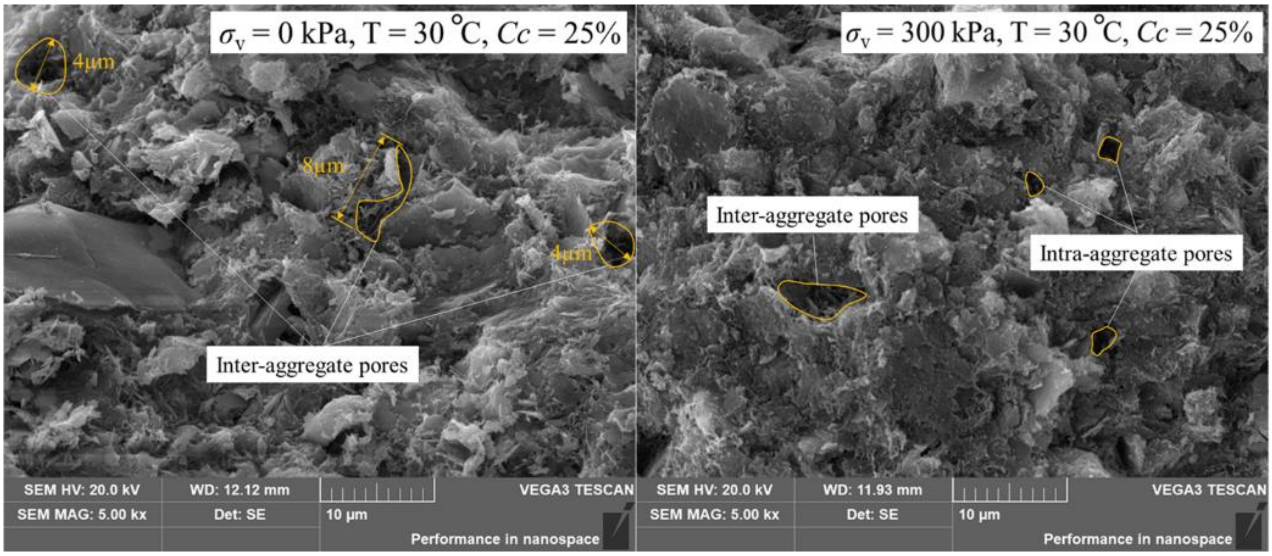


Figure 7: *SEM photomicrographs of specimens with different curing stress*

4.4 Relationship between UCS and E50 under different curing conditions

Figure 8 is a summary of the relationship between UCS and E_{50}. Curing temperature and curing stress can significantly increase UCS and E_{50}. However, their ratio does not change much. For cemented Hong Kong marine clay, the ratio UCS and E_{50} is close to 320, close to the value (300) suggested by the guideline (Bruce *et al.*, 2013) for the wet mixing method.

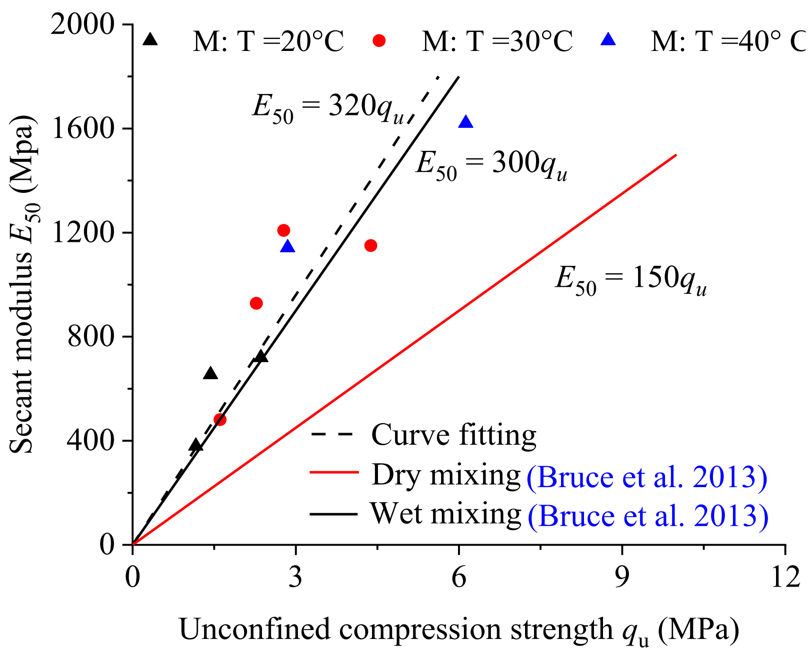


Figure 8: *The relationship between q_u and E_{50}*

5 Conclusion

This research studied the curing condition effects on the cemented Hong Kong marine clay. A series of unconfined compression tests were carried out. A temperature and stress-controlled equipment for specimen curing was developed. The works may contribute to improving deep cement mixing engineering design and reduce engineering investment. The main conclusions are as follows:

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(a) Increased temperature and stress significantly improved the strength and modulus of cemented Hong Kong marine clay. The increase in curing temperature enhances the hydration reaction rate of cement, while the overlying pressure mainly affects the structure of cement soil.
(b) The increase in curing temperature and curing stress did not change the relationship between UCS and E_{50} much.

6 Declarations

6.1 Acknowledgements

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