Experimental Study on the Durability of Soil-Cement Columns in Coastal Areas

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ABSTRACT: Deep soil mixing is one of the most commonly used ground improvement techniques. With high sulphate content in soil and seawater, stabilised soil in coastal areas can deteriorate due to sulphate attack. In this research, the degradation in strength of cement treated soil exposed to synthetic seawater is measured by uniaxial compression and needle penetration testing. Three exposure conditions, namely 100% seawater, 200% seawater and sealed condition (control samples), were used to measure the deterioration level due to the effect of sulphate. In addition, the extent of the portlandite consumption was also measured by Thermogravimetric Analysis which reflects the calcium distribution in the soil-cement columns. The test results show that the deterioration occurs deeper and faster in higher seawater environments. Furthermore, in contact with increasing sulphate concentration, the deterioration shows a close relation with calcium distribution.

KEYWORDS: Soil-cement column, Deterioration, Needle penetration test, Sulphate concentrations, Deterioration depth.

1. INTRODUCTION

The deep mixing method (DMM) is an in-situ soil treatment in which native soils or fills are blended with cementitious or other stabilizing agents (binder). Since the 1980s, this method has been applied widely in Japan, Europe, China and American with more than 100 million m^3 of soil stabilised in over one thousand projects (Bruce, 2000; Holm, 2003; Kitazume & Terashi, 2013). Soil-cement column formed by the deep mixing method has many advantages such as high strength and stiffness, low permeability, technologically simple and low costs (Bruce, 2000; Chen et al., 2013; Dehghanbanadaki et al., 2013).

Global warming and sea level rise have become major concerns of the modern world (Meehl et al., 2012). As the majority of buildings and transport infrastructure are concentrated in these coastal areas, it is very important to understand of the longevity of these structures in the face of sea level rise. In marine environments, soil-cement columns are a geotechnical solution used for ground improvement in coastal areas; however, the strength of these columns may deteriorate due to the attack of sulphate (Rajasekaran, 2005). In theory, sulphate attack reduces the amount of calcium (Ca^{2+}) and calcium silicate hydrate (C-S-H) (Mather, 1964; Rajasekaran & Narasimha Rao, 2005) which play an important role in maintaining the strength of the stabilised soil. Furthermore, these reactions create more ettringite causing the cementitious structure to swell (Mather, 1964; Rajasekaran, 2005). Besides this, the formation of magnesium hydroxide ($Mg(OH)_2$) and magnesium silicate hydrate (M-S-H) do not contribute to concrete strength (Mather, 1964; Rajasekaran, 2005). As a result, the soil-cement columns can crack reducing the strength and increasing the permeability of the columns (Mather, 1964; Neville, 1995; Rajasekaran, 2005). After long periods of exposure, the strength of these columns will decrease lowering the bearing capacity and ultimately failing in the worst case scenario. This challenge has been studied by increasing cement content and reducing water/cement ratios (Babasaki et al., 1996; Horpibulsuk et al., 2005; Tokunaga, 2005), using pozzolans (Nontananandh et al., 2004), and using sulphate resistance cement (Al-Dulaijan, 2007; Guirguis, 1998); however, they are quite expensive and complex to use (Guirguis, 1998). Consequently, studying the durability of columns constructed in coastal environments using normal deep mixing method is needed to both reduced costs whilst at the same time maximizing the life-span of structure.

2. LONG-TERM STRENGTH OF THE SOIL-CEMENT COLUMNS IN MARINE ENVIRONMENTS

There have only been a small number of investigations into durability of soil-cement columns despite this being an important aspect. In the period from 1980 to 2005, researchers in Japan found that the strength at the core of stabilised soil columns increases almost linearly with the logarithm of elapsed time (Hayashi et al., 2002; Ikegami et al., 2005; Kitazume et al., 2002; Terashi et al., 1980). In contrast, the strength at the outer boundary of the soil-cement columns reduces due to the impact of seawater (Kitazume et al., 2002). Depending on the exposure conditions, the rate of this progress is different (Hayashi et al., 2002; Ikegami et al., 2005; Kitazume et al., 2002). Nevertheless, there are very few published studies investigating deterioration as a function of depths or the effect of sulphate concentration. Kitazume et al. (2002) also made conclusions that the calcium leaching is one of major causes of the deterioration in the soil-cement columns.

In 2002, Nishida et al. applied a numerical model for the calcium leaching process from treated soil. They showed that the amount of calcium leaching from the soil-cement columns is slight even after 500 years and the degradation of the soil-cement columns in their project is small.

In terms of predicting the strength of soil-cement columns, Cui et at. (2014) determined the deterioration of cement treated soil in a saltwater estuarine region. In their research, high amounts of cement content (17.58%) was used and the sulphate concentration in the groundwater was only around 1.1 g/l (while sulphate concentration in natural seawater is 3.2 g/l). As a result, the effects of sulphate on the durability of the soil-cement columns were not clear. In addition, the correlation coefficient of the applied curve fitting were low (R^2 = 0.81 and 0.26) leading to high variations in their results.

In this paper, the deterioration progress as the function of (radial) depths of soil-cement columns exposed to different sulphate concentrations (seawater environments) will be examined by the needle penetration test and Thermogravimetric Analysis (TGA). These results could be used to predict the deterioration depths of the soil-cement columns exposed to seawater.

3. EXPERIMENTAL PROCEDURE

The soil used in the experiment was collected at 0-5 m depth from Rail Flyover Modification project - MSM Bays at the Hunter Wetlands National Park, Newcastle, NSW, Australia. The rail project used dry mixing to stabilise the ground with a cement ratio (C) of 120 kg/m^3 to achieve the required unconfined compressive strength of $[q_u] = 2.5[q_u^{28}]$ which $[q_u^{28}]$ is the required unconfined compressive strength at 28 days, $[q_u^{28}]$ = 250 kPa (NCIG, 2012). The characteristics of the soil sample are listed in Table 1.

In this research, the soil was stabilised by cement at the rate of C = 120 kg/m^3. Soil and cement were dry mixed by an electric mixer in 10 minutes (JGS, 2005). The mixture was poured into PVC molds 53 mm in diameter and 106 mm in height in 3 layers. For each layer, the mold was tapped on the floor to reduce entrained air bubbles in the mixture (JGS, 2005). Finally, the specimens were covered by plastic cling wrap and labelled before storing in a moisture room with constant humidity of 95% and relative temperature of 20 °C (JGS, 2005). After 4 weeks, these specimens were taken out of the cylinders and divided into 3 groups of 20. The first group of specimens was cured in a container at 20 °C and 95% humidity. The second and third groups were immersed in 100% and 200% (g/g) synthetic seawater respectively. The UCS and the needle penetration resistance tests were conducted at 28 days (T0), 58 days (T1), 118 days (T3) and 208 days (T6).

Table 1 Soil chemical composition and characteristic

Calcium (mg/kg)	4351.02
Magnesium (mg/kg)	2531.91
Potassium (mg/kg)	1561.31
Sodium (mg/kg)	1521.66
Phosphorus (mg/kg)	183.69
Sulphate (mg/kg)	785.61
Water content *W* (%)	37.7
Liquid limit W_L (%)	25
Plastic limit W_P (%)	19
Density (γ) (g/cm^3)	1.68

Artificial seawater was prepared by the chemical composition shown in Table 2 (D1141-98, 2008; Mather, 1964).

Table 2 The ion concentration of seawater

Analysis of seawater from Gulf St. Vincent, South Australia. Specific Gravity of seawater (25 °C) = 1.03			
Ion	**Concentration (g/100ml)**	**Ion**	**Concentration (g/100ml)**
Na^+	1.22	Cl^-	2.19
Mg^{2+}	0.145	SO_4^{2-}	0.32
Ca^{2+}	0.056	HCO_3^-	0.014
K^+	0.044	Br^-	0.008

The uniaxial compression test was conducted to measure the unconfined compressive strength of all stabilised soil samples. It was conducted by standard ASTM D2166-06. The compressive rate of 1mm/min was applied for these tests giving the axial strain rate on the specimen of 0.625%/min.

The needle penetration test system was designed and constructed in house based on the work of Japanese researchers (Hayashi et al., 2002; Kitazume et al., 2002; Takashi et al., 1999) to measure the deterioration process of stabilised soil samples. A needle with a diameter of 0.75 mm was used to conduct the test. To measure the needle penetration resistance (NPR), a load-cell (0.5 kN) was used in conjunction with a compression machine. During the test, a penetration speed of 1 mm/min was applied and the resistance forces were recorded continuously (Kitazume et al., 2002; Ulusay & Erguler, 2012). The needle penetrometer is not a standardised test but it has been used in concrete science and rock mechanics (Klimesch & Ray, 1997; Ulusay & Erguler, 2012).

The needle resistance calibration test was conducted to convert the measured NPR at the surface of soil mixing samples to the UCS at these positions. Extra specimens were made with three cement ratios, namely 120 kg/m^3, 160 kg/m^3 and 270 kg/m^3. After 3 and 7 days, the needle penetration resistance forces (*F*) of each soil-cement specimen at (radial) depths of 2, 5 and 10 mm were measured. Then, these samples were determined the unconfined compressive strength (UCS) by the compression machine. The UCS and the NPR forces were plotted in a logarithm chart as shown in Figure 1. It can be seen that the UCS has a linear relationship with the NPR. Hence, this relation can be applied to observe the strength distribution at the boundary surface of the samples.

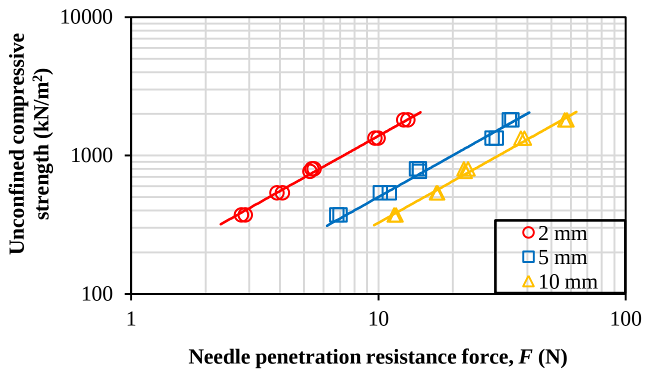

Figure 1 Relationship between the UCS and the NPR

To determine the qualitative and quantitative changes in the chemistry of the portlandite consumption with depth, all samples were analysed by a Mettler Toledo Thermogravimetric Analyser with Differential Scanning Calorimetry (TGA/DCS) (Horpibulsuk et al., 2013; Matschei, 2007). The test was conducted by heating the samples from 25 to 1000 °C at a rate of 10 °C/min under a 100% nitrogen gas atmosphere (60 ml/min) (Mertens et al., 2009). Free portlandite ($Ca(OH)_2$) and CO_2 content in the samples were determined from the mass losses in the range of 400-500 °C (dehydration) and 600-800 °C (decarbonation), respectively (Lawrence et al., 2006; Silva et al., 2014). Before conducting the test, all samples were dried and stored in a desiccator so that the initial temperature of the tests is below that of the TGA start temperature. For each test, around 10-20 mg soil-cement sample was used to do the test over 150 minutes. In the research, TGA analysis was used to determined amount of calcium consumption which reflect the level of deterioration of the soil-cement columns as Eqs. (1)-(3) (Damidot et al., 2011).

$$CH_{free} = (ML_{CH(400\text{-}500\,^{o}C)} \times MM_{CH}) / MM_{H_2O} \tag{1}$$

$$CH_{carbonation} = (ML_{CO_2\,(600\text{-}800\,^{o}C)} \times MM_{CaCO_3}) / MM_{CO_2} \tag{2}$$

$$CH_{cal\ consumption} = CH_{cal^0} - (CH_{free} + CH_{carbonation}) \tag{3}$$

where CH_{free} is the free portlandite ($Ca(OH)_2$) content; $ML_{CH(400\text{-}500^{\circ}C)}$ is the mass loss between 400 and 500 °C corresponding to portlandite dehydration; MM_{H_2O} is the molar mass of H_2O, MM_{H_2O} = 18; MM_{CH} is the molar mass of the portlandite, MM_{CH} = 74.09; $CH_{carbonation}$ is the portlandite consumed in the carbonation reaction; $ML_{CO_2\,(600\text{-}800^{\circ}C)}$ the mass loss between 600 and 800 °C corresponding to carbonate decomposition; MM_{CaCO_3} is the molar mass of $CaCO_3$, MM_{CaCO_3} = 100.08; MM_{CO_2} is the molar mass of CO_2, MM_{CO_2} = 48; CH_{cal^0} is the initial calcium content in cement (mass %), CH_{cal^0} = 65% (GP cement); and $CH_{cal\ consumption}$ is the portlandite consumed in the pozzolanic reaction.

4. SOIL-CEMENT COLUMNS CORE STRENGTH GAIN

Researchers have shown that the strength at the core of the soil-cement columns increase linearly with the logarithm of time (Hayashi et al., 2002; Kitazume et al., 2002; Saitoh, 1988). Consequently, the long-term compressive strength gain of the non-deteriorated soil-cement columns can be expressed as Eq. (4) (Hayashi et al., 2002).

$$q_u = A + B \ln t \tag{4}$$

where q_u: the strength of soil-cement column (kN/m^2); t is the age of the soil-cement column (day); A and B are constants.

Figure 2 shows the strength gain in the core portion of the soil-cement columns (q_u) cured in air (control samples) at 20 ºC and 95% humidity. It can be seen that the strength of the soil-cement samples has linear relationship with logarithm of time as supported by Hayashi et al., (2002).

$$q_u = 305.11 + 436.36 \ln t \quad (R^2 = 0.99) \tag{5}$$

where R^2 is correlation coefficient. This relationship can be used to predict the long-term strength of the soil-cement columns.

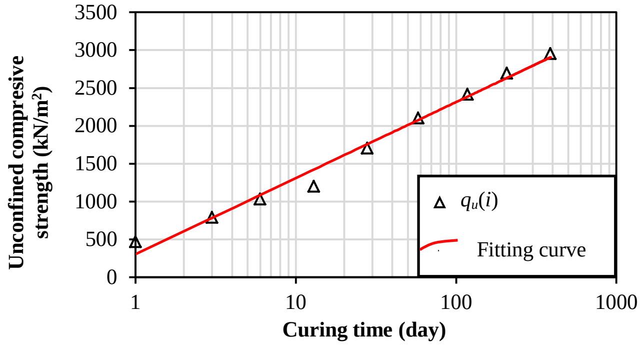

Figure 2 Strength gain of soil-cement column (C = 120 kg/m^3)

5. STRENGTH DETERIORATION SOIL-CEMENT COLUMNS SURFACES

The deterioration at the surface of the soil-cement samples exposed to synthetic seawater is expressed by the strength ratio, which is defined as the ratio of strength at each surface position (2, 5 and 10 mm) with the strength of the control samples at the same testing period. In this study, the unconfined compressive strength of the control samples is used as the strength at the core portion of the samples exposed in seawater. If the strength ratio is low, the deterioration is more serious. Figures 3-5 show the deterioration of the soil-cement columns in sealed condition, 100% and 200% SW.

The strength changes at the surface of the soil-cement samples in sealed condition are shown in Figure 3. It can be seen that the strength ratios at the surface layers are very close with the strength at the core of the samples (strength ratio ≈ 1).

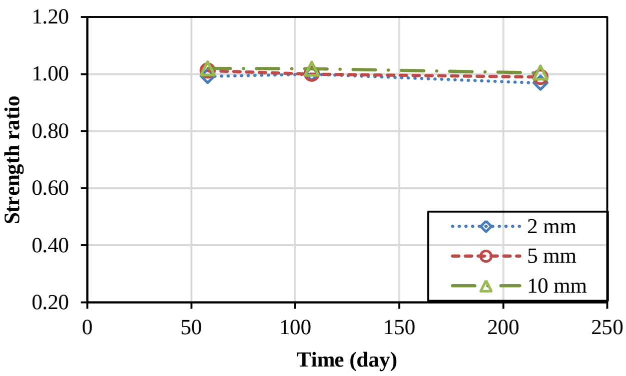

Figure 3 Strength change by time in sealed condition

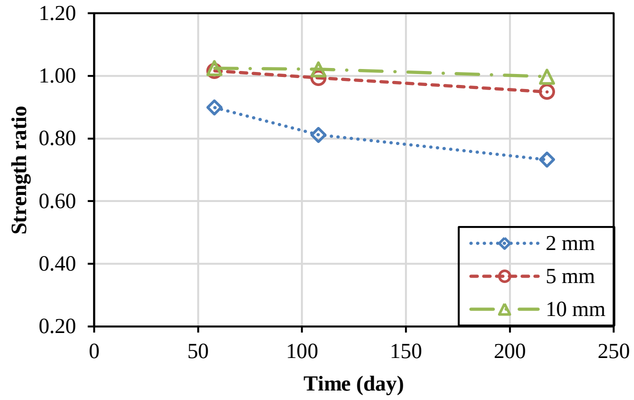

Figure 4 Strength change by time in the case of 100% SW

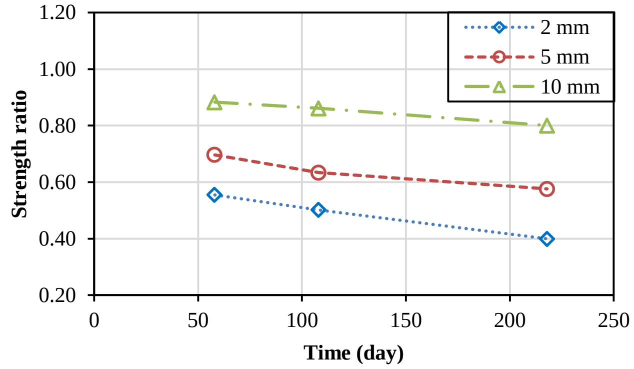

Figure 5 Strength change by time in the case of 200% SW

Figure 4 shows that the effects of seawater are obviously at 2 mm depth as the strength ratio decreases significantly from 0.9 at 58 days to around 0.8 and 0.73 at 118 and 208 days, respectively. The same trend can be seen at the position of 5 mm depth from 118 days toward. At 10 mm depth, the effect of seawater is not evident, even after 208 days.

The samples exposed to 200% SW (Figure 5) exhibit a rapid decrease in strength with the strength ratio at the outer surface (2 mm) reducing to 0.4 at 208 days. Therefore, around 60-70% strength is lost due to the attack of sulphate in seawater at that position. In addition, Figure 5 shows that the depth of deterioration in the case of 200% SW develops inward overtime. Furthermore, it is clear that the deterioration level in the case of 200% SW (Figure 5) is much higher than 100% SW (Figure 4). Consequently, with higher sulphate (seawater) concentration, the deterioration occurs faster and deeper.

6. DEPTH OF DETERIORATION

The deterioration depth was determined by the needle penetration test and TGA analysis.

For the needle penetration results, the resistance forces of control, 100% and 200% SW samples are plotted in Figures 6-8 with the logarithm of depth generating a calibration curve. Due to the effects of sulphate attack, the strength of the soil-cement at the surface of samples becomes less rigid and weaker. Consequently, the resistance forces at the surface portion of the deteriorated samples decreases to below that of the control samples. Therefore, the depth of deterioration (w) of the soil-cement samples exposed to 100% and 200% SW can then be determined by the depth at which the deterioration curves meet the control curve. Figures 6-8 show that the deterioration curves in the case of 100% SW meet the control curves at the depth 3.78 mm, 4.88 mm and 6.34 mm at 58, 118 and 208 days respectively as shown in Table 3. As a result, it is possible to determine the depth of deterioration of the soil-cement columns exposed to 100% SW by the needle penetration test.

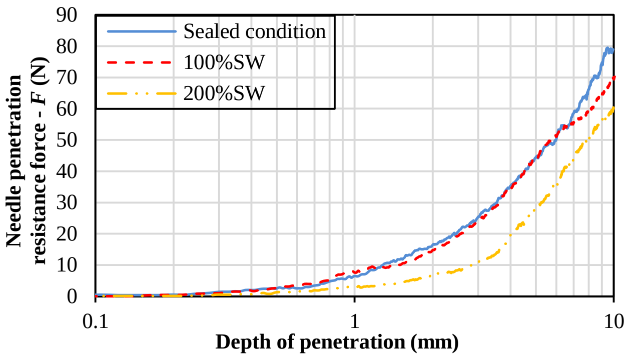

Figure 6 Needle penetration results at 58 days

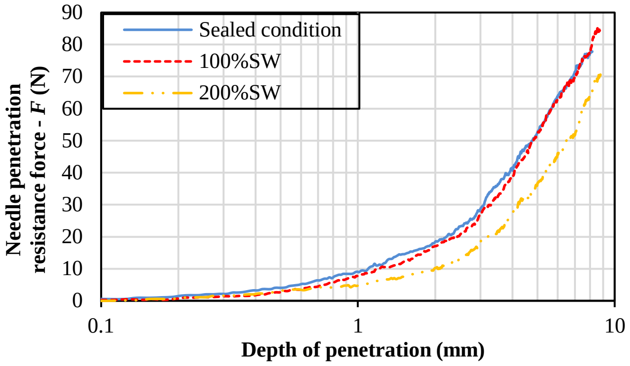

Figure 7 Needle penetration results at 118 days

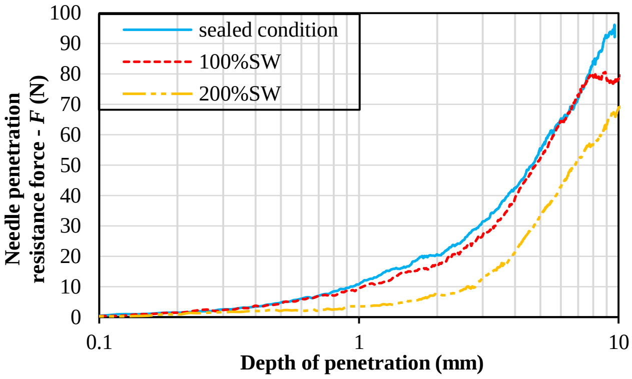

Figure 8 Needle penetration results at 208 days

The deterioration depths of the soil-cement samples exposed to 100% SW are shown in Table 3.

Table 3 Deterioration depths

Time (day)	*w* (mm)
58	3.78
118	4.88
208	6.34

In terms of 200% SW samples, the deterioration is stronger and their deterioration curves are below the control curves. Hence, the depth of deterioration of the soil-cement columns exposed to 200% SW should be determined by another method.

For the TGA analysis, the calcium consumptions in the soil-cement samples are shown in Figures 9-11. The calcium consumption is the calcium content in the samples that participates in chemical reactions to create the strength of stabilised soil. In addition, the depth of deterioration can be measured from the TGA results calculating the calcium consumption rate according to Eqs. (1)-(3). Figures 9-11 show that the depths of deterioration at 58, 118 and 208 days are similar with the results obtained from the needle penetration tests with the calcium consumption decreasing with time at the surface. It can be seen from Figures 10 and 11 that at 2 and 5 mm depth the calcium consumption by 208 days is lower than 118 days. Furthermore, the calcium consumption in the case of 200% SW is smaller than 100% SW. It means that the calcium leaching process in the soil-cement columns occurs stronger in higher sulphate environment.

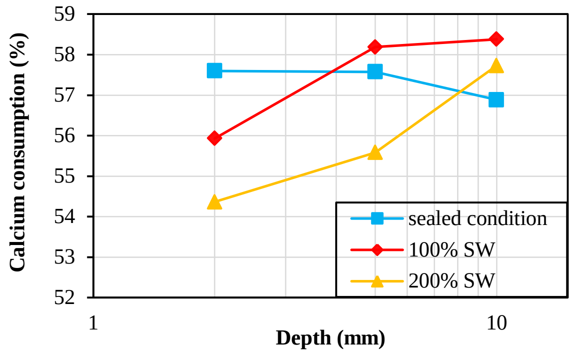

Figure 9 TGA results at 58 days

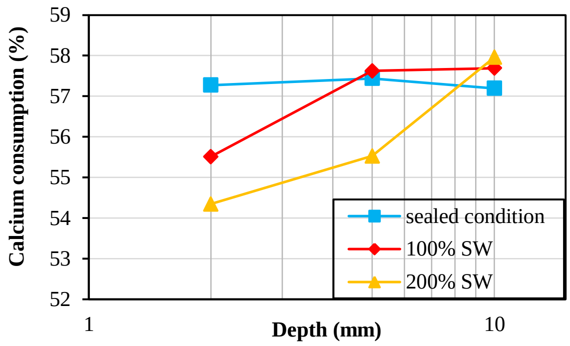

Figure 10 TGA results at 118 days

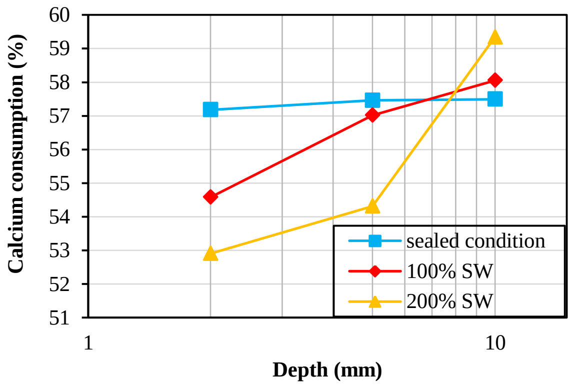

Figure 11 TGA results at 208 days

In summary, the needle penetration test and the TGA analysis indicate that the depth of deterioration of the soil-cement columns depend on the elapsed time and the concentration of sulphate.

Moreover, the TGA analysis can be used to determine the amount of calcium consumption which reflects the deterioration level in the soil-cement columns during the deterioration process. The relationship between the deterioration and the calcium consumption can be used to evaluate the durability of the soil-cement columns if the amount of calcium leaching can be calculated by a numerical modeling.

According to Ikegami et al. (2005), the deterioration depth of the soil-cement columns is determined as Eq. (6):

$$\log w = \log w_0 + 0.5\log(t - t_0) \tag{6}$$

where w is the deterioration depth at t (day); w_0 is the deterioration depth at t_0; and t is the time (day) from t_0.

In the study, the deterioration depth of the soil-cement columns was determined from the early test results of NPR test and TGA analysis as shown in Table 3. Based on these data and Eq. (6), the trend of deterioration can be expressed as Eq. (7):

$$w = 0.45\sqrt{t} \quad (R^2=1) \tag{7}$$

Eq. (7) can be applied to predict the depth of deterioration of the soil-cement columns exposed to seawater.

7. CONCLUSIONS

In the research, the strength changes of the soil-cement columns exposed to seawater were investigated based on some experimental methods included the needle penetration test, uniaxial compression test and TGA analysis. The main conclusions of the study are:

- Needle penetration test is a suitable method to measure the depth of deterioration of stabilised soil.
- At higher sulphate environment, the deterioration occurs faster and deeper. The strength of the samples exposed to high sulphate concentrations decrease significantly in a short time span and eventually they were totally destroyed.
- TGA analysis can be used to determine the extent of calcium consumption in comparison to the control samples, which reflects the deterioration level in the soil-cement columns over time.
- The long-term strength gain and the depth of deterioration of the soil-cement columns (with C = 120 kg/m^3) exposed to seawater can be estimated by Eqs. (5) and (7) respectively.

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