

The Durability of Soil-Cement Columns in High Sulphate Environments

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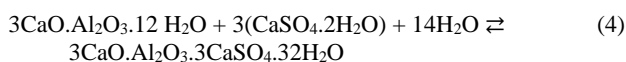
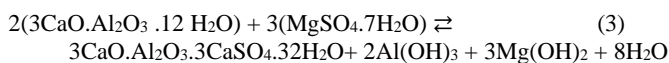
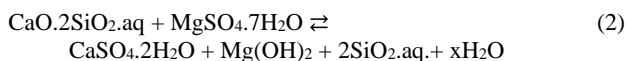
ABSTRACT: Soil-cement column is a geotechnical solution used for ground improvement in coastal areas. However, after long periods of exposure, the strength of these columns may decrease to below their designed safe bearing capacity, ultimately resulting in failure. In this paper, the effects of high sulphate concentrations (100%, 200%, 500% and 1000% that of seawater) on the durability of soil-cement samples were examined. In addition, the simple simulation model was applied to predict the deterioration depth and long-term strength of the soil-cement columns. The results show that the deterioration is more pronounced and occurs deeper in the presence of high sulphate concentrations. For instance, the strength of a 0.5 m diameter column exposed to 200% seawater will fall below the minimum design strength after 75 years. For higher sulphate environments (5 to 10 times that of normal seawater) the same column would never reach the minimum design strength requirement. Consequently, this has significant implications on soil-cement column when used to stabilise soils in high sulphate environments.

KEYWORDS: Soil-cement column, High sulphate environment, Long-term strength, Needle-penetration test.

1. INTRODUCTION

The soil-cement column is a ground improvement method formed by the deep mixing method. In this technique, the original soil is mixed in-situ with a small amount of cement and water to create a high stiffness soil-cement column (Alfaro et al., 1994; Broms & Boman, 1979). This method has the advantages of being technologically simple, with low costs, fast construction, and with the end product also having low permeability (Bruce, 2000; Chen et al., 2013; Dehghanbanadaki et al., 2013; Kitazume & Terashi, 2013).

Many factors affect the properties of the soil-cement columns such as binder type in-situ, soil characteristics, mixing and curing conditions (Kitazume & Terashi, 2013). Furthermore, in coastal areas, the soil-cement columns can deteriorate due to the effect of sulphate in seawater (SW) (Rajasekaran, 2005). When cement is mixed with soil exposed to sulphate environment, the reactions among sulphate ions and cement minerals take place (the reactions (1) - (5)) reducing the amount of calcium (Ca²⁺) and calcium silicate hydrate (C-S-H) which play a major role in maintaining the strength of the stabilised soil (Mather, 1964; Rajasekaran & Rao, 2005). Moreover, these reactions create ettringite as a result of the reaction of calcium aluminate with calcium sulphate, causing the cementitious structure to increase volume of the solid phase by as much as 227 percent (Neville, 1995) and potentially crack (Mather, 1964; Rajasekaran, 2005). Besides this, the formations of magnesium hydroxide (Mg(OH)₂) and magnesium silicate hydrate (4(MgO).SiO₂.8.5H₂O) do not contribute to the columns' strength (Mather, 1964; Rajasekaran, 2005). Consequently, the soil-cement columns can crack reducing the strength and increasing the permeability of the columns. After long periods of exposure, the bearing capacity of these columns will decrease and ultimately fail in the worst case scenario.



where: Ca(OH)₂: calcium hydroxide (portlandite); MgSO₄: magnesium sulphate; CaSO₄.2H₂O: calcium dehydrate (gypsum); Mg(OH)₂: magnesium hydroxide (brucite); SiO₂.H₂O: hydro silicate (silica gel); 3(CaO).2(SiO₂).8H₂O: calcium silicate hydrate (C-S-H); 4(MgO).SiO₂.8.5H₂O: magnesium silicate hydrate (M-S-H); 3CaO.Al₂O₃.3CaSO₄.32H₂O: ettringite.

There have only been a small number of investigations into the durability of soil-cement columns despite this being an important aspect. Since the 1980s, researchers in Japan have found that the strength at the core portion of stabilised soil-cement 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 sulphate (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). According to Mather (1964), sulphate attack processes depend on many factors such as the type of cement, concentration of sulphate and exposure period. Nevertheless, there are very few published studies investigating the deterioration as a function of depth or the effect of sulphate concentrations.

In the coastal areas, soil can contain high amounts of sulphate which may be formed naturally or via anthropogenic activities such as pyrite oxidation. Ground water and other environment conditions can transform pyrite, gypsum, iron, aluminium and other metals (Rajasekaran, 1994). For example, marine clay could contain 18 mg sulfur/kg dry soil (Rajasekaran, 1994; Westerberg et al., 2005), more than 6 times higher than the concentration of sulphate in normal seawater (around 2.84 mg/kg (Mather, 1964)). In addition, sulphates in soil could come from industrial wastes containing sulphates (Rajasekaran, 1994).

In terms of the durability of mortar and cement, Türker et al. (1997) conducted experiments with sulphate solutions at 0.6%, 4% and 16%, and they found that high sulphate concentrations damaged mortar in different stages. In addition, Amin et al. (2008) reported that the strength loss of mortar increases when the concentrations of sulphate solutions increase from 1% to 5%. The same conclusions were also found in the studies of Umoh and Olusola (2012), Yang et al. (2012) and Amin et al. (2008).

Al-Dulaijan (2007) measured the strength reduction of some types of cement mortars in different magnesium sulphate concentrations (1%, 2% and 4%) as shown in Fig. 1. It can be seen from the figure that the deterioration of cement mortar increases with increasing sulphate concentration.

There are some methods that can be used to decrease the effect of

sulphate on the soil-cement column; however, in many cases, the durability of the soil-cement column in coastal areas still needs to be carefully considered as the effects of high sulphate environments on the stabilised soil is poorly understood. Therefore, it is necessary to conduct experiments to evaluate the relationship between high sulphate concentrations and deterioration levels.

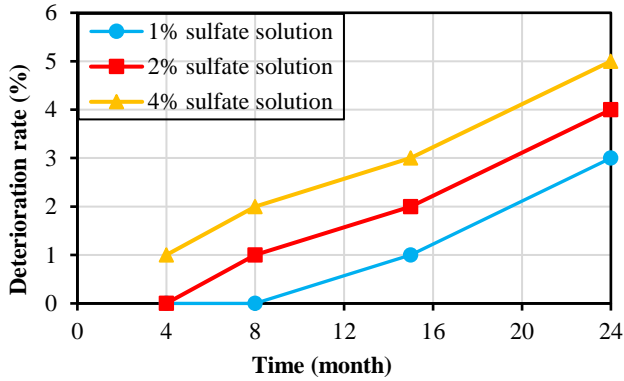


Figure 1 Effects of sulphate concentration on the deterioration [Adapted from (Al-Dulaijan, 2007)]

In this research, the effects of high sulphate concentrations (up to ten times that of seawater) on the durability of soil-cement samples were examined. In addition, the simple simulation model was applied to predict the deterioration depth and long-term strength of soil-cement columns in different sulphate environments.

2. EXPERIMENT PROCESS

A dry mixing method was applied to stabilise the soil with a cement content of 120 kg/m³ to achieve the required unconfined compressive strength of 250 kPa at 28 days. Soil-cement samples with a diameter of 53.2 mm and a height of 106.4 mm were made as per the Japanese standard (JGS, 2005).

About one hundred of samples were divided into five groups, namely G0, G100, G200, G500 and G1000. The specimens in the group G0 were used as the control samples which were sealed in a container and cured under standard conditions (20 °C and 95% relative humidity). After 28 days curing, the soil-cement samples were immersed in various sulphate concentrations (up to ten times the concentration of normal seawater), namely 100%, 200%, 500% and 1000% SW. In this research, normal seawater is 100% SW, while 200% SW is created by doubling the ion concentration in normal seawater. The experimental matrix is shown in Table 1.

Table 1 Specimens and testing time matrix

Time	Control	100% SW	200% SW	500% SW	1000% SW
42 days	G0: 1-5	G100: 1-5	G200: 1-5	G500: 1-5	G1000: 1-5
58 days	G0: 6-10	G100: 6-10	G200: 6-10	G500: 6-10	G1000: 6-10
118 days	G0: 11-15	G100: 11-15	G200: 11-15	G500: 11-15	G1000: 11-15
208 days	G0: 16-20	G100: 16-20	G200: 16-20	G500: 16-20	G1000: 16-20

The uniaxial compression tests were applied to measure the strength of all stabilised soil samples. It was conducted by standard method ASTM D2166-06 (2010) with a compression speed of 1 mm/min. Besides, a needle penetration test system was designed and constructed in-house based on the work of Kitazume et al. (2002) to determine a strength distribution of the stabilised soil indirectly. A needle with a diameter of 0.75 mm and 15 mm length was used to penetrate the sample (Figure 2). To measure the needle penetration resistance force, a load cell (0.5 kN) was used in conjunction with the compression machine. As the accuracy of the measured force increases with decreased penetration speed, a penetration speed of 1 mm/min was

applied during each test with the resistance force was recorded continuously.



Figure 2 Needle penetration resistance test system

The needle penetration resistance and the uniaxial compression tests were conducted at the time of 42, 58, 118 and 208 days. In high sulphate environments, the destruction process of the soil-cement samples begins rapidly; therefore, it is necessary to observe the early deterioration process at 42 days. For each test, about five samples were conducted the tests, a mean value and a coefficient of variation of them were presented in the following tables and figures.

3. RESULTS

The change in the physical appearance of soil-cement samples exposed to high sulphate concentration solutions is shown in Figs. 3-6 significantly over time, and the effects of high sulphate concentrations on the soil-cement samples are considerable. Fig. 3 shows the physical appearance of the samples exposed to 100% SW. It can be seen that there is no visible change in these samples over the 208-day experiment time. However, the effect of 200% SW exposure can be observed clearly from the physical appearance of the samples as shown in Fig. 4. At and 42 and 58 days, the samples appear low affected. After 118 and 208 days exposed to 200% SW, cracks have appeared on the surface of all the samples and the extent of cracking has become significant. In 500% and 1000% SW environments, the outer layer of the soil-cement column is totally destroyed at 118 and 208 days leading to the decrease of sample diameter and density.

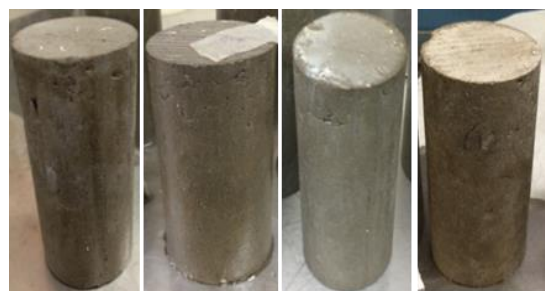


Figure 3 Soil-cement samples exposed to 100% SW (from left to right: 42, 58, 118 and 208 days)



Figure 4 Soil-cement samples exposed to 200% SW (from left to right: 42, 58, 118 and 208 days)

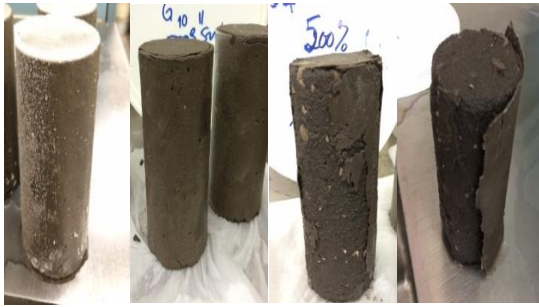


Figure 5 Soil-cement samples exposed to 500% SW (from left to right: 42, 58, 118 and 208 days)



Figure 6 Soil-cement samples exposed to 1000% SW (from left to right: 42, 58, 118 and 208 days)

The needle penetration resistance results of all samples are plotted in Figs. 7-9. The resistance forces of control samples increase by the curing time. In Fig. 9, the value of needle penetration resistance force of the soil-cement samples exposed to 1000% SW from 0-10 mm is considered as zero because the surface of these samples is destroyed due to the effects of very high sulphate environment. These results show that the deterioration is more pronounced and occurs deeper in the presence of high sulphate concentrations.

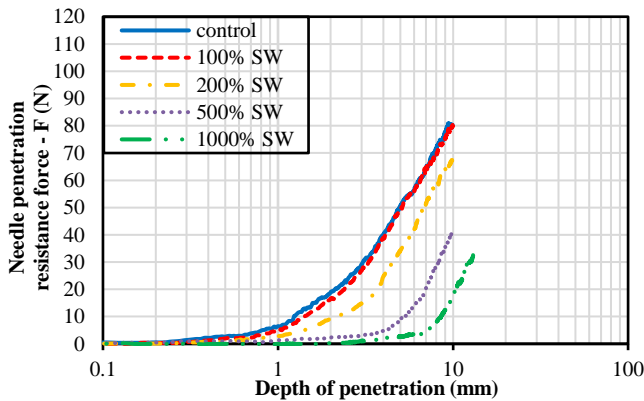


Figure 7 Needle penetration resistance results at 58 days.

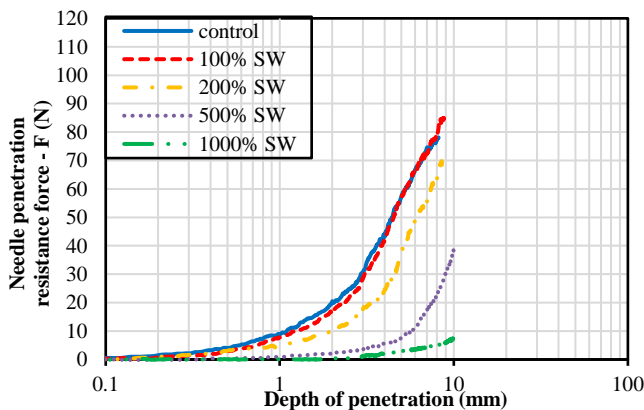


Figure 8 Needle penetration resistance results at 118 days.

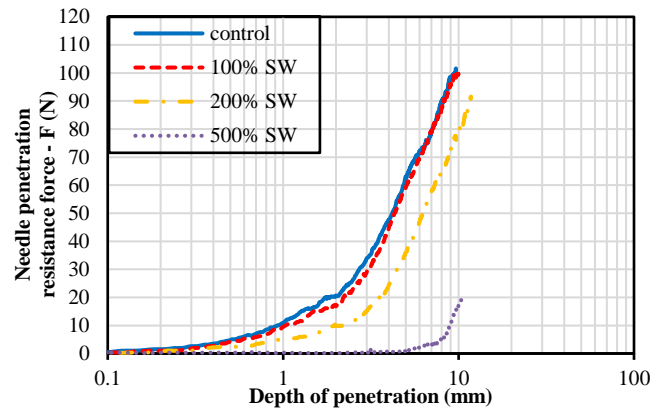


Figure 9 Needle penetration resistance results at 208 days.

To measure the deterioration depths of the samples exposed to the sulphate concentrations as a function of time, an equivalent diameter method (Cui et al., 2014) was applied. Based on the equivalent strength principle, the bearing capacity of the deteriorated column (diameter D_0) equals that of the non-deteriorated column (equivalent diameter d_{eq}) (see Fig.10). In this method, a hypothesis is applied that the strength of material within the equivalent deterioration area is considered to be zero. The total compression force (P_{tt}) (Table 2) obtained from the compression test of the deteriorated column (D_0) equals the resistance force of the column with the equivalent diameter (d_{eq}).

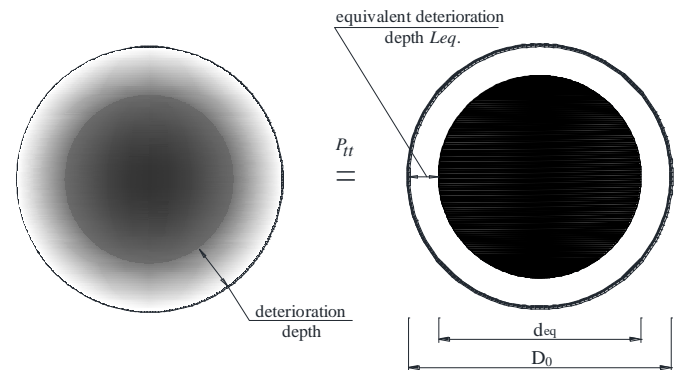


Figure 10 Equivalent diameter method

From Cui et al. (2014):

$$P_{tt} = \frac{\pi d_{eq}^2}{4} q_u \quad (6)$$

$$D_0 = 2L_{eq} + d_{eq} \quad (7)$$

where: P_{tt} : the total compression force obtained from the UCS test (kN); D_0 : the diameter of sample (mm); d_{eq} : the equivalent diameter (mm); L_{eq} : the equivalent deterioration depth (mm); q_u : the UCS of control sample which is then assumed as the UCS in the non-deteriorated portion (kN/m²).

Table 2 Total compression force

Time (day)	Compression force (kN)				
	control	100% SW	200% SW	500% SW	1000% SW
42	4.3032	4.2114	3.6205	3.5961	1.6955
58	4.7952	4.2960	3.6290	2.9100	1.0263
118	5.8948	4.5617	4.0953	2.2983	0.6549
208	6.0270	4.5954	4.4285	1.6693	0.0706

The results shown in Table 3 and Table 4 are the equivalent diameter and equivalent deterioration depth calculated from Eqs. (6) and (7). The equivalent deterioration depths were then plotted in Fig. 11.

Table 3 Equivalent diameter of the deteriorated samples (d_{eq})

Time (day)	Equivalent diameter (mm)			
	100% SW	200% SW	500% SW	1000% SW
42	52.71	50.61	48.71	33.44
58	50.99	46.86	41.96	24.92
118	49.02	46.45	34.79	18.57
208	46.59	45.74	28.80	7.20

Table 4 Equivalent deterioration depth of the samples (L_{eq})

Time (day)	Equivalent deterioration depth (mm)			
	100% SW	200% SW	500% SW	1000% SW
42	0.65	1.70	2.65	10.28
58	1.51	3.57	6.02	14.54
118	2.49	3.78	9.60	17.71
208	3.70	4.13	12.60	23.40

With the same cement ratio, Pham et al. (2017) showed that the trend of deterioration depth (L) can be expressed as:

$$L = 0.45\sqrt{t} \tag{8}$$

In this case, the trends of equivalent deterioration depths (L_{eq}) obtained from Fig. 11 are:

$$L_{eq}^{100\%} = 0.23\sqrt{t} \quad (R^2 = 1) \tag{9}$$

$$L_{eq}^{200\%} = 0.35\sqrt{t} \quad (R^2 = 0.94) \tag{10}$$

$$L_{eq}^{500\%} = 0.79\sqrt{t} \quad (R^2 = 1) \tag{11}$$

$$L_{eq}^{1000\%} = 1.65\sqrt{t} \quad (R^2 = 0.98) \tag{12}$$

where: L_{eq} : the equivalent deterioration depth (mm); t : the time (day); and R^2 : correlation coefficient.

The soil-cement samples were immersed in seawater after 28 days curing. So, before $t = 28$, the penetration depth $L_{eq} = 0$. Therefore, Eqs. (9) - (12) are applied for $t > 28$ days only.

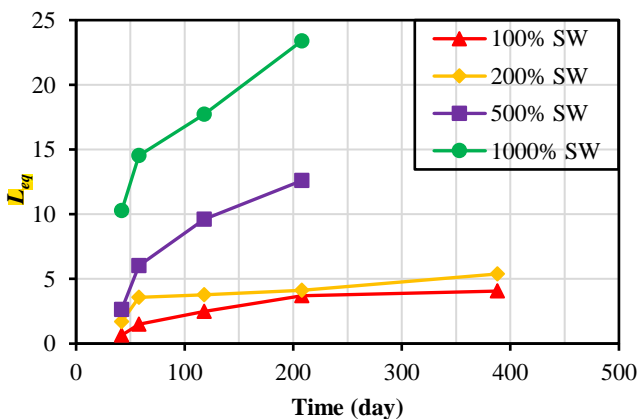


Figure 11 Equivalent deterioration depths

4. EQUIVALENT DETERIORATION DEPTH PREDICTION MODEL

4.1. Prediction of soil-cement columns core strength gain

According to Pham et.al, (2017), the unconfined compressive strength of control samples with the same cement content at different times is presented in Fig. 12. It is clear that the strength of the soil-cement samples is linear with the logarithm of time as supported by Hayashi et al., (2002). This relationship can be used to predict the long-term strength of the soil-cement columns.

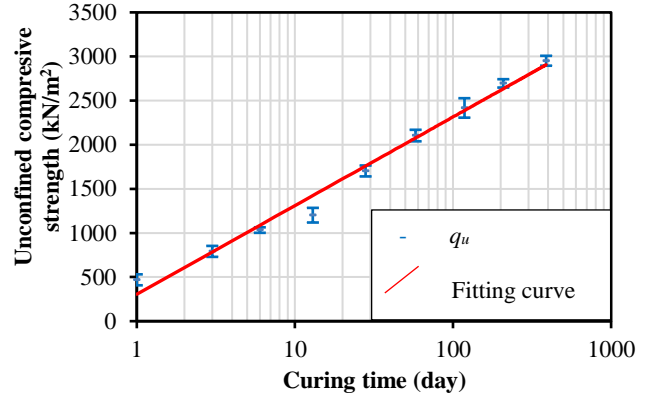


Figure 12 Strength gain of soil-cement column ($C = 120 \text{ kg/m}^3$)

The strength of the soil-cement samples obtained from Fig. 12 is:

$$q_u = 305 + 436 \ln(t) \quad (R^2 = 0.98) \tag{13}$$

where: q_u : the strength of the soil-cement samples (kN/m^2); and t : the age of the soil-cement samples (day).

4.2. Prediction of soil-cement columns strength degradation

Eqs. (9) - (12) show that the equivalent deterioration depth of the soil-cement samples is a function of the square root of time (t). So, the equivalent deterioration depth at the high sulphate concentrations can be expressed as:

$$L_{eq}^M = f(M)\sqrt{t} \tag{14}$$

where: M : the sulphate concentration (up to ten time of normal seawater); L_{eq}^M : the equivalent deterioration depth (mm); $f(M)$: the factor dependent on the sulphate concentration.

In this research, $f(M)$ was determined by a fitting method based on the experiment results. The values of $f(M)$ at 100%, 200%, 500% and 1000% SW obtained from Eqs. (9) - (12) are plotted in Fig. 13. It is clear that $f(M)$ has a linear relationship with the concentration of sulphate (M).

Therefore,

$$f(M) = 0.1644M \quad (R^2 = 1) \tag{15}$$

So,

$$L_{eq}^M = 0.1644M\sqrt{t} \tag{16}$$

Eqs. (7), (16) and (13) are substituted into Eq. (6). The total bearing capacity of the soil-cement columns in high sulphate concentrations could be determined as:

$$P_u^M = \frac{\pi(D_0 - 0.1644M\sqrt{t})^2}{4} (305.11 + 436.36 \ln(t)) \tag{17}$$

where: P_u^M : the total bearing capacity of soil-cement column in the

sulphate concentration M ; D_0 : the diameter of column (mm); and t : the age of column (day).

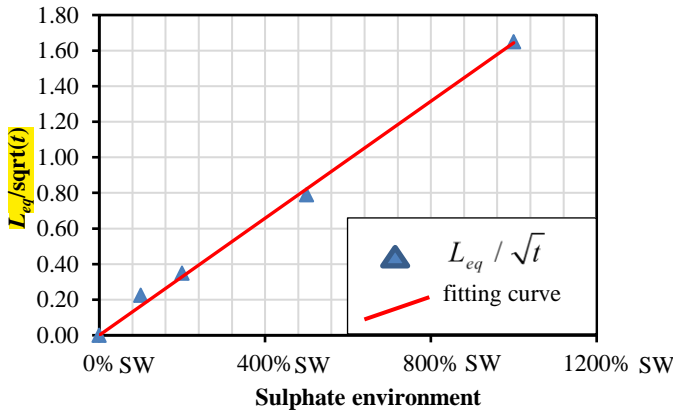


Figure 13 Relationship between factor $f(M)$ and sulphate concentrations (M)

4.3. Model application

Eq. (17) was applied to calculate the bearing capacity of the soil-cement column with $D = 0.5$ m in various sulphate environments. Table 5 and Fig. 14 show the strength change of the column exposed to 100%, 200%, 500% and 1000% SW. It is clear that the strength of the soil-cement column exposed to high sulphate concentrations (5 to 10 times as the sulphate concentration in normal seawater) decreases significantly in a short time. Especially, in very high sulphate concentration solution (10 times such as in seawater), the column will be totally destroyed ($P = 0$) within 60 years.

Table 5 Total bearing capacity of soil-cement column ($D = 0.5$ m) in high sulphate environments

Time (year)	Control	100% SW	200% SW	500% SW	1000% SW
0.00	57.06	57.06	57.06	57.06	57.06
0.02	224.41	224.41	224.41	224.41	224.41
0.08	343.63	342.13	340.31	333.95	321.70
0.20	426.04	420.96	417.34	404.74	380.66
0.60	520.52	507.84	500.25	473.99	424.72
1.00	564.45	546.13	535.56	499.20	431.81
2.00	624.07	594.78	578.42	522.66	421.83
5.00	702.87	650.26	621.69	526.23	362.62
10.00	762.48	682.00	639.13	499.27	275.72
20.00	822.09	700.51	637.17	438.10	156.34
40.00	881.70	700.18	608.47	336.84	36.15
60.00	916.57	688.40	575.89	259.66	0.50
80.00	941.31	673.72	544.54	199.10	0.00
100.00	960.50	658.23	515.12	150.75	0.00
120.00	976.18	642.69	487.65	111.89	0.00
140.00	989.44	627.39	461.98	80.69	0.00
160.00	1000.93	612.46	437.92	55.88	0.00
180.00	1011.05	597.96	415.32	36.48	0.00
200.00	1020.12	583.89	394.05	21.79	0.00
250.00	1039.31	550.58	345.85	2.14	0.00

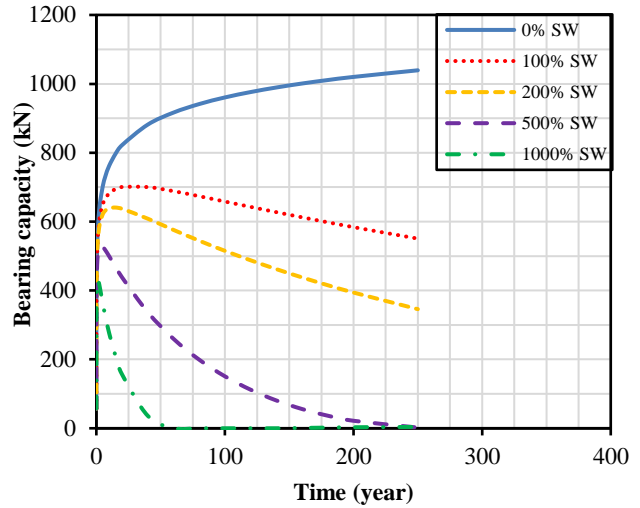


Figure 14 Total bearing capacity of soil-cement columns in high sulphate environments ($D = 0.5$ m)

Fig. 15 shows the strength loss of the columns as a function of time and sulphate concentration. The strength loss rate was calculated by dividing the strength reduction of deteriorated columns to the total strength of non-deteriorated columns. The figure shows that the soil-cement column loses about 50% of strength after 120 years exposed to 200% SW. In 500% and 1000% SW, the columns lose the same strength in only 25 and 5 years, respectively. This finding has significant implications to the stabilised soil in high sulphate environments such as acid sulphate soil which makes up approximate 95,000 km² of Australian coastline (EPA, 2007).

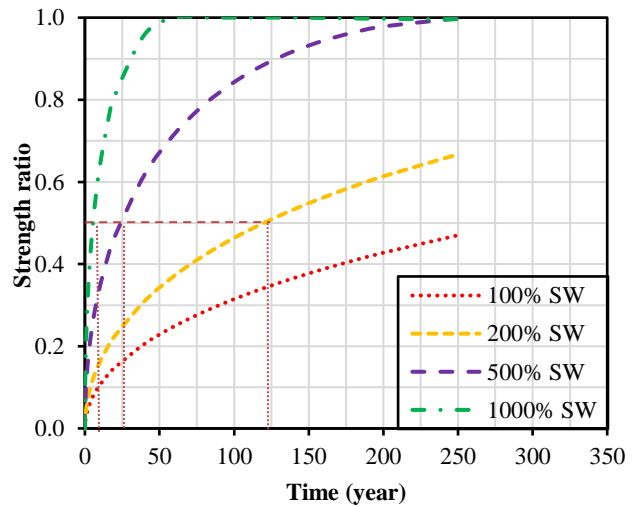


Figure 15 Strength loss rate ($D = 0.5$ m)

As an example, if the required bearing capacity of the soil-cement column is the same as that of the Newcastle Flyover project in Australia, $[P] = 122.72$ kN ($D = 0.5$ m) (Pham et al., 2017), the stability of the column can be calculated and plotted in Fig. 16. In the case of 100% SW exposure, the column with the diameter 0.5 m can stand with the attack of sulphate in over 150 years. However, for the case of 200% SW, the strength of the soil-cement column will be lower than the required strength after 75 years. It means that the structure could collapse after 75 years if the columns are designed with a diameter of 0.5 m in that environment. (Note: this assumes the worst case scenario fresh seawater flushing which would not occur naturally). For higher sulphate environment (500% and 1000% SW), the column with $D = 0.5$ m does not meet the strength requirement of the structure ($P < [P]$). Therefore, in such high sulphate environments, it is necessary to increase the diameter of the column or apply other methods to ensure that it can withstand the attacks of sulphate on its structural integrity.

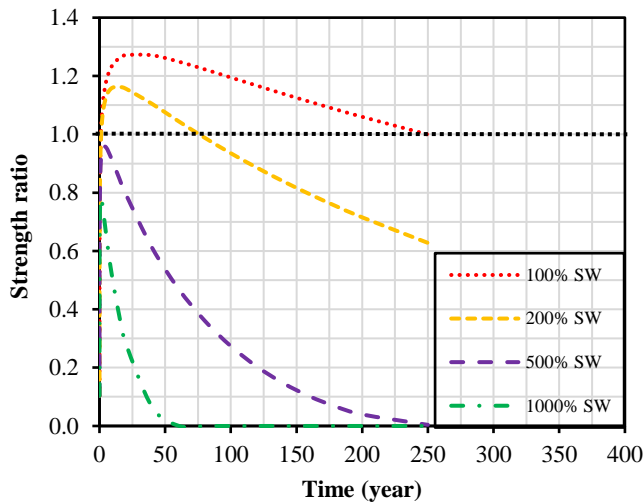


Figure 16 Durability of the soil-cement columns in high sulphate environments

5. CONCLUSIONS

In this study, experiments on the strength change of the soil-cement column exposed to different sulphate environments were conducted by the uniaxial compression test, needle penetration resistance. In addition, the strength prediction model was developed to predict the total strength change of the soil-cement columns constructed in high sulphate concentrations. It has been found that:

At higher sulphate concentrations, 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.

The experiments on the effects of high sulphate concentrations show that in a very short period of time, the depths of deterioration of the samples immersed in high concentration seawater are much deeper than others. The total bearing capacity of the soil-cement column in the high sulphate concentrations could be determined by Eq. (17). At higher sulphate environments (500% and 1000% SW), the column with $D = 0.5$ m does not meet the strength requirement of the structure ($P < [P]$), especially, the column exposed to 1000% SW could be totally destroyed ($P = 0$) within 60 years. Therefore, it is necessary to increase the diameter of the column or apply other methods to ensure that it can stand with the attacks of the high sulphate environments.

6. NOTATION

The following symbols are used in this paper:

D_0	diameter
d_{eq}	equivalent diameter
L	deterioration depth
L_{eq}	equivalent deterioration depth
M	sulphate concentration
P	bearing capacity
$[P]$	required bearing capacity
R^2	correlation coefficient
SW	seawater
UCS	unconfined compressive strength
t	time

7. ACKNOWLEDGEMENT

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