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An Investigation of the Elastic Modulus of Cement-Stabilised Soil by Wet Mixing Method for Sand Ground

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ABSTRACT: This paper presents the results of the experimental study to determine the correlation between the elastic modulus (E_{50}) and the unconfined compressive strength (q_u) of cement-treated soil by wet mixing method. Laboratory experiment program was conducted for four soil types: clayey sand, fine sand, medium sand and coarse sand with the amount of cement from 150 to 350 kg cement per cubic meter of natural soils. The unconfined compression tests were conducted, and stress-strain curves were recorded by Trapezium 2.24 software to determine q_u in all cases at the ages of 7, 14, 21, 28, and 56 days. Bayesian Model Averaging method (BMA) was used to analyse the effect of cement content, soil type, curing time to the elastic modulus E_{50} and determine the linear regression equations between E_{50} and q_u. The results can be applied for determining of the elastic modulus E_{50} of cement-treated sand by a wet-mixing method in order to calculate and design soil-cement columns bearing load for a high-rise building foundation.

KEYWORDS: Cement-treated soil, Elastic modulus (E_{50}), Unconfined compressive strength (q_u), Stress-strain curves, Soil-cement columns.

1. INTRODUCTION

Soil-cement column has been applied for soft ground improvement such as the foundation of the highways, railways, and road embankments (Al Tabbaa & Evans, 2003; Broms & Boman, 1979; Bruce, 2000; Caraşca, 2016; Masaki & Terashi, 2013). The strength of cement-treated soil has been studied in laboratory and in-situ, and it is showed that the strength of the material depends on cement content, curing time, mixing condition and soil type (Bahar et al., 2004; Baker, 2000; Bouchelaghem et al., 2010; Bruce, 2000; Chen et al., 2013; Dehghanbanadaki et al., 2013; Ho et al., 2018; Ho et al., 2017; Jacobson et al., 2003; Yin & Lai, 1998). The soil improvement for organic and soft ground by cement was successfully applied in Sweden (Åhnberg, 2006; Baker, 2000; Larsson et al., 2009). Some authors also conducted research on soil treated cement applied for sand, grain-sand ground as well as used glass or synthetic fibres to increase the strength (Güllü et al., 2017; Li et al., 2015; Maghous et al., 2014; Mengue et al., 2017; Tajdini et al., 2017). In addition, the lateral response of the soil-cement columns applied for embankment reinforcement and retaining walls have also been studies by physical and numerical (Bruce, 2000; Denies & Huybrechts, 2017; Denies et al., 2015; Jamsawang et al., 2017; Sukontasukkul & Jamsawang, 2012). For sand ground, the strength of cement-treated soil also depends on the water per cement and cement per sand ratios (Tariq & Maki, 2014).

The soil-cement column has been studied and applied in Vietnam from the 1980s for treated soft soil. In Danang city, the geology has the sand layer from 15 m to 20 m depth, so there are many applications of soil-cement column for bearing load, especially for high rise building from seven to eighteen floors (Dao & Hai, 2013).

For calculating the bending stiffness of cement-treated soil material, the elastic modulus (Young's modulus) needs to apply. The elastic modulus E_{50} is defined as secant modulus of elasticity determined on the stress-strain curve at half value of the unconfined compressive strength q_u (JieHan, 2004; Masaki & Terashi, 2013). The E_{50} value was used to design soil-cement columns, and it was calculated indirectly through the unconfined compressive strength (Szymkiewicz et al., 2015).

The previous studies have shown the regression models between E_{50} and q_u with a wide range factors of q_u. By dry mixing method with cement, Terashi et al. (1980) showed the correlation E_{50} = (75 to 1000)*q_u; otherwise, (Baker, 2000) suggested that E_{50} = (50 to 180)*q_u. With the same mixing method with cement, the E_{50} has also calculated as E_{50} = (65 to 250)*q_u and E_{50} = (100 to 500)*q_u (Bruce, 2000). For cement-stabilized soil by wet mixing method, according to the studies in Japan, the E_{50} value of clay was choice as E_{50} = (350 to 1000)*q_u (Masaki & Terashi, 2013), E_{50} = (35 to 180)*q_u (Yin & Lai, 1998), E_{50} = (50 to 150)*q_u (JieHan, 2004), E_{50} = (120 to 230)*q_u (Szymkiewicz et al., 2015) or E_{50} = 300*q_u (Filz & Navin, 2006).

Previous studies have suggested a wide range of E_{50} and q_u ratios. Therefore, it is difficult for a designer to choose the suitable value. Moreover, it is necessary to apply analytical methods to determine reliable q_u as well as the meaningful value of E_{50}. These approach methods have been shown in the researches of Pan et al. (2018) and Tinoco et al. (2011).

In this study, authors used the laboratory and field tests results of the unconfined compression strength of cement-treated soil from four projects in Danang city as was shown in the research of Dao (2012). Moreover, some methods were applied to analyse the correlation between E_{50} and q_u, such as a simple linear regression method, a BMA method with the effect of cement content and the interaction effect between cement content and q_u on E_{50} value.

2. MATERIALS AND METHODS

2.1 Soil Properties

Physical properties and grain size distributions of four soil groups are given in Table 1, Table 2, and Figure 1.

Table 1 Physical properties of soil groups

Soil type	Soil name	Unit weight ρ (kN/m^3)	Water content w (%)	Liquid limit w_L (%)	Plastic limit w_p (%)	Specific Gravity	Void ratio
Group No1	Clayey sand	17.88	41.65	34	47	2.69	1.147
Group No2	Fine sand	19.98	24.3	-	-	2.70	0.649
Group No3	Small sand	18.30	19.90	-	-	2.65	0.774
Group No4	Coarse sand	18.55	18.6	-	-	2.71	0.72

Table 2 Particle distribution of soil

Diameter (mm)	Content p (%)			
	No1	No2	No3	No4
2÷1	0	1.5	7.3	18.0
1÷0.5	1.68	2.5	11	15.2
0.5÷0.25	9.10	32	49.8	51.5
0.25÷0.1	16.30	53	29.2	11.6
0.1÷0.05	37.36	11	1.0	3.7
0.05÷0.01	25.31	0	0.7	0
0.01÷0.005	8.02	0	0	0
<0.005	2.23	0	0	0

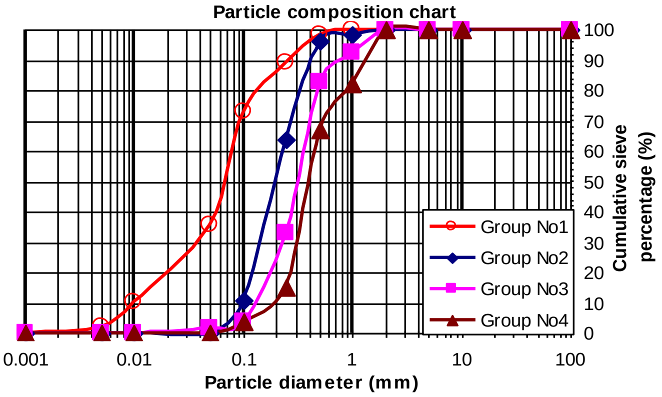


Figure 1 Particle distribution of soils

2.2 Cement

Two types of cement were utilised in the study program: Portland Cement Blended (PCB) cement grade PCB30 for soil groups No1 and No2, and PCB40 for groups No3 and No4. Five cement contents were used, included 150 kg (TH1), 200 kg (TH2), 250 kg (TH3), 300 kg (TH4) and 350 kg (TH5) per cubic meter of natural soil.

2.3 Sample Casting and Curing

Mixing and casting procedures were conducted according to Vietnamese Construction Code (TCVN9403:2012). Specimens were a cube with dimensions of 70.7 mm*70.7 mm*70.7 mm. Samples were remolded after 24 hours from casting and were cured in polystyrene boxes at curing room with humidity of 90 % and temperature of 27±2 °C (Figure 2).

A. Prepared soil for casting B. Curing sample

Figure 2 Sample casting and curing

2.4 Unconfined Compression Test

Samples were tested immediately by the compression testing machine after removal from curing room to avoid changes in humidity and temperature. Loading rate was from 10 to 15 N/s or from 1 to 2 mm/min until the sample was damaged and the compressive strength was calculated from the ultimate load. Each group included three samples, and the mean value of the compressive strength was taken. In total, sixteen groups with four hundred and eighty samples were used for testing. According to the experimental program, the samples were tested at the ages of 7, 14, 21, 28, 56 (and 112 days for group No1 only) in the laboratory.

2.5 Method for Determining q_u and E_{50}

The unconfined compressive strength of the samples was calculated according to Vietnam construction (TCVN9403:2012):

$$q_u = \frac{P}{A} \tag{1}$$

where: q_u is the unconfined compressive strength of soil-cement samples at the age of experiment (N/mm^2); P is the ultimate load (N); A is the compressed area of the samples (mm^2).

Elastic modulus characterises the ability of a material resists against elastic deformation when is subjected to longitudinal compressive load. It is determined by the ratio between normal stress (σ) and corresponding relative strain (ε):

$$E_{50} = \frac{\sigma}{\varepsilon_{50}} \tag{2}$$

For cement-stabilised soil material, the most common value is secant modulus of elasticity denoted as E_{50}. It is determined by the ratio of normal stress (σ) at the value of 50% of q_u to the corresponding strain ε_{50} on the q_u-ε (Masaki & Terashi, 2013) (Figure 3).

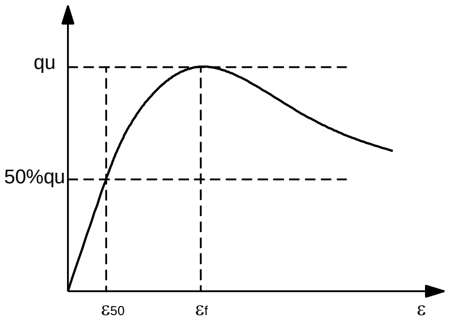
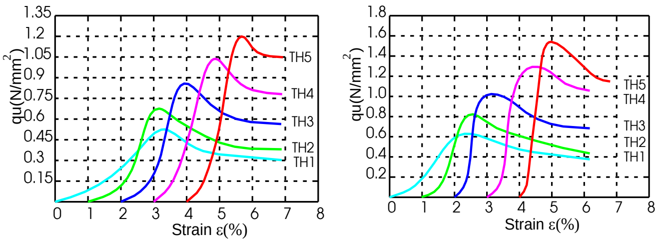


Figure 3 The curve q_u-ε for E_{50} determination

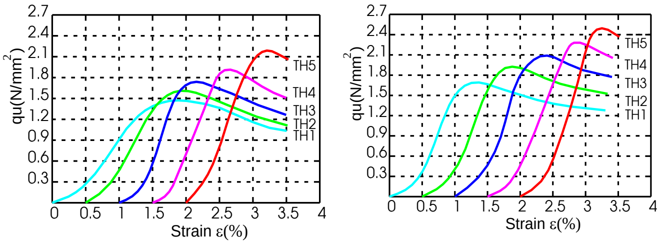
3. TESTING RESULTS

3.1 Stress-strain Curves

The stress-strain curves of four soil types (No1, No2, No3 and No4) at different ages are shown in Figures 4-7. Cement contents are 150 kg (TH1), 200 kg (TH2), 250 kg (TH3), 300 kg (TH4) and 350 kg (TH5) per cubic meter of natural soil.

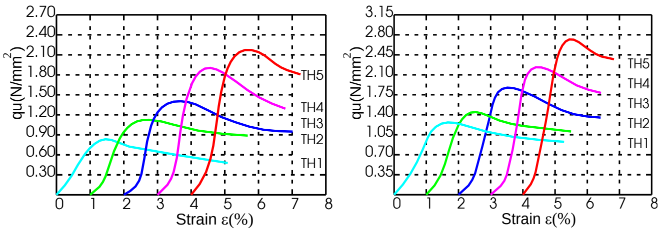


a. *q_u-ε curve at 7 days* b. *q_u -ε curve at 14 days*

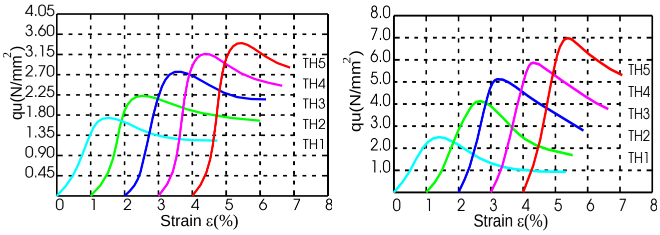


c. *q_u -ε curve at 28 days* d. *q_u -ε curve at 56 days*

Figure 4 q_u-ε curves of soil group No1 at different ages



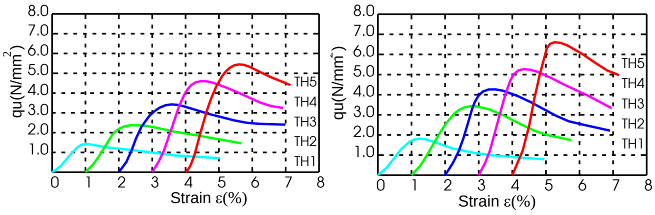
a. *q_u -ε curve at 7 days* b. *q_u -ε curve at 14 days*



c. q_u -ε curve at 28 days

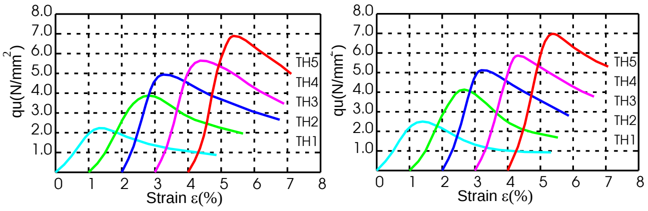
d. q_u -ε curve at 56 days

Figure 5 q_u-ε curves of soil group No2 at different ages



a. q_u -ε curve at 7 days

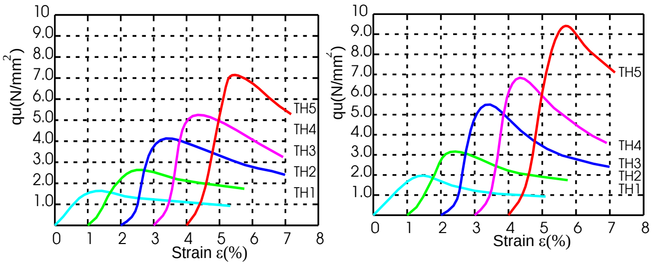
b. q_u -ε curve at 14 days



c. q_u -ε curve at 28 days

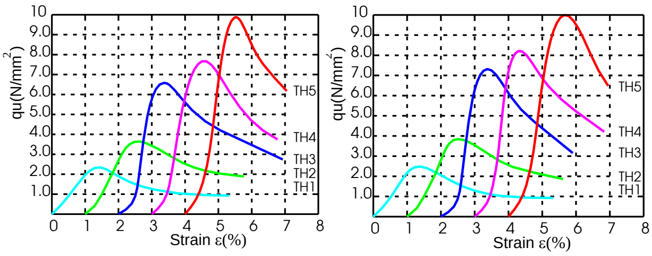
d. q_u -ε curve at 56 days

Figure 6 q_u-ε curves of soil group No3 at different ages



a. q_u -ε curve at 7 days

b. q_u -ε curve at 14 days



c. q_u -ε curve at 28 days

d. q_u -ε curve at 56 days

Figure 7 q_u-ε curves of soil group No4 at different ages

3.2 Summary of Experimental Results

The strength q_u is determined at the highest position on the q_u-ε curve. The values of q_u, 50%q_u, ε_{50} and E_{50} are presented in Tables 3 and 4.

Table 3 Summary of experimental results: q_u and 50% q_u

Soil/ Sample	days	Case/q_u (N/mm^2)					Case/50%q_u (N/mm^2)				
		TH1	TH2	TH3	TH4	TH5	TH1	TH2	TH3	TH4	TH5
No1 (75)	7	0.52	0.69	0.82	1.02	1.17	0.26	0.34	0.41	0.51	0.59
	14	0.78	0.93	1.13	1.29	1.54	0.39	0.46	0.57	0.65	0.77
	28	1.43	1.61	1.75	1.92	2.29	0.72	0.81	0.88	0.96	1.15
	56	1.68	1.93	2.09	2.29	2.49	0.84	0.97	1.04	1.14	1.25
	112	1.70	1.96	2.18	2.39	2.58	0.85	0.98	1.09	1.19	1.29
No2 (60)	7	0.85	1.15	1.45	1.88	2.25	0.43	0.58	0.73	0.94	1.13
	14	1.25	1.43	1.82	2.33	2.78	0.63	0.72	0.91	1.17	1.39
	28	1.75	2.25	2.75	3.15	3.44	0.88	1.13	1.38	1.58	1.72
	56	1.81	2.35	2.83	3.32	3.57	0.91	1.18	1.42	1.66	1.79
No3 (60)	7	1.46	2.35	3.35	4.68	5.42	0.73	1.18	1.68	2.34	2.71
	14	1.85	3.15	3.98	5.22	6.40	0.93	1.58	1.99	2.61	3.20
	28	2.45	3.98	4.85	5.66	6.80	1.23	1.99	2.43	2.83	3.40
	56	2.50	4.02	5.02	5.85	7.00	1.25	2.01	2.51	2.93	3.50
No4 (60)	7	1.58	2.61	4.05	5.25	7.08	0.79	1.31	2.03	2.63	3.54
	14	1.98	3.35	5.54	6.85	9.49	0.99	1.68	2.77	3.43	4.75
	28	2.35	3.66	6.55	7.75	9.85	1.18	1.83	3.28	3.88	4.93
	56	2.42	3.76	7.21	8.12	10.03	1.21	1.88	3.61	4.06	5.02

Table 4 Summary of experimental results: ε_{50} and E_{50}

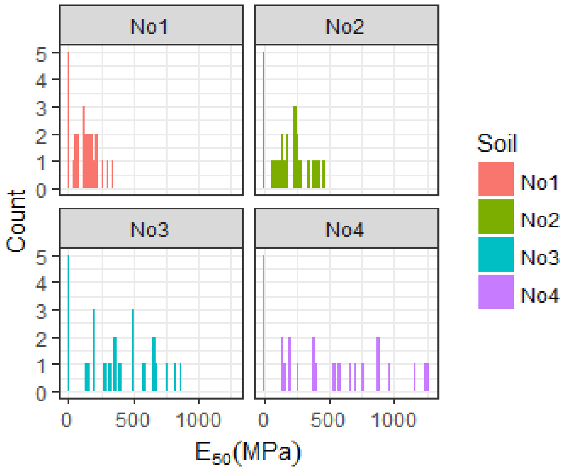
Soil/ sample	days	Case/ε_{50} (%)					Case/E_{50} (N/mm^2)				
		TH1	TH2	TH3	TH4	TH5	TH1	TH2	TH3	TH4	TH5
No1 (75)	7	2.23	1.65	1.35	1.25	1.18	23.5	41.6	60.4	81.6	99.2
	14	1.52	1.26	1.05	0.88	0.82	51.5	73.6	107.8	146.8	187.3
	28	1.25	1.12	0.93	0.85	0.79	114.6	144.1	189.2	226.4	290.3
	56	1.12	1.02	0.81	0.83	0.78	149.7	189.4	257.7	275.4	319.6
	112	1.10	10.10	0.80	0.82	0.77	154.7	19.4	272.9	291	334.7
No2 (60)	7	1.23	1.30	1.10	1.02	0.90	69.1	88.5	131.8	184.3	248.9
	14	1.28	1.16	1.05	0.94	0.81	97.7	123.3	173.3	247.9	342.4
	28	1.26	0.90	1.09	0.82	0.81	138.9	250.0	252.3	386.5	423.7
	56	1.15	0.86	1.11	0.81	0.79	157.4	273.3	2545	409.9	450.2
No3 (60)	7	1.12	1.16	1.08	0.93	0.83	130.4	202.6	310.2	505.8	651.4
	14	1.19	1.13	1.08	0.90	0.84	155.5	278.8	368.5	582.3	765.6
	28	1.23	0.99	0.97	0.84	0.83	199.2	402.0	500.0	677.8	816.3
	56	1.22	1.10	1.01	0.89	0.81	204.9	365.5	497.0	658.0	864.2
No4 (60)	7	1.15	2.00	1.07	0.91	0.81	137.4	130.5	378.5	575.7	871.8
	14	1.17	1.26	1.01	0.89	0.82	169.3	265.9	548.5	767.9	1157
	28	1.20	0.91	0.98	0.82	0.79	195.8	402.2	668.4	950.9	1247
	56	1.20	0.99	1.03	0.93	0.79	201.7	379.8	700.0	872.2	1270

4. ANALYSIS OF RESULTS

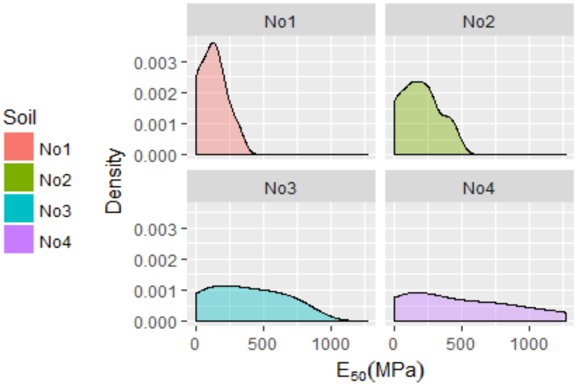
4.1 Distribution of the E_{50} Values for Each Soil Type

The distribution of E_{50} values (frequency and density) of the four soil types is shown in Figure 8. The results show that the level of dispersion of E_{50} values of the soils No1 and No2 were rather small and quite close to the normal distribution. However, for soil types No3 and No4, the distribution ranges were wider and did not follow normal distribution rule.

The difference of E_{50} values between the two soil groups (No1 and No2) and (No3 and No4) is more clearly shown in Figure 9. The median value of E_{50} between soil types No1 and No2 is approximately equal, No3 and No4 is nearly equal but much larger than those of soil group No1 and No2 (nearly double). Possibly, it is due to the presence of much larger sand particles in two soil types No3 and No4 and higher cement grade (PCB40 vs PCB30). Percentile ranges 25 % and 75 % of two soil types No3 and No4 were also much larger than those of two soil types No1 and No2, which show large variation in E_{50} values (as shown in Figure 8).



(a)



(b)

Figure 8 E_{50} distribution of 4 soil types

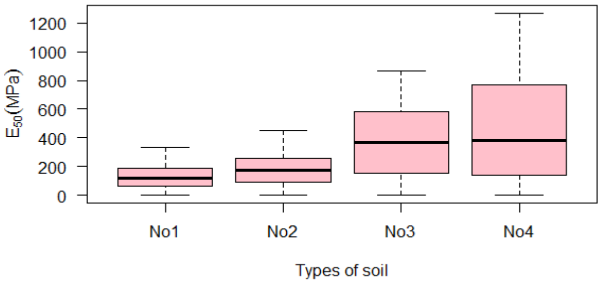


Figure 9 Effect of soil type on E_{50}

Figure 10 shows that the value of E_{50} increased significantly, but at the same time the dispersion was also greater when the cement content increased. It should be taken into consideration when stabilising the soil by increasing cement content because the strength of cement soil could not be reach an expectation value.

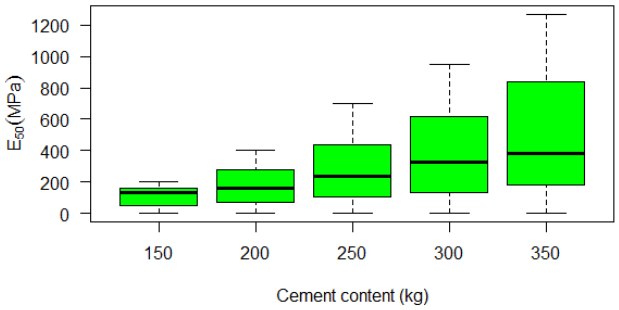


Figure 10 Effect of cement content on E_{50}

Over time, the E_{50} values increased from the beginning until 28 days. But after 28 days, the increase was almost insignificant (Figure 11). It might be because stabilised-soil strength developed with the development of the strength of cement. However, it is noteworthy that the degree of dispersion of E_{50} values was not much difference between ages, especially from 28 days to 56 days, the level of dispersion was nearly the same.

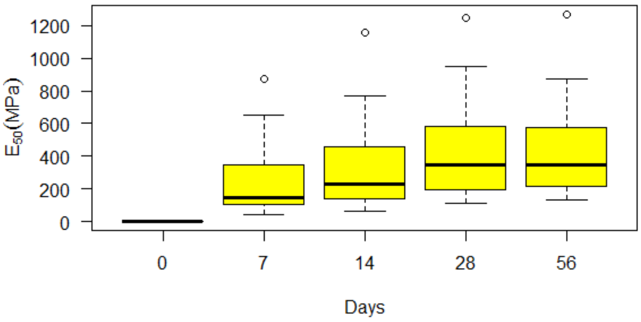


Figure 11 Effect of curing time on E_{50}

The combined effect of both soil type and cement content on E_{50} values is shown in Figure 12 where each colour corresponds to one soil type. Here, the E_{50} value gradually increased with the increase of cement content, but the increasing level varied due to soil types. For soil types No1 and No2, the E_{50} values did not increase so much with cement content. However, for soil type No3 and especially soil type No4, the difference in E_{50} was significant between cement contents due to the strong influence of sand particle content in soil and higher cement grade. It means that when treating ground types No1 and No2, it is necessary to consider the appropriate cement content to meet the requirements of strength and ensure a reasonable price as well.

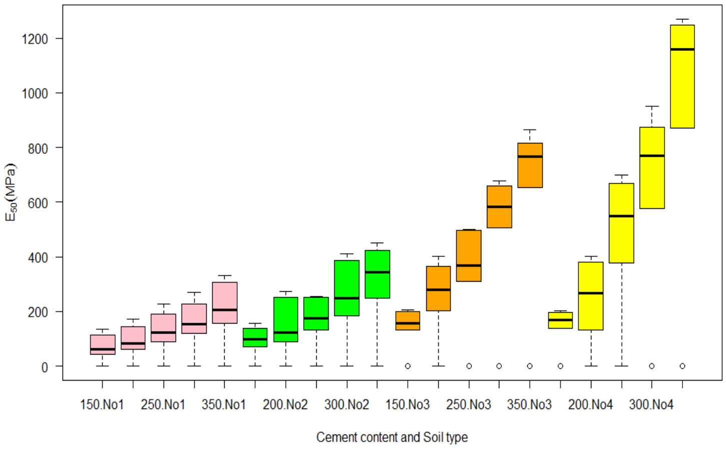


Figure 12 Combined effect of soil type and cement content on the E_{50} values

4.2 A Regression Model of the E_{50}

In order to establish a regression model of E_{50} value under predictor variables, the correlations between parameters are shown in Figure 13. The correlations between E_{50} and q_u, soil type, cement grade, cement content and age were 98 %, 39 %, 38 %, 41 % and 67 %, respectively.

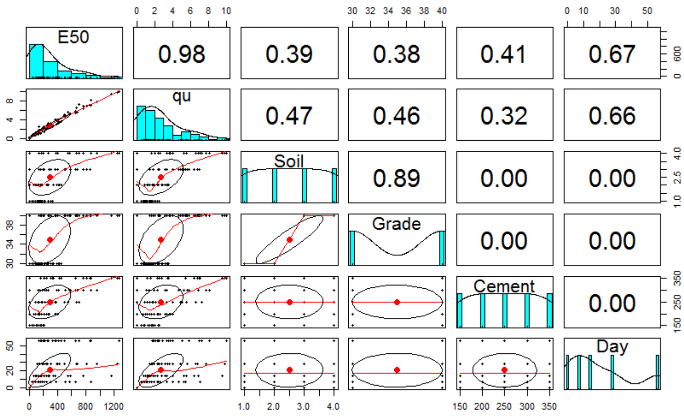


Figure 13 Correlation between parameters

Based on those correlations, the authors built two linear regression models of E_{50}: a simple model depended only on q_u, and another model using Bayesian Model Averaging (BMA) method.

4.3 A Simple Linear Regression Model of E_{50}

Correlations between E_{50} and q_u for each soil type are presented in Figure 14. It is easy to see that the regression lines expressing the correlation between E_{50} and q_u in four cases were almost parallel. It means that the relation between them did not depend on the soil type. Thus, the correlation between E_{50} and q_u of all soil types was built as shown in Figure 15. In these charts, the distributions of E_{50} and q_u values were also expressed in the right vertical axis and upper horizontal axis, respectively. In general, E_{50} and q_u values did not follow the normal distribution, but they had a solid correlation.

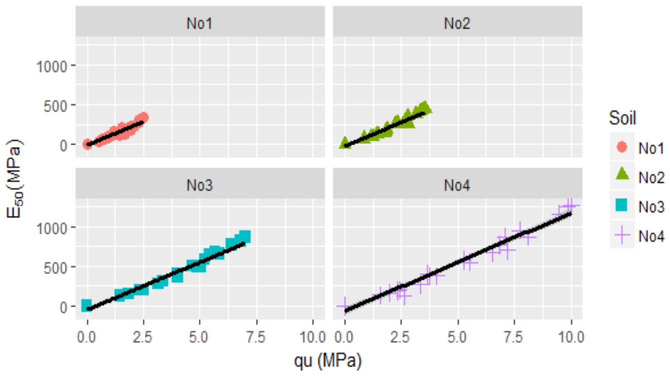


Figure 14 Correlation between E_{50} and q_u for 4 soil types

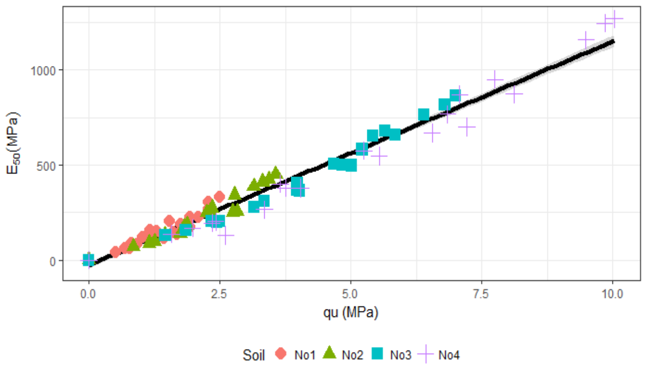


Figure 15 Correlation between E_{50} and q_u for 4 soil types

In Figure 15, the linear regression model E_{50} with q_u is as follow (Appendix 1):

$$E_{50} = -27.85 + 117.81 q_u \tag{3}$$

The factor of q_u of 117.81 was statistically significant and similar to many other studies (Baker, 2000; JieHan, 2004; Yin & Lai, 1998). Adjusted coefficient of determination (adjusted R^2 of 0.9739 meant that approximately 97.39 % of E_{50} value variance could be accounted for by the q_u values. It can be said that q_u had the greatest effect on the E_{50} value, and Eq. (3) could predict the E_{50} value accurately. This equation relationship was consistent with the result $E_{50} = -36.812 + 117.39 q_u$ by Mengue et al. (2017) for fine-grained lateritic cement-treated soil 9 %.

4.4 A Linear Regression Model Based on the Bayesian Model Averaging Method

In regression, when faced with several potential models, the analyst can either choose one model or average over the models. The Bayesian methods provide some approaches to solve these problems. The Bayesian methods also give us a numerical measure of the relative evidence in favour of competing theories (A. Hoeting et al., 1999; Raftery et al., 1997; Wasserman, 2000). According to the BMA (Brown et al., 1998, 2002) and by using R software to analyse data, the total of 11 models were selected (Figure 16), where five models were the best ones with cumulative posterior probability up to 80.66% (Appendix 2). In eleven selected models, two variables q_u and the cement content always occurred. Hence, besides q_u, cement content also affected E_{50}. In addition, the grade of cement also had a significant influence on the E_{50} value because it appeared in four models (Figure 16).

Details of BMA analysis (Appendix 2) showed that among eleven models, there were two models which could predict the E_{50} value as follows.

Model 1: The E_{50} value was predicted with two predictor variables named q_u and cement content by Eq. (4).

$$E_{50} = -121.18 + 112.95 q_u + 0.43C \tag{4}$$

where: C is cement content (kg).

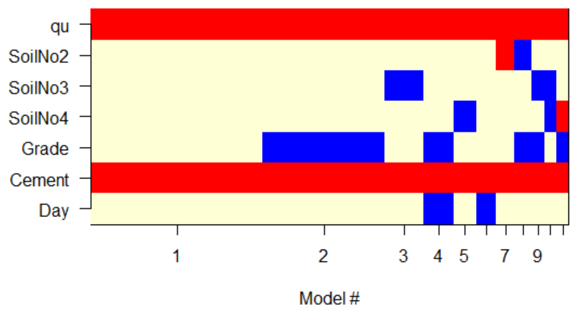


Figure 16 Regression models selected by the BMA method

In model 1, R^2 is 0.983, Bayesian information criterion (BIC) is -398.5, and posterior probability is 38.1%.

Model 2: The E_{50} value was predicted with three predictor variables named q_u, cement content and grade of cement by Eq. (5).

$$E_{50} = -57.59 + 115.08 q_u + 0.4C - 1.77G \tag{5}$$

where: C is cement content (kg); G is the grade of cement.

In model 2, R^2 is 0.984, BIC is -397.8, and posterior probability is 25.5 %.

The factor of q_u in Eqs. (4) and (5), the coefficient of determination and BIC value in models 1 and 2 were nearly equal; thus, two predictive models were quite similar. However, model 1 used only two predictor variables and it had a higher posterior probability than model 2. As a result, model 1 should be used rather than model 2.

Comparing the model 1 to the model with only q_u in section 4.2.1 (Eq. 2), factors of q_u in both models are nearly the same, but the model selected by the BMA method predicts the E_{50} value a little bit better than the traditional model (with only q_u). However, the model selected by the BMA method had the disadvantage that it used two predictor variables q_u and cement content, but these two variables were not completely independent of each other (Figure 13).

4.5 Linear Regression Model Considering the Interactive Effect Between q_u and Cement Content

As described above, the model using two predictor variables q_u and cement content could predict the E_{50} value more accurate than the model with only q_u, but these two variables were not independent of each other. It means that q_u itself was also dependent on cement content. It is, therefore, necessary to consider an extended model including two predictor variables as q_u and cement content but additionally considering the interactive effect between them on the E_{50}.

The linear regression equation is as follow (Appendix 3):

$$E_{50} = 4.88 + 46.11 q_u - 0.02C + 0.22 q_u.C \tag{6}$$

However, the factor of cement content was not statistically significant (P = 0.726 > 0.5), so the regression equation can be rewritten:

$$E_{50} = 4.88 + 46.11 q_u + 0.22 q_u.C \tag{7}$$

This model had the highest R^2 = 0.994 among all models, which meant the best predictability. However, due to the interactive effect of cement content on q_u, a factor of q_u in the proposed model did not similar to those in all the models above.

5. CONCLUSIONS

The relationship between the E_{50} and q_u with many results and the distribution spectrum is very wide, ranging from 75 to 1000 times, it is difficult for application and necessarily have more experimental studies to apply for each location soil, especially soil-cement column as the semi-rigid pile for bearing load high-rise building.

From the experiments, four sandy soils with cement content of 150 to 350 kg per cubic meter of natural soil showed that the strength q_u increased as the cement content increased, and the soil type moving from sandy silt to coarse sand – the strength q_u reached 10.3 Mpa with 350 kg cement at 56 days, it is suitable for soil-cement column bearing load.

The correlation coefficient between E_{50} and q_u in this study was 0.98. Based on that a linear regression equation: $E_{50} = -27.85 + 117.81q_u$. The E_{50} values calculated from this equation were in the scope of Table 1, but with a smaller range. In simple designs, this equation is recommended to apply.

Based on the Bayesian Model Averaging (BMA) method, the authors built a regression model that not only predicted E_{50} value by q_u but also additionally consider the effect of both variables cement content: $E_{50} = -121.18 + 112.95q_u + 0.43C$ and cement grade: $E_{50} = -57.59 + 115.08q_u + 0.4C - 1.77G$. Analysing results indicated that the regression model based on two variables q_u and cement content was more suitable than others. This is an important point in analysing data by applied statistic to suit local conditions using soil-cement column.

Finally, the authors have established a regression model including two predictor variables q_u and cement content, to consider the interactive effect between them on E_{50}. The results showed that the E_{50} depended on q_u and the interactive between q_u and cement content, and the effect of only cement content was not statistically significant according to equations: $E_{50} = 4.88 + 46.11q_u - 0.02C + 0.22q_u.C$ and $E_{50} = 4.88 + 46.11q_u + 0.22q_u.C$. The coefficient of determination of this model of 0.994 was the highest one among those in all models, so, it is the best model to predict the E_{50} value.

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8. APPENDICES

Appendix 1:

```
summary(model1)
##
## Call:
## lm(formula = E50 ~ qu, data = E50qu)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -149.125  -34.799    8.168   27.852  115.865
##
## Coefficients:
##             Estimate Std. Error t value
Pr(>|t|)
## (Intercept)  -27.852      7.064  -3.943
0.000151 ***
## qu           117.807      1.940  60.730  < 2e-
16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*'
0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 47.56 on 98 degrees of
freedom
## Multiple R-squared:  0.9741, Adjusted R-
squared:  0.9739
## F-statistic:  3688 on 1 and 98 DF,  p-value: <
2.2e-16
```

Appendix 2:

```
summary(BMA)
##
## Call:
## bicreg(x = xvars, y = yvar, strict = FALSE, OR
= 20)
##
##
##   11  models were selected
##  Best  5  models (cumulative posterior
probability =  0.8066 ):
##
##            p!=0    EV        SD        model 1
model 2    model 3
## Intercept  100.0  -92.25275  43.12217  -
121.1825   -57.5939  -118.0010
## qu         100.0  114.08531   2.27523
112.9486   115.0752   113.3714
## Soil2        7.5   -0.22106   3.34742      .
.          .
## Soil3       13.2   -1.45215   5.46141      .
.       -11.4774
## Soil4        9.7   -0.68560   4.42346      .
.          .
## Grade       40.7   -0.77035   1.12063      .
-1.7720      .
## Cement     100.0    0.41005   0.06274
0.4257     0.3965     0.4198
## Day         10.6   -0.02564   0.11101      .
.          .
##
## nVar                                         2
3          3
## r2                                       0.983
0.984      0.983
## BIC                                     -
398.4794  -397.7822  -395.4790
## post prob                                0.361
0.255      0.081
##            model 4    model 5
## Intercept   -32.6115  -119.0108
## qu          117.0468   113.5287
## Soil2           .          .
## Soil3           .          .
## Soil4           .       -6.9739
## Grade        -2.2518       .
## Cement        0.3694     0.4177
## Day          -0.3206       .
##
## nVar            4          3
## r2            0.984      0.983
## BIC        -395.0335  -394.3471
## post prob     0.064      0.046
```

Appendix 3:

```
summary(model4)
##
## Call:
## lm(formula = E50 ~ qu + Cement + qu:Cement, data
= E50qu)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -107.119   -7.563   -0.840    7.031   77.513
```

```
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  4.88249   13.37797   0.365    0.716
## qu          46.11293    5.43208   8.489  2.6e-
13 ***
## Cement      -0.01794    0.05108  -0.351    0.726
## qu:Cement    0.22216    0.01771  12.547  < 2e-
16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05
'.' 0.1 ' ' 1
##
## Residual standard error: 23.94 on 96 degrees of
freedom
## Multiple R-squared:  0.9936, Adjusted R-squared:
0.9934
## F-statistic:  4948 on 3 and 96 DF,  p-value: <
2.2e-16
```