Analysis and Assessment of Laboratory Strength Development in Cement Stabilized Coarse Grained Soils

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Abstract : This paper deals with the formulation of a phenomenological model to assess the laboratory strength development in cement stabilized coarse grained soils with low fine fraction. Since both soil and cement are interacting materials with pore fluid, soil-water/cement ratio, *w/C* has been found to be an appropriate parameter in the analysis of strength development in their stabilized state. The proposed model is useful to assess the strength wherein water content, cement content and compaction energy vary over a wide range using the test result of a single laboratory trial. This capability enables to pursue the reverse process to obtain required strength of soil-cement road, consistent with the in-situ properties of the soil.

1. Introduction

Highway pavement generally consists of base and sub-base, which are constructed by suitable materials. Due to lack of them in some construction sites, it is expensive to bring the materials from far off boring pit. An alternative way, which is widely practiced in Thailand is to compact the in-situ soil mixed with cement. In addition, the Department of Highways, Thailand, has used this method of cementation to restore damaged pavement since 1965. This method is designated as the pavement recycling technique. The damaged pavement (coarse grained material) would be dug up and mixed with cement. The soil-cement mixture would be immediately field compacted by rollers. This technique is economical because cement is readily available at reasonable cost in Thailand. Moreover, adequate strength can be achieved in a short time.

At a particular curing time, besides water content and cement content, the compaction energy is one of the influential factors controlling the strength development in cement stabilized coarse-grained soils. The effects of water content and cement content on the engineering characteristics of cement admixed high water content clay have been extensively researched [1 and 2]. Miura et al. [3] have introduced the clay-water/cement ratio hypothesis based on the critical state and state boundary surface concepts. It is a fundamental in analyzing and assessing the strength development of cement admixed clay. In this paper, the application of clay-water/cement ratio would be thus extended to analyze and assess the laboratory strength development of cement stabilized coarse grained soils.

Generally, in practice, many laboratory trial mixes are needed for determination of strength before the execution of soil-cement pavement. In order to exercise judgment in the field with regard to the quantity of cement to be stabilized, with due consideration to several field parameters, it is desirable to provide a simple method to geotechnical engineers to

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predict strength development with time for various combinations of soil water content, cement content and compaction energy, by minimum laboratory trials. In this paper, an attempt has been made to meet this objective.

2. Experimental Investigation

This paper studies the strength characteristics of cement stabilized soil, and analysis and assessment of the laboratory strength development. The soils used in this study are lateritic soil and crushed rock, which are typical coarse grained soils often used in the earth work. The lateritic soil is composed of 28.5 percent fine-grained particles and 71.5 percent coarse grained particles, which are 32.7 percent gravel and 38.8 percent sand. It is non-plastic with liquid limit of 22.5%. The crushed rock is composed of 91% coarse grained particles with remaining part being fine grained. Lateritic soil and crushed rock are classified as silty sand (SM) and well graded silty gravel (GW-GM), respectively according to the Unified Soil Classification System (USCS). Grain size distribution and compaction characteristics of both soils are presented in Figure 1 and Table 1, respectively.

Both soils were mixed with Type I Portland cement at water contents of 0.6, 0.8, 1.0, 1.2 and 1.4 times optimum water content (OWC). At each of the water content, the soil-cement mixture was compacted under four energy levels i.e. 296.3, 592.5, 1346.6 and 2693.3 kJ/m^3 in a standard 100 mm diameter mold (diameter : height = 1:1). After 24 hours, the samples were dismantled, wrapped in vinyl bags and stored in a humidity room of constant temperature (25±2^{o}C). After 7, 14, 28, 60 and 120 days of curing, unconfined compression test was run on the samples. For each curing time and for each of combination of water content and cement content, at least three samples were tested under the same condition to check the consistency of the test. In most cases, the results under the same testing condition are reproducible. All the test results were analyzed to develop a phenomenological model of predicting strength. Test result of the other cement stabilized lateritic soil has been taken to verify the proposed model. The result of lateritic soil was from Ruenkrairergsa and Charatkorn [1]. The liquid and plastic limits of the soil are in the order of 36% and 16%, respectively.

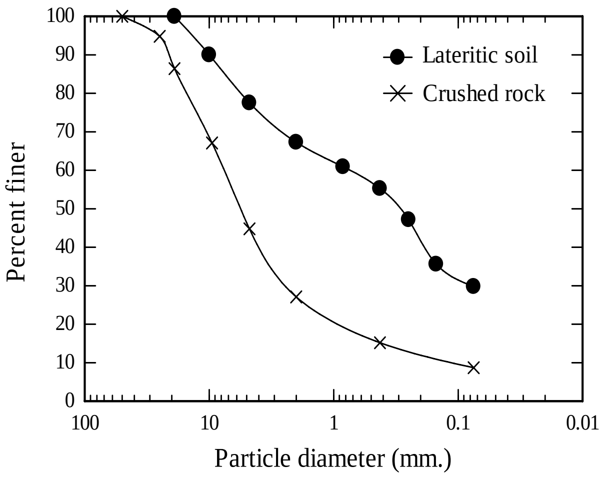


Figure 1. Grain size distribution curves of the soil samples.

Table 1. Compaction characteristics of both soils.

Energy per unit volume (kJ/m^3)	Lateritic Soil		Crushed Rock	
	OWC (%)	$\gamma_{d,max}$ (kN/m^3)	*OWC* (%)	$\gamma_{d,max}$ (kN/m^3)
296.3	8.0	19.2	8.3	19.1
592.5	6.8	19.5	7.4	19.4
1346.6	6.2	20.0	5.5	20.6
2693.3	5.4	20.6	4.8	20.9

3. Test Results

Typical compaction curve and unconfined compressive strength of cement stabilized soil are shown in Figure 2, which is the result of cement stabilized lateritic soil. It is seen that the compaction curve is the same for all cement contents and exhibits higher dry unit weight than that of untreated compacted soil. Compaction curve is symmetrical around optimum water content (OWC) for the range of the water content tested. Whereas the symmetry is realized only when water content ranges from 0.8 to 1.2 times optimum water content for the relationship between unconfined compressive strength and water content. This is because the water content lower than 0.6 OWC is not enough for hydration as illustrated by scanning electron photographs (Figure 3).

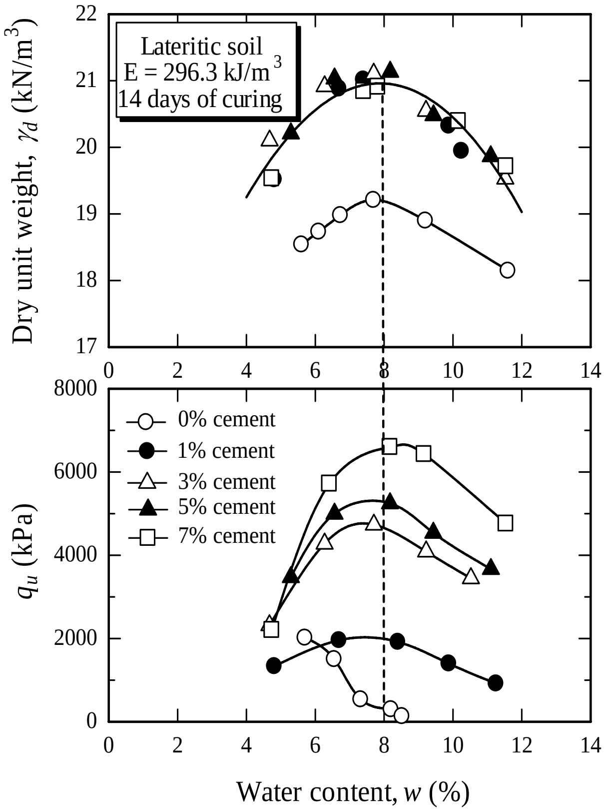
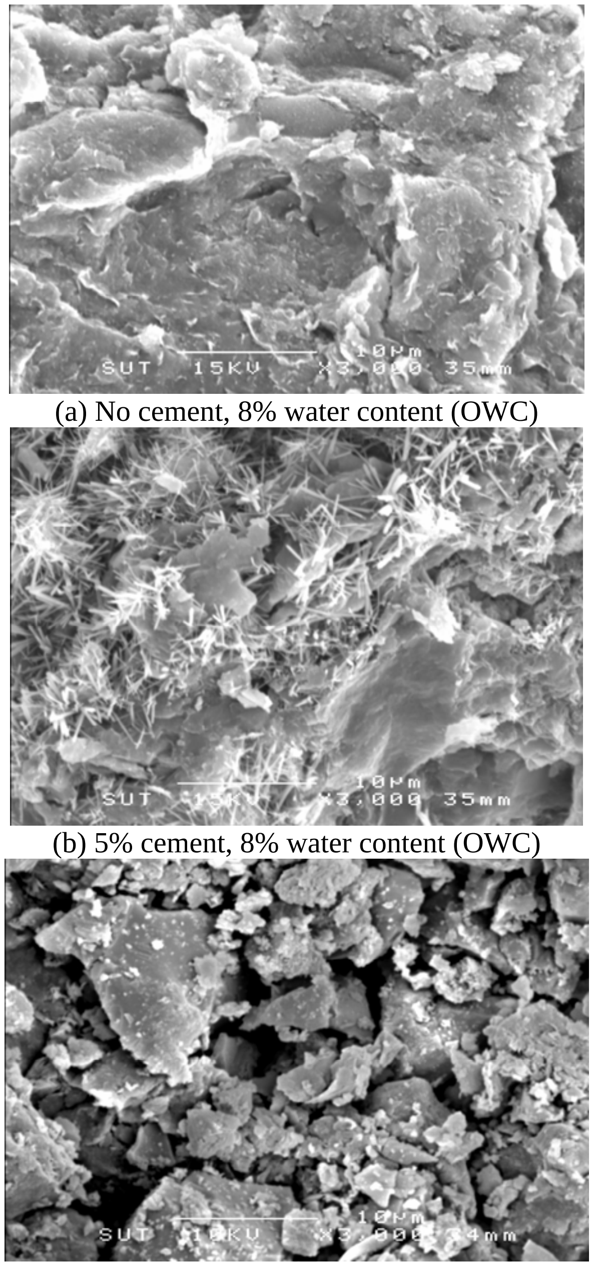


Figure 2. Relationship between water content-dry unit weight and strength of lateritic soil at 14 days of curing under compaction energy of 296.6 kJ/m^3.

Figures 3a and 3b show the photographs of compacted lateritic soil and 5% cement stabilized lateritic soil at the same initial water content of 8% (OWC) and under the same compaction energy of 296.3 kJ/m^3, respectively. Both photographs were magnified 3000 times. Figure 3b clearly shows the presence of cementing products in the pores with the well-knitted framework among the soil particles. These cementing products impart the strength and resistance to deformation to the stabilized soil. No such cementing product between pores appears for the soil stabilized at low water content (4.8% or 0.6OWC) as shown in Figure 3c. Due to the very low water content, the pore space is large and the degree of hydration is very low. It leads to the conclusion that practically, the relationship between strength and water content is symmetrical in shape when water content is between 0.8 and 1.2 times the optimum water content. Moreover, it is noted that the water content corresponding to the maximum strength and maximum dry unit weight is optimum water content.



(a) No cement, 8% water content (OWC)

(b) 5% cement, 8% water content (OWC)

(c) 5% cement, 4.8% water content (0.6 OWC)

Figure 3. Scanning electron micrographs of (a) compacted lateritic soil and (b) and (c) cement stabilized lateritic soil after 14 days of curing under the same compaction energy of 293.3 kJ/m^3.

Effect of curing time on unconfined compressive strength at water content between 80% and 140% the OWC is presented in Figure 4, which shows the results of 7% cement samples compacted under compaction energy of 592.5 kJ/m^3. It is clear that the longer the curing time, the greater the strength. The water content corresponding to the maximum strength is the optimum water content for all curing time.

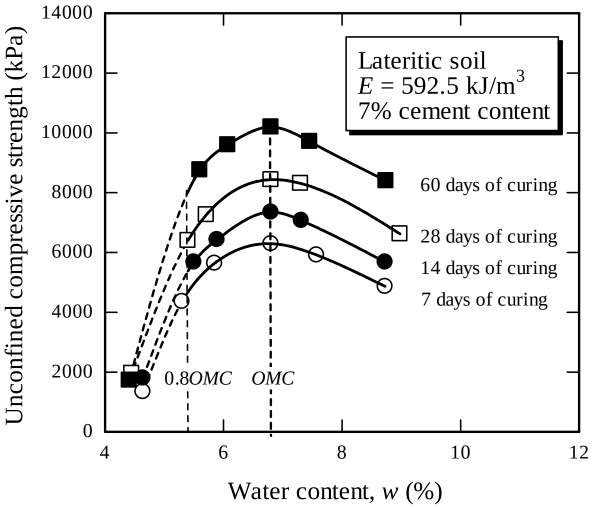


Figure 4. Relationship between unconfined compressive strength and water content of cement stabilized lateritic soil at different curing time.

Influence of cement content on the strength development of the cement stabilized soil at a particular water content, compaction energy, and curing time is presented in Figure 5. The strength increase is classified into three zones. As the cement content increases, the cement content per grain contact point increases and upon hardening, imparts a commensurate amount of bonding at the contact points. This zone is designated as soil-cement interaction zone. Beyond this zone, the strength development slows down with gradual increase. The incremental gradient becomes nearly zero and does not make any further significant improvement. The zone is referred to as the transitional zone (cement content ranging from 7-18%). The considerable strength increase appears again when cement content is higher than 18%. This zone is identified as the cement-soil interaction zone. This finding is consistent with the work (cement admixed high water content clay) reported by Horpibulsuk et al. [5]. In the development of a phenomenological model to assess the strength development, the experimental investigation is limited to the soil-cement interaction zone.

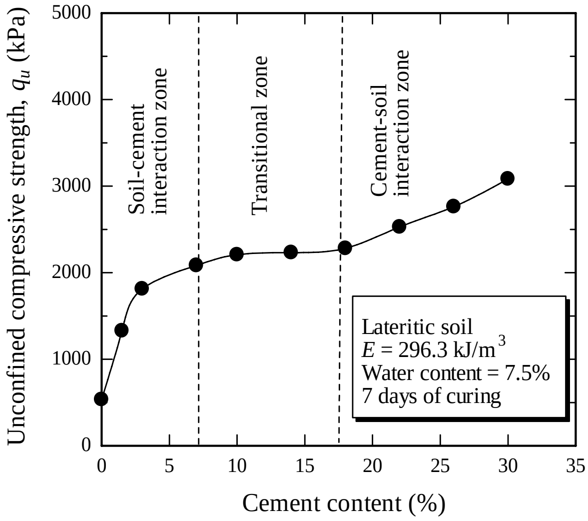


Figure 5. Role of cement content on strength development.

4. Analysis and Assessment of Strength Development

Recent research work on assessment of the cement admixed clay based on Abrams' law reveals that at a particular curing time, strength of cement admixed high water content clay (no compaction) is dependent upon clay-water/cement ratio, w_c/C [3 and 6]. This is a prime parameter taking the combined effects of water content and cement content into account. The lower the clay-water/cement ratio, the greater the strength. The present paper extends this premise to analyze the strength development in the stabilized soil compacted under various compaction energies at the OWC and on the wet side of optimum. The prime parameter is herein re-designated as soil-water/cement ratio, w/C. The investigation on the role of w/C has been done on the cement stabilized crushed rock and at three levels of compaction energy (296.3, 592.5, and 1346.6 kJ/m^3) at three levels of water content (10.2, 8.3, and 7.3 percentage) as shown in Figure 6. The samples were mixed with cement at different levels to obtain w/C values of 0.5, 1.0, 2.0 and 4.0 and cured for 14 days.

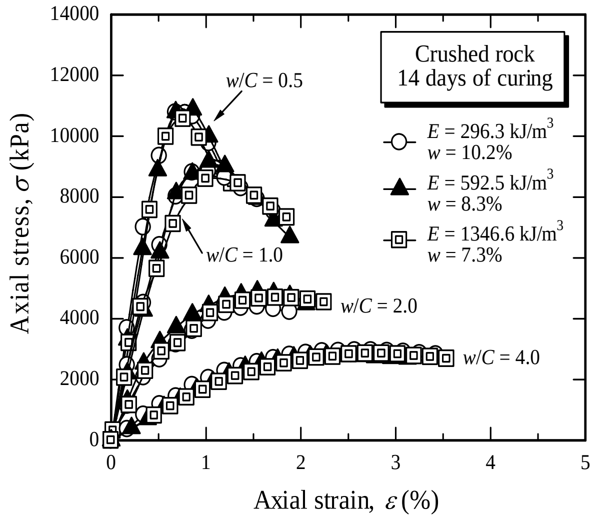


Figure 6. Compression test results of cement stabilized crushed rock under different levels of compaction energy.

From this figure, it can be premised that even though the samples are of different levels of water content, cement content, and compaction energy, the stress-strain relationship and strength are practically the same for equal value of *w*/*C*. The lower the *w*/*C*, the greater the strength.

Figure 7 shows unconfined compressive strength against *w*/*C* of the cement stabilized lateritic soil under compaction energy of 592.5 kJ/m^3 at 14 and 60 days of curing. It can be seen that for a particular curing time at the OWC and beyond on to the wet side of optimum, a unique q_u, versus *w*/*C* trend is noticed. The strength development under different energy (from 296.3 to 2963.3 kJ/m^3) is further analyzed based on the *w*/*C* as shown in Figure 8 for cement stabilized lateritic soil. The functional relation is expressed as

$$q_u = \frac{A}{(w/C)^B} \quad (1)$$

where *A* and *B* are empirical constants. In all cases (*vide* Table 2), the parameter *A* varies widely, depending upon soil type and curing time. However, the parameter *B* only varies between 0.64 and 0.66, irrespective of soil type and curing time. The parameter *B* can thus be taken as a constant for the range of compaction energy and curing time considered.

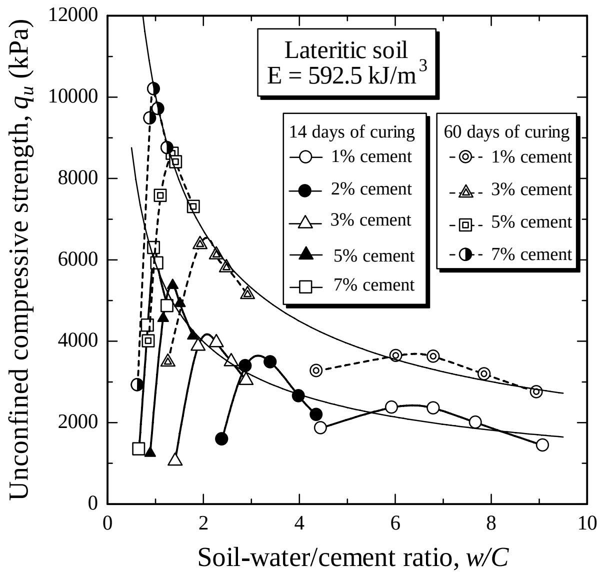


Figure 7. (q_u, *w*/*C*) relationship of cement stabilized lateritic soil at 14 and 60 days of curing time.

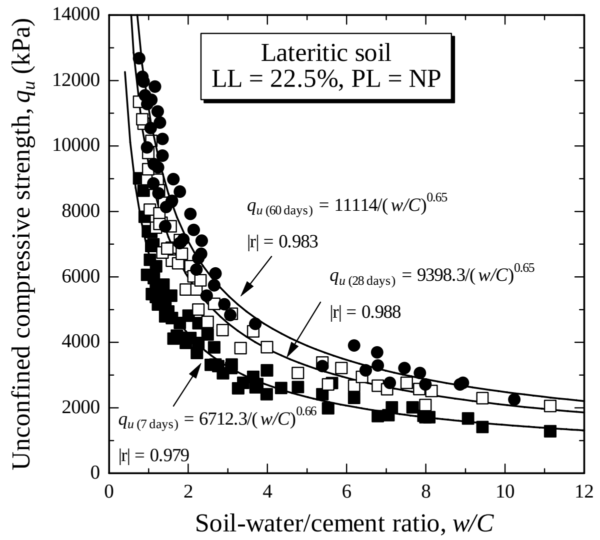


Figure 8. (q_u, *w*/*C*) relationship of cement stabilized lateritic soil at OWC and on the wet side of optimum.

Table 2. *A* and *B* values of both soils.

Curing Time (Days)	Lateritic Soil		Crushed Rock	
	A	*B*	*A*	*B*
7	6712.3	0.66	4230.6	0.65
14	7877.7	0.66	4768.0	0.66
28	9398.3	0.65	5808.2	0.65
60	11114.0	0.65	7146.1	0.65
120	12881.0	0.64	7798.7	0.65

While considering the strength ratio of cement stabilized soils, the parameter A is eliminated as shown by taking the ratios of strength developed at different soil-water/cement ratios. This results in the following relation:

$$\frac{q_{(w/C)_1}}{q_{(w/C)_2}} = \frac{A/\left(w/C\right)_1^B}{A/\left(w/C\right)_2^B} = \left[\frac{\left(w/C\right)_2}{\left(w/C\right)_1}\right]^{0.65} \quad (2)$$

where $q_{(w/C)_1}$ is the strength to be estimated at soil-water/cement ratio of $(w/C)_1$ and $q_{(w/C)_2}$ is the strength value at soil-water/cement ratio of $(w/C)_2$. Based on the test results, the parameter B is taken as 0.65.

The analysis shows that at a particular value of w/C, strength development with time is controlled only by the value of A since B is regarded as constant. The value of A for different stabilized soils depends on soil type. However, the rate of strength development with time is identical for various soils since it is influenced predominantly by the hydration process. As such, it is possible to generalize the strength development (as has been done for concrete by Nagaraj and Zahida Banu [7]) using the compressive strength of cement stabilized soil at an age of 28 days as a reference value. By considering the curing time (days) in natural logarithmic scale, the strength variation with time can be expressed as linear variation. Figure 9 depicts such linear plots for cement stabilized lateritic soil. The strength ratio plot after normalization is also shown in the figure. The following relation is obtained

$$\frac{q_D}{q_{28}} = a + b\ln D \quad (3)$$

where q_D is the strength after D days of curing, q_{28} is the 28-day strength, a and b are constants. From this investigation, the values of a and b are 0.308 and 0.208 for the cement stabilized lateritic soil and 0.244 and 0.277 for the cement stabilized crushed rock. It is found that these two sets of values yield practically the same line for the range of curing time considered. To account for soil type, linear regression analysis gives the following relationship:

$$\frac{q_D}{q_{28}} = 0.269 + 0.219\ln D \quad (4)$$

with a high degree of correlation of 0.969. This normalization accounts for the effects of difference in soil type, water content, cement content and compaction energy.

The generalized interrelationship among strength, curing time and w/C for predicting strength development of cement stabilized soils at the OWC and on the wet side of optimum for w/C ranging from 0.5 to 11 is expressed by combination of Equations (2) and (4).

$$\left\{\frac{q_{(w/C)_D}}{q_{(w/C)_{28}}}\right\} = \left[\frac{\left(w/C\right)_{28}}{\left(w/C\right)_D}\right]^{0.65}\left(0.269 + 0.219\ln D\right) \quad (5)$$

where $q_{(w/C)_D}$ is the strength of cement stabilized soil to be estimated at soil-water/cement ratio of $(w/C)_D$ after D days of curing and $q_{(w/C)_{28}}$ is the strength of cement stabilized soil at soil-water/cement ratio of $(w/C)_{28}$ after 28 days of curing. This expression is valid only when the soil is at the OWC and on the wet side of optimum.

It remains now to assess the strength development for cement stabilized soils on the dry side of optimum. As mentioned earlier, the relationship between strength and water content is practically symmetrical around OWC in the range of 0.8 to 1.2 times the OWC. As a result, the phenomenological model for assessing the strength development at a soil-water/cement ratio, compaction energy and curing time is proposed as shown in Figure 10.

The implication of the model is that one laboratory test value of strength developed over a specific curing time at a soil-water/cement ratio and at a compaction energy is needed. Also the compaction curves under different compaction energy are required to examine the state of water content (dry or wet sides of optimum). These compaction curves can simply be assessed by the phenomenological model proposed by Horpibulsuk et al. [8].

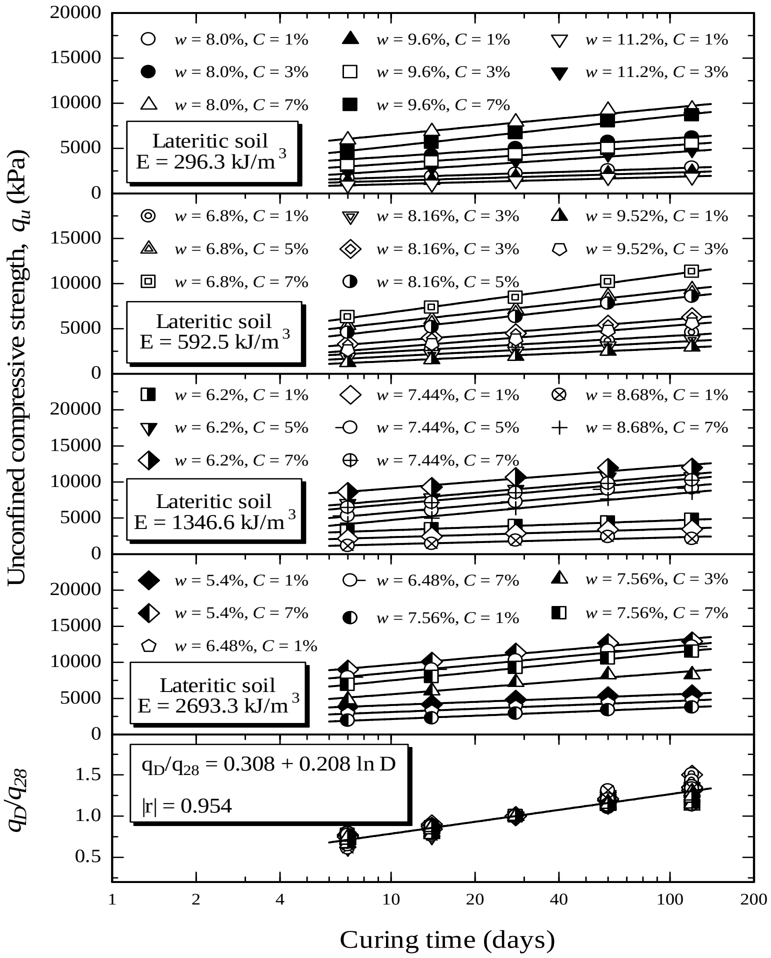


Figure 9. Strength development of cement stabilized lateritic soil with and its generalization.

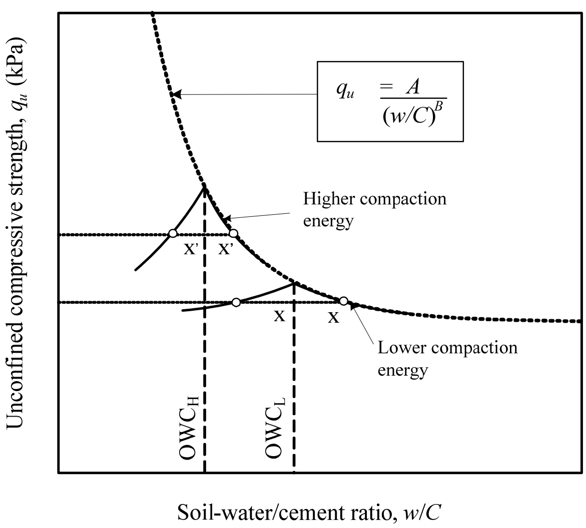


Figure 10. Schematic diagram for assessment of strength of cement stabilized soils.

The strength development in the cement stabilized soils on the dry side of optimum can be determined by considering that the relationship between strength and water content is symmetrical when the water content is in the range of 0.8 to 1.2 times OWC. The result of the application of the proposed model to determine the strength development for a lateritic soil are presented in Table 3. It is found that the predicted values are in agreement with the observed values. This shows that the error from the prediction is acceptable, reinforcing the applicability of the proposed model. This model is simple and requires strength data for only one trial mix at a particular compaction energy and compaction curves.

Table 3. Strength prediction of cement stabilized lateritic soil (data from Ruenkrairergsa and Charatkorn [4]).

Energy, E (kJ/m^3)	Water content, w (%)	Curing Time, D (days)	Cement content, C (%)	w/C	Observed strength, q_u (kPa)	Predicted strength, q_{up} (kPa)
296.3	13.5	3	5	2.7	1185	1102
296.3	13.5	7	5	2.7	1562	1504
296.3	13.5	14	5	2.7	1718	1832
296.3	13.5	14	7	1.9	2279	2280
296.3	13.5	28	5	2.7	2248	2160
296.3	13.5	28	7	1.9	2868	2688
592.5	11.5	7	3	3.8	1536	1197
592.5	11.5	14	5	2.3	2281	2033
592.5	11.5	28	3	3.8	1786	1720
592.5	11.5	28	7	1.6	3039	Reference

5. Conclusions

The soil-water/cement ratio, w/C, is the appropriate parameter in the analysis of strength development of cement stabilized coarse grained soil at the OWC and beyond on to the wet side of optimum. The proposed phenomenological model is useful in estimating the strength of cement stabilized coarse grained soil in which the water content, cement content and compaction energy vary over a wide range. Besides data from a single trial can be extrapolated to a variety of component ratios.

6. Acknowledgement

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References

[1] M. Kamon and D.T. Bergado, "Ground improvement techniques", Proceedings of 9th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Vol.2, 1992, pp.526-546.

[2] F. Tatsuoka, and A. Kobayashi, "Triaxial strength characteristics of cement-treated soft clay", Proceedings of 8th European Conference on Soil Mechanics and Foundation Engineering, 1986, pp.421-426.

[3] N. Miura, S. Horpibulsuk, and T.S. Nagaraj, "Engineering behavior of cement stabilized clay at high water content", Soils and Foundations, Vol.41, No.5, 2001, pp.33-45.

[4] T. Ruenkrairergsa, and S. Charatkorn, "Compressive strength of soil-cement under different density", Report of Research and Development Center, Department of Highways, Thailand, 2001.

[5] S. Horpibulsuk, N. Miura, and T.S. Nagaraj, "Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis", Geotechnique, Vol.53, No.4, 2003, pp.439-444.

[6] S. Horpibulsuk, N. Miura, and T.S. Nagaraj, "Clay-water/cement ratio identity of cement admixed soft clay", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.131, No.2, 2005, pp.187-192.

[7] T.S. Nagaraj, and Zahida Banu, "Generalization of Abrams' law", Cement and Concrete Research Journal, Pergamon press, USA. Vol.26, No.6, 1996, pp.933-942.

[8] S. Horpibulsuk, R. Rachan, and W. Katkan, "Phenomenological modeling of compaction curve", Proceedings of 5th International Symposium on Ground Improvement and Geosynthetics, Bangkok, Thailand, 2004, pp.131-137.