

## STRENGTH DEVELOPMENT IN CEMENT STABILIZED LOW PLASTICITY AND COARSE GRAINED SOILS: LABORATORY AND FIELD STUDY

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### ABSTRACT

Laboratory and field strength development of cement stabilized coarse-grained soils are studied in this paper. A phenomenological model to assess the laboratory strength development is developed. The model is divided into the dry and the wet sides of optimum water content. At the optimum and on the wet side of optimum, the strength development in cement stabilized soils at a particular curing time is dependent only upon the soil-water/cement ratio,  $w/C$ , which can reflect the combined effects of water content and cement content. It is moreover premised that the relationship between strength and water content is symmetrical around the optimum water content (OWC) in the range of 0.8 to 1.2 times the OWC. The proposed model is useful for assessing the strength development wherein water content, cement content and compaction energy vary over a wide range. Only the test result of a single laboratory trial is needed. From the field study, it is found that the field roller-compacted strength,  $q_{ufr}$  is lower than the laboratory strength,  $q_{ul}$  under the same dry unit weight, soil-water/cement ratio and curing time due to several field factors. The ratio  $q_{ufr}/q_{ul}$  varies from 50 to 100%. Non-uniformity in mixing soil with cement is realized by the ratio of field hand-compacted strength to laboratory strength,  $q_{ufh}/q_{ul}$  ranging from 0.75 to 1.2. For most data, the field roller-compacted strength is 55 to 100% the field hand-compacted strength. This might be caused by the difference in compaction method and curing condition between laboratory and field stabilization. From this field observation and the proposed model, a practical procedure for repairing damaged roads using the pavement recycling technique is introduced. The procedure consists of the determination of cement content, the execution of the field stabilization and the examination of the field strength. It can save on sampling and laboratory testing and hence cost.

**Key words:** cement stabilized coarse-grained soil, compaction energy, pavement recycling technique, soil-water/cement ratio, unconfined compressive strength (IGC: D6/D10)

### INTRODUCTION

Highway pavement generally consists of base and sub-base, which are constructed from suitable materials. When no suitable materials are available and it is expensive to bring the materials from distant sources; an alternative way which is widely practiced in Thailand is to compact the in-situ soil mixed with cement. This method is economical and the engineering properties of the soil-cement mixture can be controlled. The strength and resistance to deformation increase with time. 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 would be dug up and mixed with cement. The soil-cement mixture would be immediately field compacted by rollers as illustrated in Fig. 1. This technique is economical because cement is readily available at reasonable cost in Thailand.

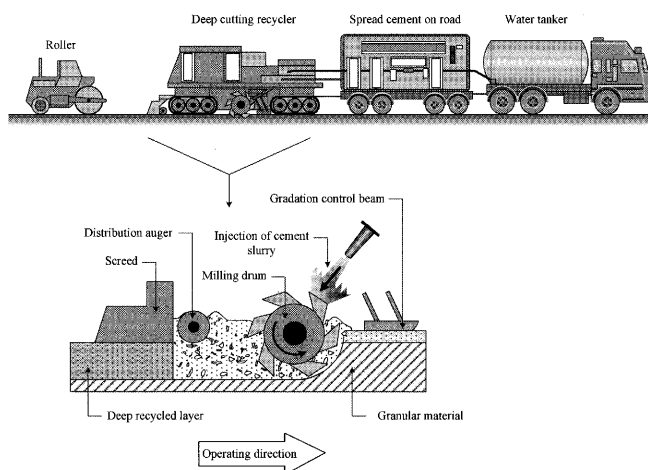


Fig. 1. Typical characteristics of pavement recycling technique

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Moreover, adequate strength can be achieved in a short time and the pavement is ready for use after about 24 hours.

Since the inception of the pavement recycling technique, the developments in the machinery as well as associated field techniques have surpassed the basic understanding of strength developments in soil (generally coarse-grained) stabilized with cement both in the laboratory and field. The stabilization is begun with mixing of the soil in a relatively dry state with cement and water specified for compaction. The soil, in the presence of moisture and cementing agent gets transformed into modified soil i.e., grouping of particles takes place due to physico-chemical interactions with soil ~ cement ~ water interactions. Since these are at particle level, it is not possible to get a homogeneous mass, which can exhibit the desired levels of strength. The compaction effort is needed to remove air from the soil (to increase degree of saturation) and to make soil particles slip over each other and move into a densely packed state. At this state, the soil particles can be well welded by chemical (cementation) bond (in which the bond strength is controlled by molding water content and cement content) and become an engineering material. The same is not the case when high water content clays are mixed with cement. The cementing agents can be premised to drift to the spacing between clusters to clusters due to the electro-chemical nature of interaction and weld the fabric by gel as subsequent hydration of cement takes place (Miura et al., 2001). As such, 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 (Terashi et al., 1979, 1980; Kawasaki et al., 1981; Clough et al., 1981; Tatsuoka and Kobayashi, 1983; Kamon and Bergado, 1992; Uddin, 1994; Nagaraj et al., 1997; Yin and Lai, 1998; Consoli et al., 2000; Kasama et al., 2000; Kitazume et al., 2000; Horpibulsuk et al., 2003, 2004a and others). These studies considered cement content, either as the ratio of cement to soil by weight or in kgs of cement per cubic meter of soil along with its water content. Horpibulsuk et al. (2005) and Miura et al. (2001) have demonstrated that it would be advantageous to have a parameter to reflect the combined effects of clay, cement and water in the analysis of strength and deformation of cement admixed clays. Clay-water/cement ratio which is the ratio of clay water content to cement content (both reckoned in percentage) has been found to meet the above need. Miura et al. (2001) and Horpibulsuk and Miura (2001) 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 laboratory strength development of cement admixed clay. 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 in this paper.

In addition to laboratory study, field observations are also necessary to investigate the field strength development. This leads to the understanding of the difference between field and laboratory strengths and consequently, the estimate of the optimal input of cement to achieve the target field strength. The strength difference between laboratory and field stabilization has been investigated by Horpibulsuk et al. (2004b). They have concluded that one of the main factors controlling the field strength development is non-uniformity in mixing soil with cement. For a specific volume of soil stabilized by cement, the strength of the whole stabilized material is not uniform due to the variation in amount of cement during mixing. For most data, it is found that the field strength is lower than the laboratory strength.

In practice, many laboratory trial mixes are needed to arrive at a proper strength before the execution of soil-cement pavement. This laboratory strength must be high enough to compensate for conditions which are uncontrollable in the field. At the service time, the field strength must meet the designed strength. To facilitate the determination of proper quantity of cement to be stabilized, which compensates for strength reduction in the field, the engineer needs a simple and rotational model to predict laboratory and field strength with time for various compaction energies and combinations of water content and cement content by minimum laboratory trials. The present paper attempts to propose such a phenomenological model. The model is well adapted for the pavement recycling technique. A stepwise procedure for repairing damaged roads is moreover introduced consisting of determination of cement content, execution of field stabilization and examination of field strength.

## LABORATORY AND FIELD INVESTIGATION

This investigation consists of laboratory and field studies to formulate a phenomenological model for assessing laboratory and field strength and to suggest a stepwise procedure for the pavement recycling technique.

### *Laboratory Investigation*

The laboratory study covers two different soils; namely, lateritic soil and crushed rock which are of typical coarse-grained materials often used in earth work in tropical countries. The lateritic soil was sampled by an excavator from a borrow pit in Nakhon-Ratchasima Province, Thailand at a depth of about 4 to 5 meters where the ground water table was deeper. The lateritic soil is composed of 28.5 percent fine-grained particles and 71.5 percent coarse-grained particles in which 32.7 percent is gravel and 38.8 percent is sand. It is non-plasticity with liquid limit of 22.5%. The crushed rock was taken from a quarry in Phetchabun Province, Thailand. It is composed of 91% coarse-grained particles with remaining part being fine grained. The lateritic soil and crushed rock are classified as silty sand (SM) and well

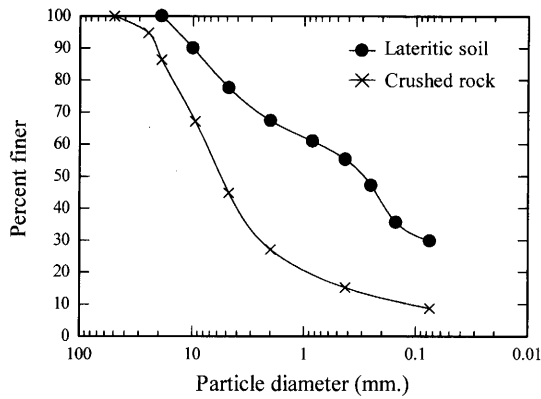


Fig. 2. Grain size distribution curves of the soil samples

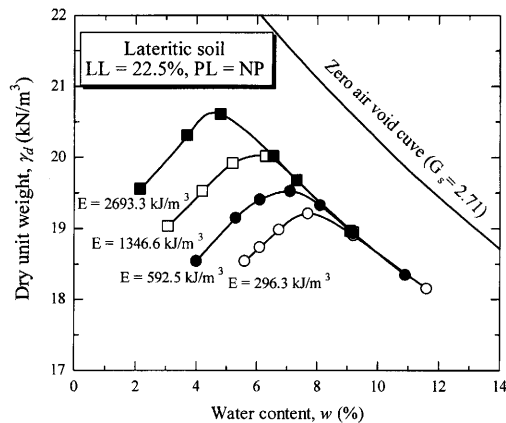


Fig. 3. Compaction curves of lateritic soil

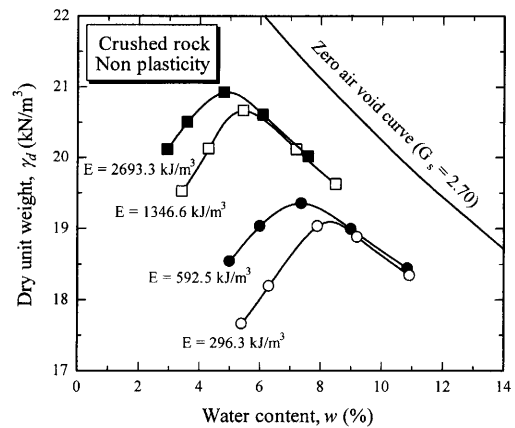


Fig. 4. Compaction curves of crushed rock

bags and stored in a humidity chamber of constant temperature ( $25 \pm 2^\circ\text{C}$ ). Unconfined compression test was run on samples after 7, 14, 28, 60 and 120 days of curing. The rate of vertical displacement was fixed at 1 mm/min. For each curing time and each combination of water content and cement content, at least three samples were tested under the same condition to check for consistency of the test. In most cases, the results under the same testing condition were reproducible. All test results were analyzed to generate a phenomenological model for assessing laboratory strength.

In addition, test results for three other stabilized soils (lateritic soil and two mixed soils) were obtained to verify the model. The results of lateritic soil were from Ruenkrairergsa and Charatkorn (2001). The liquid and plastic limits are 36% and 16%, respectively. The results of the two mixed soils were from the authors' own work. The mixed soils are the combination of Phetchabun lateritic soil and the crushed rock in the ratio of 80:20 and 60:40. The Phetchabun lateritic soil consists of about 80% coarse-grained materials. The liquid and plastic limits are 38.9% and 20.4%, respectively. Based on the USCS, the Phetchabun lateritic soil is classified as clayey gravel (GC). The basic properties of the mixed soils are presented in Table 1.

#### Field Investigation

The field study investigates the strength reduction due to several field factors such as non-uniformity in mixing soil with cement, and difference in compaction method and curing condition between laboratory and field stabilization. The pavement recycling was performed in Phetchabun (3 sites) and Utaradid (1 site) provinces, Thailand. The input of cement for each site was obtained from trial modified proctor tests at the optimum water content to attain a 7-day strength of 2750 kPa for Phetchabun 1, Phetchabun 3 and Utaradid, and of 3500 kPa for Phetchabun 2 as shown in Table 2. About 20-cm thickness of the damaged pavement was dug up and mixed with cement and water. At each station 150 meters apart, soil-cement mixture was collected, thoroughly mixed by hand and passed through a 19-mm sieve to

graded silty gravel (GW-GM) respectively, according to the Unified Soil Classification System (USCS). The grain size distribution curves of both soils are shown in Fig. 2.

Both soils were passed through a 19-mm sieve to remove coarser particles. The soils were air-dried for at least three days and then the water content was adjusted for compaction test. At least five compaction points for each soil were generated. For each point, the air-dried soil was thoroughly mixed with water by hand and kept in a plastic bag for 24 hours to achieve uniform water distribution. The compaction was carried out according to ASTM D 698 in a standard 100-mm diameter mold under four compaction energy levels (296.3, 592.5, 1346.6 and 2693.3 kJ/m<sup>3</sup>) which are equal to the energy of half standard, standard, half modified and modified Proctor, respectively. The compaction curves of both soils at different levels of compaction energy are shown in Figs. 3 and 4.

Having obtained the compaction curves, the water content of the soils was adjusted to 0.6, 0.8, 1.0, 1.2 and 1.4 times the optimum water content. The soils with their water content were thoroughly mixed with Type I Portland cement at cement content from 1 to 7%. The soil-cement mixture was compacted under the four energy levels in a standard 100-mm diameter mold. After 24 hours, the samples were dismantled, wrapped in vinyl

**Table 1. Basic properties of the mixed soils**

Materials	USCS	OWC (%)	$\gamma_{dmax}$ (kN/m <sup>3</sup> )	LL (%)	PL (%)
Phetchabun lateritic: Crushed rock = 80:20	GC	8.0	21.92	29.4	12.1
Phetchabun lateritic: Crushed rock = 60:40	SC	7.8	22.02	28.1	10.4

manually compact in the laboratory. These samples are herein referred to as field hand-compacted samples. The water content ( $w_m$ ) and the dry unit weight ( $\gamma_{dfr}$ ) of the field hand-compacted samples were controlled to be within 2% of the optimum water content (OWC) and higher than 95% maximum dry unit weight ( $\gamma_{dmax}$ ), respectively as shown in Fig. 5. The OWC and  $\gamma_{dmax}$  are 6.4% and 23.05 kN/m<sup>3</sup> for Phetchabun 1, 6.3% and 22.63 kN/m<sup>3</sup> for Phetchabun 2, 5.7% and 22.61 kN/m<sup>3</sup> for Phetchabun 3, and 5.9% and 22.54 kN/m<sup>3</sup> for Utaradid. Immediately after mixing, the soil-cement mixture was compacted by a vibratory roller, going back and forth for 3 passes and followed by a pneumatic roller for 5 passes and a smooth wheel roller for 3 passes. The vibratory roller supplies frequency of 1500 cycles per minute. The pneumatic roller consists of 6 rubber tires with contact pressure under the tires of about 600 kN/m<sup>2</sup>. The smooth wheel roller employs two smooth metal rollers with ground contact pressure of about 350 kN/m<sup>2</sup>. The vibratory and pneumatic rollers are effective in compacting granular material containing a small amount of fines whereas the smooth wheel roller is used to provide a smooth finished grade. This field compaction results in the ratio of dry unit weight ( $\gamma_{dfr}/\gamma_{dfrh}$ ) at each station higher than 95%. The  $\gamma_{dfr}$  is the dry unit weight of field-mixed and roller-compacted samples, which is obtained from sand cone test within 1 hour after field compaction. The  $\gamma_{dfrh}$  is the dry unit weight of field hand-compacted sample at each station (presented in Fig. 5). This ratio at various stations from the four sites is presented in Fig. 6. It is seen that this ratio ranges from 95 to 105% for most samples showing the effectiveness of the field compaction.

For each station, the field-mixed and roller-compacted samples were taken by a coring cutter from the improved pavement after 7, 14 and 28 days of curing to conduct the unconfined compression test. These samples were trimmed to a ratio of diameter to height of 1.0 which is the same as those prepared in the laboratory. They are herein referred to as field roller-compacted samples. Since the samples are hard and carefully cored and trimmed, the effect of sample disturbance on the strength can be neglected. The field roller-compacted strength would be compared with laboratory and field hand-compacted strengths to investigate the factors controlling strength reduction.

## LABORATORY TEST RESULT

Typical compaction curve and unconfined compressive strength of cement stabilized lateritic soil and crushed

rock are shown in Figs. 7 and 8. It is seen that for a particular soil stabilized with cement between 1% and 7%, the compaction curve is the same for all cement contents and exhibit higher dry unit weight than that of compacted unstabilized soil. The compaction curve is symmetrical around the OWC for the range of the water content tested whereas the strength curve is symmetrical for the water content ranging from 0.8 to 1.2 times the OWC. This is because the water content lower than 0.6 OWC is not enough for hydration. At 0.6 OWC, the strength of cement stabilized soil is almost the same for all cement contents and for compacted soil without cement. This leads to the conclusion that for practical purpose, the relationship between strength and water content is symmetrical around the OWC in the range of 0.8 and 1.2 times the OWC. Moreover, it is noted that the water content corresponding to the maximum strength and maximum dry unit weight is the optimum water content.

Effect of curing time on the unconfined compressive strength at water content between 80% and 140% the OWC is presented in Fig. 9, which shows the results of 7% cement samples compacted under compaction energy of 592.5 kJ/m<sup>3</sup>. 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. This would be valid only for the laboratory soil-cement mixture cured in the humidity chamber in which the loss of water during laboratory curing is insignificant.

Figure 10 depicts the influence of compaction energy on the strength. On the dry side of optimum ( $0.6 \text{ OWC} < w < \text{OWC}$ ), at a given water content and cement content, the strength increases with the compaction energy. At the optimum and on the wet side of optimum, the data points practically lie in the same line. This implies that for a specific cement content, the strength of stabilized samples when mixed at OWC and on the wet side of optimum is dependent upon only water content. The role of compaction energy is only to reduce the optimum water content.

## MATERIAL CHARACTERISTICS OF COMPACTED SOIL AND CEMENT STABILIZED COARSE GRAINED SOIL

For compacted coarse-grained soils, friction at contact point and matric suction control the strength and resistance to deformation (Kohgo et al., 1993). As such, when the water content of the compacted soil increases, strength and stiffness decrease (*vide* Fig. 11). This is

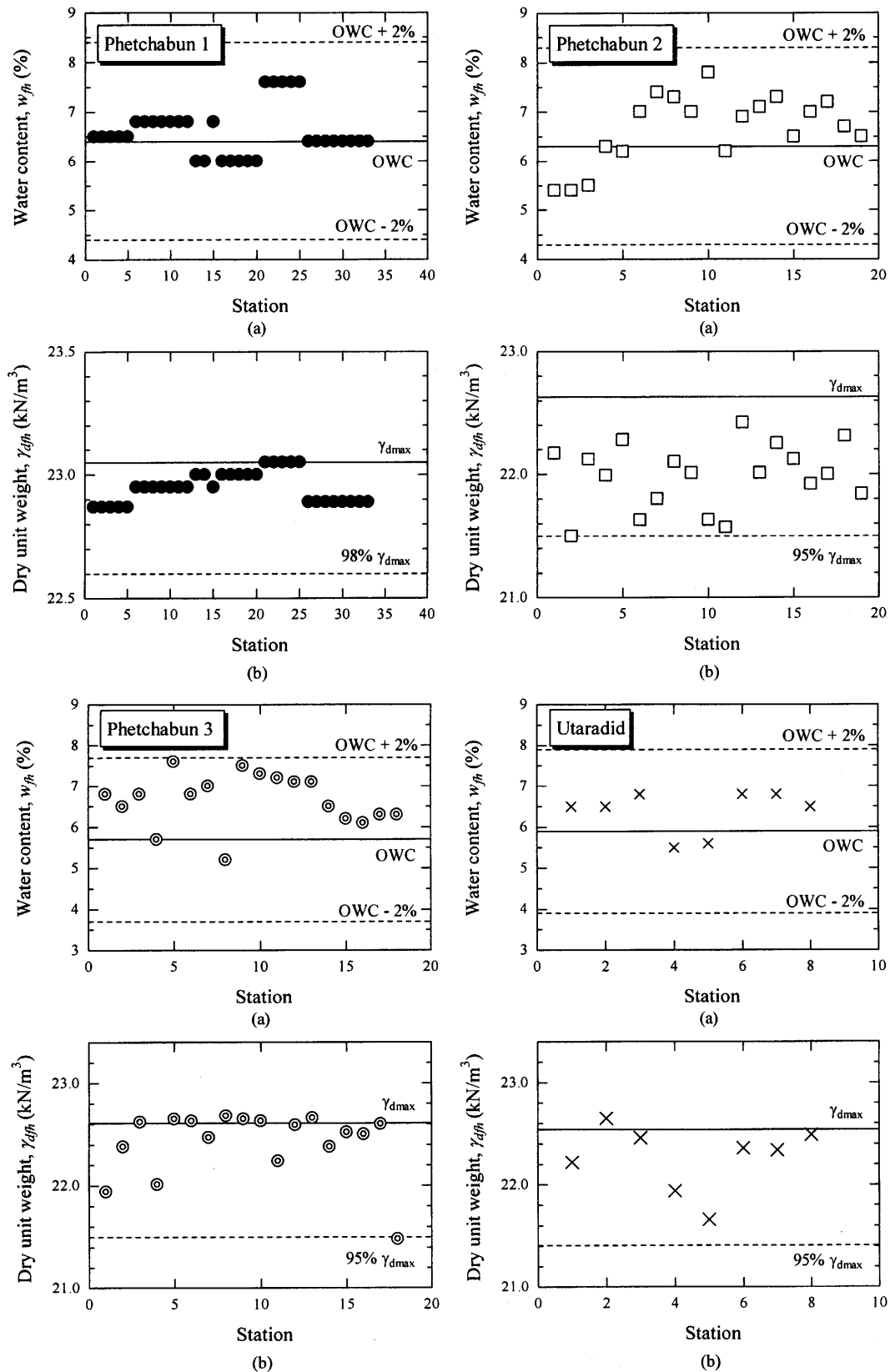


Fig. 5. Dry unit weight and water content of the field-hand compacted samples at various stations

attributed to the reduction in matric suction. This characteristic is different from that of cement stabilized soils in which the maximum strength is at the optimum water content.

Effect of water content on the strength development in cement stabilized soil is illustrated by scanning electron photographs. Figures 12(a) and 12(b) show the photographs of compacted lateritic soil and 5% cement

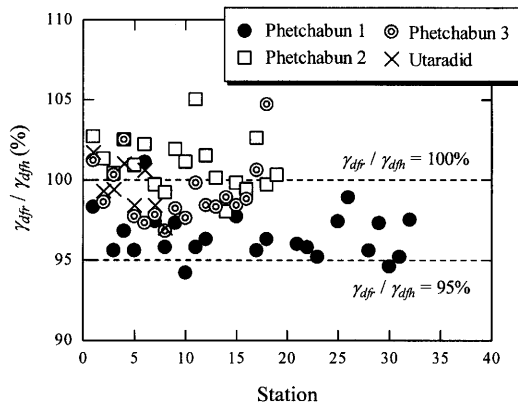


Fig. 6. Ratio of dry unit weight at various stations

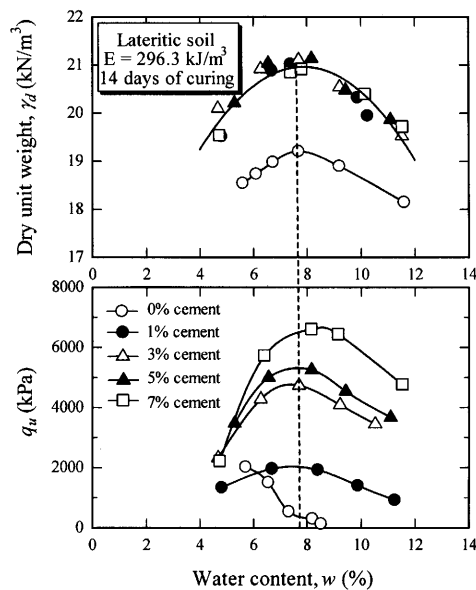


Fig. 7. Relationship between water content, dry unit weight and strength of lateritic soil at 14 days of curing under compaction energy of 296.6 kJ/m<sup>3</sup>

stabilized lateritic soil at the same initial water content of 7.5% (OWC) and under the same compaction energy of 296.3 kJ/m<sup>3</sup>, respectively. Both photographs were magnified 3000 times. Figure 12(b) 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 (4.5% or 0.6 OWC) as shown in Fig. 12(c). Due to the very low water content, the pore space is large and the degree of hydration is very low. As a result, the strength slightly increases even with an increase in the input of cement as shown in Fig. 7. These photographs and laboratory test results show that the strength of cement stabilized soil at a particular compaction energy and cement content depends mainly on state of water content. On the dry side of optimum, the higher the water content, the greater the degree of hydration,

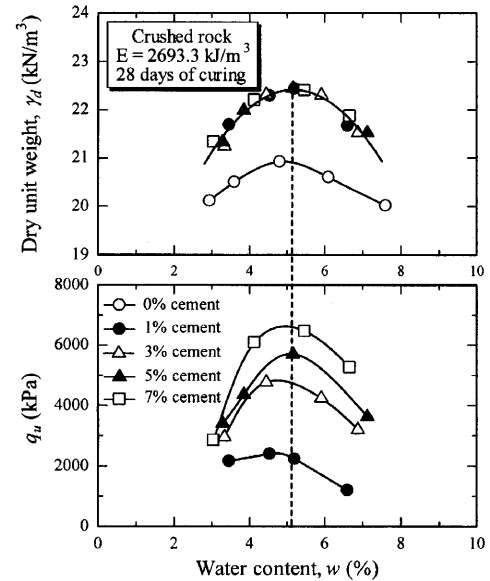


Fig. 8. Relationship between water content, dry unit weight and strength of crushed rock at 28 days of curing under compaction energy of 2693.3 kJ/m<sup>3</sup>

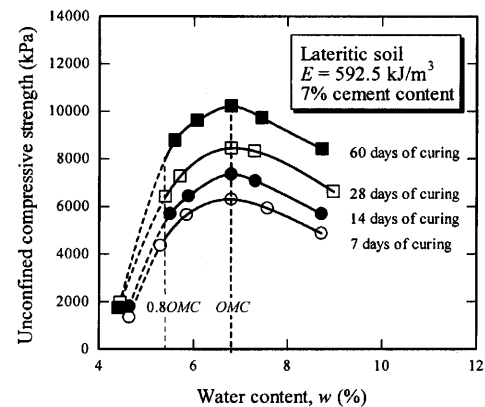


Fig. 9. Relationship between unconfined compressive strength and water content of cement stabilized lateritic soil at different curing time

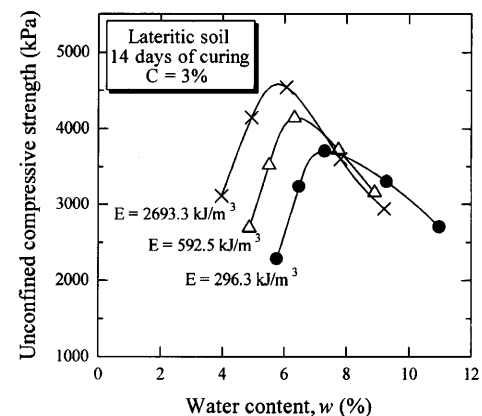


Fig. 10. Effect of compaction energy on the strength development of cement stabilized lateritic soil

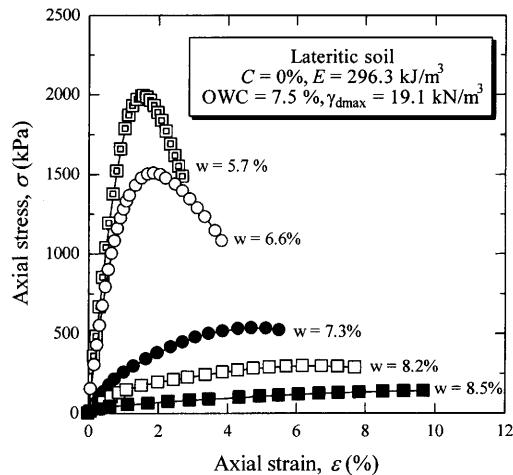


Fig. 11. Unconfined compression test result of compacted lateritic soil under compaction energy of 296.3 kJ/m<sup>3</sup>

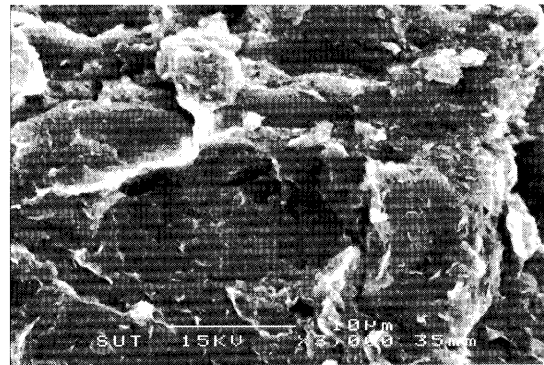
resulting in strength increase. On the wet side of optimum, the higher the water content, the larger the pore space, leading to strength decrease.

Influence of the cement content on the strength development of the cement stabilized soil at a particular water content, compaction energy, and curing time is presented in Fig. 13. The strength increase can be 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 reported Horpibulsuk et al. (2003). In the development of a phenomenological model to assess the strength development, the experimental investigation is limited to the soil-cement interaction zone.

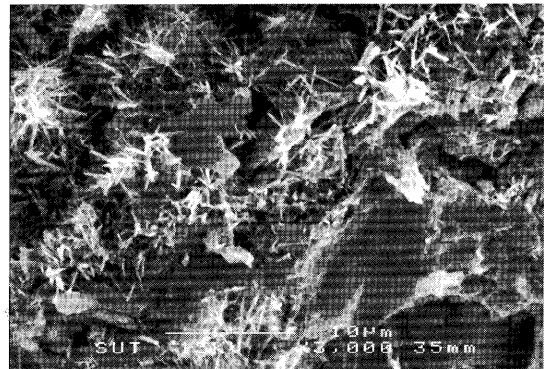
## PHENOMENOLOGICAL MODEL FOR STRENGTH DEVELOPMENT

### Laboratory Strength Development

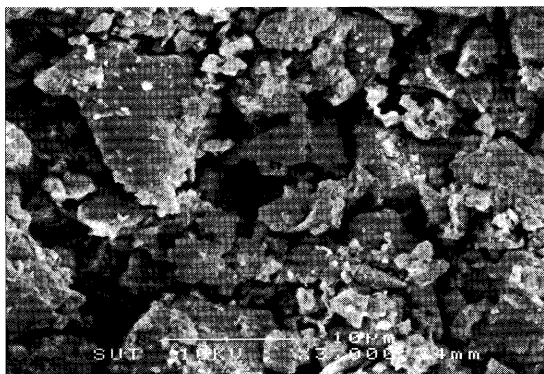
Recent research work on assessment of the cement admixed clay based on Abrams' law reveals that at a particular curing time, strength of cement admixed high water content clay (no compaction) is dependent upon clay-water/cement ratio,  $w_c/C$  (Horpibulsuk et al., 2005; Miura et al., 2001). This is 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



(a) no cement



(b) 5% cement, 7.5% water content



(c) 5% cement, 4.5% water content

Fig. 12. Scanning electron photographs 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<sup>3</sup>

at 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<sup>3</sup>) at three levels of water content (10.2, 8.3, and 7.3 percentage). The samples are mixed with cement at different levels to obtain  $w/C$  values of 0.5, 1.0, 2.0 and 4.0.

Figure 14 shows the unconfined compression test results of cement stabilized crushed rock at two levels of water content (7.3% and 10.2%) under the same compaction energy of 1346.6 kJ/m<sup>3</sup> at 14 days of curing. Figure 15 shows the unconfined compression test results of cement stabilized crushed rock at 14 days of curing

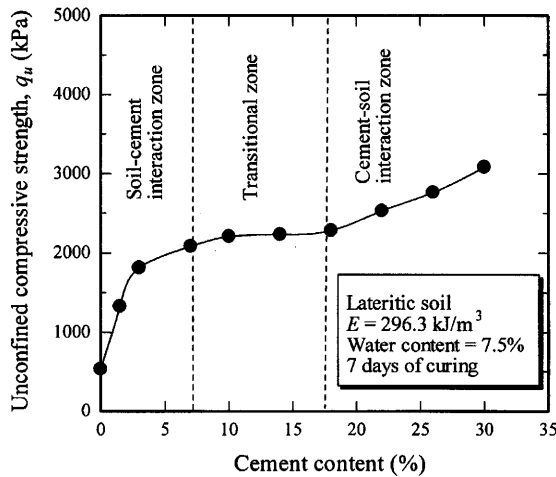


Fig. 13. Improvement zones

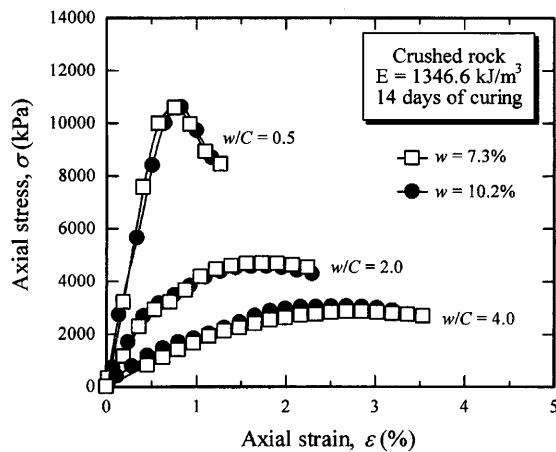
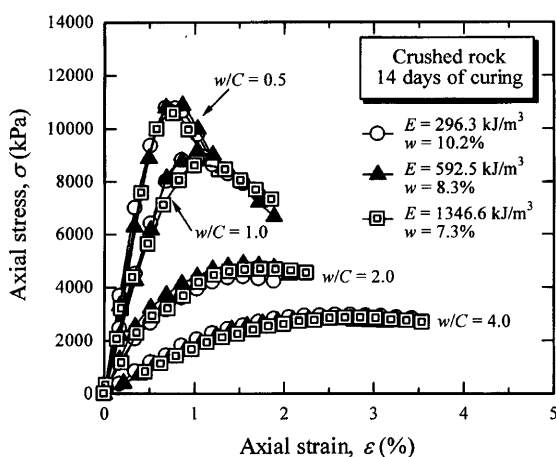
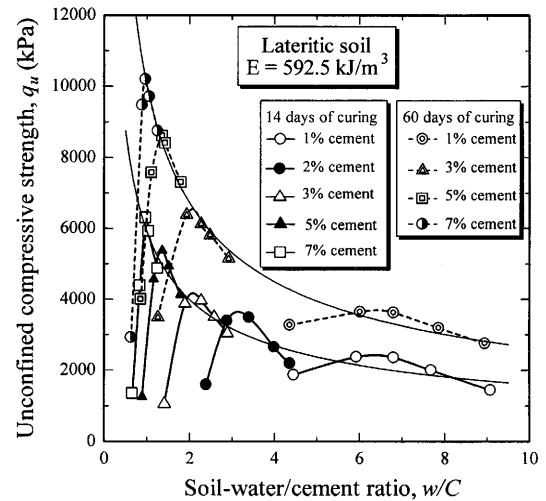
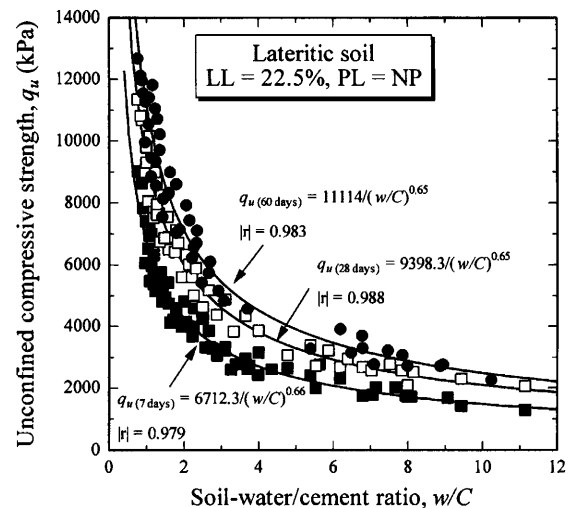
Fig. 14. Unconfined compression test results of cement stabilized crushed rock at three levels of  $w/C$  of 0.5, 2.0, 4.0 and under compaction energy of  $1346.6 \text{ kJ/m}^3$ 

Fig. 15. Compression test results of cement stabilized crushed rock under different levels of compaction energy

under different compaction energy ( $296.3$ ,  $592.5$  and  $1346.6 \text{ kJ/m}^3$ ) and water content ( $10.2\%$ ,  $8.3\%$ , and  $7.3\%$ ). From these two figures, it can be premised that even though the samples are of different levels of water

Fig. 16.  $(q_u, w/C)$  relationship of cement stabilized lateritic soil at 14 and 60 days of curing timeFig. 17.  $(q_u, w/C)$  relationship of cement stabilized lateritic soil at OWC and on the wet side of optimum

content and cement content, 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.

The strength of the cement stabilized coarse-grained soils at the OWC and on the wet side of optimum is dependent upon only the  $w/C$ . To obtain high strength, the stabilized soil must possess low  $w/C$  value, which can be achieved either by increasing input of cement or decreasing water content. However, at a given compaction energy, the minimum water content corresponding to maximum strength is the optimum water content. In order to reduce the water content, compaction energy must be increased. The compaction energy is not a direct contributing factor but its role is only to reduce the optimum water content, resulting in low  $w/C$  value.

Figure 16 shows unconfined compressive strength against  $w/C$  of the cement stabilized lateritic soil under compaction energy of  $592.5 \text{ kJ/m}^3$  at 14 and 60 days of curing. It can be seen that for a particular curing time at



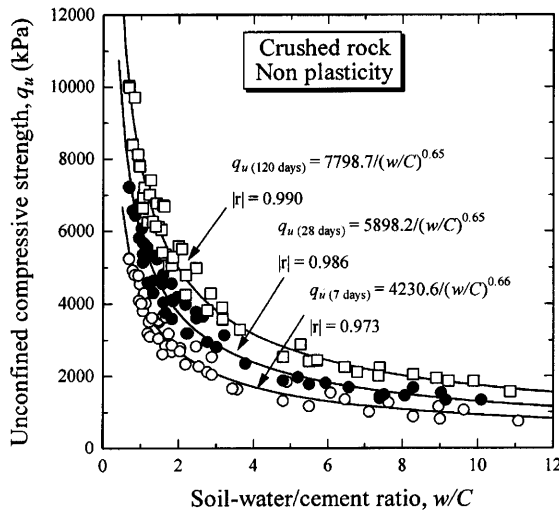


Fig. 18. ( $q_u$ ,  $w/C$ ) relationship of cement stabilized crushed rock at OWC and on the wet side of optimum

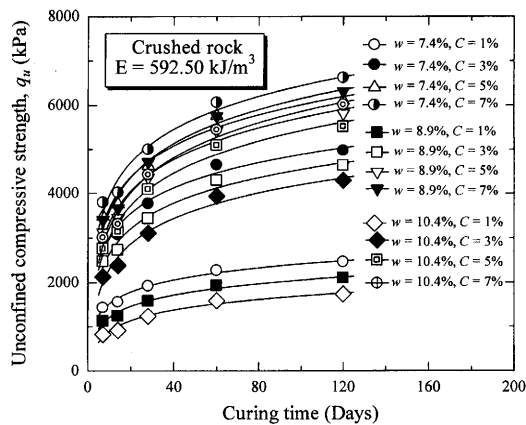


Fig. 19. Strength development with time of cement stabilized crushed rock at OWC and on the wet of optimum

the OWC and on 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<sup>3</sup>) is further analyzed based on the  $w/C$  as shown in Figs. 17 and 18 for cement stabilized lateritic soil and crushed rock, respectively. 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, the parameter  $A$  varies widely depending upon soil type and curing time. However, the parameter  $B$  only varies between 0.65 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.

The parameter  $A$  can be eliminated by taking the ratio of strength developed at two soil-water/cement ratios. This is based on the fact that the parameter  $A$  for the same soil and the same curing time does not vary as the  $w/C$  varies. Taking the parameter  $B$  as 0.65 results in the

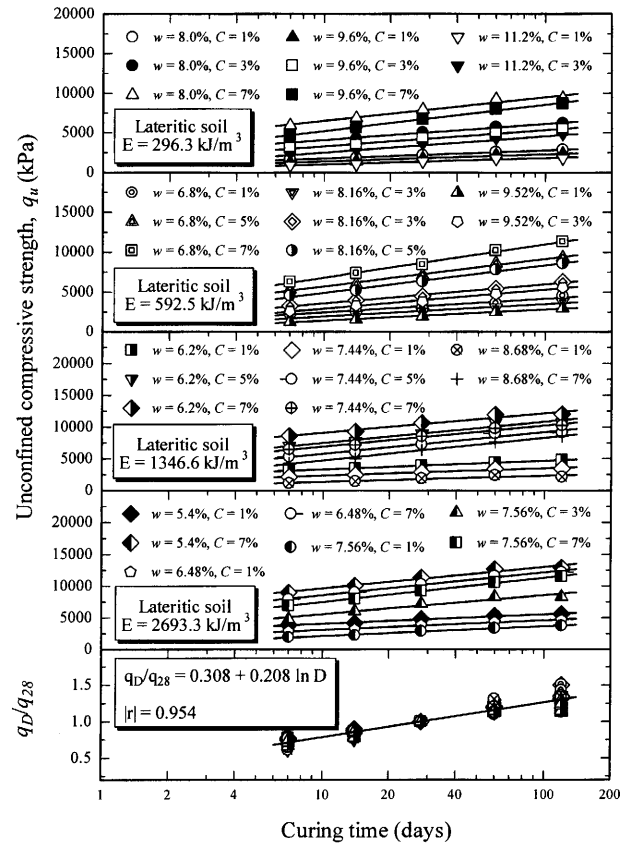


Fig. 20. Strength development in cement stabilized lateritic soil and its generalization

following relation:

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

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  $(w/C)_2$ . From the above equation, it would be possible to assess the strength at any other soil-water/cement ratio of the stabilized soil compacted at the OWC and on the wet side of optimum.

Figure 19 shows the typical relationship between unconfined compressive strength and curing time at different levels of water content (OWC and on the wet side of optimum) and cement content of the cement stabilized soil. It is found that the strength increases logarithmically with time.

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, 1996) 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

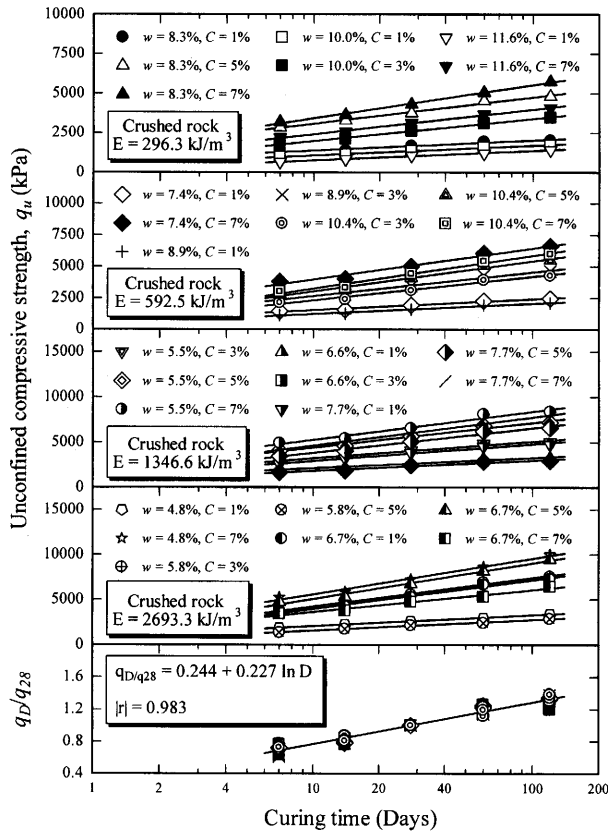


Fig. 21. Strength development in cement stabilized crushed rock and its generalization

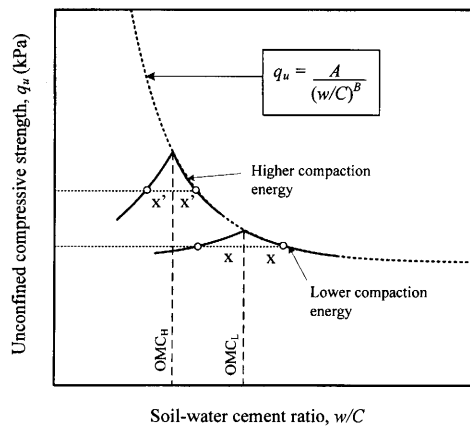


Fig. 22. Schematic diagram for assessment of strength of cement stabilized soils

strength variation with time can be expressed as linear variation. Figures 20 and 21 depict such linear plots for cement stabilized lateritic soil and crushed rock, respectively. The strength ratio plots after normalization are also shown in these figures. 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

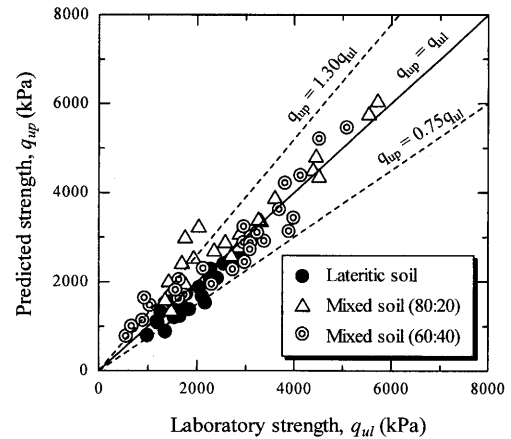


Fig. 23. Comparison between predicted and laboratory strengths

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:

$$\frac{q_D}{q_{28}} = 0.270 + 0.219 \ln D \quad (4)$$

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. It is valid for the range of curing time between 7 and 120 days in which the usual service time of recycled pavement is within 30 days.

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 12 is obtained by combining Eqs. (2) and (4).

$$\left\{ \frac{q_{(w/C)_D}}{q_{(w/C)_{28}}} \right\} = \left[ \frac{(w/C)_{28}}{(w/C)_D} \right]^{0.65} (0.270 + 0.219 \ln D) \quad (5)$$

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

The remaining portion now to assess is 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 Fig. 22. The implication of the model is that one laboratory test value of strength developed over a specific

**Table 2.** 7-day trial mix for determination of input of cement for the tested sites

Tested site	OWC (%)	C (%)	$q_{ul}$ (kPa)	Fitting curve	Designed C (%)
Phetchabun 1	6.4	1	1700	$q_u = 835.57C + 796.33$ $R^2 = 0.994$	2.3
	6.4	2	2355		
	6.4	3	3300		
	6.4	4	4100		
	6.4	5	5170		
	6.4	6	5700		
Phetchabun 2	6.3	1	1650	$q_u = 884.86C + 809.33$ $R^2 = 0.987$	3.0
	6.3	2	2400		
	6.3	3	3700		
	6.3	4	4375		
	6.3	5	5410		
	6.3	6	5903		
Phetchabun 3	5.7	1	1742	$q_u = 612.46C + 1260.40$ $R^2 = 0.991$	2.4
	5.7	2	2538		
	5.7	3	3145		
	5.7	4	3846		
	5.7	5	4353		
	5.7	6	4800		
Utaradid	5.9	1	1730	$q_u = 754.57C + 1044.00$ $R^2 = 0.989$	2.3
	5.9	2	2480		
	5.9	3	3500		
	5.9	4	4000		
	5.9	5	5000		
	5.9	6	5400		

**Table 3.** Strength prediction of cement stabilized lateritic soil (Ruenkrairergsa and Charatkorn, 2001)

Compaction energy $E$ (kJ/m <sup>3</sup> )	Optimum water content OWC (%)	Curing time $D$ (days)	Cement content $C$ (%)	Water content $w$ (%)	Soil-water/cement ratio $w/C$	Laboratory strength $q_{ul}$ (kPa)	Predicted strength $q_{up}$ (kPa)
296.3	13.5	3	3	13.5	4.5	986	791
296.3	13.5	3	5	13.5	2.7	1185	1102
296.3	13.5	3	7	13.5	1.9	1843	1372
296.3	13.5	7	3	13.5	4.5	1200	1079
296.3	13.5	7	5	13.5	2.7	1562	1504
296.3	13.5	7	7	13.5	1.9	2048	1871
296.3	13.5	14	3	13.5	4.5	1265	1314
296.3	13.5	14	5	13.5	2.7	1718	1832
296.3	13.5	14	7	13.5	1.9	2279	2280
296.3	13.5	28	3	13.5	4.5	1479	1550
296.3	13.5	28	5	13.5	2.7	2248	2160
296.3	13.5	28	7	13.5	1.9	2868	2688
592.5	11.5	3	3	11.5	3.8	1354	878
592.5	11.5	3	5	11.5	2.3	1651	1223
592.5	11.5	3	7	11.5	1.6	2169	1522
592.5	11.5	7	3	11.5	3.8	1536	1197
592.5	11.5	7	5	11.5	2.3	2107	1669
592.5	11.5	7	7	11.5	1.6	2415	2077
592.5	11.5	14	3	11.5	3.8	1682	1459
592.5	11.5	14	5	11.5	2.3	2281	2033
592.5	11.5	14	7	11.5	1.6	2807	2530
592.5	11.5	28	3	11.5	3.8	1786	1720
592.5	11.5	28	5	11.5	2.3	2551	2397
592.5	11.5	28	7	11.5	1.6	3039	Reference

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.

(2004c).

Using this strength model, the strength of cement stabilized soils can be predicted as shown in Tables 3 to 5 and Fig. 23. Table 3 shows the comparison of predicted and laboratory strength of cement stabilized lateritic soil at the OWC. The laboratory strength was obtained from

**Table 4. Strength prediction of cement stabilized mixed soil (Phetchabun lateritic soil: crushed rock = 80:20)**

Energy (kJ/m <sup>3</sup> )	OWC (%)	Water content w (%)	Curing time D (days)	Cement content C (%)	w/C	Laboratory strength q <sub>ul</sub> (kPa)	Predicted strength q <sub>up</sub> (kPa)
2693.3	8.0	8.4	7	3	2.80	1761	1921
2693.3	8.0	7.6	7	5	1.68	2350	2678
2693.3	8.0	9.3	7	5	1.86	1930	2507
2693.3	8.0	7.5	7	7	1.20	3312	3333
2693.3	8.0	10.6	7	7	1.51	2578	2865
2693.3	8.0	8.1	14	3	2.70	1688	2397
2693.3	8.0	10.8	14	3	3.60	1419	1988
2693.3	8.0	8.6	14	5	1.72	2034	3213
2693.3	8.0	9.7	14	5	1.94	1755	2972
2693.3	8.0	7.0	14	7	1.30	3600	3855
2693.3	8.0	9.1	14	7	1.30	3599	3855
2693.3	8.0	11.2	14	7	1.60	3261	3368
2693.3	8.0	8.6	28	1	8.60	1470	1331
2693.3	8.0	7.5	28	3	2.80	2860	2761
2693.3	8.0	9.4	28	3	3.13	2703	2566
2693.3	8.0	8.6	28	5	1.72	3822.7	Reference
2693.3	8.0	7.5	28	7	1.20	4450	4788
2693.3	8.0	9.3	28	7	1.33	4390	4482
2693.3	8.0	9.7	100	1	9.70	1346	1575
2693.3	8.0	10.5	100	3	3.50	2878	3054
2693.3	8.0	10.2	100	5	2.04	4513	4338
2693.3	8.0	7.4	100	7	1.23	5720	6027
2693.3	8.0	9.3	100	7	1.33	5541	5733

**Table 5. Strength prediction of cement stabilized mixed soil (Phetchabun lateritic soil: crushed rock = 60:40)**

Energy (kJ/m <sup>3</sup> )	OWC (%)	Water content w (%)	Curing time D (days)	Cement content C (%)	w/C	Laboratory strength q <sub>ul</sub> (kPa)	Predicted strength q <sub>up</sub> (kPa)
2693.3	7.2	8.9	7	1	8.90	558	776
2693.3	7.2	6.4	7	3	2.66	1740	1701
2693.3	7.2	8.6	7	3	2.87	1622	1620
2693.3	7.2	10.0	7	3	3.33	1040	1469
2693.3	7.2	8.4	7	5	1.68	2128	2293
2693.3	7.2	10.0	7	5	2.00	1632	2047
2693.3	7.2	6.6	7	7	1.11	3110	3001
2693.3	7.2	8.3	7	7	1.19	2961	2875
2693.3	7.2	8.2	14	1	8.20	668	997
2693.3	7.2	8.8	14	3	2.93	2301	1944
2693.3	7.2	9.8	14	3	3.27	1563	1813
2693.3	7.2	6.3	14	5	1.62	3100	2860
2693.3	7.2	7.9	14	5	1.58	3381	2907
2693.3	7.2	7.9	14	7	1.13	3692	3618
2693.3	7.2	9.4	14	7	1.34	2962	3231
2693.3	7.2	8.7	28	1	8.70	891	1131
2693.3	7.2	6.4	28	3	2.67	2980	2437
2693.3	7.2	8.9	28	3	2.97	2734	2276
2693.3	7.2	6.5	28	5	1.58	3990	3428
2693.3	7.2	9.1	28	5	1.82	3894	3127
2693.3	7.2	7.5	28	7	1.07	4343.4	Reference
2693.3	7.2	7.2	100	1	7.20	929	1636
2693.3	7.2	6.3	100	3	2.70	3240	3095
2693.3	7.2	9.9	100	3	3.30	3090	2717
2693.3	7.2	6.5	100	5	1.58	4133	4385
2693.3	7.2	8.4	100	5	1.68	3812	4213
2693.3	7.2	6.4	100	7	1.13	5089	5452
2693.3	7.2	8.5	100	7	1.21	4519	5203

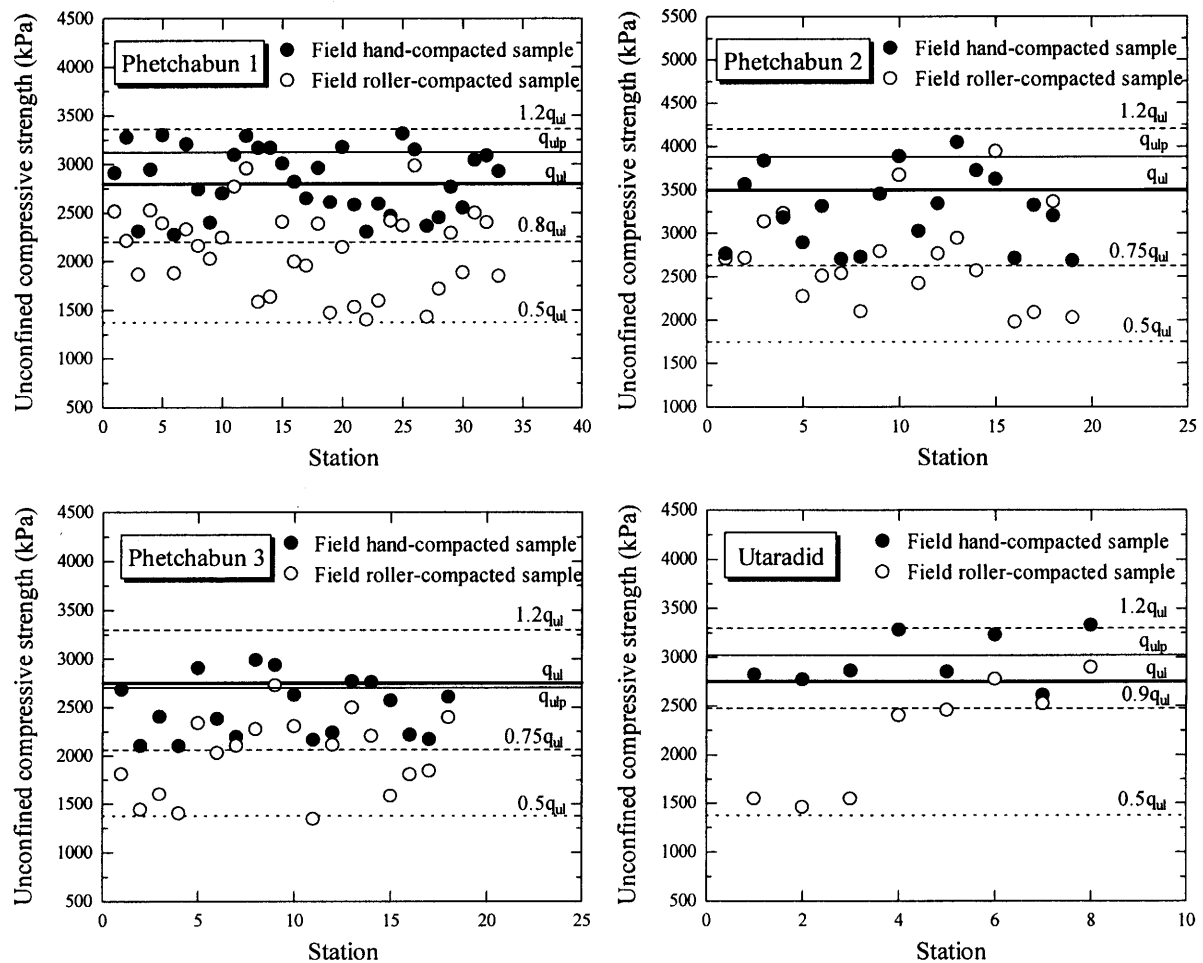


Fig. 24. Field roller-compacted and field hand-compacted strengths at 7 days of curing

Ruenkairergsa and Charatkorn (2001). Tables 4 and 5 show the predicted and laboratory strength of cement stabilized mixed soils (Phetchabun lateritic soil: crushed rock = 80:20 and 60:40). Since many variations affect the field strength development in cement stabilized soils, the accuracy of the predictions can be regarded as adequate ( $0.75 < q_{up}/q_{ul} < 1.30$  for most data as shown in Fig. 23) as a first step to arrive at cement content and compaction energy.

#### Field Strength Development

Figure 24 shows the field hand-compacted strength ( $q_{ufh}$ ) and field roller-compacted strength ( $q_{ufr}$ ) compared with the laboratory strength ( $q_{ul}$ ) for the four sites. Both field hand-compacted and laboratory samples were compacted under the same energy and cement content with practically the same water content and dry unit weight (*vide* Fig. 5). It is however revealed that the field hand-compacted strength ( $q_{ufh}$ ) is between 0.75 and 1.2 times laboratory strength ( $q_{ul}$ ). The variation in strength ( $q_{ufh}/q_{ul}$ ) is probably attributed to the non-uniformity in mixing soil with cement which is almost equal to the ratio of predicted and laboratory strengths (as shown in Fig. 23). Figure 24 also shows the predicted and laboratory strengths at the four tested sites. The strength predic-

tion is done using the 5% cement strength as a reference value (data shown in Table 2). It is found that the predicted laboratory strengths ( $q_{up}$ ) are slightly different from the laboratory strengths and within the boundary of the field hand-compacted strengths. This shows that the error from the strength prediction is acceptable, reinforcing the applicability of the proposed model.

Although effectiveness of the compaction is generally high enough ( $\gamma_{dfr}/\gamma_{dfh} > 95\%$ ), test result (Fig. 24) shows large difference between field roller-compacted and field hand-compacted strengths. For most data points, the field roller-compacted strength ranges from 0.55 to 1.0 times field hand-compacted strength as shown in Fig. 25. The field hand-compacted samples are mixed by the machine at the location where the field roller-compacted samples are cored. Thus both samples have the same water content and cement content, and practically the same dry unit weight ( $95\% < \gamma_{dfr}/\gamma_{dfh} < 105\%$ ) but different compaction method and curing condition. The different compaction method causes the difference in soil structure as explained by Day and Daniel (1985) and Prapaharan et al. (1991). The field curing causes more loss of water than laboratory curing due to higher field temperature. The loss of water during field curing might result in incomplete hydration and minor cracks in the

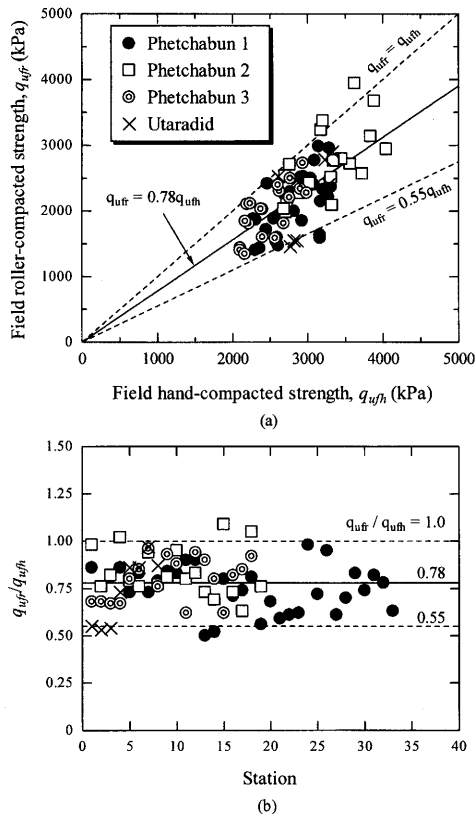


Fig. 25. Relationship between field roller-compacted, field hand-compacted and laboratory strengths

field roller-compacted samples. These two factors result in the field-roller compacted strength being lower than the field-hand compacted strength. To conclude, the field strength reduction is caused by the non-uniformity in mixing soil with cement, and the difference in compaction method and curing condition between the laboratory and the field. Due to these factors, the ratio  $q_{ufr}/q_{ul}$  ranges from 50–100% as also shown in Fig. 24. Since the study is at the optimum water content, this finding might not be valid for other conditions of water content.

Based on the assumption that the field hand-compacted and field roller-compacted strength development with time is the same as laboratory strength development, the field hand-compacted and field roller-compacted strength development can be assessed by Eq. (5) as shown in Fig. 26. In this assessment, the 7-day strength is taken as a reference value. Also from the above finding ( $q_{ufr} = 50\text{--}100\% q_{ul}$ ), the boundary of the field roller-compacted strength is between the dashed lines, which are approximated from laboratory strength.

### SUGGESTED PROCEDURE FOR PAVEMENT RECYCLING TECHNIQUE

Based on the laboratory and field study, the suggested procedure of repairing damaged roads by the pavement recycling technique is summarized in Fig. 27 and presented as follows.

Determination of input of cement compensating for field

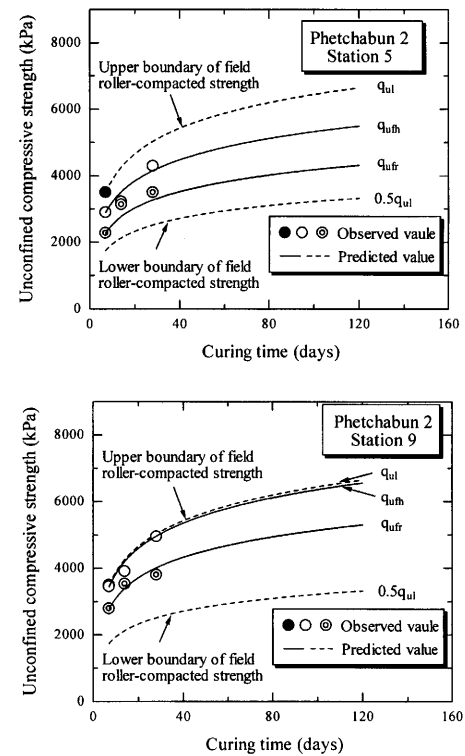


Fig. 26. Prediction of strength development in field hand-compacted and field roller-compacted samples

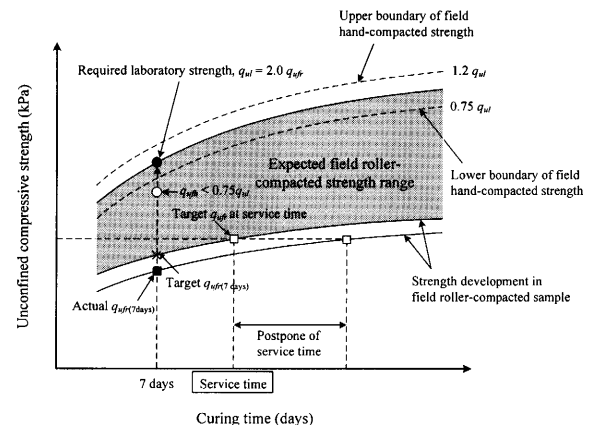


Fig. 27. Suggested procedure for pavement recycling technique

factors

1. From the target field strength at service time (open square symbol), estimate the target field strength at 7 days of curing (Target  $q_{ufr}(7\text{days})$ ) (cross symbol) which can be approximated using Eq. (4).
2. Determine the laboratory strength at 7 days of curing ( $q_{ul}(7\text{days})$ ), using the field strength reduction of 2.0 ( $q_{ufr}/q_{ul} = 0.5$ ) (black circle symbol).
3. Determine the cement content to attain the laboratory strength at 7 days of curing ( $q_{ul}(7\text{days})$ ) and service time at optimum water content and designed compaction energy. This task can simply be done by using Eq. (5).

Field execution and examination of field strength

4. Take field soil-cement mixture to conduct the laboratory compaction test (field hand-compacted sample). The water content and dry unit weight of the field hand-compacted samples must be within 2% of OWC and higher than 95%  $\gamma_{dmax}$ , respectively.
5. Compact the field soil-cement mixture by rollers to achieve the ratio of dry unit weight higher than 95%.
6. Determine the field hand-compacted strength ( $q_{ufh(7days)}$ ) of samples obtained from step 4 at 7 days of curing.
7. If the  $q_{ufh(7days)} > 0.75q_{ul(7days)}$ , it is concluded that the  $q_{ufr}$  meets the requirement.
8. If the  $q_{ufh(7days)} < 0.75q_{ul(7days)}$ , take cored sample to determine actual  $q_{ufr(7days)}$ .
  - 8.1 If the actual  $q_{ufr(7days)}$  is higher than the target field strength (target  $q_{ufr(7days)}$ ), the requirement is met.
  - 8.2 If the actual  $q_{ufr(7days)}$  is slightly lower than the target  $q_{ufr(7days)}$  (black square), the service time of the station should be postponed to increase curing time.
  - 8.3 If the actual  $q_{ufr(7days)}$  is much lower than target  $q_{ufr(7days)}$ , this station must be re-improved.

## CONCLUSIONS

This paper deals with the characteristics of strength development in cement stabilized low plasticity and coarse-grained soils. A phenomenological model to predict the laboratory and field strength development based on a single trial test is presented. A practical procedure for repairing the damaged road by the pavement recycling technique is introduced. The following conclusions can be drawn:

1. Relationship between strength and water content of cement stabilized soils is a symmetrical bell shape for water content in the range 80% to 120% OWC. The water content corresponding to maximum strength is the optimum water content of the compacted soils.
2. At OWC and on the wet side of optimum, the soil-water/cement ratio,  $w/C$  is the appropriate parameter in the analysis of strength development of cement stabilized soils for a particular curing time. The lower the  $w/C$ , the greater the strength. The role of compaction energy is only to reduce the optimum water content. The samples having the same  $w/C$  exhibit the same stress-strain relationship and strength, even though they are compacted with different water content, cement content and compaction energy.
3. The field strength is lower than laboratory strength resulted from the non-uniformity in mixing soil with cement, and the difference in compaction method and curing condition between the laboratory and field stabilization. Due to these factors, the field roller-compacted strength is 0.5–1.0 times the laboratory strength for the same cement content, water content and dry unit weight.
4. The proposed phenomenological model can assess

the laboratory and field strength of cement stabilized soils in which the water content, cement content, curing time and compaction energy vary over a wide range. The model is verified using data of the previous researcher and of the authors.

5. The suggested procedure for repairing damaged roads by the pavement recycling technique is useful in terms of engineering and economical viewpoints. The procedure can save on sampling and laboratory testing and hence cost.

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