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FEASIBILITY OF LATERITE-CEMENT MIXTURE AS PAVEMENT BASE COURSE AGGREGATE*

S. JARITNGAM[1**], O. SOMCHAINUEK[2] AND P. TANEERANANON[1]

[1]Dept. of Civil Eng., Faculty of Engineering, Prince of Songkla University, Thailand
Email: jaritngam@gmail.com
[2]Dept. of Highways, Songkhla, Thailand

Abstract– In many developing countries, crushed rock is employed as a base course material for road pavement. Since crushed rock is required in large quantities, its shortages coupled with fuel price hike are having the effect of pushing up highway construction cost. In addition, the production of crushed rock involves drilling, blasting, crushing and road haulage, all of which create dust which is detrimental to the environment. Although lateritic soil is obtainable in many areas, it is too brittle and thus not suitable as road base course material. This paper presents the idea of adding cement to stabilize the lateritic aggregate. It compares the strength characteristics of cement-enhanced lateritic soil against those of crushed rock, and at the same time discusses their microstructure which was investigated using an X-ray diffraction machine (XRD) and a Scanning Electron Microscope (SEM). Mineralogical influences and the mechanism of soil-cement reaction of stabilized soils were also studied. Strength of the materials was measured using the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) methods. The UCS and CBR tests indicated that when cement is added to lateritic soil at only 3% by weight, the resulting laterite-cement mixture exhibited a compressive strength as high as that of crushed rock. This shows that cement-enhanced lateritic soils are a viable substitute for crushed rock for road pavement construction.

Keywords– Lateritic, crushed rock, cement, pavement, materials, environment

1. INTRODUCTION

Commonly paved as a road base course, crushed rock has large particles that do not separate when water is added to it; thus, severe loss of strength does not occur when crushed rock is subject to wetness.

Lateritic soils are found in a variety of red, brown, and yellow, fine grained matrices with nodular gravels and cemented soils, whose cohesiveness may very from being loose materials to dense granules. Their colors are caused by presence of iron and aluminum oxides or hydroxides in the soil matrix.

Ordinary Portland Cement (PC) type I is one of the most suitable materials typically employed for road stabilization [1-4]. PC is used to modify the base course materials in order to improve their performance [5]. In chemical stabilization, conventional binders including cement, lime and bitumen, or alternative binders with pozzolanic properties such as fly ash [6] and natural raw material, e.g. porphyritic volcanic rock [7] can be used to improve the properties of the problematic soil. The addition of cement reduces plasticity and provides cementitious bonds that help to improve the shear strength of the base course.

This case study, conducted in Songkhla province in southern Thailand, was to investigate the increases in compressive strength of the material samples after they have been mixed with PC at a mix proportion of 3%, 5%, 7% and 9% by dry soil weight, and at optimum moisture content (OMC). Modified

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**Corresponding author

compaction specimens were prepared for UCS tests at curing times of 7, 14 and 28 days. XRD and SEM were performed to study the soil-cement specimens for growth of chemical and mineral components in the microstructure, while UCS and CBR were conducted to test the specimens' mixing properties. Some theoretical aspects relating to the strength of the stabilized soils had also been investigated by the authors [8].

There are compelling reasons for switching from crushed rock to cement-stabilized laterite as a material for road pavement. One of these is the reduction in use of crushed rock for environmental reasons: the quarrying of crushed rock creates excessive air-borne dust; as quarries become depleted, rock will have to be obtained from far away sources thus increasing haulage cost; more and more restrictions will be imposed on the extraction of natural resources, including barriers on fuel used and road haulage of the materials; and the crushed rock production process consumes a considerable amount of energy in its mining, transportation and burning, all of which generate CO_2 emissions.

2. SOIL PROPERTIES

The lateritic soil used in this study came from Songkhla province in southern Thailand, while the crushed rock was obtained from Satun. Properties of the specimens including Atterberg limits, water content, shear strength and specific gravity are shown in Table 1.

Table 1. Properties of laterite sample from Songkhla, Thailand

Soil Properties	Lateritic soil	Crushed rock
Liquid limit	50%	20.1%
Plastic limit	34.2%	13.2%
PI	15.8%	6.9%
Water content	26.72%	16.3%
Unit weight (ton/m^3)	2.076	2.170
Specific Gravity	2.69	2.8
AASHTO Classification	A-2-7	A-2-4
Unified Classification	SC	GC

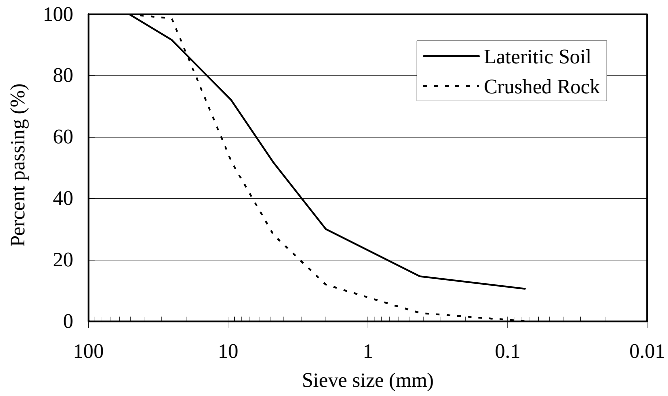


Fig. 1. Grain size distribution in laterite and crushed rock samples

The lateritic soil sample passed sieves No.200 and No.4 at 10.6% and 51.8% respectively. Their basic properties as measured by Atterberg limits tests are: LL=50%; PI=15.8%. The samples can be classified as clayey sand (SC) with gravel content at 49.2%, or clayey sand with gravel. On AASHTO classification the samples are identified as A-2-7 which is Clayey Gravel Sand.

For the crushed rock sample, percent passing sieve No.200 and No.4 are 0.1% and 28.3% respectively. Basic properties from Atterberg limit tests are: LL=20.1%; PI=6.9%. The soil can be classified as clayey gravel (GC) with gravel content at 71.7%, or as clayey with fines. On AASHTO classification, the sample is identified as A-2-4 which is Clayey Gravel.

3. MECHANISM OF SOIL-CEMENT STABILIZATION

Cement stabilization involves three processes: cement hydration; cation exchange reaction and pozzolonic reaction carbonation [9].

Cement hydration is a chemical reaction between cement and water whereby calcium hydroxide or hydrated lime ($Ca(OH)_2$) is produced. The soil-cement reaction involves the replacement of divalent calcium (Ca^{2+}), adsorption of $Ca(OH)_2$ by particles and cementation at inter-particle contacts by the tobemorite gel. Calcium silicate, the chief constituent (75%) of the PC, produces lime ($Ca(OH)_2$) and tobemorite gel which are responsible for strength increases in the treated soil.

Cation exchange reaction involves replacement of univalent sodium (Na+) and hydrogen (H+) ions in the soil with Ca^{2+} from cement. Clay particles continue to absorb $Ca(OH)_2$ until the clay is saturated with it. Such exchanges reduce the plasticity, improve workability and shear strength of the soil. The reaction starts immediately upon mixing cement into the soil.

Pozzolonic reaction and carbonization involves the reaction between the clay particles and $Ca(OH)_2$ that is produced by cement hydration. This contributes to the long-term strength of the cement paste and pozzolanic materials.

Strength of the stabilized soil increases with time due to pozzolanic reaction. Calcium hydroxide in the soil water reacts with the silicates and aluminates (pozzolans) in the soil to form cementing materials or binder, consisting of calcium silicate hydrates. A flow chart showing the soil-cement chemical reaction is shown in Fig. 2.

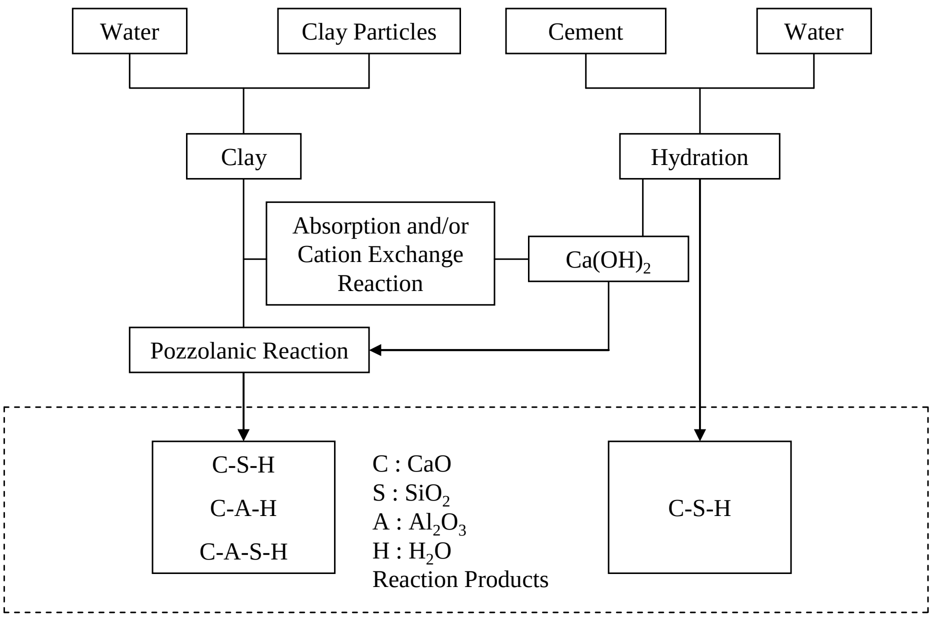


Fig. 2. Chemical reaction between soil and cement [10]

When PC is added to lateritic soil, a soil-cement mixture – known as calcium aluminate silicate hydrate (CASH) – is formed. As the pozzolanic reaction progresses, CASH is slowly converted into a well-crystalline phase to form calcium silicate hydrate (CSH) and calcium aluminium hydrate (CAH) which hardens with age to form a permanent compound that binds the soil particles. As a result, the shear strength of the stabilized soil is improved.

4. INVESTIGATION OF SOIL MICROSTRUCTURE

XRD and SEM techniques were employed to study the soil samples in terms of their microstructural changes relating to strength increases and identification of new compounds formed as a result of pozzolanic reaction. Tests to determine the soil mineral content were carried out at the Scientific Equipment Center, Prince of Songkhla University, Thailand.

a) X-ray diffraction

X-ray diffraction (XRD) is the primary investigation technique for classification and characterization of minerals. It can be used to characterize complex interstratifications, to identify particular polytypes and to provide quantitative analysis of mixtures [1]. A quantitative assessment of soil mineral composition was performed using Philips X'Pert-MPD X-ray Diffractometer.

XRD investigation was conducted at 7 curing days to evaluate the samples at 0% and 3% cement mixing. Mineral compounds identified in the tests can be categorized as clay minerals, non-clay minerals, and additive and new reaction products. Diffraction patterns of the crushed rock and lateritic soil before and after mixing with cement are shown in Figs. 3 and 4. As shown in Table 2, minerals found in the crushed rock sample before and after treatment are kaolinite and illite; and the non-clay minerals, quartz, dolomite and calcite. Kaolinite is the main clay mineral found in the laterite while the non-clay minerals are made up of quartz and calcite. The composition of laterite particles before and after treatment is shown in Table 3.

Table 2. Summary of mineral presence in decreasing order by XRD of untreated and 7 days cement-treated crushed rocks

Soil description	Mineral		Composition
	Untreated soil	Cement treated soil	
Crushed rock	Quartz[1]	Quartz[1]	SiO_2
	Illite[2]	Illite[2]	$(K, H_3O)Al_2(Si_3AlO_{10})(OH)_2$
	Kaolinite[2]	Kaolinite[2]	$Al_2(Si_2O_5)(OH)_4$
	Dolomite[3]	Dolomite[3]	$CaMg(CO_3)_2$
	Calcite[3]	Calcite[3]	$CaCO_3$

Note: 1: Non-clay minerals; 2: Clay minerals; 3: Cementitious products, where $CaCO_3$ is the mineral group of Carbonates.

Table 3. Summary of mineral presence in decreasing order by XRD of untreated and 7 days cement treated lateritic soils [11]

Soil description	Mineral		Composition
	Untreated soil	Cement treated soil	
Lateritic soil	Quartz[1]	Quartz[1]	SiO_2
	Kaolinite[2]	Kaolinite[2]	$Al_2(Si_2O_5)(OH)_4$
		Calcite[3]	$CaCO_3$

Note: 1: Non-clay minerals; 2: Clay minerals; 3: Cementitious products, Where $CaCO_3$ is the mineral group of Carbonates.

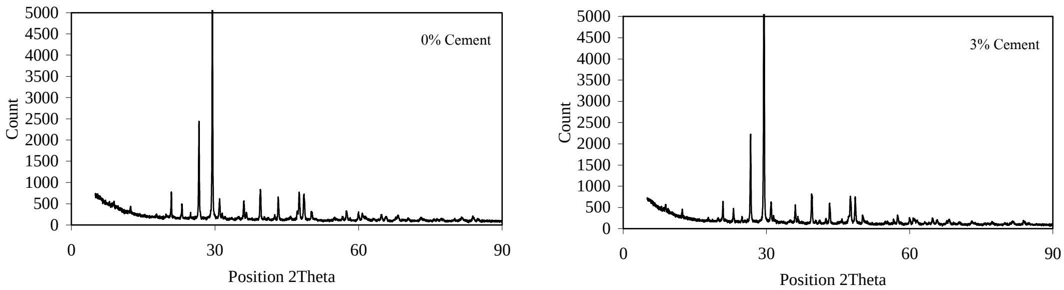


Fig. 3. X-ray diffraction patterns of crushed rock before and after mixing with cement

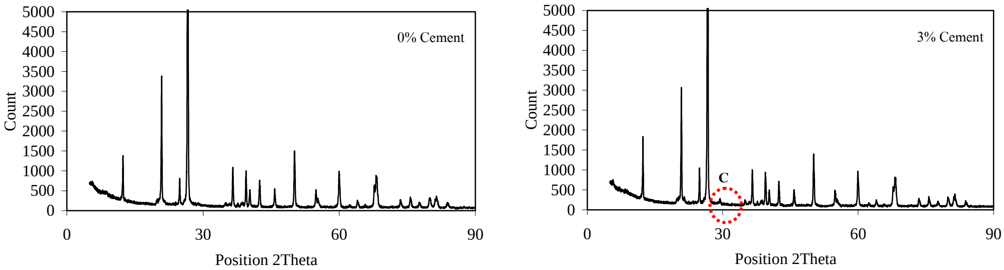
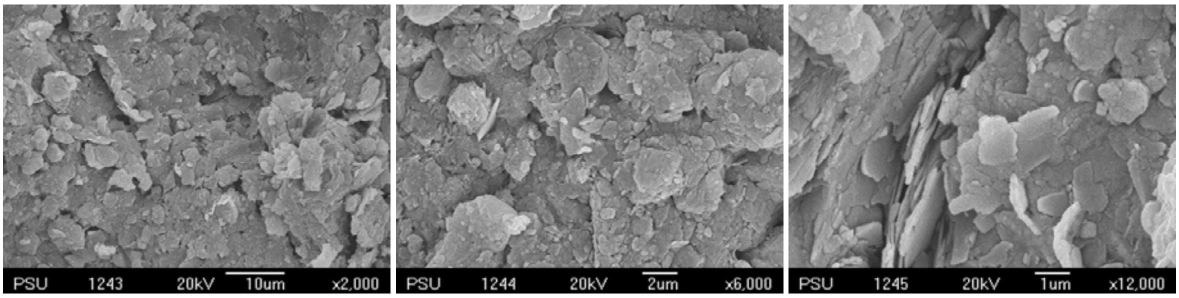


Fig. 4. X-ray diffraction patterns of lateritic soil before and after mixing with cement [11]

XRD patterns of the 3% cement showed intensities belonging to calcium silicate hydrate (CSH) that was produced upon the addition of cement. Analysis of the results showed that CSH was the key reaction product contributing to strength development of the stabilized lateritic soils. However, the XRD images of crushed rock displayed no such intensities.

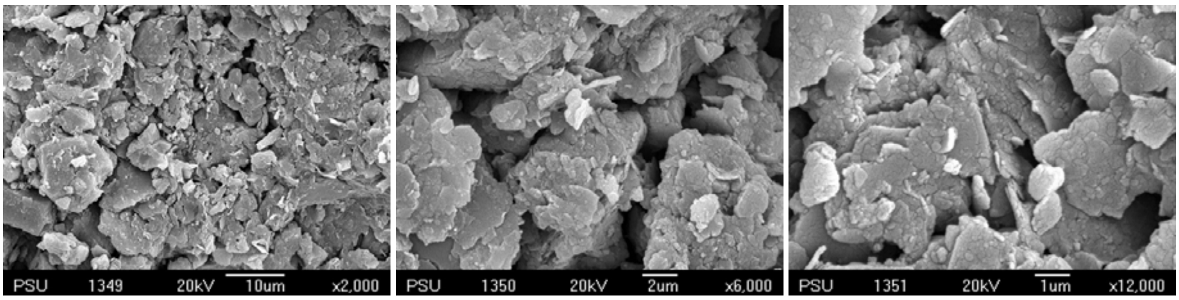
b) Scanning electron microscope

The microstructure of the samples before and after treatment was observed through the JEOL JSM-5800LV Scanning Electron Microscope on high vacuum mode. The SEM provided micrographs that show up the bond formation, surface texture, mineral structure and geometry of the specimens.



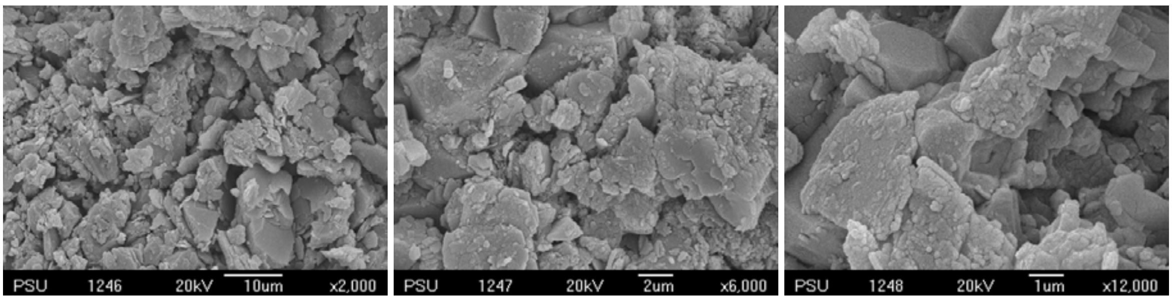
(a) Mag.= x2,000 (b) Mag.= x6,000 (c) Mag.= x12,000

Fig. 5. SEM of crushed rock before mixing with 3% cement



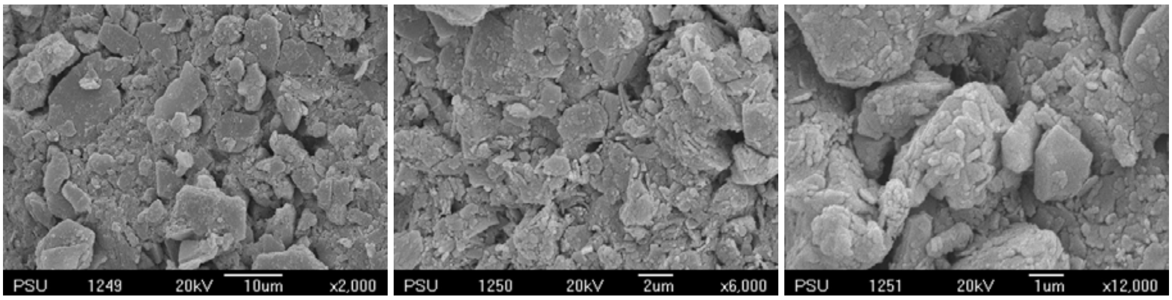
(a) Mag.= x2,000 (b) Mag.= x6,000 (c) Mag.= x12,000

Fig. 6. SEM of crushed rock after mixing with 3% cement



(a) Mag.= x2,000 (b) Mag.= x6,000 (c) Mag.= x12,000

Fig. 7. SEM of lateritic soil before mixing with 3% cement [11]



(a) Mag.= x2,000 (b) Mag.= x6,000 (c) Mag.= x12,000

Fig. 8. SEM of lateritic soil after mixing with 3% cement [11]

SEM images of the soil microstructure before and after treatment are shown in Figs. 5 to 8. At low magnification (x2000), it appears that the soil-cement mixture is rather homogeneous as shown in Figs. 6a and 8a, and soil particles are well bonded together by the cement when compared to that shown in Fig. 6b and Fig. 8b. At high magnification (x12000), the cement and soil are seen to have formed separate lumps as shown in Fig. 6c and Fig. 8c, indicating that the soil-cement mixture is not as homogeneous as it appears in low magnification.

Figures 5 and 7 show SEM images of untreated crushed rock and lateritic soil. Flaky arrangements of clay particle (Kaolinite) can be seen as matrix between the fine grains. Figure 8 shows the soils as they are being coated and bound by the silicate gel. The resulting cementation products, identified by XRD, are known as CSH. A new phase of the soil-cement mixtures, consisting of an interlocking network, can be seen in the micrographs.

Investigation of the laterite-cement mixture indicated changes in its microstructure which culminated in a denser structure than that of the untreated soil. Before treatment, SEM observations revealed that the soil had a high void ratio. After stabilizing with 3% cement, the soil particles became flocculated, resulting in a reduced void ratio.

5. STRENGTH CHARACTERISTICS

The moisture-density relationship for each untreated sample was determined and noted. Compaction was achieved by the modified Proctor procedure (ASTM D-1557). Cement was then mixed in at 3%, 5%, 7% and 9% of the soil's dry weight in order to obtain stabilized samples. The effect of cement content, curing time and unit weight on the strength and stiffness characteristics of the mixtures was then investigated.

Specimens for unconfined compression test were prepared based on the optimum moisture content (OMC) and the maximum dry density according to the procedure for modified Proctor compaction test. After compaction, the specimens were wrapped in plastic sheet and cured at a temperature of about 28^{o}C for periods of 7, 14 and 28 days. At the end of each curing period, a specimen was submerged in water for two hours before testing. Results of the unconfined compression tests are summarized in Table 4.

Laboratory tests were conducted to assess the increase in shear strength of the stabilized soil. It was observed that samples cured to 7 days exhibited a greater degree of failure due to brittleness than those with longer curing times.

The minimum cement content for initial stabilization can be determined by using modified compaction tests. For full stabilization more cement is required, and the amount can be established in the same manner. UCS tests were performed on the stabilized soils at various ages and cement contents. The results of UCS at 7 days are shown in Fig. 9. UCS tests indicate the effect of cement content on the rate of increases in soil strength.

Table 4. Results of Test Series

Test #	C_C	T	UCS_1	UCS_2	CBR_1	CBR_2
C0T0	0	0	-	-	40	84
C3T7	3	7	22.65	24.94	53	98
C5T7	5	7	39.19	55.18	61	115
C7T7	7	7	54.66	71.75	82	134
C9T7	9	7	66.75	79.07	97	147
C3T14	3	14	24.69	30.60	-	-
C5T14	5	14	45.73	64.90	-	-
C7T14	7	14	61.61	103.08	-	-
C9T14	9	14	73.69	114.44	-	-
C3T28	3	28	34.57	35.14	-	-
C5T28	5	28	54.68	72.13	-	-
C7T28	7	28	69.06	123.29	-	-
C9T28	9	28	83.30	145.01	-	-

Note: C_C = cement content, T = curing time, UCS_1 = unconfined compressive strength of lateritic soil (ksc), UCS_2 = unconfined compressive strength of crushed rock (ksc), CBR_1 = California Bearing Ratio of lateritic soil (%), CBR_2 = California Bearing Ratio of crushed rock (%)

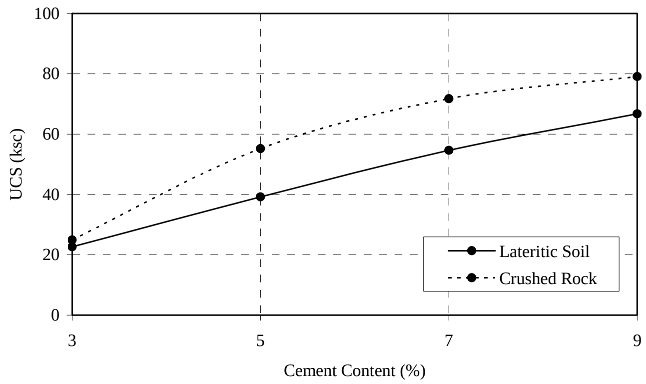


Fig. 9. UCS at 7 days with varying cement content

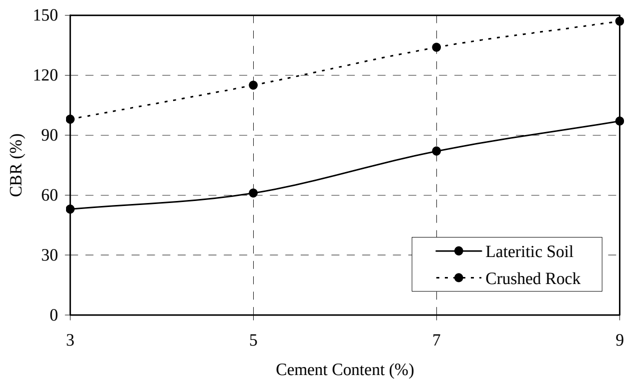


Fig. 10. CBR at 7 days with varying cement content

Initial reaction within the cement-treated laterite was observable in the first 7 days after treatment. In this study, a cement content of 3% was established that resulted in an optimum strength gain. According to the Highways Department specification for base course material, a suitable soil-cement aggregate must have a UCS of at least 17.5 ksc and a soaked CBR above 50%.

The resulting strength of the treated soil improves with increases in cement content and curing time. According to our test data, the UCS of treated lateritic soil at 7 days and 28 days, with 0% cement and 3% cement, are 22.65-66.75 ksc and 34.57-83.30 ksc, respectively; and the CBR at 7 days curing time with 0% cement and 3% cement are 40% and 53%, respectively.

6. CONSTRUCTION COST ANALYSIS FOR CEMENT-STABILIZED BASE

The use of laterite-cement to maintain the pavement for highway construction projects in Thailand is shown in Fig. 11. The figure illustrates the preparation area for mixing lateritic soil with cement, and construction of the base layer and the pavement surface.

Fig. 11. Pavement maintenance using cement-stabilized lateritic soil

Comparison of the costs of crushed rock and laterite-cement bases is shown in Table 5. Crushed rock is found to cost significantly more due to the expenses associated with its extraction which involves rock blasting and crushing — not to mention the higher cost of its mining concession. Note that the cost of materials transportation is not included in Table 5. If this cost component is added – especially in the case of Songkhla where crushed rock must be sourced from elsewhere – then the total cost of crushed rock would be quite substantial. On the other hand, laterite-cement base is more cost effective. Cost analysis of the highway works shown herein, which involved pavement maintenance over a 44 m^2 area, indicated that its cost would be some 48% cheaper if laterite-cement base had been used instead of crushed rock. It was also found that the most expensive item was cement which took up some 39.7% of total cost. The cost comparison in Table 5 is made for the case of crushed rock (without cement stabilization) versus laterite mixed with 3% cement, the latter having passed the UCS criteria set by the Highways Department. The actual amount of cement used, however, is slightly higher than 3% due to the fact that bagged cement was employed and allowance for wastage had to be made for the purpose of this pilot test. This study served as a preliminary investigation of the feasibility of substituting crushed rock with laterite-cement mixture. Further study will be required to cover other characteristics of both materials for better understanding of their long-term performances. This will include studies on durability enhancement of the stabilized aggregate, comparison of life-cycle costs of the materials, for instance.

Table 5. Cost comparison between crushed rock and laterite-cement bases [12]

List	Unit	Amount	Cost (Baht)	
			Lateritic soil	Crushed rock
Material	m^3	10	1,900	9,800
Cement	bag	12	2,100	-
Backhoe-loader	hr.	1	311	311
Water truck	day	1	976	976
Total cost	Baht		5,287	11,087
Unit cost	Baht/m^2		132.17	251.97

As the cost of crushed rock is being pushed up by the high prices of energy as well as environmental charge, further research will be needed that investigates new ways of enhancing the performance of locally available materials in terms of strength, cost, energy consumption, manufacturing facility, transportation and environmental consideration.

7. CONCLUSION

Stabilization is the process of adding cement to a lateritic soil or crushed rock to produce a material whose strength is greater than that of the original. The use of stabilization to improve the properties of a material is becoming more widespread due to the increased strength and load spreading ability that these materials can offer. The Ordinary Portland Cement (Type I) could be effectively used to stabilize lateritic soil. Engineering properties, such as unconfined compressive strength and California Bearing Ratio, are found to improve markedly in the stabilized sample. It could be concluded that formation of reaction products, such as CSH, contribute to strength development of the cement stabilized soil; and that the formation of these reaction products are influenced by the cement content – all of these were substantiated by experimental XRD patterns, SEM micrographs, UCS and CBR results. UCS and CBR of the laterite sample would increase significantly after cement stabilization.

A cement quantity of as small as 3% is found to be sufficient for stabilizing the laterite sample to the required strength of 17.5 ksc, which points to the economic advantage of the method. Lower costs as well as its concomitant environmental benefits are characteristics that make this method attractive.

This present study has demonstrated the feasibility of using lateritic-soil cement mixture to replace crushed rock aggregate as the laboratory tests have shown that the soil-cement mixture can meet the strength requirement. However, more in-depth study will be required to justify the long term performance of the lateritic-soil cement mixture versus crushed rock base course pavement material which can be carried out through durability tests and field trials.

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