NUEJ
Naresuan University
Engineering Journal

Assessment of Performance and Durability in Cement-Stabilized Quarry By-Product Soil as Road Pavement Bases

Nattanon Khumkud[1], Korakod Nusit[2*], Peerapong Jitsangiam[3], Polpreecha Chidburee[2], Susit Chaiprakaikeow[4], Suriyavut Pra-ai[5] and Purichai Keawma[1]

[1] Department of Civil Engineering, Faculty of Engineering, Naresuan University, Phitsanulok, Thailand
[2] Center of Excellence on Energy Technology and Environment. Faculty of Engineering, Naresuan University, Phitsanulok, Thailand
[3] Department of Civil Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand
[4] Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand
[5] RS2GH Research Unit, School of Engineering, University of Phayao, Phayao, Thailand

* Corresponding author e-mail: korakodn@nu.ac.th

(Received: 11 October 2022, Revised: 9 February 2023, Accepted: 14 February 2023)

Abstract

The knowledge of polymer-modified concrete has been well established and employed in real field applications for over a decade. On the other hand, research on polymer-stabilized soil is still limited. Therefore, this study aims to evaluate the performance and durability of polymer-stabilized soil for pavement applications. This study used the same polymer types for concrete modification as soil stabilizers. Two types of polymers used in this research are the Styrene Acrylic (SA) polymer and Styrene-Butadiene Rubber (SBR). The engineering performance, water absorption, and durability tests were conducted to characterize the polymer-stabilized soils. Preliminary results reveal that the strength and durability of polymer-stabilized quarry by-product soil can be improved by the proper dosage of polymers and cement. However, stabilized soil with the polymer alone cannot resist moisture damage at an early age; these are indicated by the dramatic drops in CBR values of the soaked specimens. Therefore, the stabilized soil requires little cement to gain its early strength. The test results indicate the possibility of employing polymer-stabilized cemented soil as road pavement materials. Besides the strength improvement by 21% to 29%, the polymer additives also enhanced the durability and reduced the water absorption rate of the cemented soil.

Keywords: Polymer-stabilized Pavement Materials, Quarry by-product, Durability, Water Absorption

1. INTRODUCTION

Stabilizing soil with chemical and mechanical additives is becoming more widely used for road pavement constructions. Among these methods, adding cement to enhance the performance of pavement materials seems to be the most common and simply used procedure. The strength and stiffness of pavement materials can be greatly improved by adding a small amount of Portland cement to the material mixtures. However, the cement-stabilized pavement materials are still susceptible to moisture damage (Erlingsson et al., 2017; Jitsangiam and Nikraz, 2012) and fatigue failure (Jitsangiam et al., 2016).

Currently, the pavement materials that successfully prevent damage from moisture ingress are unavailable (Jitsangiam and Nikraz, 2012). An innovative pavement material with water-resistant properties is required to protect the road structure from moisture damage. The water-resistant or 'hydrophobic' behaviors of geotechnical materials were discovered by Tillman et al. (1989). Polymer additives also increase the water repellent of treated soils (Raucah et al., 1993). Consequently, polymer additives are becoming more widely used for pavement material stabilization in recent years. The polymers are added to the soils for two main purposes which are (1) to improve the strength and stiffness (Ates, 2013; Azzam, 2014; Baghini et al., 2016; Iyengar et al., 2013; Naenini et al., 2012; Rezaeimalek et al., 2017a),
and (2) to enhance the long-term performances and reduce moisture susceptibility (Al-Khanbashi and Abdalla, 2006; Cameron et al., 2016; Orts et al., 2007; Liu et al., 2017; Rezaeimalek et al., 2017b). However, the polymer types evaluated in the previous research are unavailable worldwide. Moreover, Thailand's polymer applications for soil stabilization are still limited and rarely encountered. In-depth research is, therefore, required for the future development of hydrophobic road pavement materials in the country.

Liquid polymers have also been popularly used to improve the waterproof ability and workability of concrete for more than a decade (Ohama, 1998). Wang et al. (2016) listed the major types of polymer latex popularly used for enhancing concrete properties: butyl benzene latex (SBR latex), styrene-acrylic emulsion (SA latex), neoprene emulsion (CR latex), polyvinyl chloride-vinylidene chloride emulsion (PVDC latex), etc. In previous research, natural latex was not recommended to be used as the concrete modification because of its incompatibility. The polymer latex for concrete modification has been extensively used in Thailand; therefore, they are very easy to find and purchase at a reasonable price. Accordingly, the possibility of employing these concrete-modify polymers as soil stabilizers should be assessed.

This research aims to study the engineering performances, moisture susceptibility, and durability of soil enhanced by polymers for road pavement constructions. The Thailand Department of Highways (DOH) specifications were used as the criteria in this research. Moreover, the quarry by-products soil was targeted for modification and enhancement.

2. Materials and Methods

2.1Materials

2.1.1 Parent material

Presently, manufactured aggregates from the quarry are the main sources of road construction materials in Thailand. In the quarry process, waste aggregates from the production line were usually screened out and stockpiled in the quarry area. This material is usually traded at a low price for the landfill purpose; because its gradations and some engineering properties do not satisfy the pavement design criteria. However, the physical properties of this quarry by-product soil (i.e., Atterberg limits, Los Angeles abrasion, and soundness) are aligned with the values required by the specifications. Table 1 illustrates the physical and engineering properties of the quarry by-product soil, which was employed as the parent material for stabilized soil in this research. This selected quarry by-product soil is classified as limestone

Figure 1 presents the gradation of the selected quarry by-product soil determined from the sieve analysis test (ASTM C136). It can be seen from Table 1 and Figure 1 that, based on the DOH specifications, the quarry by-product soil is not suitable for road base and subbase materials.

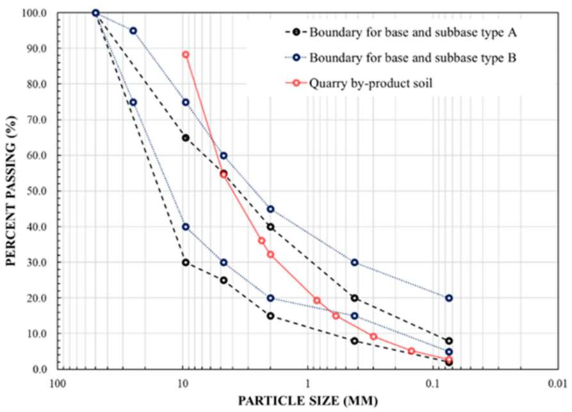


Figure 1 Particle size distribution (PSD) of quarry by-product soil compared with the gradations required for road base and subbase

2.1.2 Cement

The 'Portland cement type I' is recommended as the stabilizing agent for cement-stabilized pavement materials (both base and subbase materials) by the DOH specifications. The selected cement must be certified by the Thai Industrial Standard (TIS) No. 15 – Portland cement. However, the 'mixed cement types,' according to TIS No. 80, may be employed as the stabilizing agent for road subbase. In this research, only the Portland cement type I was chosen to prepare the polymer-stabilized cemented soils.

2.1.3 Liquid polymers

Two types of liquid polymer were employed as the main stabilizing agent in this research - (1) the SA and (2) the SBR of which important information about these two polymers is summarized in Table 2. Both types of liquid polymers are commonly used for concrete modification purposes. The SA and SBR provide excellent strength, environmental protection, and enhanced workability of the modified cement mortar (Aggarwal et al. 2007). It means that both liquid polymers are readily available in the markets. These liquid polymers were targeted and selected as the soil-modifying agents in this research.

Table 2 Properties of liquid polymers used in this research

Poly-mer	Form	Type	pH	Total Solid (%)	Ionic Nature
SA	Liquid Polymer	Dispersible	7.0 – 9.0	54 - 56	Anionic
SBR	Liquid Polymer	Dispersible	8.5 – 11.0	45 - 47	Anionic

2.2 Methodology and Test Methods

This research intends to modify the quarry by-product soil with liquid polymer and use it as the pavement material in Thailand. Therefore, the engineering properties of polymer-stabilized soil were compared with the values recommended by the DOH specifications (see Table 1). The research methodology was established for evaluating the modified soil's performances and properties, as shown in Figure 2.

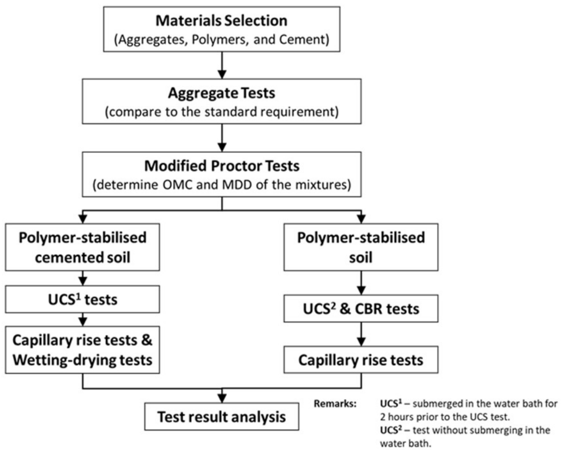


Figure 2 Research methodology

2.2.1 Modified Proctor tests

A series of modified Proctor tests (or modified compaction test) were performed in this research to determine the optimum moisture content (OMC) and the maximum dry density (MDD) of the admixtures. The specimen preparation and the test procedure proceeded according to ASTM D1557 (ASTM, 2012)

Table 1 Engineering properties of quarry by-product soil

Engineering properties (unit)	Test standards	Tested values	Recommended values from DOH* Standard			
			Base (DH-S 201)	Subbase (DH-S 205)	Cement-stabilized Base (DH-S 204)	Cement-stabilized Subbase (DH-S 206)
Liquid limit (%)	ASTM D4318	20	< 25	< 35	< 40	< 40
Plastic limit (%)	ASTM D4318	24	-	-	-	-
Plastic index (%)	ASTM D4318	4	< 6	< 11	< 15	< 20
CBR (%)	ASTM D1883	**5.4**	> 80**	> 25**	-	-
LAA (%)	ASTM C131	24	< 40	< 60	< 60	-
Soundness (%)	ASTM C88	2	< 9	-	-	-
USCS Group	ASTM D2487	SW	-	-	-	-
MDD (kN/m^3)	ASTM D1557	22	-	-	-	-
OMC (%)	ASTM D1557	8.2	-	-	-	-
UCS (MPa)	ASTM D1633	0.14	-	-	> 1.72***	> 0.69***
Remarks:	* Thai department of highways. ** 95 percent of MDD obtained from modified Proctor test. *** 7-day specimens molded by water equivalent to OMC (OMC was determined from a modified Proctor test).					
Abbreviations:	CBR: California Bearing Ratio LAA: Los Angeles Abrasion USCS: Unified Soil Classification System MDD: Maximum Dry Density OMC: Optimum Moisture Content UCS: Unconfined Compressive Strength					

The air-dried soils were scattered all over the mixing tray to prepare the polymer-stabilized soil specimens. Then, the defined amount of liquid polymer was evenly added to mix with the dry soil. The polymer-soil admixtures were hand-mixed until they became homogeneous.

The assigned amount of cement was thoroughly mixed with the air-dried soil in the mixing tray to prepare the polymer-stabilized cemented soils. Then, the liquid polymer was poured and mixed with the cement-soil admixtures. After that, the similar mixing process with the polymer-stabilized soil was continued until the liquid polymer was nicely blended with the cement-soil admixture. The mixing process after adding liquid polymer should be completed within 2 – 3 minutes. The limited mixing time was established to avoid the cementitious bonding developed at an early age. After the admixtures were ready, the modified Proctor tests were commenced immediately.

The primary strength test in this research reveals that 2% cement by weight of dried soil was enough to improve the compressive strength of the quarry by-product soil. The improved strength values attained the DOH requirement for the cement-stabilized subbase (greater than 0.69 MPa as specified in Table 1). For achieving the strength required for the cement-stabilized base, 3% of Portland cement is needed. Therefore, for primary investigation and economical purposes, the cement quantity equivalent to 2% by weight of dried soil was chosen to prepare the polymer-stabilized cemented soil in this research.

2.2.2 Unconfined compressive strength (UCS) test

The UCS values of the polymer-stabilized and cemented soil were determined according to ASTM D1663 (ASTM, 2000). The DOH specification required the strength of the 7-day specimens to be greater than 1,724 kPa and 689 kPa for the cement-stabilized base and subbase, respectively. For preparing the 7-day specimens, the compacted specimens were wrapped in the cling wrap to prevent moisture loss and placed in the controlled temperature chamber at 23±1.7 ºC. Before the UCS test, the specimens were submerged in the water bath for 2 hours (required by DOH standard). The water was drained from the specimen for 15 minutes before commencing the UCS tests. However, the polymer-stabilized specimens (both SA-stabilized and SBR-stabilized) dissolved and crumbled in the submerged water after 30 minutes; therefore, the water-submerging process was only performed with the polymer-stabilized cemented specimens in this research.

According to the specification (DH-S 204 and DH-S 206), the required UCS should be determined from the specimens compacted at OMC. However, the effects of molded moisture content on the UCS of stabilized soil were also investigated in this research; accordingly, the UCS test was measured from the specimens prepared from different moisture contents.

2.2.3 California bearing ratio (CBR) test

In this research, the CBR testing procedures complied with ASTM D1883 (ASTM, 2016). Based on the DOH specifications, the crushed rock base and aggregate subbase should have the minimum CBR values of 80% (for asphalt pavement) and 25%, respectively. For preparing the CBR specimens, the compacted specimens were left in the steel mold for seven days before the testing commenced. This process was performed to ensure a similar curing condition with the specimens prepared for the UCS test. In this research, the CBR values were only determined from the polymer-stabilized specimens.

2.2.4 Capillary rise test

Many researchers performed capillary rise tests to assess the water absorption potential of the compacted specimens. In this research, the Australian Standard, AS 1141.53 (Standard Australia, 1996), was used to evaluate the water absorption behavior of the polymer-stabilized soil and polymer-stabilized cemented soil specimens. For this test, the 7-day specimens were placed in the aluminum trays with the water filled up to 10-mm height (see Figure 3). The water height absorbed by the compacted specimens was then measured at the specified times and recorded for 72 hours (3 days). The capillary rise (C.R.) values at different times of measuring can be calculated based on Eq. (1)

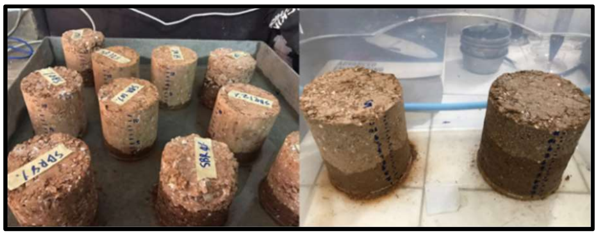


Figure 3 Water absorption and capillary rise tests

$$\text{CR}\ (\%) = \frac{h}{H} \times 100 \qquad (1)$$

where h is the height of the capillary rise, and H is the initial height of the specimen. The capillary rise test is not compulsory for stabilized road pavement design; however, the CR value of the stabilized pavement material is generally limited to 25% of the specimen height (Kodikara et al., 2003). Previous research demonstrated that the results from CR test might unappropriated describe the moisture ingress characteristics of field material (Kodikara et al., 2003); accordingly, the CR test results were only used for the comparison purpose in this research. The moisture ingress behavior of the quarry by-product specimens, the cement-stabilized specimens, the polymer-stabilized specimens, and the polymer-stabilized cemented soils was evaluated in the next section.

2.2.5 Wetting and drying test

The wetting and drying test is commonly used to evaluate cemented soil's wet and dry durability (Wen et al., 2014). The testing procedure according to ASTM D559 (ASTM, 2015) was performed in this research. Twelve cycles of the wetting and drying process for every specimen were completed to investigate the weight loss of the test specimens. Only the weight losses of polymer-stabilized cemented soils were determined and evaluated in this research because the polymer-stabilized soils and quarry by-product soil cannot endure the submerging water process.

Based on ASTM D559, the wetting process was performed by submerging the specimens in the water for 5 hours before drying. Then, the specimens were transferred to the oven at the controlled temperature of 71±3 ºC for 42 hours. After the drying process was completed, one of two replicated specimens was brushed with the wire scratch brush, as shown in Figure 4. Finally, the weight loss of each specimen was calculated and recorded. The process of wetting and drying is continued for eleven more cycles. Therefore, the test requires at least one and a half months. Eq. (2) illustrates the weight loss calculation at every wetting and drying test cycle.

$$\text{Weight loss}\ (\%) = \frac{A}{B} \times 100 \qquad (2)$$

where A is the original dry mass minus final dry mass, and B is the original dry mass.

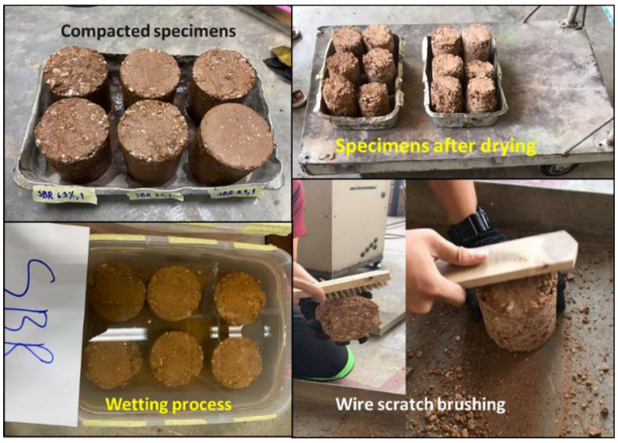


Figure 4 Wetting and drying test

3. TEST RESULTS

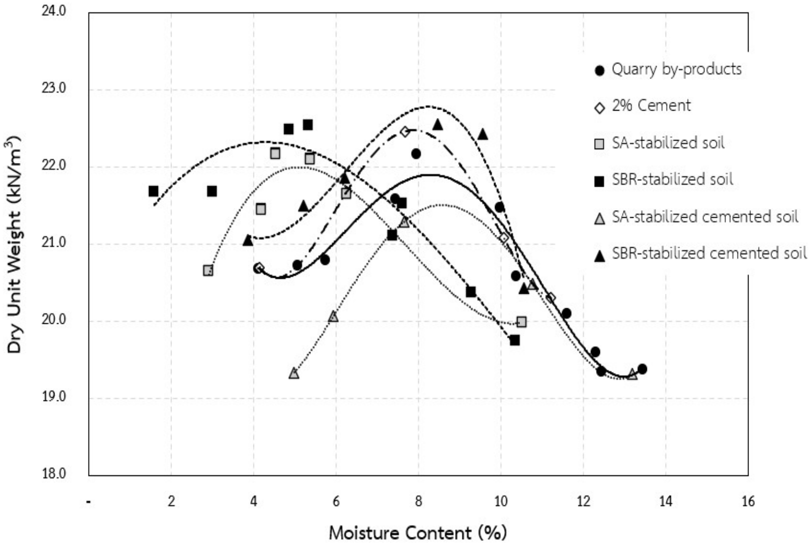
3.1 Modified Proctor test results

Figure 5 presents the results of the modified Proctor test performed in this research. The OMCs of the polymer-stabilized soils (both SA-stabilized and SBR-stabilized soils) are less than those obtained from the quarry by-product soil and the cement-stabilized soil. On the other hand, the OMCs of the polymer-stabilized cemented soils were higher than those determined from the quarry by-product and cement-stabilized soil. The maximum dry densities of all materials vary between 21.5 and 22.5 kN/m^3.

3.2 UCS test results

The UCS test results of the soil specimens and the modified soil specimens are presented in Figure 6. The UCS values of the quarry by-product soil and the quarry by-product soil stabilized by 2% of cement were also provided in Figure 6 as the reference.

The UCS test of quarry by-product soil was conducted instantly after the compaction process of the test specimen was completed (without submerging the specimen into the water bath). The compressive strength of the compacted quarry by-product specimen is 0.14 MPa.



OMC%	MDD (kN/m³)
8.2	22.0
8.0	22.5
5.0	22.0
6.0	22.5
8.5	21.5
8.5	22.5

Figure 5 Modified Proctor test results

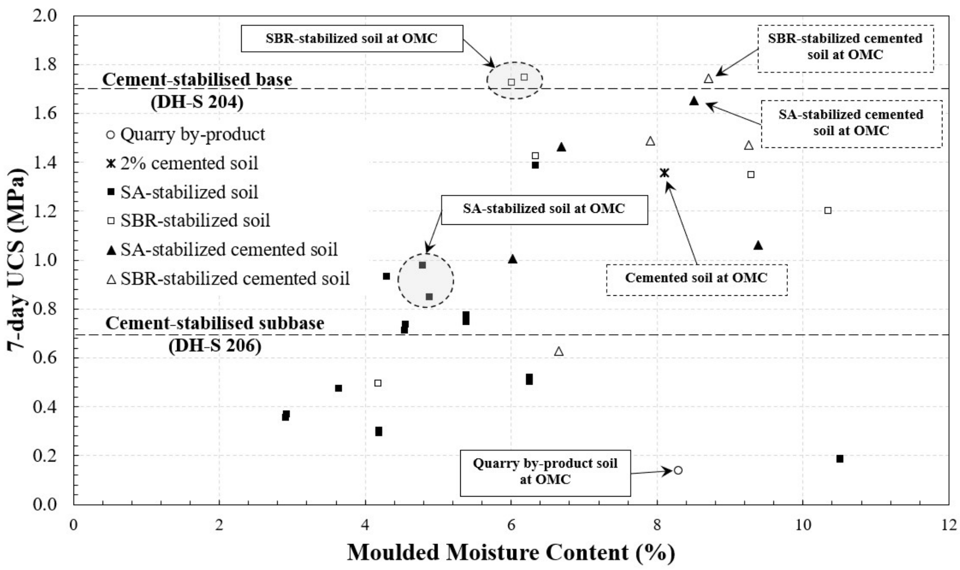


Figure 6 The UCS test results

This UCS value was averaged from 3 replicated specimens molded at OMC. On the other hand, the 2% cemented soil specimens were cured for seven days before testing. The average UCS value of 2% cemented soil is 1.36 MPa. Similar to the quarry by-product soil, it was determined from 3 replicated specimens molded at OMC.

Figure 6 shows that compressive strengths of the polymer-stabilized soil and polymer-stabilized cemented soil are greater than the value required for cement-stabilized road subbase (0.69 MPa) when an amount of water equivalent to OMC was used to mold the specimen. However, the strength tests of polymer-stabilized soils were performed without submerging the specimens into the water bath for 2 hours. There would be a reason that the strength of SBR-stabilized cemented soil (1.75 MPa) is mostly equivalent to the strength of SBR-stabilized soil (1.73 MPa). However, the strength of SA-stabilized cemented soil (1.65 MPa) is 68% greater than that of SA-stabilized soil (0.95 MPa). The great difference between USC values observed from SA-stabilized soil and SA-stabilized cemented soil required further investigation. The water suction force highly influences the compressive strength of unsaturated soil (Kohgo et al., 1993; Leroueil and Hight, 2013). Therefore, suction force may contribute to high strength values obtained from the polymer-stabilized specimens; since the polymer-stabilized specimens were tested without a water-submerging process, the degree of saturation was low (Nusit et al. 2016).

3.3 CBR test results

For the road base and subbase soils, DOH specifications require the CBR values equivalent to 80% and 25%, respectively (see Table 1). In this research, the CBRs were determined from the polymer-stabilized soils only. There would be because the CBR test is not mandatory for the cement-stabilized road base and subbase soils (see Table 1). Table 3 illustrates the results of the CBR test obtained from this research. The different ratio (%) in Table 3 is defined by Eq. (3)

Table 3 CBR test results

Road base or subbase materials	Moisture content (%)	CBR (%) (Compaction degree, %)		Different ratio** (%)	Swell index (%)
		Soaked	Unsoaked		
SA-stabilized soil	3.4	26.1 (91.8)	100.1 (91.8)	74	1.3
	5.4*	**30.0 (96.4)**	**83.2 (97.3)**	**64**	**0.9**
	7.4	7.9 (94.3)	47.4 (94.1)	83	0.2
SBR-stabilized soil	3.8	4.2 (92.4)	59.9 (91.6)	93	0.1
	5.8*	**15.8 (95.2)**	**96.2 (95.2)**	**84**	**0.6**
	7.8	59.3 (97.8)	88.0 (94.7)	33	0.9
Quarry by-product soil	**8.3***	**5.4 (95.4)**	**6.6 (98.2)**	**18**	**0.9**
Remarks	* Moisture contents equivalent to OMC were used to mold the specimens. ** Calculated based on Eq. 3.				

$$\text{Difference ratio (\%)} = \frac{CBR_{unsoaked} - CBR_{soaked}}{CBR_{unsoaked}} \times 100 \quad (3)$$

In Eq (3), CBR_{soaked} is the CBR of soaked specimens, and $CBR_{unsoaked}$ is the CBR of unsoaked specimens. The different ratio (%) value indicates a high level of water sensitivity; the CBR of the test specimen may dramatically reduce if the specimen is submerged in the water.

3.4 Capillary rise test results

The capillary rise (CR) test results are presented in Figure 7 - 9. Figure 7 illustrates the CR development of polymer-stabilized soils compared to the results obtained from the quarry by-product specimens and the 2% cement-stabilized specimens. The CR test results of SA-stabilized cemented soil are presented in Fig. 8, while Fig. 9 shows the CR development measured from SBR-stabilized cemented soil molded at different moisture contents.

It can be seen from Figure 7 that the SA-stabilized soil absorbed water slower than the other specimens. The absorbed water took more than two days (48 hours) to reach the top of SA-stabilized specimens. The 2% cement-stabilized specimen shows better water susceptibility performance than the quarry by-product specimen. However, the capillary rise test of cement-stabilized soil was completed after 16 hours. Similar absorption behavior of cement-stabilized material was discovered in the previous research. Kodikara et al. (2003) observed that the capillary rose to the top of the specimen height is normally encountered if the optimum binder content was used to prepare that specimen. The optimum binder content is defined as the minimum

amount of cement required to increase cement-stabilized materials' strength to the specification values.

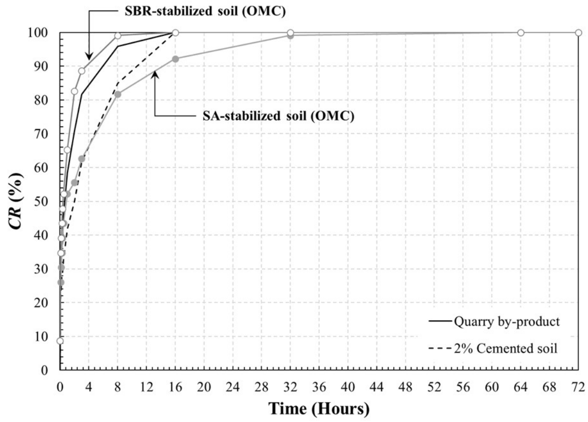


Figure 7 The CR development of the polymer-stabilized soils

The SA-stabilized cemented soil displays superior water susceptibility performance, as indicated by Figure 8. The minimum value of CR (84%) at 72 hours was obtained from the SA-stabilized cemented soil molded at OMC. Table 4 presents the compaction degrees of the capillary-rise-test specimens. For SA-stabilized cemented soil, the CR values at the same measuring times increase with the decreases in compaction degree. At about the same degree of compaction, the specimens compacted by water equivalent to the wet-side of optimum absorbed water slower than the specimens molded by water equivalent to the dry-side of optimum. The SBR-stabilized cemented soil behaves similarly to SA-stabilized soil, as demonstrated by Figure 9. However, the water rises in SBR-stabilized cemented soil developed faster than those measured from the SA-stabilized cemented soil.

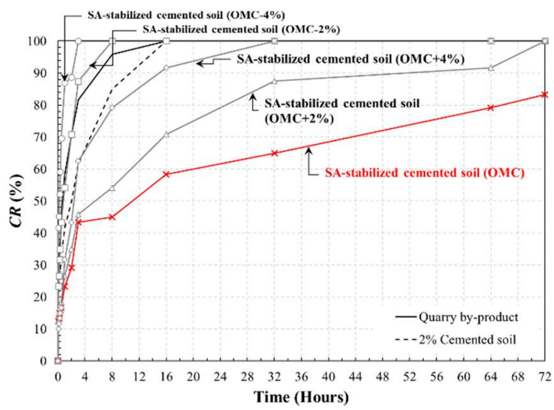


Figure 8 The CR test results of SA-stabilized cemented soil at different compacted moisture contents

Table 4 Compaction degree of the capillary-rise-test specimens

1	Quarry by-product	OMC	0	21.65	98.4
2	2% cement-stabilized soil	OMC	7	22.32	99.2
3	SA-stabilized soil	OMC	7	21.52	97.8
4	SBR-stabilized soil	OMC	7	21.67	96.3
5	SA-stabilized cemented soil	4.5% (OMC–4%)	7	20.12	93.6
6	SA-stabilized cemented soil	6.5% (OMC–2%)	7	20.81	96.8
7	SA-stabilized cemented soil	8.5% (OMC)	7	21.05	97.9
8	SA-stabilized cemented soil	10.5% (OMC+2%)	7	20.68	96.2
9	SA-stabilized cemented soil	12.5% (OMC+4%)	7	20.38	94.8
10	SBR-stabilized cemented soil	4.5% (OMC–4%)	7	21.22	94.3
11	SBR-stabilized cemented soil	6.5% (OMC–2%)	7	21.51	95.6
12	SBR-stabilized cemented soil	8.5% (OMC)	7	22.09	98.2
13	SBR-stabilized cemented soil	10.5% (OMC+2%)	7	21.71	96.5
14	SBR-stabilized cemented soil	12.5% (OMC+4%)	7	21.11	93.8

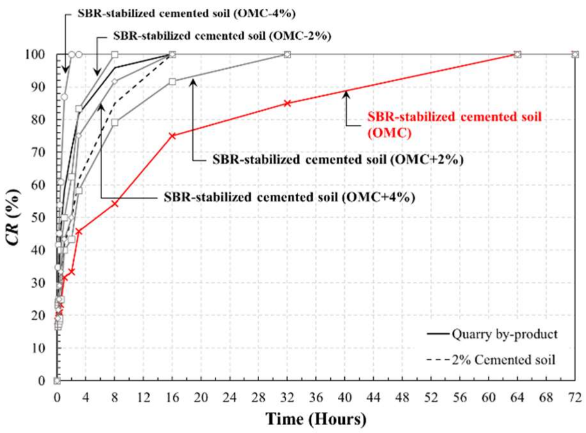


Figure 9 The CR test results of SBR-stabilized cemented soil at different compacted moisture contents

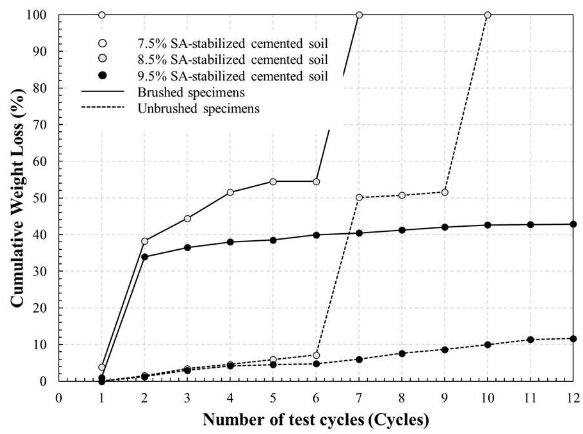


Figure 10 Wetting and drying test results of SA-stabilized cemented soils

3.5 Wetting and drying test results

Figure 10 presents the wetting and drying test results of SA-stabilized cemented soil. The test results of SBR stabilized cemented soil are demonstrated in Figure 11. Each mixture contains two replicate specimens; one was brushed after the drying process, while another was only gone through the wetting and drying process. Therefore, the weight loss due to the wire scratch brushing is the different values of weight loss between 2 replicated specimens (see Figure 11)

Figure 10 indicates 10% to 100% weight losses of SA-stabilized cemented soil. A hundred percent weight loss represents a completed specimen failure in this research. Both specimens molded by 7.5% of SA collapsed after the 1st cycle of the wetting process cycle

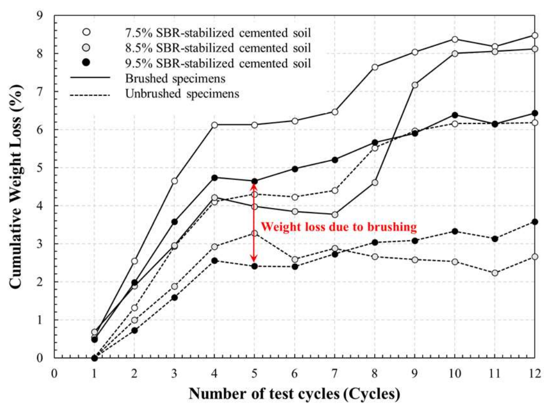


Figure 11 Wetting and drying test results of SBR-stabilized cemented soils

However, the specimens molded with 9.5% of SA survived the 12-cycle test. The final weight losses of these specimens were 12% for unbrushed specimens and 43% for brushed specimens. The huge shifts in weight loss came from two main reasons (see Figure 12); (1) the specimen was broken after the drying process, and (2) the specimen was broken after the wetting process.

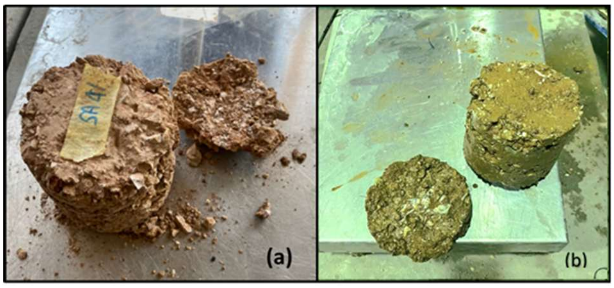


Figure 12 The specimen broken after (a) drying process, and (b) wetting process

The weight losses of less than 10% were observed from the SBR-stabilized cemented soil, as shown in Fig. 11. From the test results of this research, the SBR-stabilized cemented soils showed predominant durability performance compared to the SA-stabilized cemented soils. The greater UCS values of SBR-stabilized cemented soil may be the reason for better durability. For the SBR-stabilized cemented soils, the weight loss of brushed specimens differed from the unbrushed specimens from 1% to 5%. Moreover, all SBR-stabilized cemented specimens completed the 12 cycles of the wetting and drying process.

The weight losses of polymer-stabilized cemented soil increased concerning the wetting and drying cycles and the amount of liquid polymer added. Similar weight loss behavior can be inspected from both SA-stabilized and SBR-stabilized soil.

4.DISCUSSION

Table 5 summarises the test results evaluated in this research. The compressive strengths measured from the SA-stabilized and polymer-stabilized cemented soil attain the stabilized base specification strength criteria. Based on the UCS criteria, the 2% cemented and SBR-stabilized soil may be used as the stabilized subbase soil. However, only the SA-stabilized soil has CBR values higher than the subbase specification. The low CBR value determined from the soaked specimens is the most concerning issue in this study. The CBR of polymer-stabilized soil seems severely sensitive to moisture ingress, indicated by the different ratios in Table 3.

The capillary rise test illustrates that SA polymers can be used to reduce the water absorption rate of the stabilized soil. It also helps to decrease the capillary rise of the cement-stabilized soil. The compaction degree also greatly affects the water absorption behavior of the polymer-stabilized cemented soil. However, from the wetting and drying test, the SBR-stabilized cemented soil has the best durability performance among the test specimens. This excellent improvement may result from the increased strength of SBR-stabilized cemented soil.

Table 5 Test results determined in this research compared with the DOH specifications

Types	UCS (MPa)			CBR (%)			CR to the max. height** (Hours)	Final weight loss from wet-dry test*** (%)
	Test results	DOH base	DOH sub-base	Test results*	DOH base	DOH sub-base		
Quarry by-product soil	0.14	>1.72	>0.69	5.4	>80	>25	16	N.A.
2% cement-stabilized soil	1.36			N.A.			16	N.A.
SA-stabilized soil	0.95			30			64	N.A.
SBR-stabilized soil	1.73			15			16	N.A.
SA-stabilised cemented soil	1.65			N.A.			>72	100
SBR-stabilised cemented soil	1.75			N.A.			64	8.1
Remarks	* CBR values of soaked specimens. ** Specimens molded by water equivalent to OMC. *** Values determined from brushed specimens (molded by water equivalent to OMC). N.A. – Not Available.							

5.CONCLUSIONS

This research aims to improve the quarry by-product soil with SA and SBR polymers and employ the modified soils as road pavement materials in Thailand. The mandatory tests, i.e., physical property tests, UCS tests, and CBR tests, were performed along with the capillary rise test and wetting and drying test. The test values were then compared with the criteria issued by the Thailand department of highways. The key findings of this research are illustrated below;

- The increase in strength of the polymer-cement stabilized soil from the cemented soil at equivalent cement content causes the stabilized soil to employ as the stabilized road base materials. In addition, polymer additives may be substituted by the amount of cement added to the stabilized soil to obtain appropriate strength. The polymers, therefore, may be an environmental-friendly additive for soil stabilization in the future.
- The CBR of the polymer-stabilized soils is very sensitive to the increase in the degree of saturation. The CBR of soaked specimens reduced greatly from the unsoaked CBR, demonstrated by the different ratios in this research.
- The water absorption rate of the quarry by-product soil and the cement-stabilized soil can be reduced by adding the polymer equivalent to the OMC. The SA-stabilized cemented soil presents a superior performance in water absorption reduction. In addition, the compaction degree significantly influenced the water absorption behavior of the polymer-stabilized cemented soil. The specimens molded by the polymer on the optimum wet-side behaved differently from those molded by the dry-side.
- The study used the weight losses from 12 wetting and drying test cycles to compare the durability performance of polymer-stabilized cemented soil. The wetting and drying test results of the polymer-stabilized soil and the quarry by-product soil were unavailable since both types of soil dissolved in the water during the 1st wetting cycle. According to the

test results of this research, the SBR-stabilized cemented soil displayed the best durability performance. The increased amount of stabilized polymer reduced weight loss during the wetting and drying test.

Based on the test results, the SA-stabilized and SBR-stabilized cemented quarry by-product soil can be used as the road-stabilized subbase. The benefits of adding polymers to the cement-stabilized soil include; (1) increasing the UCS by 21% to 29%, (2) reducing the water absorption rate, and (3) enhancing the durability performances of cement-stabilized soil.

6.ACKNOWLEDGMENTS

This work was supported by Naresuan University Faculty of Engineering Scholarships and the Thailand Research Fund (TRF) scheme "TRF Research Grant for New Scholar (2019-2020)" Grant no. MRG6280053 and "TRF Research Career Development Grant (2016-2018)" Grant no. RSA5980070. Special thanks to Dr. Nanticha Kalapat for the great advice on this study. In addition, the Civil Engineering Department research team at Naresuan University, Chiang Mai University, Kasetsart University and Phayao University, Thailand, are also gratefully acknowledged for providing overview guidance and valuable input into this work.

7. REFERENCES

Aggarwal, L. K., Thapliyal, P. C., Karade, S. R., 2007. Properties of polymer-modified mortars using epoxy and acrylic emulsions. *Construction and Building Materials*,21(2),379-383. https://doi.org/10.1016/j.conbuildmat.2005.08.007

Al-Khanbashi, A., Abdalla, S. W., 2006. Evaluation of three waterborne polymers as stabilizers for sandy soil. *Geotechnical & Geological Engineering*, 24(6), 1603-1625.

ASTM., 2000. Standard test methods for compressive strength of molded soil-cement cylinders. *ASTM D1663*. West Conshohocken, PA.: ASTM International.

ASTM., 2007. Standard test method for particle-size analysis of soils. *ASTM C136*. West Conshohocken, PA.: ASTM International.

ASTM., 2012. Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)). *ASTM D1557*. West Conshohocken, PA.: ASTM International.

ASTM., 2015. Standard test methods for wetting and drying compacted soil-cement mixtures. *ASTM D559*. West Conshohocken, PA.: ASTM International.

ASTM., 2016. Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. *ASTM D1883*. West Conshohocken, PA.: ASTM International.

Ateş, A., 2013. The Effect of Polymer-Cement Stabilization on the Unconfined Compressive Strength of Liquefiable Soils. *International Journal of Polymer Science*, 2013, 356214.

Azzam, W. R., 2014. Utilization of polymer stabilization for improvement of clay microstructures. *Applied Clay Science 93-94*, 94-101. doi:https://doi.org/10.1016/j.clay.2014.03.006

Baghini, M. S., AIsmail, A., Naseralavi, S. S., et al., 2016. Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement. *International Journal of Pavement Research and Technology, 9(4)*, 321 – 336.

Cameron, D., Hopkins, C., Rahman, M., 2016. Hydrophobic Polymer Additive for Stabilization of Aggregates in Local Government Roads. *Procedia Engineering*,143,26-33. doi:https://doi.org/10.1016/j.proeng.2016.06.004

Erlingsson, S., Rahman, S., Salour, F., 2017. Characteristic of unbound granular materials and subgrades based on multi stage RLT testing. Transportation Geotechnics, 13, 28-42. doi:https://doi.org/10.1016/j.trgeo.2017.08.009

Jitsangiam, P., Nikraz, H., 2012. Coarse bauxite residue for roadway construction materials. *International Journal of Pavement Engineering*, 14(3), 265-273.

Jitsangiam, P., Nusit, K., Chummuneerat, S., et al., 2016. Fatigue Assessment of Cement-Treated Base for Roads: An Examination of Beam-Fatigue Tests. *Journal of Materials in Civil Engineering 28(10),* 04016095.

Kodikara, J., Lee, K. Y., Chakrabarti, S. 2003. Laboratory assessment of capillary rise in stabilized pavement materials. *Paper presented at the Proceedings of the 21st ARRB and 11th REAAA conference*, Cairns, Australia.

Kohgo, Y., Nakaho, M., Miyaki, T., 1993. Theoretical aspects of constitutive modeling for unsaturated soils. *Soils and Foundations*, 33(4), 49-63.

Leroueil, S., Hight, D. W., 2013. Compacted soils: From physics to hydraulic and mechanical behaviour. In B. Caicedo, C. Murillo, H. Laureano, J. E. Colmenares, & I. R. Berdugo (Eds.), *Advances in unsaturated soils* (pp. 41-59). Broken Sound Parkway, N.W.: CRC Press.

Liu, J., Wang, Y., Lu, Y., et al., 2017. Effect of Polyvinyl Acetate Stabilization on the Swelling-Shrinkage Properties of Expansive Soil. *International Journal of Polymer Science*, 2017, 8128020.

Naeini, S. A., Naderinia, B., Izadi, E., 2012. Unconfined compressive strength of clayey soils stabilized with waterborne polymer. *KSCE Journal of Civil Engineering*, 16(6), 943-949.

Nusit, K., Jitsangiam, P., Kodikara, J., et al., 2016. Advanced Characteristics of Cement-Treated Materials with respect to Strength Performance and Damage Evolution. *Journal of Materials in Civil Engineering 29(4)*, 04016255.

Ohama, Y., 1998. Polymer-based admixtures. Cement and Concrete Composites 20(2), 189-212. doi:https://doi.org/10.1016/S0958-9465(97)00065-6

Orts, W. J., Roa-Espinosa, A., Sojka, R. E., et al., 2007. Use of Synthetic Polymers and Biopolymers for Soil Stabilization in Agricultural, Construction, and Military Applications. *Journal of Materials in Civil Engineering19(1),*58-66. doi:doi:10.1061/(ASCE)0899-1561(2007)19:1(58)

Raucah, A. F., Katz, L. E., Liljestrand, H. M., 1993. *An Analysis of the mechanisms and efficacy of three liquid chemical soil stabilizers: volume 1*: Texas Department of Transportation.

Rezaeimalek, S., Nasouri, A., Huang, J., et al., (2017a. Comparison of short-term and long-term performances for polymer-stabilized sand and clay. *Journal of Traffic and Transportation Engineering (English Edition)*, 4(2), 145-155. doi:https://doi.org/10.1016/j.jtte.2017.01.003

Rezaeimalek, S., Huang, J., Bin-Shafique, S., 2017b. Evaluation of curing method and mix design of a moisture activated polymer for sand stabilization. *Construction and Building Materials*, 146, 210-220. doi:https://doi.org/10.1016/j.conbuildmat.2017.04.093

Standard Australia., 1996. Methods for sampling and testing aggregates - Absorption, *swell and capillary rise of compacted materials*. AS 1141.53. Sydney, NSW: Standard Australia.

Tillman, R., Scotter, D., Wallis, M., et al., 1989. Water repellency and its measurement by using intrinsic sorptivity. *Soil Research*, 27(4), 637-644.

Wang, M., Wang, R., Yao, H., et al., 2016. Research on the mechanism of polymer latex modified cement. *Construction and Building Materials*, 111, 710-718. doi:https://doi.org/10.1016/j.conbuildmat.2016.02.117

Wen, H., Muhunthan, B., Wang, J., et al., 2014. Characterization of cementitiously stabilized layers for use in pavement design and analysis *(NCHRP Report No. 789)*. Retrieved from Washington, D.C.; NCHRP.