Lowland Technology International 2019; Volume 21 (Issue 3):134-142
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

Effect of Polymer and Portland Cement on Strengthen Crushed Rock for Pavement Base

S. Chaiyaput [1], D.T. Bergado [2] and J. Ayawanna [3]

ARTICLE INFORMATION

Article history:

Received: 06 April, 2019
Received in revised form: 15 June, 2019
Accepted: 10 September, 2019
Publish on: 04 December, 2019

Keywords:

Base
CBR
Pavement
Polymer
Strength

ABSTRACT

The effect of concurrent use of liquid polymer and Portland cement as a reinforced material in crushed rock pavement base was investigated in this work. The strength of polymer-treated crushed rock (treated crushed rock) and ordinary crushed rock (untreated crushed rock) were characterized and compared. In strength analysis, the California bearing ratios (CBR) of untreated and treated crushed rock were determined under unsoaked and soaked conditions to simulate post-flood pavement damage. The unconfined compressive strength (UCS) was evaluated under unsoaked conditions for 2h, 1-day, 3-day, 7-day, and 28-day curing periods. The results showed that the CBR of untreated and treated crushed rock under soaked and unsoaked conditions were positively correlated with dry density. The CBR under the unsoaked condition of untreated crushed rock was identical to that of treated crushed rock. Meanwhile, under the soaked condition, the CBR of treated crushed rock was twice as higher than the untreated crushed rock. The swelling indices were 0% for both untreated and treated samples. The UCS of treated crushed rock showed positively correlation with the curing time. The use of liquid polymer and Portland cement, therefore, improved the strength of crushed rock pavement base in which effectively mitigate the post-flood pavement damage.

1. Introduction

The engineering properties (i.e., strength and durability) of natural aggregates, including fine-grained soil and coarse-grained soil (crushed rock), have been attempted to improve (Horpibulsuk et al., 2006; Department of Highways, 2013; Chummuneerat, 2014; Puppala, 2016). There are two conventional techniques (i.e., mechanical and chemical) to improve the engineering properties of natural aggregates. The mechanical technique uses static or dynamic compaction to increase soil density and bearing capacity. The chemical method uses mixing of the natural aggregate with traditional (e.g., cement, bitumen, fly ash) or nontraditional stabilizing materials (e.g., resins, ionic, polymer).

Portland cement mixed with soil (i.e., soil cement) was first used in 1935 to improve soil strength (Korakod, 2017) for highway construction (Das, 1990; Mitchell et al., 1959). The strength of soil cement, including fine-grained soil and coarse-grained soil, was assessed by California

---

[1] Assistant Professor, Department of Civil Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, 1 Soi Chalongkrung 1, Chalongkrung Rd., Ladkrabang, Bangkok 10520, THAILAND. E-mail: salisa.fern@gmail.com; salisa.ch@kmitl.ac.th
[2] Professor Emeritus, Asian Institute of Technology, Pathumthani, THAILAND 12120, E-mail: dbergado@gmail.com
[3] Assistant Professor, School of Ceramic Engineering, Institute of Engineering, Suranaree University of Technology, 111, University Avenue, Suranaree District, Muang, Nakhon Ratchasima 30000, THAILAND. E-mail: jiratchaya@sut.ac.th
Note: Discussion on this paper is open until June 2020

bearing ratio and unconfined compressive strength test (PCA, 1956; Austroads, 2006; Naeini et al., 2012; Saha and Pal, 2013; and Esklsar, 2015). According to Zang and Tao (2018), the unconfined compressive strength of soil is subject to water cement (w/c) ratio and curing time (Lorenzo and Bergado, 2004; Hong, 2017).

Garber et al. (2011) experimented using a mixture of crushed rock, cement, and water (i.e., cement treated base (CTB)) for pavement structure by varying cement content between 3% - 8% by aggregate weight, depending on the required strength. According to Austroads (2010), cement contents of 4 – 5% by CTB aggregate weight resulted in a modulus of 500 MPa - 5000 MPa. Thus, lower cement contents are suitable for coarse grained soil and high cement contents for fine grained soil.

The increasing of CTB cement content contributed to stiff base material and susceptibility to brittleness (Abboud, 1973; Sariosseiri and Muhunthan, 2009). According to Scullion (2002), reductions in CTB volume induced cracks in the CTB layer that effected to the damage of pavement surface. This means that the cracking became more pronounced with increased cement contents. Therefore, the cement stabilization is banned for road construction in many countries (Guthrie et al., 2002). Besides, previous research investigated the mechanism to minimize CTB cracking damage (Norling, 1973; Wang, 1973; Teng, and Fulton, 1974, Mohammad, 2006).

In addition, polymer materials with high-elastic-modulus was incorporated in soil to mitigate the brittle crack (Wang et al., 2016). According to Ding et al. (2009), polymer chain possessed efficient film forming and adhesive properties. The polymer improved the flexibility, durability, and water proofing of soil cement (Ohama, 1987; Fowler, 1999; Daniels et al., 2003; Daniels and Inyang, 2004; Newman and Tingle, 2004; Gemert et al., 2005; Al-Khanbashi and Abdalla, 2006; Mirzababaei et al., 2007; and Menhosh et al., 2018). Page (2006) experimentally applied spraying poly(vinyl alcohol) to enhance the stability of clay soils and subjected to simulated heavy rain. Mirzababaei et al. (2009) investigated the effect of poly(methyl methacrylate) (3-10%) and poly(vinyl acetate) (1-3%) on the free swell potential of different fat clay soils; and reported reduction in free swell potential and formation of aggregated clay-granular matrices with increased polymers.

According to Assaad J.J. (2018), styrene-butadiene rubber below 0.4% of cement mass and polyvinyl acetate below 0.3% of cement mass improved the tensile and adhesive (bonding) properties of the soil cement. Naeini et al. (2012) studied clayey soil mixed with bentonite and various polymer contents (0%, 2%, 3%, 4%, 5% by soil weight), and reported that the strength of treated soil was inversely correlated with plasticity index. Ateş (2013) investigated the effect of vinyl acrylic copolymer and cement on sandy soil by varying the polymer between 1%, 2%, 3%, and 4%; and cement between 10%, 20%, 30%, and 40% by soil dry weight; and documented that the unconfined compressive strength was positively correlated with polymer and cement contents.

From the usefulness of polymer and cement mentioned above, the polymer can improve the flexibility, durability, and water proofing of soil cement. The tensile and adhesive properties of the soil cement have been improved due to the reduction of cracking damage. Therefore, the concurrent use of liquid polymer and Portland cement as a reinforced material in crushed rock pavement base was proposed in the study. The strength of polymer-treated crushed rock (treated crushed rock) and ordinary crushed rock (untreated crushed rock) were characterized and compared. The California bearing ratios of untreated and treated crushed rock were determined under unsoaked and soaked conditions in order to simulate the post-flood pavement damage. Furthermore, the unconfined compressive strength under unsoaked condition was evaluated and reported under variable curing durations from 2h to 28 days.

2. Experimental Setup and Methodology

2.1 Atterberg's limits soil classification of untreated crushed rock

The liquid limit, plastic limit, and plasticity index of untreated crushed rock were characterized using Atterberg's limits test in accordance with ASTM D4318. In this research, the liquid limit (LL) is the water content that transforms untreated crushed rock from liquid state to plastic state, and the plastic limit (PL) from plastic state to semisolid state. The plasticity index (PI) is the difference between LL and PL of untreated crushed rock.

In LL analysis, 15 g of untreated crushed rock was first mixed with tap water and deposited in the cup of Casagrande liquid limit device and the surface smoothened. In this research, the initial moisture content was 17.46%. In the analysis, the cup was dropped 10 mm on the hard rubber base at a rate of 2 blows/second and terminated when the groove closes a distance of 12.7 mm and the number of blows recorded. A small sample of untreated crushed rock was taken, and the water content determined.

At the 17.46% moisture content, the number of blows at the groove closed a distance of 12.7 mm was 42. According to ASTM D4318, the LL of a material is the water content corresponding to 25 blows. Thus, the moisture content was further increased and varied between 17.85%, 18.14%, 18.73%, and 19.23%, with the corresponding number of blows of 32, 26, 18, and 13 blows, respectively. The LL of untreated crushed rock corresponding to 25 blows was 18.22%.

In PL analysis, 15 g of moist untreated crushed rock was manually rolled into cylindrical shape of 3 mm in diameter and continued until cracks developed. The roll was oven-dried and PL determined. The experiments were carried out in triplicate. The average PL of untreated crushed rock was 13.72%. The PI (from LL-PL) of untreated crushed rock was 4.50%.

2.2 Sieve analysis

Sieve analysis was carried out to determine the distribution of particle sizes of untreated crushed rock in accordance with ASTM D-421. In the analysis, 2000 g of untreated crushed rock was shaken by a series of sieves (from top to bottom): 2" (50.00 mm) (sieve identification (opening size)), 1" (25.00 mm), 3/8" (9.50 mm), #4 (4.75 mm), #10 (2.00 mm), #40 (0.425 mm), and #200 (0.075 mm). After sieving, the weight of particles retained on each sieve in relation to total sample weight was determined and expressed in percentage.

Figure 1 illustrates the grain size distribution of untreated crushed rock as a function of the percentage of passing by weight and the size of particle by diameter. Specifically, the untreated crushed rock passing sieve no. 2”, 1”, 3/8”, #4, #10, #40, and #200 were 100%, 98.65%, 84.40%, 69.19%, 43.77%, 17.75%, and 4.99%, respectively. In the figure, the 10% (D_{10}), 30% (D_{30}), and 60% (D_{60}) passing by weight were 0.18 mm, 1.00 mm, and 3.50 mm. The coefficient of uniformity (C_u) and coefficient of gradation (C_c) are a function of D_{10}, D_{30}, and D_{60} as:

$$C_u = D_{60}/D_{10} \qquad [1]$$

$$C_c = (D_{30})^2/(D_{10} \times D_{60}) \qquad [2]$$

where $C_u > 4$ and $C_c \approx 1\text{-}3$ denote well-graded gravel, $C_u > 6$ and $C_c \approx 1\text{-}3$ well-graded sand, and $C_u \approx 1$ poor-graded sand. In this research, C_u and C_c of untreated crushed rock were 19.44 and 1.59.

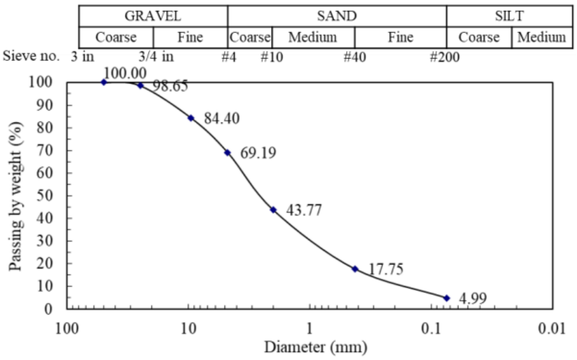

Fig. 1. Grain size distribution curve of crushed rock

According to the unified soil classification system (USCS), the particle passing sieve #200 less than 50% is classified as coarse-grained soil (gravel or sand). Sieve #4 is subsequently used to classify between gravel and sand, where the particle retained on sieve #4 >50% is classified as gravel and <50% as sand. In this research, the particles of untreated crushed rock passing sieve #200 and #4 were 4.99% (<50%) and 69.19% (>50%), respectively, indicating that the untreated crushed rock was sand. Given $C_u = 19.44$ and $C_c = 1.59$, the experimental untreated crushed rock was of well-graded sand ($C_u > 6$ and $C_c \approx 1\text{-}3$).

According to the American Association of State Highway and Transportation Officials (AASHTO), the maximum percent passing sieve #10, #40, and #200 are 50%, 30%, and 15%. In this research, the percent passing sieve #10, #40, and #200 of the untreated crushed rock were 43.77%, 17.75%, and 4.99%, which is classified as A-1-a. The untreated crushed rock is thus of high quality as pavement base material.

2.3 Portland cement

Portland cement (Type 1, TPI) was composed of MgO, SO_3, $3CaO.SiO_2$, $3CaO.Al_2O_3$. The physical properties of Portland cement consisted of 3500 cm^2/g fineness, and 0.01% soundness.

2.4 Liquid polymer

The experimental liquid polymer was vinyl copolymer emulsion (Soiltac, Soilworks LLC) of milky white color, pH 4.5-6.0, a specific gravity of 1.05-1.10, evaporation rate < 1 (BuAc = 1), vapor density > 1, boiling point > 100 °C, freezing point < 0 °C, and completely (100%) of solubility in water as detailed in Table 1.

Table 1. Physical properties of experimental liquid polymer

Property	Characteristics/Value
Physical State	Liquid polymer
Color	Milky White color
Component	Vinyl Copolymer Emulsion
pH	4.5-6.0
Specific Gravity	1.05 to 1.10.
Evaporation Rate	< 1 (BuAc = 1)
Vapor Density	> 1 (Air = 1)
Boiling Point	> 100 °C (< 212 °F)
Freezing Point	< 0 °C (< 32 °F)
Solubility in Water	Completely (100%) (until cured)

2.5 Testing condition

The polymer was first diluted (10.5 cc/390 g tap water) and mixed with Portland cement (Type 1, TPI) and crushed rock for the treated crushed rock. The ratio of diluted polymer to Portland cement was 5 g:100 g, and cement to crushed rock was 3.5 g:100 g.

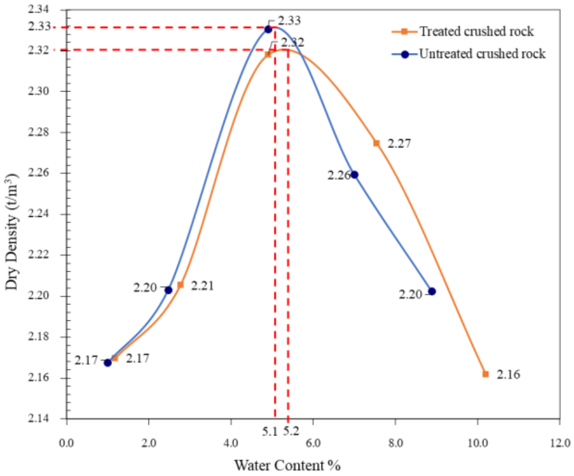

Fig. 2. The compaction curve of untreated and treated crushed rock as a function of dry density and water content

2.6 *Compaction test*

According to ASTM D1557, the modified proctor compaction is a function of the dry density and water content of a material. In compaction analysis, this research determined the maximum dry density ($\gamma_{d, max}$) and optimal water content (OWC) of untreated and treated crushed rock, and the OWC was subsequently used for analysis of California bearing ratio (CBR) and unconfined compressive strength (UCS).

In the preparation of untreated and treated crushed rock samples, tap water of arbitrary amounts (i.e., five variations each for untreated and treated crushed rock) was added to the crushed rock and manually mixed until the color and texture became uniform. The mixture was transferred to cylindrical molds of 152.4 mm in diameter in sequential order of five equal amounts of crushed rock (to the mold top surface). Each layer of crushed rock was compacted 56 blows, using a 44.48 N hammer dropping from a height of 457.2 mm, equivalent to 2700 kN-m/m^3 compaction effort (approximately 4.5 times that of the standard proctor test), before subsequent layer was deposited into the mold and the procedure repeated.

The molds containing compacted crushed rock were weighted and the content extruded by an ejector, oven-dried, and the water content determined. The water contents of untreated crushed rock were 1.01%, 2.48%, 4.90%, 7.01%, and 8.89%, and the corresponding dry densities were 2.17 t/m^3, 2.20 t/m^3, 2.33 t/m^3, 2.26 t/m^3, and 2.20 t/m^3, respectively. Meanwhile, those of treated crushed rock were 1.19%, 2.77%, 4.90%, 7.55%, and 10.20%, and the dry densities were 2.17 t/m^3, 2.21 t/m^3, 2.32 t/m^3, 2.27 t/m^3 and, 2.16 t/m^3, respectively.

Figures 2 illustrate a bell-shape of the compaction curves of untreated and treated crushed rock as a function of water content and dry density, whose peak represents the $\gamma_{d, max}$ at the OWC value. This compaction curve behavior can be attributed to the water lubrication resulting in minimized surface tension and space between adjacent soil particles. A rearrangement of the soil particles simultaneously took place and increased the density of soil mixtures up to the optimum moisture content. At the OWC point (at the top of peak), the maximum dry density was obtained indicating that the adjacent particles are very close leaving a space as small as possible. From the result, the $\gamma_{d, max}$ of untreated and treated crushed rock were 2.33 t/m^3 (OWC = 5.10%) and 2.32 t/m^3 (OWC = 5.20%). OWC is a similarity between untreated and treated crushed rock, this means that liquid polymer and Portland cement have no effect on the OWC of treated crushed rock.

2.7 *California bearing ratio*

California bearing ratio (CBR) describes the strength of a material in relation to the bearing capacity of well-graded crushed rock whose CBR is 100% at the maximum dry density. The bearing capacity of a material is governed by water content, dry density, and material type. In this research, the CBR of untreated and treated crushed rock is subject to ASTM D1883.

In CBR analysis, the untreated and treated crushed rock passing sieve#4 were mixed with tap water (5.10% and 5.20% OWC, respectively) and kneaded. The rocks were transferred to cylindrical molds of 152.4mm inner diameter and 177.8 mm in height (three molds each for untreated and treated crushed rock) in sequential order of five equal amounts of crushed rock (to the mold top surface). Each layer of crushed rock was compacted 10, 25, and 56 blows, using a 44.48 N hammer dropping from a height of 457.2 mm, before subsequent layer was deposited into the mold and the procedure repeated. The crushed rock samples were subjected to axial loading by a penetration test machine with 50 kN maximum capacity and 0.00001 - 5.99999 mm/min speed (CONTROLS Triaxial tester T400 Digital).

In penetration testing, a 10-pound surcharge weight, comprising two five-pound circular discs, was placed on top of the surface of untreated and treated crushed rock (unsoaked samples). A steel penetration piston of 50 mm in diameter connected to proving ring was inserted through the center point and penetration carried out at a rate of 1.27 mm/min. The load measurements corresponding to the following deformation were taken:

0.64 mm, 1.27 mm, 1.91 mm, 2.54 mm, 3.18 mm, 3.81 mm, 4.45 mm, 5.08 mm, 7.62 mm, 10.16 mm, and 12.70 mm. The untreated and treated crushed rock samples were removed from the mold and the top-layer water content determined.

The swelling behavior of untreated and treated crushed rock were characterized under soaked condition to simulate flooding whereby the crushed rock samples (in the mold) loaded with 10-pound surcharge weight were submerged for 96 h prior to penetration test. The submersion enabled free access of water throughout the crushed rock samples. The swelling after 96 h-submersion was calculated by:

$$\%\,\text{swell} = \left[\frac{\text{Sample extension during soaking (in.)}}{4.584\,\text{(in.)}}\right]\times 100 \qquad [3]$$

The soaked crushed rock samples were removed from the water tank and dried for 15 min prior subjecting to axial loading by the penetration test machine, following the same procedure as the unsoaked crushed rock samples.

The load and deformation at 0.2-inch penetration depth under unsoaked and soaked conditions were converted into CBR of untreated and treated crush rock. The resulting CBR were compared against that of standard crushed rock at 0.2-inch penetration depth (i.e., 1500 psi). The CBR can thus be expressed as

$$\text{CBR (\%)} = \left[\frac{\text{Test unit load}}{\text{Standard unit load}}\right]\times 100 \qquad [4]$$

2.8 Unconfined compressive strength

In this research, unconfined compressive strength (UCS) was determined for treated crushed rock under variable curing periods, in accordance with ASTM D2166. In UCS analysis, 6000 g of treated crushed rock was first oven-dried and mixed with Portland cement (210 g) and diluted polymer (10.5 cc liquid polymer / 390 g tap water). Tap water (at 5.20% OWC) was added to the mixture for maximum dry density (2.32 t/m^3), as shown in Figure 3.

Fig. 3. Sample preparation for unconfined compressive strength (UCS) experiment

The mixture was transferred to cylindrical molds in sequential order of five equal amounts of crushed rock (to the mold top surface). Each layer of crushed rock was compacted 56 blows, using a 44.48 N hammer dropping from a height of 457.2 mm, before subsequent layer was deposited into the mold and the procedure repeated. The crushed rock samples were extruded from the mold and cured in open air environment for 2 h, 1 day, 3 days, 7 days, and 28 days. The experiments were carried out in triplicate. The diameter and height of cured samples were measured by Vernier caliper, and the weight taken.

The UCS of cured treated crushed rock samples were determined using UCS test machine with 2000 kN maximum capacity (K. Thaithamrong Engineering, KC-2000 model). The load measurement was taken every 0.1 mm deformation until visible cracks were about 20% of sample height.

3. Results and discussions

Table 2 demonstrates the CBR of untreated and treated crushed rock under unsoaked and soaked conditions, given 10, 25, and 56 blows. Figure 4 compares the CBR of untreated crushed rock under soaked and unsoaked conditions. Under the unsoaked condition, the CBR at $\gamma_{d,max}$ of 2.03 t/m^3 (10 blows), 2.15 t/m^3 (25 blows), and 2.29 t/m^3 (56 blows) were 75.74%, 119.46%, and 218.58%, respectively. Under the soaked condition, the CBR at $\gamma_{d,max}$ of 2.12 t/m^3 (10 blows), 2.23 t/m^3 (25 blows), and 2.35 t/m^3 (56 blows) were 104.46%, 152.50% and 157.84%, respectively.

In Figure 4, the unsoaked CBR of untreated crushed rock was positively correlated to compaction blows. Meanwhile, the CBR of soaked untreated crushed rock, given 10, 25, and 56 compaction blows, were similar, suggesting that compaction blows have minimal effect on the CBR. The achievable maximum dry density, given any OWC, is 95%. Thus, $\gamma_{d,max}$ of untreated crushed rock was 2.215 t/m^3 (i.e., 95% of $\gamma_{d,max}$ of 56 modified compaction blows). The CBR of unsoaked and soaked

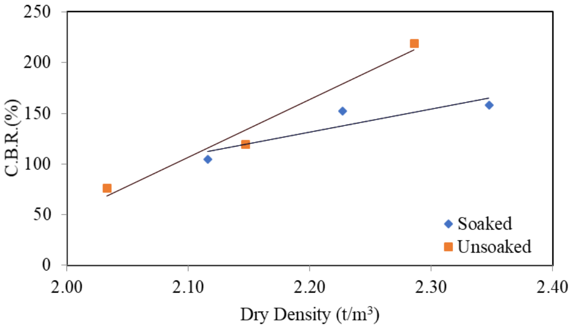

Fig. 4. California bearing ratio (CBR) of untreated crushed rock under unsoaked and soaked conditions

Table 2. Comparison between untreated and treated crushed rock under unsoaked and soaked conditions given 10, 25, and 56 compaction blows

No.of Blows	Unsoaked			Soaked		
	Density	C.B.R. (%)		Density	C.B.R. (%) / Swell (%)	
	(t/m^3)	Untreated crushed rock	Treated crushed rock	(t/m^3)	Untreated crushed rock	Treated crushed rock
10	2.03	75.74	80.83	2.12	104.46 / 0.00	292.80 / 0.00
25	2.15	119.46	135.47	2.23	152.50 / 0.00	297.38 / 0.00
56	2.29	218.58	220.45	2.35	157.84 / 0.00	328.64 / 0.00

untreated crushed rock, given $\gamma_{d,max}$ of 2.215 t/m^3, were 172.87% and 135.21%, respectively. The strength of material is directly affected by water content. Specifically, the CBR of untreated crushed rock decreased once submerged in water for an extended time period (96 h) because the water was absorbed into the soil particles of untreated crushed rock and decreased the CBR. This explains the post-flood damage to untreated pavement.

Figure 5 illustrates the CBR of treated crushed rock under unsoaked and soaked conditions. The unsoaked CBR at $\gamma_{d,max}$ of 2.03 t/m^3 (10 blows), 2.15 t/m^3 (25 blows), and 2.29 t/m^3 (56 blows) were 80.83%, 135.47%, and 220.45%, respectively. The soaked CBR at $\gamma_{d,max}$ at 2.12 t/m^3 (10 blows), 2.23 t/m^3 (25 blows), and 2.35 t/m^3 (56 blows) were 292.80%, 297.38%, and 328.64%, respectively. Given the achievable maximum dry density of 95% of modified proctor compaction, $\gamma_{d,max}$ of treated crushed rock was also 2.215 t/m^3 (95% of $\gamma_{d,max}$ of 56 modified compaction blows). The unsoaked and soaked CBR were 179.83% and 307.72%, respectively. The soaked CBR of treated crushed rock was higher than that under the unsoaked condition, indicating that the use of liquid polymer and Portland cement improved the strength of treated crushed rock. The polymer produced the film for wrapping the soil particle, therefore water cannot absorb into the soil particles of treated crushed rock to decrease the CBR under soaked condition. In other words, the properties of treated crushed rock under soaked condition were nearly similar as the properties of treated crushed rock under unsoaked condition. Furthermore, the strength of Portland cement was continuously developed with increasing curing time.

Figure 6 compares the CBR of untreated and treated crushed rock under unsoaked condition. The unsoaked CBR of untreated and treated crushed rock of 10, 25, and 56 compaction blows were almost identical, suggesting that the treatment has minimal effect on crushed rock strength under unsoaked condition. Figure 7 compares the CBR of untreated and treated crushed rock under soaked condition (96 h). The soaked CBR of untreated crushed rock of 10, 25, and 56 compaction blows were 104.46%, 152.50%, and 157.84, while the CBR of treated crushed rock with those three compaction blows were 292.80%, 297.38% and 328.64%. The soaked CBR of treated crushed rock was approximately twice as high as that of untreated crushed rock due to the polymerization and cementation effects. The polymer chain generated efficient film wrapping the soil particle, which increased adhesive properties and decreased water absorption. Moreover, the strength of Portland cement increased with increasing curing time.

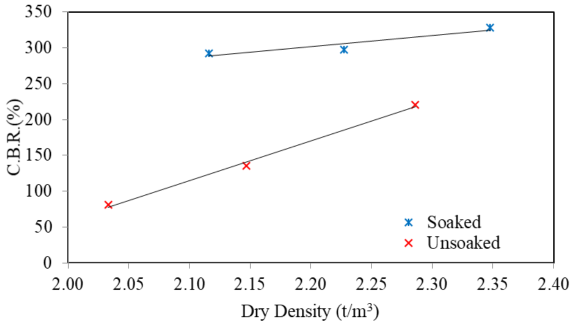

Fig. 5. California bearing ratio (CBR) of treated crushed rock under unsoaked and soaked conditions

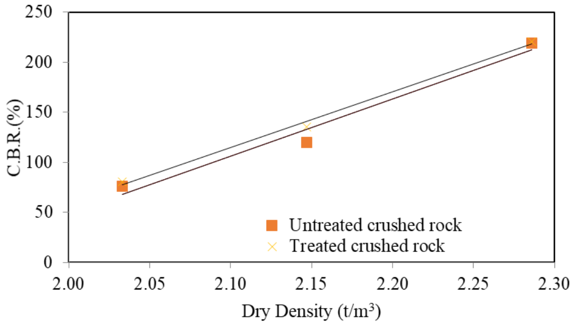

Fig. 6. CBR of untreated and treated crushed rock under unsoaked condition

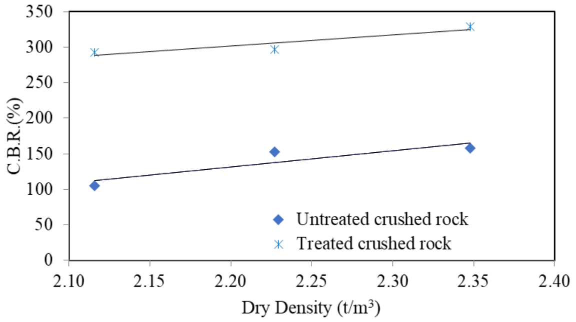

Fig. 7. CBR of untreated and treated crushed rock under soaked condition

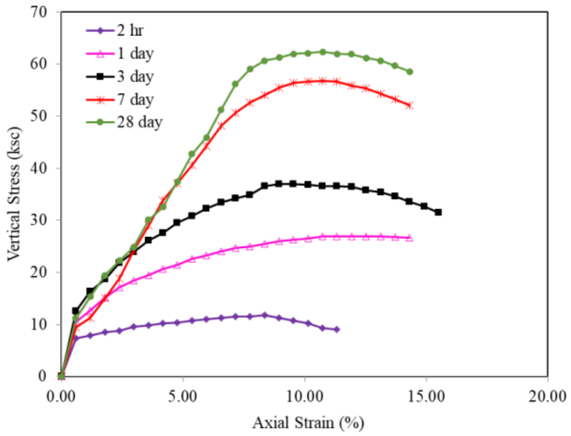

Fig. 8. Stress-strain relationship of treated crushed rock given variable curing durations

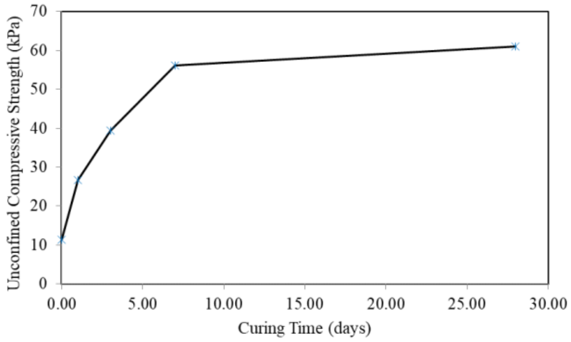

Fig. 9. Unconfined compressive strength (UCS) of treated crushed rock relative to curing time

Table 2 presents the swelling index of untreated and treated crush rock under soaked condition, and the swelling indices were 0% for untreated and treated samples. This indicates that liquid polymer and Poland cement have no impact on the crushed rock submerging in water. Figure 8 shows the UCS of treated crushed rock as a function of vertical stress and axial strain, given open-air curing periods of 2 h, 1 day, 3 days, 7 days, and 28 days. Each experiment was carried out in triplicate. Figure 9 depicts the average UCS of treated crushed rock relative to curing time: 11.41 ksc, 26.63 ksc, 39.38 ksc, 56.10 ksc, and 60.98 ksc for 2-h, 1-, 3-, 7-, and 28-day curing periods, respectively. The highest UCS of treated crushed rock was achieved under 28-day curing time, followed by 7 days, 3 days, 1 days, and 2 h. The UCS accelerated during the initial 7 days and increased at a decreasing rate beyond 7 days, suggesting that the optimal curing time of treated crushed rock was 7 days. The compressive strength of treated crush rock was usual behavior of cement-treated materials as more water evaporated.

4. Conclusions

This research proposed the concurrent use of liquid polymer and Portland cement as a reinforced material in crushed rock pavement base for road construction. The strength of polymer-treated crushed rock was evaluated in relation to ordinary (untreated) crushed rock. The California bearing ratio (CBR) of untreated and treated crushed rock under unsoaked and soaked conditions were investigated and reported along with the unconfined compressive strength (UCS) under unsoaked condition, given 2-h, 1-day, 3-day, 7-day, and 28-day curing periods. The soaked condition simulated the post-flood pavement damage. The findings are as follows:

1. The CBR of untreated and treated crushed rock under soaked and unsoaked conditions were positively correlated with dry density.
2. Under the unsoaked condition, the CBR of untreated crushed rock was almost identical to that of treated crushed rock. However, under the soaked condition, the CBR of treated crushed rock was twice as high as that of untreated crushed rock due to the polymerization and cementation effects. Importantly, the CBR of untreated crushed rock decreased when submerged under water for an extended period, whereas treated crushed rock substantially increased once submerged.
3. The swelling indices were 0% for untreated and treated samples. The liquid polymer and Portland cement had no impact on the swelling index of the crushed rock under submerged condition.
4. The UCS of treated crushed rock was positively correlated to the curing time. The UCS increased rapidly during the first 7 days and increased with a decreasing rate after 7 days. The optimal curing time of treated crushed rock was 7 days.

In essence, the concurrent use of liquid polymer and Portland cement improved the strength of crushed rock as pavement base material. Furthermore, the polymer-treated crushed rock could effectively mitigate the post-flood pavement damage.

Acknowledgements

This research was supported by King Mongkut's Institute of Technology Ladkrabang Research Fund (KREF016105). Institute of Engineering, Suranaree University of Technology was also acknowledged.

References

Abboud, M. M., 1973. Mechanical properties of cement-treated soils in relation to their use in embankment construction. Ph. D dissertation, University of California, Berkeley, CA.

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

Assaad, J.J., 2018. Development and use of polymer-modified cement for adhesive and repair applications. Construction and Building Materials, **163** (28): 139-148.

Ateş, A., 2013. The effect of polymer-cement stabilization on the unconfined compressive strength of liquefiable soils. International Journal of Polymer Science.

Austroads, 2010. Guide to pavement technology par 2: pavement structural design. Austroads, Sydney.

Austroads, 2010. Guide to pavement technology part 4D: Stabilised materials. AGPT04D-06, Austroads, Australia.

Chummuneerat, S., 2014. Performance, evaluation, and enhancement of hydrated cement treated crushed rock base (HCTCRB) as a road base material for Western Australian roads Bentley. Ph.D. Thesis, Curtin University, WA, Australia.

Daniels, J. L. and Inyang, H. L., 2004. Contaminant barrier material textural response to interaction with aqueous polymers. Journal of Material and Civil Engineering, **16** (3): 265-275.

Daniels, J. L., Inyang, H. I., and Iskandar, I. K., 2003. Durability of Boston blue clay in waste containment applications. Journal of Material and Civil Engineering, **15** (2):144-155.

Das, B.M., 1990. Principle of foundation engineering. PWS-KENT, Boston.

Department of Highways., 2013. Cement modified crushed rock base. Standard No.DH-S 203/2556, Bangkok, Thailand.

Ding, B., Kim, H., Lee, S., Shao, C., Lee, D., Park, S., and Choi, K., 2002. Preparation and characterization of a nanoscale poly(vinyl alcohol) fiber aggregate produced by an electrospinning method. Journal of Polymer Science Part B: Polymer Physics, **40** (13): 1261-1268.

Esklsar, T., 2015. Influence of cement treatment on unconfined compressive strength and compressibility of lean clay with medium plasticity. Arabian Journal for Science and Engineering, **40** : 763-772.

Fowler, D.W., 1999. Polymers in concrete: a vision for the 21st century. Cement Concr. Compos, **21** (5): 449–452.

Garber, S., Rasmussen, R.O., and Harrington, D., 2001. Guide to cement-based integrated pavement solutions. Portland Cement Association, Skokie.

Gemert, D. V., Czarnecki, L., Maultzsch, M, 2005. Cement concrete and concrete–polymer composites: two merging worlds. Cement Concr. Compos. **27** (9-10): 926–933.

Guthrie, W. S., Sebesta, S., and Scullion, T., 2002. Selecting optimum cement contents for stabilizing aggregate base materials. Report 4920-2. Texas Transportation Institute, Texas A&M University System, College Station, TX.

Hong, S., 2017. Influence of curing conditions on the strength properties of polysulfide polymer concrete. Applied Sciences. **7** (8): 833.

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W., Rachan, R., 2006. Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. Soils and Foundations, **46** (3): 351-366.

Korakod, N., Jitsangiam, P., Kodikara, J., Bui, H.H., 2017. Advanced characteristics of cement-treated materials with respect to strength performance and damage evolution. Journal of Materials in Civil Engineering, **29** (4): 04016255.

Lorenzo, G. A. and Bergado, D. T., 2004. Fundamental parameters of cement-admixed clay new approach. Journal of Geotechnical and Geoenvironmental Engineering, **130**: 1042-1050.

Menhosh, A.M., Wang, Y., Wang, Y., and Augusthus-Nelson, L., 2018. Long term durability properties of concrete modified with metakaolin and polymer admixture. Construction and Building Materials, 172: 41-51.

Mirzababaei M., Arulrajah M., and Ouston M., 2017. Polymers for Stabilization of Soft Clay Soil. Procedia Engineering, **189**: 25-32.

Mirzababaei, M., Yasrobi, S., and Al-Rawas, A., 2009. Effect of polymers on swelling potential of expansive soils. Proceedings of the ICE Ground Improvement, **162** (3): 111-119.

Mitchell, James K., and Dean R. Freitag., 1959. A review and evaluation of soil-cement pavements. Journal of the Soil Mechanics and Foundation Division, American Society of Civil Bngineers, **85** (SM 6): 49-73.

Mohammad, J.K., 2006. Durability and mechanistic characteristics of fiber reinforced soil-cement mixtures. The International Journal of Pavement Engineering, **7** (1): 53-62.

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

Newman, K. and Tingle, J. S., 2004, Emulsion polymers for soil stabilization. In FAA Worldwide Airport Technology Transfer Conference, Atlantic City, New Jersey.

Norling, L. T., 1973. Minimizing reflective cracks in soil-cement pavements: A status report of laboratory studies and field practices." In Highway Research Record 442, TRB, National Research Council, Washington, D.C.: pp. 22- 33.

Ohama, Y., 1987. Principle of latex modification and some typical properties of latex-modified mortars and concretes adhesion; binders (materials); Bond (paste to aggregate); carbonation; chlorides; curing; diffusion. ACI Mater. J, **84** (6): 511–518.

Page, E.R., 2006. The effect of poly(vinyl alcohol) on the crust strength of silty soils. European Journal of Soil Science, **30** (4); 643-51.

PCA. 1956. Soil-cement laboratory handbook. Portland Cement Association, Chicago, Illinois.

Puppala, A.J., 2016. Advances in ground modification with chemical additives: from theory to practice. Transportation Geotechnics, **9**: 123-138.

Sariosseiri, F. and Muhunthan, B., 2009. Effect of cement treatment on geotechnical properties of some Washington State soils. Engineering Geology, **104 (**1-2): 119-125.

Saha, S. and Pal, S.K., 2013. Influence of fly ash on unconfined compressive strength of soil and fly ash layers placed successively. The Electronic Journal of Geotechnical Engineering, **18**:1593-1602.

Scullion, T., 2002. Field investigation: Pre-cracking of soil-cement bases to reduce reflection cracking. In Transportation Research Board 81st Annual Meeting Compendium of Papers. CD-ROM. TRB, National Research Council, Washington, D.C.

Teng, T. C., and Fulton. J. P., 1974. Field evaluation program of cement-treated bases. In Transportation Research Record 501, TRB, National Research Council, Washington, D.C.: pp. 14-27.

Wang, M., Wang, R., Yao, H., Farhan, S., Zheng, S., Wang, Z., Du, C., and Jiang, H., 2016. Research on the mechanism of polymer latex modified cement. Construction and Building Materials,111 :710-718.

Wang, J. W. H., 1973. Use of additives and expansive cements for shrinkage crack control in soil cement: A review. In Highway Research Record 442, TRB, National Research Council, Washington, D.C.: pp 11-21.

Zhang, Z., and Tao, M., 2008. Durability of cement stabilized low plasticity soils”. Journal of Geotechnical and Geoenvironmental Engineering, **134** (2): 203–213.