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Research Article

Physical and Mechanical Properties of Carboxylated Styrene-butadiene Emulsion Modified Portland Cement Used in Road Base Construction

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Abstract

Objective: The effects of type and amount of portland cement as a traditional additive and carboxylated styrene-butadiene emulsion (Rovene® 4045) as a non-traditional additive on the short-term and long-term performance of road base layer were investigated using laboratory mechanistic evaluation of stabilized soil-aggregate mixtures. **Methodology:** Cylindrical specimens were stabilized with portland cement (0-6%), Rovene® 4045 (5-10%); then, the specimens were molded; cured for 7, 28 and 60 days and then subjected to different stress sequences to study their unconfined compressive strength, indirect tensile strength and indirect tensile resilient modulus. The long-term performance (durability) of stabilized soil-aggregate specimens was investigated by conducting wetting and drying (WD) cycling tests on 7 days cured specimens. **Results:** The WD cycling tests showed that the addition of a 4% portland cement 7% Rovene® 4045 mixture resulted in a 410.6% improvement in water absorption, a volume change of 498.18% and a weight change of 1012% as compared to the sample with 4% cement after 12 WD cycles. **Conclusion:** This study presents the finding of a correlation conducted to determine the influences of affective variables using non-linear regression analysis to establish significant models with the aim of predicting the strength based on mixture parameters.

Key words: Portland cement, non-traditional additive, stabilized, long-term performance, durability

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

For road bases, there are a variety of soils or granular materials available for construction, but they may exhibit insufficient properties (e.g., low bearing capacity, susceptibility to frost damage, etc.) which then results in substantial pavement distress and reduction of pavement life. However, the addition of a stabilizing agent can improve the properties of soil. Soil stabilizers are categorized as traditional and non-traditional. Traditional additives include cement, lime, fly ash and bituminous materials, while non-traditional additives include enzymes, liquid polymers, resins, acids, silicates, ions and lignin derivatives. Among these different stabilized materials, Cement Treated Base (CTB) develops significantly high stiffness and strength and exhibits good service ability and high durability for pavement. Since 1917, several experimental studies have been published on cement-treated soil[1-7]. In other hand, polymer stabilizers are typically vinyl acetates or acrylic copolymers suspended in an emulsion by surfactants. The polymer stabilizer coats soil particles and physical bonds are formed when the emulsion water evaporates, leaving a soil-polymer matrix. The emulsifying agent can also serve as a surfactant, improving penetration for topical applications and particle coating for admix conditions. The use of polymers, since the early 1980s, as modifiers in new structures seems to be a significant effect in increasing the durability and improving microstructure of mixtures[8-12]. The molecular structure of Styrene Butadiene Emulsion (SBE) comprises both the rigid styrene chains and the flexible butadiene chains, the marriage of which gives SBE-modified soil-cement many admirable specifications such as water absorption, good mechanical properties and erosion resistance. Previous studies have indicated that the admixing of SBE latex into the mixture has a significant effect on the work ability of the mixture and improve its resistance to chloride ion penetration[13-18]. The literature usually refers to the more commonly used styrene-butadiene polymer materials. These materials are known to possess superior durability over portland-cement-based concrete, recognized by resistance to acid attack, ice-melting, soil-cement loss, water and volume change and chloride diffusion. Several authors have shown that polymer impregnation of soil-cement materials may lead to increased durability depending of the type of polymers used[11,13,19-22]. A cement-SBE-treated base (CSBETB) can provide cost-effective solutions to many common designs and construction situations and provide additional strength and support without increasing the total thickness of the pavement layers. Depending on project needs, CSBETB can increase construction speed and enhance the structural capacity of the pavement. In addition, a stiffer base reduces deflections due to heavy traffic loads, thereby extending pavement life[4,23-29]. Moreover, CSBETB can distribute loads over a wider area and reduce the stresses on the subgrade. It has a high load-carrying capacity, does not consolidate further under load, reduces rutting in hot-mix asphalt pavements and is resistant to freeze-thaw, wetting-drying deterioration[30-32]. The focus of this study is to assess the effected variables on the performance and strength of cement-Rovene® 4045-treated base (CRTB) based on laboratory tests for Indirect Tensile Strength (ITS), Unconfined Compressive Strength (UCS), Indirect Tensile Resident Modulus (ITRM) and wetting and drying (WD), which are the most frequently employed methods to evaluate the quality of road base stabilization. Another purpose was to determine the optimum of portland cement and Rovene® 4045 content. The last and most important aim was to assess and compare the effects of these additives on CRTB using significant predicting models.

MATERIALS AND METHODS

Standard requirements for graded soil aggregate use in bases of highways: Quality-controlled graded aggregates are expected to provide appropriate stability and load support for use as highway or airport bases or sub-bases. This requirement delineates the aggregate size, variety and ranges of mechanical analysis results for qualified sizes of aggregate and screenings for use in the pavement construction and maintainance of several types of highways. The gradation of the final composite mixture is required to conform to an approved job mix formula within the design range prescribed in Table 1 according to ASTM D 448, ASTM D 1241 and ASTM D 2940, subject to the appropriate tolerances.

Strength requirements for mixed stabilized material: After obtaining the fitting aggregates and choosing the initial cement content by weight, the specimens were prepared according to their optimum dry density and the maximum moisture composition. The average UCS of the cement-treated specimens after 7 days curing time was obtained using a hydraulic compressive strength testing machine. Table 2 lists the UCS requirements of CTB after 7 days of curing. It must be observed that the UCS requirements depend strongly on the road class and material type relies heavily on the required UCS.

Experimental methods: To achieve the goals of this study, three major tasks-a literature review, laboratory investigation and data processing and analysis were accomplished. The soil-aggregate properties were evaluated prior to the design

Table 1: Grading requirements for final mixtures[33]

	Design range (mass percentages passing)		Job mix tolerances	
Sieve size (square openings)	Bases	Sub-bases	Bases	Sub-bases
50 mm (2 inch)	100	100	-2	-3
37.5 mm (11/2 inch)	95-100	90-100	±5	+5
19.0 mm (3/4 inch)	70-92	NA	±8	NA
9.5 mm (3/8 inch)	50-70	NA	±8	NA
4.75 mm (No. 4)	35-55	30-60	±8	±10
600 µm (No. 30)	12-25	NA	±5	NA
75 µm (No. 200)	0-8	0-12	±3	±5

Table 2: Strength requirements for CTB

Country	Other research	Compressive strength (MPa)	Cement content (%)	References
	CTB	2-4.13		ACI Committee 230[32], Davidson[34] and Little and Nair[35]
	CTB	5.2		Little and Nair[35] and UFC[36]
	CTB	2-5.5		Garber *et al.*[23]
	CTB	3-6		Freeme *et al.*[25] and DFID[37]
	CTB	Min-3.44		Gaspard[38]
	CTB	Min-4.13		PCA[31]
South Africa		4-8		DFID[37] and SAPEM[39]
United Kingdom		2.5-4.5		BS[40] and Xuan *et al.*[41]
Australia		Min-3		TMRS[42] and Molenaar *et al.*[43]
China		3-5		Molenaar *et al.*[43] and JTJ[44]
New Zealand		Min-3		CCANZ[45]
United States (ASTM)			3-5	Xuan[26], ASTM[33] and Xuan *et al.*[41]
United States (AASHTO)			3-5	Xuan[26], Xuan *et al.*[41] and AASHTO[46]

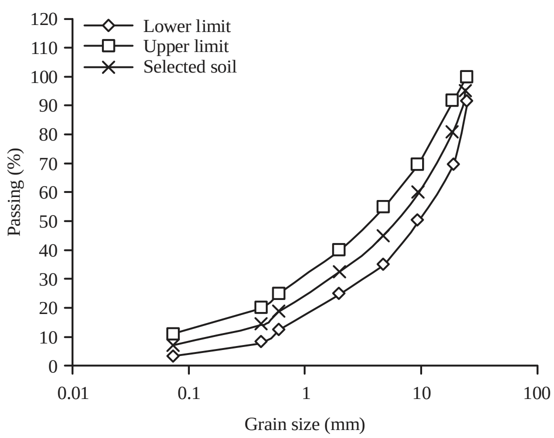

Fig. 1: Grading curves of soil aggregate

of the mixture. The cement used was type II portland cement. The nontraditional stabilizer used, Rovene® 4045, is a water-based liquid emulsion and is a novel additive in this study. To evaluate the short-term performance of the stabilized soil-aggregate specimens under various stress sequences, the UCS, ITS and ITRM tests were determined. The long-term performance of these specimens was investigated by subjecting them to WD cycling (durability). Finally, on the basis of the results of the data analysis, significant models were developed to demonstrate the relationship among the characteristics of the mixture.

Soil aggregate: Crushed granite aggregate from the Kajang Rock Quarry (Malaysia) was used in this research as the granular base layer material. Figure 1 illustrates the grading curves of soil aggregates within the specification limits for highways or/and airports according to the American Society for Testing and Materials (ASTM) standards. One of the most important factors in CTB is organic content and pH. A soil with a pH less than 5.3 and/or an organic content greater than 2%, in all probability is not suitable due to its reaction with cement[32]. If the pH of the mixture is greater than 12.0, it indicates that the organics present will not interfere with hardening[47,48]. In this study, the results of a pH test according to ASTM D 4972 indicated that adding cement to the soil aggregate increases the pH from 8.26-12.13 and adding a cement-Rovene® 4045 mix to the soil aggregate increases the pH from 8.26-12.79. This is a positive effect of additives in the mixture.

The general properties of the used soil aggregates are summarized in Table 3.

Portland cement: Numerous different kinds of portland cement have been used effectively for soil stabilization. In this research, portland cement type II was used as a treatment material for the granular mixtures because of its greater sulfate resistance and moderate heat of hydration compared to another types of portland cement, while the cost is often

Table 3: Properties of soil-aggregates

Property	Requirements	Test result	Test method
Water content (%)	NA	6.621	ASTM D 698
Unit weight (g cm^{-3})	NA	2.19	ASTM D 698
pH	5.3-Min	8.26	ASTM D 4972
Unified classification	NA	GP-GM	ASTM D 2487
AASHTO classification	NA	A-1-a	ASTM D 3282/ AASHTO M 145
Liquid limit (%)	25-Max	21.4	ASTM D 4318
Plastic limit (%)	29-Max	19.6	ASTM D 4318
Plastic index (%)	4-Max	1.8	ASTM D 4318
Coefficient of curvature (C_c)	NA	2.39	ASTM D 2487
Coefficient of uniformity (C_u)	NA	71.5	ASTM D 2487
Group Index	NA	0	ASTM D 3282
Specific gravity (OD)	NA	2.659	ASTM C 127/C 128
Specific gravity (SSD)	NA	2.686	ASTM C 127/C 128
Apparent specific gravity	NA	2.731	ASTM C 127/C 128
Water absorption (%)	2-Max	0.973	ASTM C 127/C 128
Linear shrinkage (%)	3-Max	1.5	BS 1377: Part 2
Elongation index (%)	25-Max	13.03	BS 812: Section 105.2
Flakiness index (%)	25-Max	7.68	BS 812: Section 105.1
Average least dimension (mm)	NA	5.5	BS 812: Section 105.1
Sand equivalent (%)	35-Min	84	ASTM D 2419
Los angeles abrasion (%)	50-Max	17.5	ASTM C131
UCS (MPa)	NA	0.25	ASTM D 2166/D 1633
CBR (%)	80-Min	101.32	ASTM D 1883

Min: Minimum and Max: Maximum

Table 4: Properties of type II portland cement

Component and Properties	Requirements (%)	Test result (%)	Test method
Silicon dioxide (SiO_2)	20 Min	20.18	ASTM C 150- C 114
Aluminum oxide (Al_2O_3)	6.0 Max	5.23	ASTM C 150- C 114
Calcium oxide (CaO)	Not applicable	64.40	ASTM C 150- C 114
Ferric oxide (Fe_2O_3)	6.0 Max	3.34	ASTM C 150- C 114
Magnesium oxide (MgO)	6.0 Max	1.80	ASTM C 150- C 114
Sulfur trioxide (SO_3)	6.0 Max	3.03	ASTM C 150- C 114
Loss on ignition	3.0 Max	2.17	ASTM C 150- C 114
Insoluble residue	0.75 Max	0.18	ASTM C 150- C 114
Na_2O	Not applicable	0.07	ASTM C 150- C 114
K_2O	Not applicable	0.44	ASTM C 150- C 114
Equivalent alkalies ($Na_2O + 0.658\ K_2O$)	0.75 Max	0.3595	ASTM C 150- C 114
Tricalcium aluminate (C_3A)	8 Max	3.21	ASTM C 150- C 114
Tricalcium silicate (C_3S)	Not applicable	53.95	ASTM C 150- C 114
Sum of (C_3S) and (C_3A)	58 Max	57.16	ASTM C 150- C 114
Compressive strength (MPa)			
3 days	10 Min	27.50	ASTM
7 days	17 Min	40.30	C 109/C 109M
28 days	28 Min	57.70	
Fineness, specific surface ($m^2\ kg^{-1}$)			
Air permeability test	280 Min	338.10	ASTM C 204
Autoclave expansion (Soundness)	0.8 Max	0.50	ASTM C 151
Time of setting			
Initial set	60 Min	126.00	ASTM C 266
Final set	600 Min	174.00	

the same. High soil sulfate content results in swell and heave problems and it can have a deleterious influence on cementitious and stabilization mechanisms. In this study, portland cement was required to conform to the respective standard chemical and physical requirements prescribed by ASTM C 150. The cement shall be rejected if it does not meet any of the required specifications. The properties of portland cement are presented in Table 4.

Table 5: Properties of Rovene® 4045

Chemical name	Carboxylated styrene butadine
Physical state	Liquid
Boiling point	100°C at 17 mm Hg
Color	White and milky
Solids content	45.0-45.7%
Vapor density	1<
Vapor pressure	17 mm Hg at 20°C
Solubility in water	Miscible
pH	8.33
Specific gravity	1.00-1.03
Emulsifiers	Anionic
Viscosity (Brookfield #2/20 rpm)	900 max cps
Particle diameter	0.18 microns
Glass transition temp. (Tg)	+24°C
Water content (% by weight)	53.54

Water: The mixing water should be free of acids, alkalis, oils and in general be suitable for drinking due to ASTM D 1632 and ASTM D 4972. According to ASTM D1193, the water is specified in 4 grades, type 1-4, due to their physical, chemical and biological specification. All mixing water used for these tests method should be ASTM type III or better. It is prepared by distillation, ion exchange, continuous electrode ionization reverse osmosis, or a combination thereof. Water prepared by distillation is of type III, which is used in current study.

Rovene® 4045: Rovene® 4045 is a styrene-butadiene emulsion that provides soil aggregate binding strength and moisture resistance properties. It can be used in cases where stabilization of soil aggregate and binding are required. This material mostly used in road construction, landscaping, agriculture, dust control and erosion control applications. Rovene® 4045 provides good wetting of different types of soil aggregate, imparts dry and wet strength to the soil aggregates. The properties of Rovene® 4045 are presented in Table 5.

RESULTS AND DISCUSSION

Moisture-density relations of the mixtures: One of the basic factors that significantly affects the strength of CTB is dry density-water content relationship of compacted soil aggregate. In this case, water is required to reach maximum dry unit weight and to aid in cement hydration. Moisture content-dry density relation of the soil without additive was determined according to ASTM D 698 method C. The soil was compacted in a 152.4 mm diameter mold with a 24.4-N rammer dropped from a height of 305 mm producing a compactive effort of 600 KN m m^{-3}. The soil aggregate was placed into a mold in three equal layers at a selected water content, with each layer compacted by 56 blows receiving

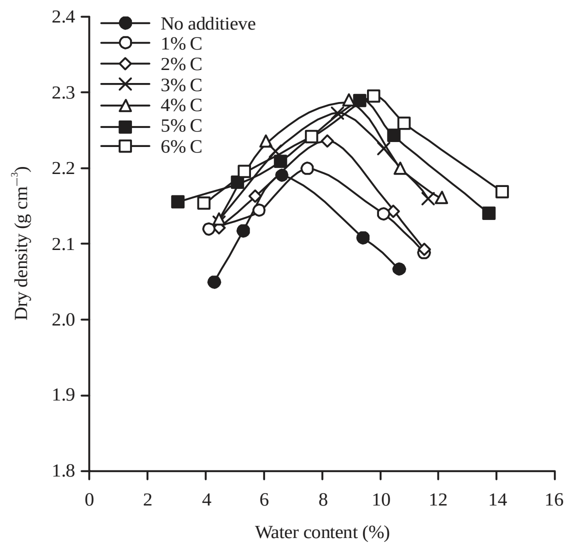

Fig. 2: Relation between moisture content and dry density at various cement contents, C: Cement

from the rammer to a total height of 130 mm. From the compacted curve, the optimum moisture content-maximum dry density relationship was determined. According to ASTM D 558 method B, the water content-dry density relationship of soil-cement mixture was determined using a cylindrical metal mold with a capacity of 944 cm^3 and an internal diameter of 101.60 mm. The soil aggregate was compacted using a 2.49 kg metal rammer with a diameter of 50.80 mm dropped from a 305 mm height. To prepare the samples, the required amount of cement was added to the soil according to specifications ASTM C 150 and C 595 and it was mixed thoroughly to a uniform color. Then, water was added to the mixture and specimen was formed by compacting the prepared soil-cement mixture in the mold in three equal layers with each layer compacted by 25 blows from the rammer. Same process was applied for the mixing of cement and Rovene® 4045. Figure 2 shows compaction curves that indicate the relationship between cement-dry unit weight and cement-water content obtained for non-stabilized soil aggregate and stabilized soil aggregate prepared with different cement content. In addition, the maximum dry density of cement-Rovene® 4045 mixture was obtained with 5-10% of Rovene® 4045 content, which can be used as an important variable to predict models.

Figure 2 shows that the water content and dry density increase with an increase in the cement percentage where the compaction moisture is increased by about 0.25% for each 1.0% increase in cement content added to the specimen. This can be explained using the theoretical formulation of the overall void ratio of the mixture comprising soils with varying

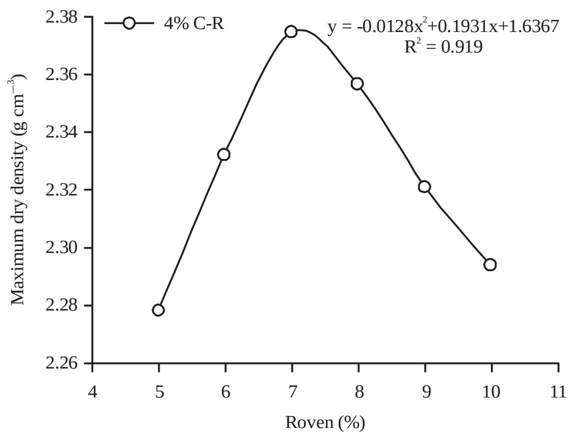

Fig. 3: Plot of maximum dry density vs. content of Tylac® 4190 in the cement-Tylac® 4190 mixture, T: Tylac® 4190, y: Maximum dry density (g cm^{-3}), x: Tylac® 4190 content (%)

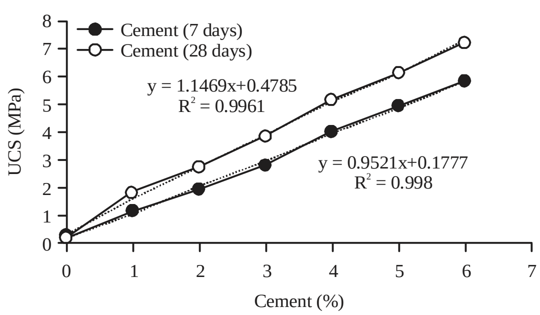

Fig. 4: Plot of UCS vs. cement content for 7 and 28 days of curing, y: UCS (MPa), x: Time (days)

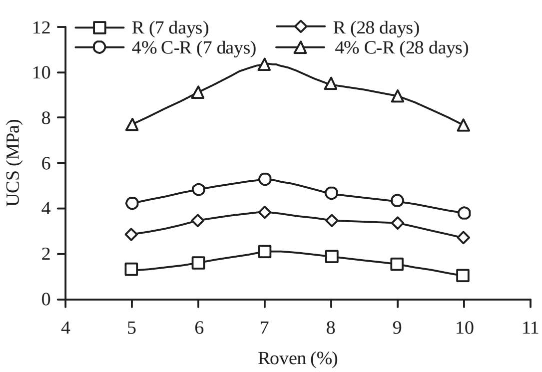

Fig. 5: Plot of UCS vs. Rovene® 4045 content

grain sizes. Lade *et al.*[49] showed that when small particles are added to a large sized particle matrix, the overall void ratio decreases until all the voids are filled with small particles. This means the dry density increases up to a specific mixing ratio of small to large particles. A previous research shows that the dry unit weight of cement stabilized coarse-grained materials is higher than the unstabilized materials because specific gravity of cement is greater than unstabilized materials[50].

The plot of the maximum dry density versus the content of Rovene® 4045 in the cement-Rovene® 4045 mixture is shown in Fig. 3.

From the experimental data, the non-linear model in Fig. 3 shows the relationship between the content of Rovene® 4045 in the cement- Rovene® 4045 mixture and the maximum dry density as obtained for the CRTB mixture according to ASTM D 558. It is seen that the maximum dry density increases with increasing Rovene® 4045 content up to 7%. This trend can be explained by the consolidation of both the rigid styrene chains and the flexible butadiene chains of the SBE molecular structure, which enhances the mechanical properties of the mixture. Rovene® 4045 has very small particles (nanosized) and so it spreads and penetrates throughout the soil-aggregate-cement structure to provide toughness and flexibility. However, after that, the maximum dry density decreases with increasing Rovene® 4045 content on account of the higher water content of 49.12% of Rovene® 4045; this leads to a decrease in the strength of the mixture. The presence of too much water in the mixture poses a problem because it inhibits adequate compaction and decreases the toughness and flexibility of the soil-aggregate-cement structure, resulting in a decrease in the dry unit weight.

Unconfined compressive strength: The basic aim of the UCS test is to gain the approximate compressive strength of a mixture that has adequate cohesion to permit testing in the unconfined state. The mixture was prepared according to ASTM D 1632 using a metal cylinder with an internal diameter of 101.60 and 116.4 mm height. The specimens were placed in the molds and placed in moist room to cure for 12 h, which them enabled subsequent removal of the specimens using a sample extruder. Then, the specimens remained in the moist room and were wrapped in plastic to protect them from free water for the specific moist curing period. The average UCS of the specimens after 7, 28 and 60 days curing time was obtained using a hydraulic compressive strength machine by applying load at a constant rate within the limits of 140±70 kPa sec^{-1} according to ASTM D 1633. Finally, the unit compressive strength (MPa) was measured by dividing the ultimate load (N) by the cross-sectional area (mm^2). The results of UCS are presented in Fig. 4-6.

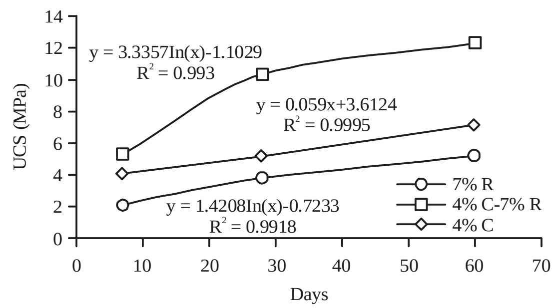

Fig. 6: Plot of UCS vs. curing time, y: UCS (Mpa), x: Time (days)

Figure 4 shows the values of UCS against the various percentages of cement for 7 and 28 days of curing. It shows a proportional relationship where an increase in portland cement content enhances the strength of the mixture due to the hydration products of the portland cement that fills in the pores of the matrix thus increasing the hardness of its construction by forming a large number of rigid bonds in the soil. The optimum percentage of cement content was chosen as 4% due to the strength requirements for CTB in Table 2 (section 3) and results of Fig. 4. Based on the experimental data, models to estimate the relations between UCS and cement content after 7 and 28 days of curing time have been developed as shown in Fig. 4 where, y is the UCS (MPa) and x is the cement content (%).

Figure 5 shows the values of UCS against various percentages of Rovene® 4045 for 7 and 28 days of curing. It indicates that an increase in Rovene® 4045 content increases the strength of the mixture until 7% of Rovene® 4045 content. This can be explained that the consolidation of both rigid styrene chains and flexible butadiene chains of SBE molecular structure, which increases the strength of the mixture. In other hand, the styrene provides toughness, while the butadiene provides flexibility to help absorb energy from impact or stress. Because the Rovene® 4045 is very small particle size (nano size), its 'Spreads' throughout the soil/cement structure to provide toughness and flexibility to the aggregate/cement structure. However, after that it decreases because of the water content of Rovene® 4045, which is 53.54%, decreases the strength of the mixture because excessive water decreases the toughness and flexibility of the soil/cement structure and decreases the dry unit weight of the mixture.

In Fig. 6, it can be seen that the strength increases with an increase in curing time, which indicates that strength increases of 72% due to the addition of 4% portland cement 7% Rovene® 4045 as compared to a sample with only 4% cement. It shows the influence of curing time on UCS using a linear and non-linear model where, y is UCS (MPa) and x is the time (days).

Influence of cement content, water content, dry density and Rovene® 4045 content on the UCS: From Fig. 5, it is observed that the UCS increases linearly with increasing cement content and non-linearly with increasing dry density and Rovene® 4045 content as shown in Fig. 4 and 6, respectively. These results are in agreement with previous findings on the influence of cement content and dry density on cement-treated materials[41,51]. Xuan *et al*.[51] employed an adapted model to demonstrate the relationship between the UCS and the variables affecting it, i.e., the cement content, water content and additive content as shown in Eq. 1:

$$f_c = K_1 \times (C/W) \times (D)^{k_2} \times e^{k_3 \times M} \quad (1)$$

where, f_c is the UCS (MPa), K_1, K_2 and K_3 are adjustable variables, C is the cement content (%), D the dry density (g/cm^3), W the moisture content (%) and M the additive content (%).

Based on the experimental results, models for estimating the UCS of a mixture cured for 7 and 28 days are developed and expressed as following Eq. 2 and 3:

$$f_c = 0.022 \times (C/W) \times D^{7.228} \times e^{-0.034M}, \ R^2 = 0.914 \quad (2)$$

$$f_c = 0.029 \times (C/W) \times D^{7.472} \times e^{-0.008M}, \ R^2 = 0.933 \quad (3)$$

where, M is the Rovene® 4045 content (%).

Influence of curing time: One of the important factors that significantly affects the strength of UCS is curing time. The UCS development with curing time for cement content of 4% is shown in Fig. 6. It can be noted that UCS increases approximately linearly with curing time. Several studies have reported its effect on UCS[52-57]. For example, the effect of curing time on UCS can be given as[58] Eq. 4:

$$f_c(t) = f_c(t_0) + k_1 \times \log\left(t/t_0 \right) \quad (4)$$

where, $f_c(t)$ is the UCS at a t days of curing (MPa) and $f_c(t_0)$ is the UCS at t_0 of curing days. Lim and Zollinger[59] proposed a prediction model which investigates the effect of curing time on UCS as shown in Eq. 4. This model is founded on the calibration of the American Concrete Institute (ACI) Committee model, which introduces two adjustable variables (k_1 and k_2) for UCS estimation. Compared to the log-scale model given in Eq. 4, this model presents a more accurate estimation of UCS-curing time relationship given in Eq. 5 as:

$$f_c\left(t\right) = f_c\left(28\right) \times \frac{t}{k_1 + k_2 \times t} \tag{5}$$

where, $f_c(28)$ is the 28 day UCS (MPa). Herein, another adopted model that shows the UCS-curing time relationship is illustrated in the following Eq. 6 using 3 adjustable variables (k_1, k_2 and k_3)[60]:

$$f_c(t) = k_1 \times k_2^{f_c(28)} \times t^{(k_3)} \tag{6}$$

So far, for road base stabilization, common models that consider the influence of curing time have been reported, such as the exponential model, the log-scale model and the ACI model as shown in Eq. 7-9, respectively[51,59,61]:

$$f_c = k_1 \times (C/W) \times D^{k_2} \times e^{(k_3.M)} \times e^{\left[1-\left(28/t\right)^{k_4}\right]} \tag{7}$$

$$f_c = k_1 \times (C/W) \times D^{k_2} \times e^{(k_3.M)} \times \left[1 + k_4 \log(t/28)\right] \tag{8}$$

$$f_c = k_1 \times (C/W) \times D^{k_2} \times e^{(k_3.M)} \times t/(5.1 + k_4 \times t) \tag{9}$$

Based on the experimental data derived from this research, the above three estimation models are expressed as Eq. 10-12, respectively:

$$f_c(t) = 0.032 \times (C/W) \times D^{7.409} \times e^{(-0.013M)} \times e^{\left[1-\left(28/t\right)^{0.369}\right]},\ R^2 = 0.988 \tag{10}$$

$$f_c(t) = 0.032 \times (C/W) \times D^{7.409} \times e^{-0.013M} \times \left[1 + 0.810 \times \log(t/28)\right],\ R^2 = 0.988 \tag{11}$$

$$f_c(t) = 0.018 \times (C/W) \times D^{7.409} \times e^{-0.013M} \times t/(5.1 + 0.392 \times t),\ R^2 = 0.988 \tag{12}$$

Indirect tensile strength: The ITS can be used to assess the relative quality of a mixture in conjunction with laboratory mix design testing and to estimate the potential for tensile strength and cracking[33]. The mixture was prepared according to ASTM D 1632 and ASTM D 6926 using a metal cylindrical specimen mold with an internal diameter of 101.60 and 70 mm height. The average ITS of the cement-treated specimens after 7, 28 and 60 days of curing time was obtained using a hydraulic compressive strength machine. According to ASTM D 6931 a vertical compressive ramp with a rate of 50 mm min^{-1} was applied until the maximum load reached. Equation 13 shows the calculation of ITS:

$$S_t = {2 \times P}/{\pi \times t \times D} \tag{13}$$

where, S_t is the ITS (MPa), P is the ultimate load (N), t is the specimen height (mm) and D is the specimen diameter (mm). The results of ITS are presented in Fig. 7-9.

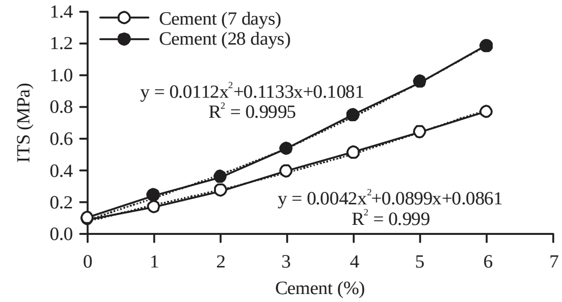

Fig. 7: Plot of ITS vs. cement content, y: ITS (Mpa), x: Time (days)

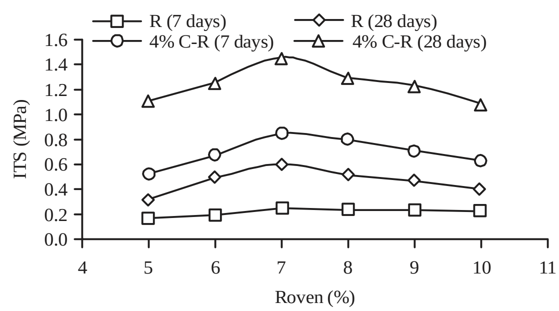

Fig. 8: Plot of ITS vs. Rovene® 4045 content

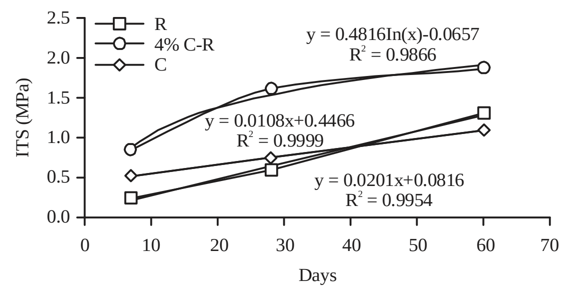

Fig. 9: Plot of ITS vs. curing time, y: UCS (MPa), x: Time (days)

Figure 7 illustrates the values of ITS versus various percentages of cement for curing times of 7 and 28 days. The results indicates that an increase in cement content increases the tensile strength. Based on the experimental data, the 2 non-linear models in Fig. 7 show the relations between ITS and cement content for 7 and 28 days, where, y is the ITS (MPa) and x is the cement content (%).

Figure 8 shows that the tensile strength increases up to a Rovene® 4045 content of 7% and decreases after that because of the same mechanism described in section 5.2, which also indicates that the optimum Rovene® 4045 content is 7%. The following Eq. 14 and 15 show the influence of cement content, moisture content, density and Rovene® 4045 content on ITS:

$$S_t(7) = 0.008 \times (C/W) \times D^{5.458} \times e^{0.057M},\ R^2 = 0.957 \quad (14)$$

$$S_t(28) = 0.074 \times (C/W) \times D^{3.886} \times e^{0.013M},\ R^2 = 0.926 \quad (15)$$

The value of ITS increases with an increase in curing time, which indicates that curing time is an important factor in CRTB as shown in Fig. 9. The results of ITS showed strength increases of 68% due to the addition of 4% portland cement 7% Rovene® 4045 as compared to a sample with only 4% cement. It shows the influence of curing time on ITS using linear models where, y is ITS (MPa) and x is the time (days). The following Eq. 16-18 show the influence of cement content, moisture content, density, Rovene® 4045 content and curing time on ITS:

$$S_t(t) = 1.179 \times (C/W) \times D^{8.926} \times e^{-0.004M} \times e^{\left[1-\left(28/t\right)^{0.341}\right]},\ R^2 = 0.980 \quad (16)$$

$$S_t(t) = 1.179 \times (C/W) \times D^{8.926} \times e^{-0.004M} \times \left[1 + 0.754\log(t/28)\right],\ R^2 = 0.980 \quad (17)$$

$$S_t(t) = 0.775 \times (C/W) \times D^{8.926} \times e^{0.004M} \times t/(5.1 + 0.476 \times t),\ R^2 = 0.980 \quad (18)$$

Resilient modulus of elasticity: The resilient modulus test can be used to assess the relative quality of a mixture for pavement design and analysis. In recent years, based on elastic theory, pavement design methods necessitates the elastic properties of pavement materials as input. The resilient modulus of a mixture can be calculated in the indirect tensile mode, which is the most common form of stress-strain evaluation used to assess elastic properties. Factors such as loading rate, rest periods, temperature, loading frequencies, etc., are influential in this test method[62,63].

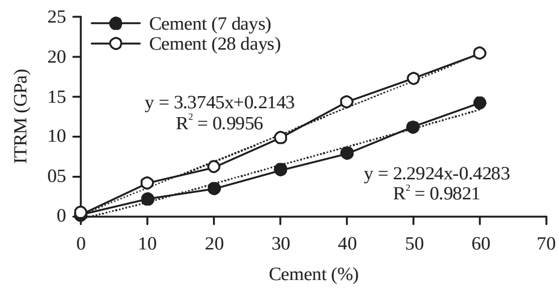

Fig. 10: Plot of ITRM vs. cement content

The mixture for testing was prepared according to ASTM D 1632 and ASTM D 6926 using a metal cylindrical specimen mold with an internal diameter of 101.60 mm and 70 mm height. An indirect tension repeated-load for determining the resilient modulus of each mixture was conducted according to ASTM D 4123 by applying 2000 N vertical compressive loads at 25°C with a haversine waveform at 1.0 Hz (1000 ms) for loading frequencies (the recommended load range can be 10-50% of the indirect tensile strength). The resulting horizontal deformation of a specimen with an assumed Poisson's ratio[58,64] of 0.2 was measured and 5 conditioning pulse counts were used to calculate the resilient modulus. The values of horizontal deformation were measured using Linear Variable Differential Transducers (LVDTs). The LVDTs should be at mid-height opposite each other on the specimen's diameter. Each specimen was tested twice for resilient modulus. Following the first test, the specimen was rotated approximately 90°C and the test was repeated. Equation 19 shows the calculation of ITRM:

$$E_{RT} = P(\upsilon_{RT} + 0.27) \times \Delta H_T \quad (19)$$

where, is the resilient modulus of elasticity (Mpa), υ_{RT} is the repeated load (N), is resilient Poisson's ratio and ΔH_T is the total recoverable horizontal deformation. The results of ITRM are presented in Fig. 10-12.

Figure 10 shows the values of ITRM versus various percentages of cement for curing times of 7 and 28 days. It can be seen that an increase in cement content increases the ITRM. Based on experimental data, the 2 linear models in Fig. 10 show the relations between ITRM and cement content for curing times of 7 and 28 days where, y is the ITRM (GPa) and x is the cement content (%). It should be noted that the

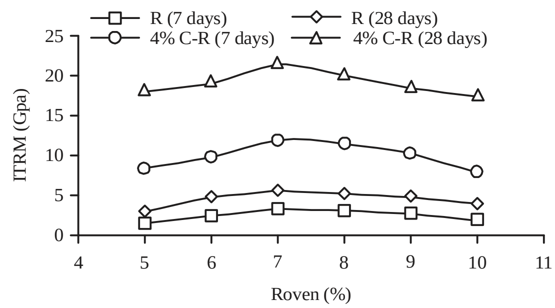

Fig. 11: Plot of ITRM vs. Rovene® 4045 content

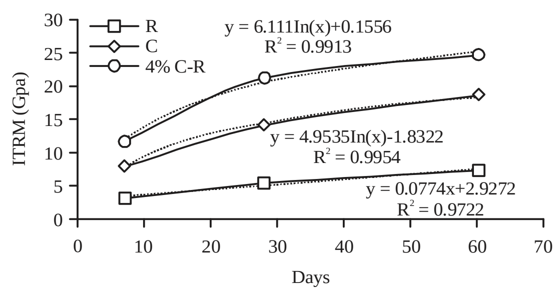

Fig. 12: Plot of ITRM vs. curing time, y: ITRM (GPa), x: Curing time (days)

test was also conducted at 40°C of temperature which the results was same as 25°C, resulted good performance of additives in high temperature.

Figure 11 shows that the ITRM increases until the Rovene® 4045 content reaches 7% and decrease after that, which indicates the optimum Rovene® 4045 content is 7%. The following Eq. 20 and 21 show the influence of cement content, moisture content, density and Rovene® 4045 content on ITRM:

$$E_{RT}(7) = 0.161\times(C/W)\times D^{5.420}\times e^{0.010M},\ R^2 = 0.950 \quad (20)$$

$$E_{RT}(28) = 2.003\times(C/W)\times D^{3.394}\times e^{(-0.004M)},\ R^2 = 0.958 \quad (21)$$

The strength increases with an increase in curing time, which indicates that curing time is an important factor in CRTB as shown in Fig. 12. The results of ITRM test showed strength increases of 32% due to the addition of 4% portland cement 7% Rovene® 4045 as compared to a sample with only 4% cement. It shows the influence of curing time on ITRM using non-linear models where y is ITRM (GPa) and x is the time (days). The following Eq. 22-24 show the influence of cement content, moisture content, density, Rovene® 4045 content and curing time on ITS:

$$E_{RT}(t) = 0.218\times(C/W)\times D^{5.997}\times e^{(-0.009M)}\times e^{\left[1-\left(28/t\right)^{0.355}\right]},\ R^2 = 0.975 \quad (22)$$

$$E_{RT}(t) = 0.218\times(C/W)\times D^{5.977}\times e^{(-0.009M)}\times\left[1+0.782\log(t/28)\right],\ R^2 = 0.975 \quad (23)$$

$$E_{RT}(t) = 0.134\times(C/W)\times D^{5.977}\times e^{(-0.009M)}\times t/(5.1+0.432\times t),\ R^2 = 0.975 \quad (24)$$

Wetting and drying: The WD test methods can be used to specify the resistance of compacted specimens to repeated wetting and drying. These test methods were developed to determine the minimum amount of an additive required in a mixture to achieve a degree of hardness adequate to resist field weathering[33,65]. The ASTM D 559 comprises steps to discover volume changes (swell and shrinkage), water content changes and the soil-cement losses, produced by 12 cycles of repeated WD of hardened soil-cement specimens. The specimens were compacted into a cylindrical metal mold with a capacity of 944 cm^3 and an internal diameter of 101.6 mm using the compaction procedure described in section 5.2 according to ASTM D 558. The specimens were placed in the moist room and they were protected from free water for 7 days. The specimens were weighed and measured at the end of the curing time to prepare data for evaluating their water content and volume. The specimens were submerged in potable water at room temperature for 5 h and then removed. Again, the specimens were weighed and measured (volume and moisture change of the specimen). Then they were placed in an oven at 71°C for 42 h after which they were removed, weighed and measured. They were next given 2 firm strokes on sides and each ends areas with a wire scratch brush (20 brush strokes for sides and four strokes for each ends). The specimens were then submerged in water and this process was repeated for 12 cycles. Figure 13 shows the process of WD test.

The volume change was calculated as a percentage of the subsequent volumes of the specimens and original volume of specimens at the time of molding. The water content of specimen at the time of molding and subsequent water contents as a percentage of the original oven-dry weight of the specimens was calculated. The soil-cement loss was calculated as a percentage of the final oven dry weight and original oven dry weight of the specimens. The results of the WD test are shown in Fig. 14-18.

Fig. 13: Process of WD test

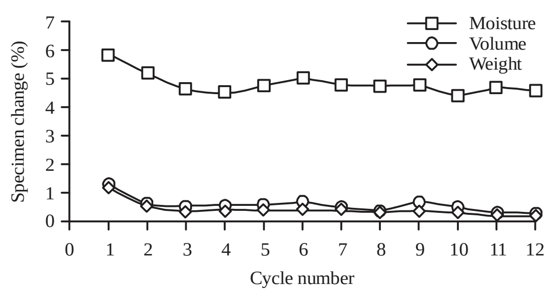

Fig. 14: Moisture, volume and weight changes of cement over 12 WD cycles

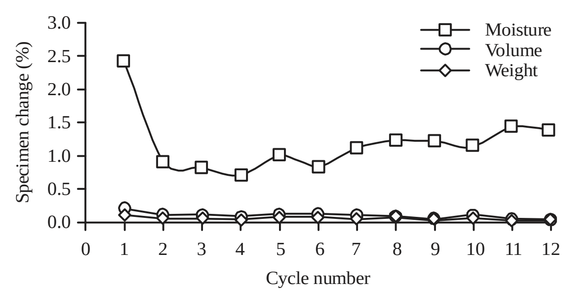

Fig. 16: Moisture, volume and weight changes of cement Rovene® 4045 mixture over 12 WD cycles

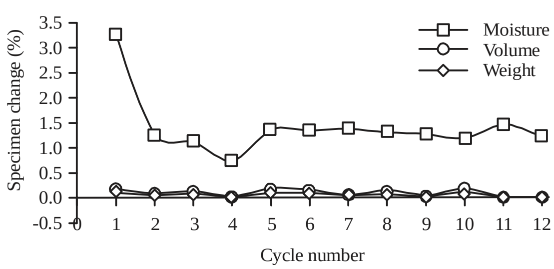

Fig. 15: Moisture, volume and weight changes of Rovene® 4045 over 12 WD cycles

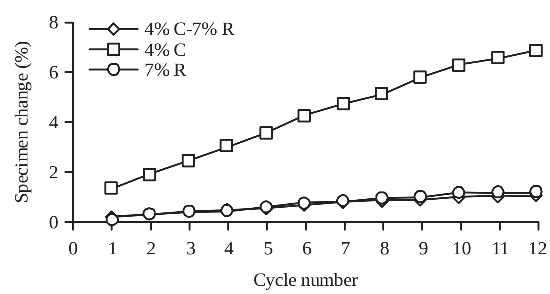

Fig. 17: Total volume change over 12 WD cycles

Figure 14-18 show the results of soil-aggregate-cement losses, water content changes and volume changes for 4% cement, 7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 mixture, respectively, induced by subjecting hardened soil-aggregate-cement specimens to 12 WD cycles. From the Fig. 14-18, it is clear that the average water absorptions of 4% cement, 7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 cement, 7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 mixture was 4.842, 1.405 and 1.179%, respectively, for each WD cycle. This result indicates that use of the 4% cement 7% Rovene® 4045 mixture improved the water absorption in each cycle by 410.58% as compared to the use of only cement in the mixture. Further, the average volume change of 4% cement,

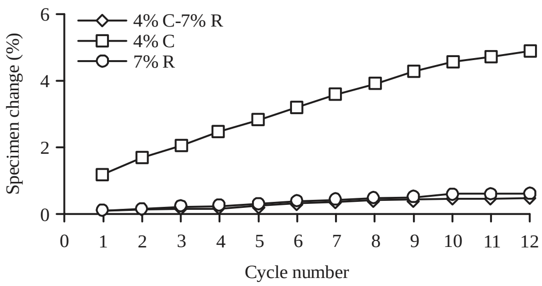

Fig. 18: Total weight loss over 12 WD cycles

7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 mixture was 0.572, 0.115 and 0.096%, respectively, for each WD cycle. This result indicates that use of the 4% cement 7% Rovene® 4045 mixture improved the volume change in each cycle by 498.18% as compared to the use of only cement in the mixture. Finally, it is seen from the figures that the average weight changes of 4% cement, 7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 mixture were 0.407, 0.051 and 0.040%, respectively, for each WD cycle. This result indicates that use of the 4% cement 7% Rovene® 4045 mixture improved the weight change in each cycle by 1012.8% as compared to the use of only cement in the mixture. It should be noted that the soil-aggregate sample without any additive failed in cycle 1 because of 100% water absorption, 100% volume change and 100% weight loss.

Figure 17 and 18 show the results of the total volume change and total soil-aggregate-cement losses for 4% cement, 7% Rovene® 4045 and the 4% cement 7% Rovene® 4045 mixture induced by subjecting hardened soil-aggregate-cement specimens to 12 WD cycles. It is seen that the total volume changes of cement, Rovene® 4045 and the cement-Rovene® 4045 mixture were 6.863, 1.378 and 1.155%, respectively, after 12 WD cycles. Further, the total weight changes of cement, Rovene® 4045 and the cement-Rovene® 4045 mixture were found to be 4.885, 0.616 and 0.483%, respectively, after 12 WD cycles. The results show that the addition of the 4% portland cement 7% Rovene® 4045 mixture resulted in an 410.6% improvement in water absorption, a volume change of 498.18% and a weight change of 1012% as compared to the specimen with only 4% cement after 12 WD cycles.

CONCLUSION AND FUTURE RECOMMENDATION

The effects of moisture content, dry density, cement content, Rovene® 4045 content and curing time on the strength of road base material were investigated using a series of UCS, ITS, ITRM and WD tests to evaluated the short and long-term performance of the mixture. The strength of the layer increases with higher content of cement and longer curing time. It should be noted that in choosing the optimum portland cement content, it is not cost effective to select the highest percentage of cement, also using excessive cement resulted shrinkage cracks, which are a major problem for pavement owing to water infiltration. The results of the tests show that with an increase in Rovene® 4045 content, strength increases up to 7% and decreases afterward. The findings from the tests showed that CRTB is an effective treatment when applied to soil in order to improve its strength, reduce water vulnerability and enhance the pavement bearing capacity effectively. In addition, the total number of roadway layers can be reduced by using CRTB because of its higher bearing capacity, which effectively reduces the construction time and cost. The results of WD test show that the mix of portland cement-Rovene® 4045 can reduce soil-cement losses and reduce volume changes (swell and shrinkage) of CRTB. This implies that introducing portland cement and Rovene® 4045 to soil mixtures reduces moisture susceptibility because portland cement and Rovene® 4045 are effective adhesive agents for mixtures. The future recommendations are as follows:

- The CRTB has good mechanical properties for road base. The results indicate that CRTB produce a good cemented road base with a high load-spreading capacity
- The findings of the present study recommend using 4% cement in pavement base layer as optimum content
- The results show that the addition of portland cement and Rovene® 4045 increases compressive strength, pH, resilient modulus and tensile strength
- The results of UCS, ITS and ITRM test showed strength increases of 72, 68 and 32%, respectively due to the addition of 4% portland cement 7% Rovene® 4045 as compared to a sample with only 4% cement
- The WD cycling (durability) tests showed that the addition of the 4% portland cement 7% Rovene® 4045 mixture resulted in improvements of 410.6% water absorption, a volume change of 498.18% and a weight change of 1012% as compared to the specimen with only 4% cement after 12 WD cycles
- Three estimation models for UCS, ITS and ITRM of CRTB were developed in relation to mixture variables such as the ratio of cement to water content, dry density, Rovene® 4045 content and the curing time
- It is recommended that other CRTB structural properties should also be considered, including flexural strength (modulus of rupture), creep (deformation) behavior and the chemical reaction properties

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