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Table of Content

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Full Length Research Paper

Compaction and strength characteristics of recycled pavement material: Cement mixtures used for road pavement purposes

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The implementation of conventional soil-cement stabilization techniques is hindered by the relatively large particle size of road pavement materials. This study aims to investigate the effects of the gradations of soil particles, cement content, and water content on the soil-cement materials (real construction materials collected from the field) used for pavement. Recycled crushed rock obtained from the pulverizing process of pavement was reconstituted into five groups with different particle sizes (from large to small). A series of modified compaction tests and unconfined compressive strength tests were performed. The main results of this study determine that the addition of cement can alter the compaction characteristics of the reconstituted recycled material-cement mixtures. From the compaction tests, the different gradations of soil particles and cement content do not have a great effect on the maximum dry unit weight of a soil-cement mixture used for pavement. Furthermore, the difference in the gradation of soil particles has a much lesser effect on unconfined compressive strength of the soil-cement used for pavement than its cement content and water content. Finally, at a given cement content, maintaining a moisture levels in a soil-cement mixture during construction (compaction) is necessary for the consistent performance of soil-cement materials.

Key words: Soil-cement stabilization, road pavement, recycled pavement material, unconfined compressive strength, soil particle size distribution

INTRODUCTION

Soil stabilization techniques have gained more popularity for use in road pavement construction, due to required material quality improvements (Hashemian et al., 2014; Ismail et al., 2014; Puppala, 2016). As well known, cement stabilization is the most widely used ground improvement technique for improving either physical or

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or engineering properties of unsuitable soil. This stabilization generally refers to improving the *in-situ* soil properties by adding cement admixtures. However, such cement stabilization method is apparently distinguished from those used in pavement constructions. Cement-stabilized pavement materials are products of a cement stabilization method for creating a better and suitable road base or subbase material for pavements from sub-standard pavement materials.

For the context of the conventional soil-cement stabilization, it was found that the amounts of water, cement, soil, including soil types, and curing conditions play a main role in the performance in terms of the strength of a soil-cement product. Miura et al. (2001) and Horpibulsuk et al. (2005) studied the compressive strength of soil-cement materials under varying cement content, water content and curing time. In those studies, the soil water-cement ratio was determined to be another important factor affecting the strength of soil-cement materials. Felt (1955), Norling and Peckard (1958), Davidson et al. (1962) and Metcalf (1977) investigated the effect of soil type on the soil-cement strength. A gravel-cement material provided the highest compressive strength, followed by a sand-cement material and a clay-cement material, respectively. With soil being a combination of sand and clay, a soil-cement material showed a decrease in compressive strength when its clay content was larger than 25% by mass.

For the context of the soil-cement stabilization for pavements, the soil-cement material focuses on two main conditions during construction (compaction) and after construction (in-service). Compaction characteristics of the soil-cement material under the compaction process are necessary to understand the behavior of such material during construction (Chummuneerat, 2014). For example, soil-cement materials compacted with higher than optimum moisture content (the wet side compaction) showed higher compressive strength for every observed curing period and compaction energy level (Korakod et al., 2017). Horpibulsuk et al. (2006, 2010) investigated the differences in compressive strength between soil-cement materials prepared under laboratory conditions and those collected from the field. Compaction in the field decreased the compressive strength by 25%, when compared to the laboratory samples, using the same curing conditions for both cases. The long-term strength of the soil-cement material is a crucial factor for evaluating its performance in service (Jitsangiam and Nikraz, 2009). The soil-cement pavement materials are either mixed in place or in plant. For the in-plant manufacturing, the transportation is needed to haul the ready-to-construct materials to the construction site. The cement stabilized materials are then compacted at site to form the pavement layers. The soil-cement material for pavement construction could be theoretically categorized as fully bound materials, which generally have much better tensile resistance than general-purpose road base materials or unbound granular materials with inferior tensile resistance (Austroads, 2006).

Kwon et al. (2010) demonstrated one major of their study findings that soil gradation directly affects the strength and dry density of a soil-cement product as a compressed soil-cement block. Soil as a construction material for a road base (layers underneath an asphalt surface) generally has relatively large particle sizes. Due to the process of pulverizing and mixing the old multi-layered pavement materials, uncertainty in grain size results, affecting suitable cement content and water content that could be altered. Conventional soil-cement material, however, is not greatly affected by different grain size distributions when stabilized with cement, but how this applies to road construction requires further investigation. Therefore, this study aims to capture compaction and strength characteristics of cement-stabilized recycled crushed rock from the pavement pulverizing process with varying grain size distributions, cement content, and water content. A series of modified compaction tests and unconfined compressive strength tests were performed. The outcome of this study is beneficial to the field of geomaterials for road pavement construction. The effect of gradation characteristics, water content, and cement content on the pavement recycling technique with cement stabilization have been documented within.

MATERIALS AND METHODS

Soil samples used in this study were taken from pulverized crushed rock sourced from National Highway No. 22 (between reference distances 11+700 km and 116+950 km). Soil samples were then reconstituted into five groups with distinguished grain size distributions. Gradations of five soil groups were plotted against the grading envelope specification for pavement materials in accordance with DH-S 203/2556 of the Department of Highways (DOH), Thailand (Department of Highways, 2013) as shown in Figure 1. Five groups of soil samples were as follows:

(1) Sample I: Passing through and with a maximum size of a 50 mm sieve
(2) Sample II: Passing through and with a maximum size of 25 mm sieve
(3) Sample III: Passing through and with a maximum size of 19 mm sieve
(4) Sample IV: Passing through and with a maximum size of 12.5 mm sieve
(5)Sample V: Passing through and with a maximum size of 9.5 mm sieve

It would be noticed that all five soil groups have different gradations, but all falls into the grading envelope of the specification. Ordinary Portland cement (OPC) Type 1 was used in this study with a specific gravity of 3.14 and a grain size distribution illustrated in Figure 1.

Test methods

The test methods address physical properties, mechanical properties and compressive strength characteristics for a series of

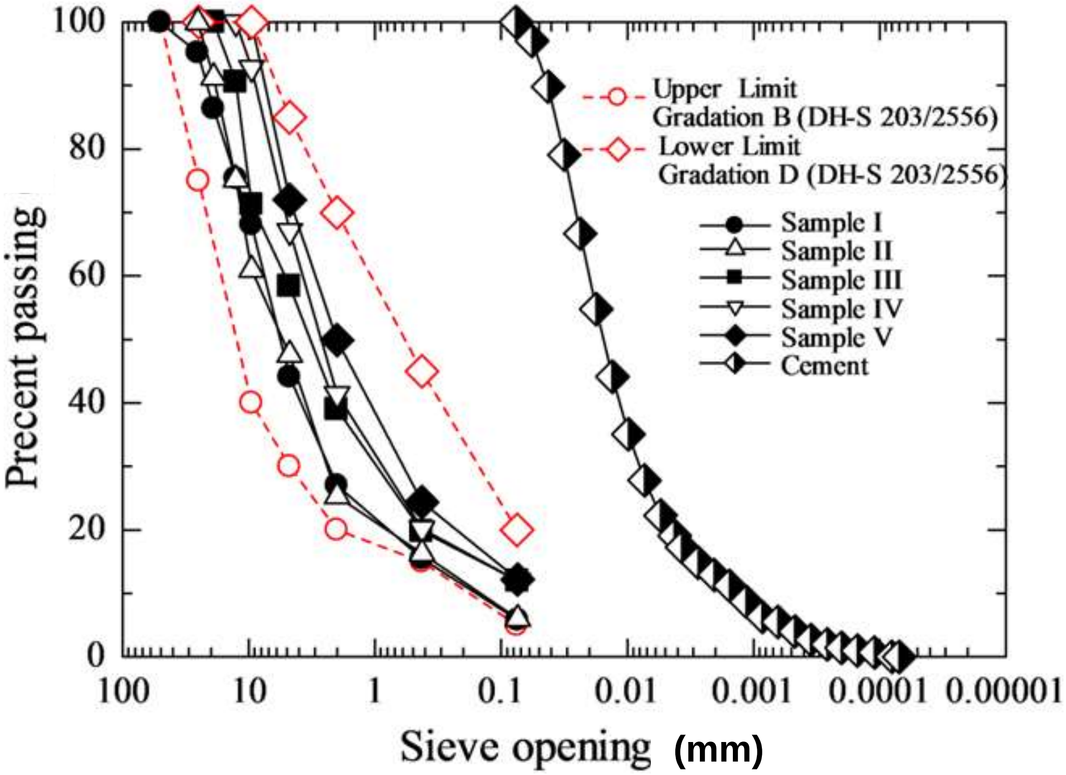

Figure 1. Grained size distribution of recycled crushed rock and cement.

cement-pulverized crushed rock mixtures in this study. Physical properties include:

(1) Specific Gravity in accordance with ASTM D 854
(2) Sieve Analysis in accordance with ASTM D 422
(3) Liquid Limit in accordance with ASTM D 4318
(4) Plastic Limit in accordance with ASTM D 4318
(5) Mechanical properties include:
(6) Modified Compaction Test in accordance with ASTM D 1557-00
(7) Abrasion Test by Los Angeles Machine in accordance with ASTM C 131
(8) Compressive strength characteristics include:
(9) Testing the property compressive strength in accordance with ASTM D 2166

Sample preparation for the unconfined compressive strength tests

The test samples were compacted in the standard 100 mm mold based on the modified compaction effort. Three target water contents were selected. The optimum water content (*OWC*) was used, as well as the *OWC*-2% (an optimum water content less 2%) to replicate compaction at dry side condition, and the *OWC*+2% (an optimum water content plus 2%) to replicate the compaction at wet side condition. It should be noted that a moisture content range of OWC+2% and OWC-2% is normally the working range of water applied in the construction field and the standard of ASTM D806-11 also specified such range as a mixing range of water during the sample preparation. All unconfined compressive strength tests were conducted at using a seven-day curing period. In this study, the results under the same test conditions were kept at a standard deviation (SD) of less than 10%.

RESULTS AND DISCUSSION

Basic properties of soil samples

Based on the sieving test results illustrated in Figure 1, it was found that there were smaller maximum coarse particle size aggregates (from I to V), and larger quantities of relatively fine particle portions. For the fine particle sizes of 4.76 (No. 4 of the sieving meshes) and 0.074 mm (No. 200 of the sieving meshes), the cumulative passing percentages of the No. 4 mesh are 44.1, 47.6, 58.4, 67.1 and 72.0% and the cumulative passing percentages of the No. 200 mesh are 5.8, 6.0, 11.8, 12.0 and 12.2% for samples I, II, III, IV and V, respectively.

Table 1 shows details of the basic property test results of all study soil samples. Table 1 shows that with consideration of the nominal particle size, soil particles can be arranged in order from the largest to the smallest among five study samples as Samples I to V. Based on the fields of geotechnical engineering and pavement engineering, the commonly used soil classification systems of the AASHTO soil classification system (American Association of State Highway and

Table 1. Basic properties of soil samples.

Sample	Sample I	Sample II	Sample III	Sample IV	Sample V
1. Sieve No.			%Finer		
50 mm	100				
25 mm	95.2	100			
19 mm	86.4	91.3	100		
12.5 mm	75.4	75.2	90.6	100	
9.5 mm	68.1	61.0	81.3	92.8	100
4.75 mm	44.1	47.6	58.4	67.1	72.0
2 mm	27.0	25.3	39.1	41.5	49.7
0.425 mm	15.5	16.3	19.9	20.3	24.2
0.075 mm	5.8	6.0	11.8	12.0	12.2
2. Plasticity index, PI	N-P	N-P	N-P	N-P	N-P
3. AASHTO classification system	A - 1- a	A - 1- a	A - 1- a	A - 1- a	A - 1- a
4. USCS classification system	GW-GM	GW-GM	SW-SC	SW-SC	SM
5. Abrasion loss	27.3	28.4	29.3	30.3	31.2
6. Specific gravity	2.702	2.700	2.692	2.685	2.682

Transportation Officials; AASHTO, 1982), and the unified soil classification system (USCS) (ASTM D 2487-69) were used to classify all five soil samples. It was found that for USCS, the study soil samples are in a range of gravel (G) to sand (S) with combination of silt (M) and clay (C) and for AASHTO; all five soil samples can be classified as A-1-a, which is the granular material with main components of stone fragments, gravel and sand and the good rating to be a pavement construction material. When considering the resistance to wearing through the abrasion test result for all five samples, the results indicate that the smaller material has a less wearing resistant tendency towards a larger abrasion loss result.

Compaction test

Figure 2 shows a series of compaction curves for the constituted soil samples of I to V. It clearly demonstrates that with a larger proportion of relatively fine particles (from Samples I to V), the maximum dry unit weight decreases with an increase in the optimum water content. Figure 2 also shows that all soil samples have approximately the same degree of saturation (85%) at the maximum dry unit weight.

Effects of cement and water content on the dry unit weight

Effects of cement water contents on the dry unit weight of compacted test samples were investigated through a series of compaction tests with cement contents of 0, 2, 3, 4 and 5% by dry mass. The water contents were observed at the dry side (OWC-2%), the optimum water content (OWC) and the wet side (OWC+2%) for each reconstituted soil-cement mixture.

Figure 3 demonstrates the maximum dry unit weight values of all reconstituted soil samples (without cement) in correspondence with the three levels of water content (OWC-2%, OWC, and OWC+2%). Based on Figure 3, the maximum dry unit weight values decreased with an increase in the corresponding optimum contents. The dry unit weight values corresponding to the dry side (OWC-2%) and the wet side (OWC-2%) are nearly the same for all soil groups in this study. This complies with the symmetrical rules of the ideal compaction curve for soil.

Figure 4 shows the compaction results of the reconstituted soil-cement mixtures. It clearly indicates that added cement alters the compaction characteristics of the materials. In every batch of the studied cement contents (2, 3, 4 and 5%), the dry unit weight values of the wet side compaction (with OWC+2% water content) are higher than those of the dry side compaction (with OWC-2% water content). This is different from the compaction characteristics of equal dry and wet side compaction with no cement. However, the water content that provides the highest dry unit weight is at the OWC for all cement contents. It should be remarked that as results shown in Figure 4, varying cement content does not affect the maximum dry unit weight of the material. There were almost identical maximum dry unit weight values of different cement contents (2, 3, 4 and 5%) for all conditions of OWC-2%, OWC, and OWC+2%. Therefore, it could be said that based on the compaction test results of this study, different gradations of the study material and cement content would not affect the

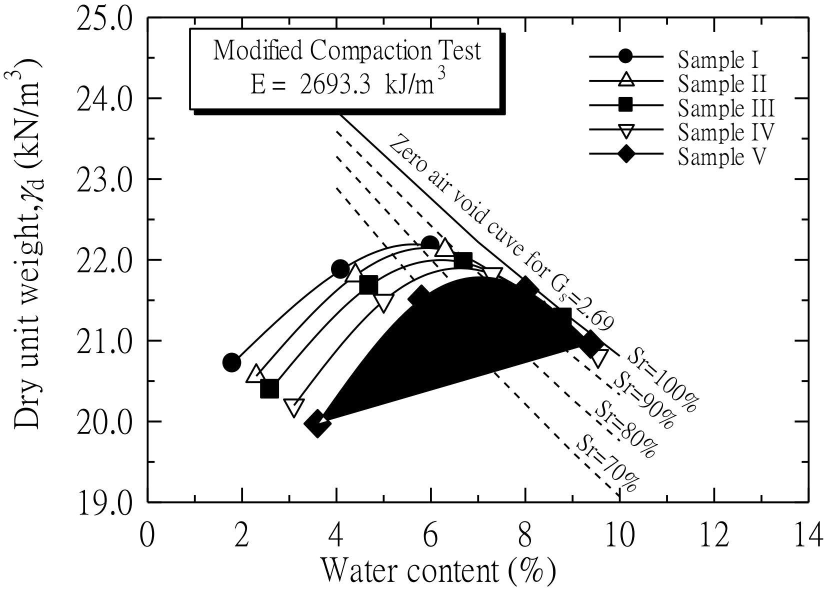

Figure 2. Compaction curves of all reconstituted soil samples.

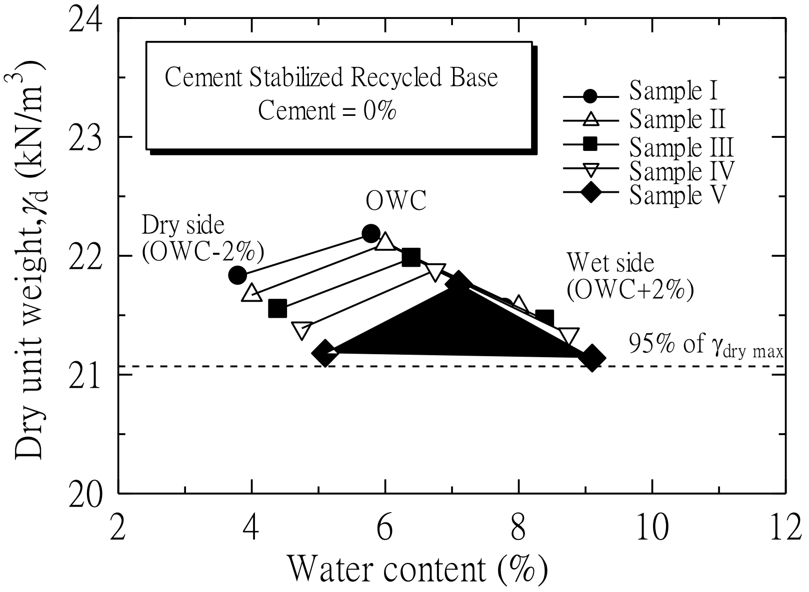

Figure 3. Relation between dry unit weight and water content (without cement).

maximum dry unit weight of the material. Only a water content level has an effect on the values of the maximum dry unit weight of all study samples.

Influence of cement and water content on unconfined compressive strength

Figure 5a to d shows the unconfined compressive strength values of the reconstituted samples (I to V) with varying cement content (2, 3, 4 and 5% by dry mass) and water content (OWC-2%, OWC, OWC+2%) under a seven-day curing period. With the same modified compaction efforts, the OWC-2% water content level provided less unconfined compressive strength than OWC or OWC+2%. The highest unconfined compressive strength values were from OWC for all cement contents. The unconfined compressive strength values of the wet

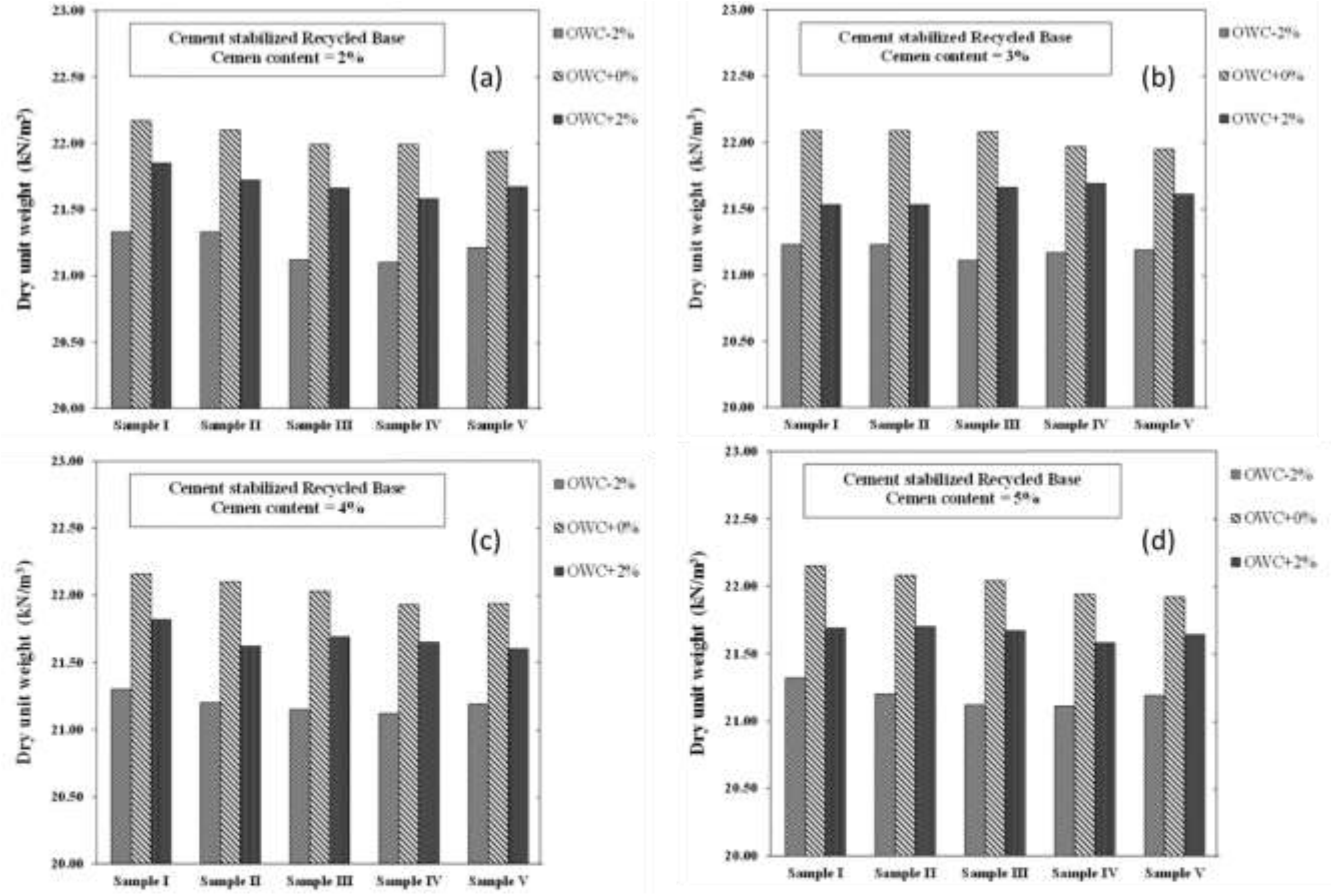

Figure 4. Dry unit weight of the test samples with varying cement water content.

side compaction were always higher than the dry side.

Horpibulsuk et al. (2006) explained why dry side compaction provided the lowest unconfined compressive strength for a soil-cement material. It was due to insufficient water to fully generate the hydration reaction between cement and water in a soil-cement mixture. Therefore, the unconfined compressive strength of soil-cement mixtures under a dry side compaction condition was not fully governed by cementitious bonding. The wet side compaction provided higher unconfined compressive strength than the dry side, but lower strength than that of the optimum water content compaction. This is a consequence of relatively high soil-water/cement ratio (w/c). This complies with results of previous studies (Miura et al., 2001; Horpibulsuk et al., 2006).

Figure 6 highlights why the outcomes of this study are significant. A series of unconfined compression test results are illustrated against with the standard value of unconfined compressive strength for a cement-stabilized base material, following the American Concrete Institute (ACI) (American Concrete Institute, 1990). All reconstituted soil samples I to V compacted at OWC with 5% cement content by dry mass completely passed the ACI’s compressive strength requirement. Besides cement content, the moisture content is another crucial factor for the performance of a soil-cement mixture. The three water content levels of OWC-2%, OWC, and OWC+2% can provide a dry unit weight higher than the 95% maximum dry unit weight (a commonly used compaction requirement for road pavement constructions). However, only the compaction at OWC yielded the satisfactory unconfined compressive strength for all soil samples. Compaction at OWC+2% (a wet side compaction) for soil samples I and II was also satisfactory. Remarkably, all compaction at OWC-2% (a dry side compaction) for all study soil group failed to meet the ACI’s compressive strength requirement. This indicates that any fluctuation in moisture level in a soil-cement mixture during construction (compaction) must be avoided. Specifications that can ensure consistent moisture levels in a soil-cement mixture should be carefully established. For the difference in soil gradation, it can be clearly seen in Figure 6 that compressive strength slightly decreases from Samples I to V (large to small nominal particle size) for each batch of the cement content and the water content. Difference in gradation of soil particles (but within the grading envelope of specifications) does not have a significant effect on the performance

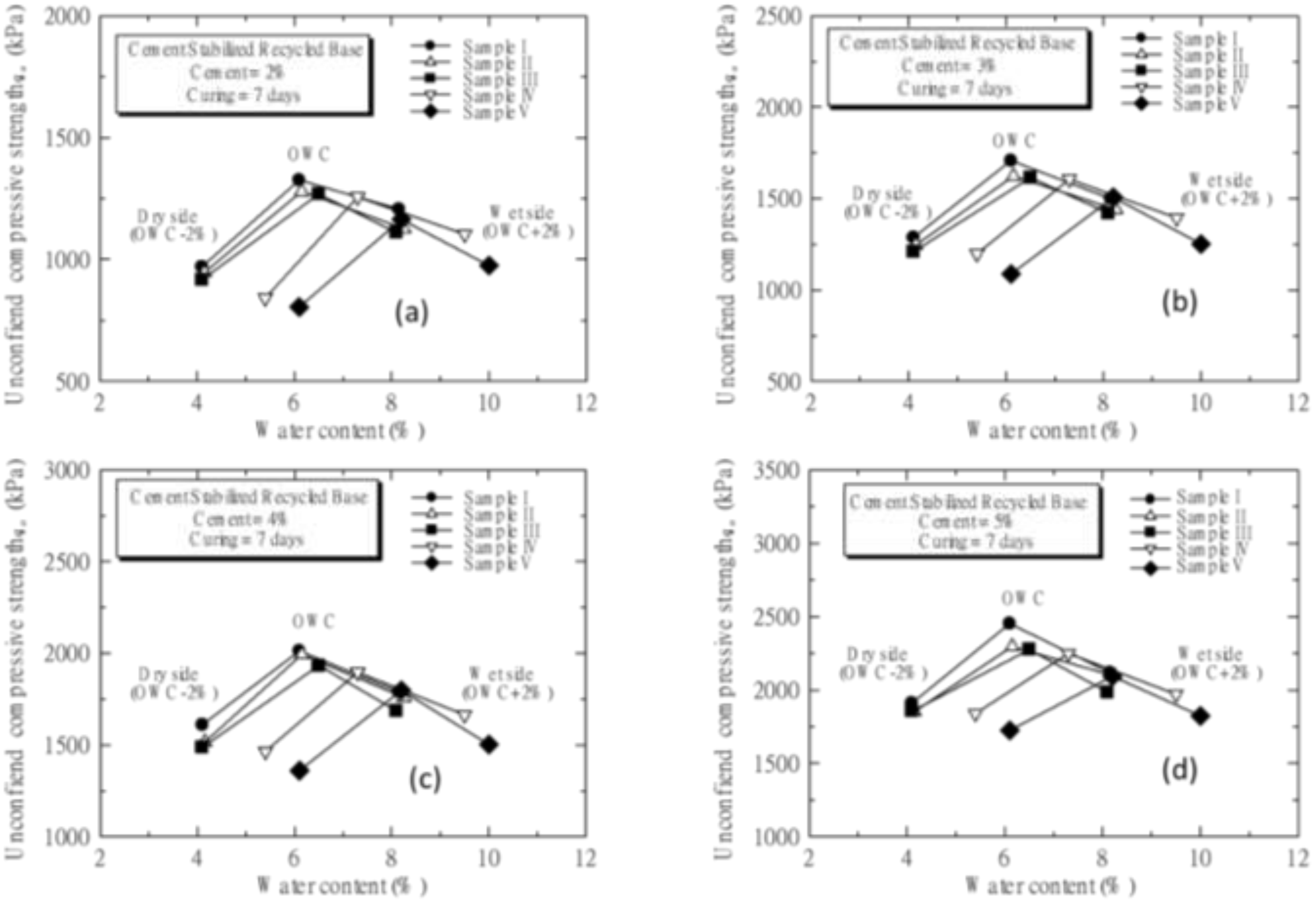

Figure 5. Unconfined compressive strength with varying cement and water contents for seven-day curing time.

(compressive strength) of a soil-cement material; cement content and water content have much great effect on such performance.

Conclusions

This study aimed to investigate the soil-cement stabilization technique used for road pavement. The relatively large particle size of road pavement materials hindered implementation of conventional soil-cement stabilization techniques. Therefore, in this study, strength characteristics of cement-stabilized recycled crushed rock from the pavement pulverizing process were determined. A series of modified proctor compaction tests and unconfined compressive strength tests were performed to investigate the effects of grain size, cement and water content. The following conclusions can be drawn.

(1) With larger amounts of relatively fine particles (from Samples I to V), the maximum dry unit weight decreased with an increase in the optimum water content. The addition of cement altered the compaction characteristics of the reconstituted soil-cement mixtures. The wet side compaction provided a higher dry unit weight than that of the dry side compaction. The highest dry unit weight value was at OWC for all cement contents. The different gradation of soil particles and cement content do not have a great effect on the maximum dry unit weight of a soil-cement mixture for pavement.

(2) For all different gradations of the study soil samples (I to V), unconfined compressive strength values of the soil-cement mixtures for pavement strongly depended upon the levels of cement content and water content. The higher the cement content, the higher the unconfined compressive strength. This test results are in line with the conventional knowledge of the soil-cement stabilization.

(3) For all cement contents, unconfined compressive strength values dependent on water content levels. The highest unconfined compressive strength values were at OWC for all cement contents. Notably, the unconfined compressive strength values of wet side compaction were always higher than for dry side compaction.

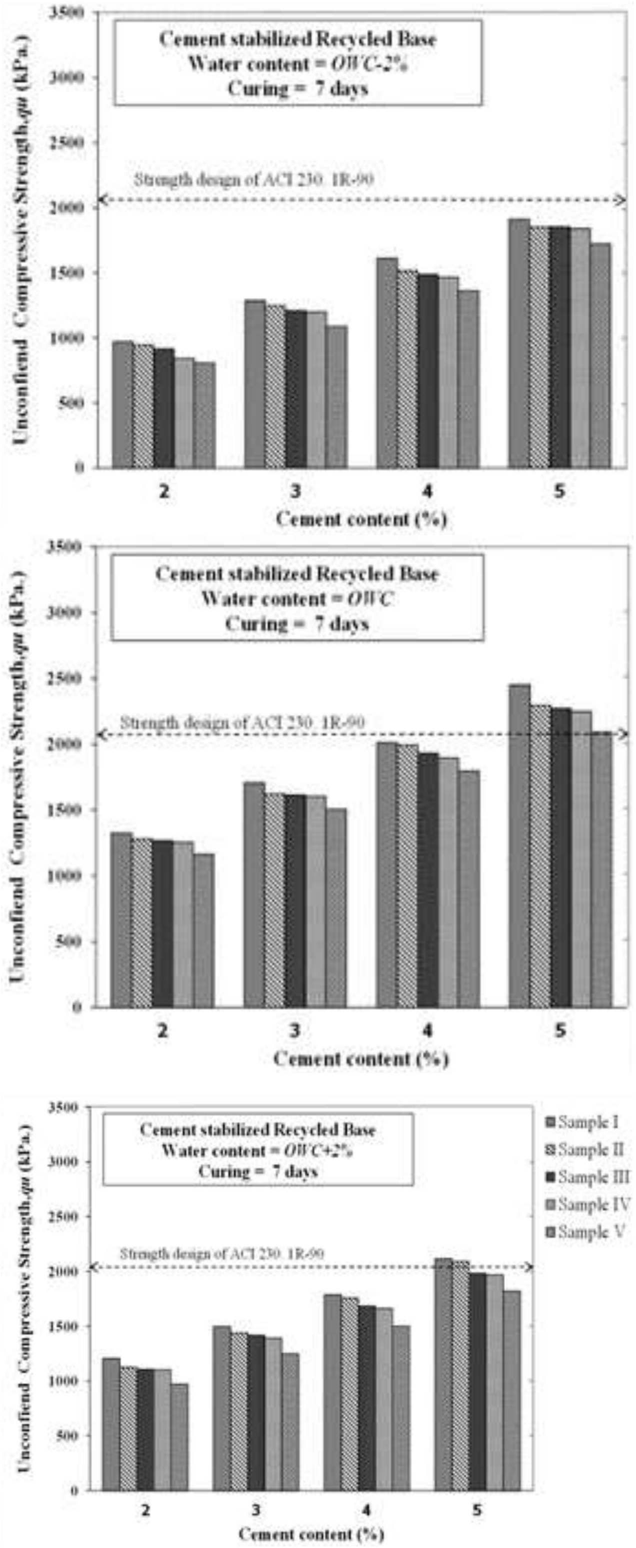

Figure 6. Unconfined compressive strength with varying cement and water contents under a seven-day curing period.

(4) Water content was crucial for the performance of a soil-cement mixture for pavement. All reconstituted soil samples (Group I to V) compacted at OWC with 5% cement content by dry mass completely passed the ACI's compressive strength requirement. For the three water content levels, only compaction at OWC provided satisfactory unconfined compressive strength for all study soil groups. Compaction at OWC+2% for soil groups of I and II also provided satisfactory strength results. All compaction at OWC-2% failed to meet the ACI's compressive strength requirement.

(5) The difference in gradation of soil particles has a much lesser effect on the performance in terms of unconfined compressive strength of the soil-cement for pavement than its cement content and water content. If a material gradation falls into the specification envelope, variations of a material gradation would not have an effect on the strength of the soil-cement material used for pavement. Degrees of water content and cement content would be rather concerned.

(6) Finally, the significant outcome of this study is that any large fluctuations in moisture level in a soil-cement mixture during construction (compaction) should therefore be avoided. Specifications that improve consistent moisture levels in a soil-cement mixture should be carefully established, in order to translate these results to road construction applications.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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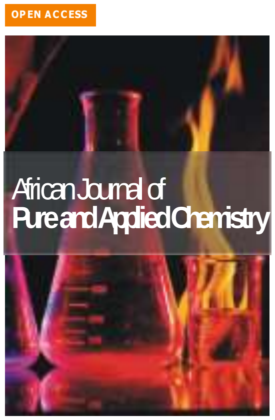

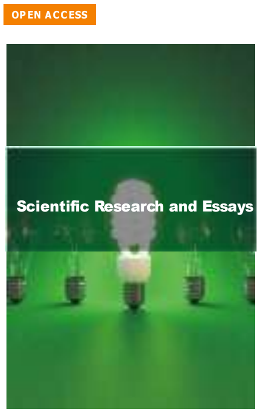

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