Mechanical Properties of Clayey Sand Treated with Cement-Rubbershreds

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Abstract: Residual soils of clayey sand composition can potentially be treated to construct a 2-layer pavement system. Using cement as the primary binder and recycled rubbershreds (<2 mm thick, 0.425 mm - 12 mm in length) as filler material, the improved ground can serve as a reliable road foundation, overlain with a surface capping layer. In order to determine the performance of this treated foundation layer, the relevant mechanical properties were examined using suitable laboratory tests, i.e. compaction, unconfined compressive strength and bender element tests. From the test results, it can be concluded that a mixture of cement and recycled rubbershreds effectively enhanced the mechanical properties of the soil. The cement dosage was kept at a minimum to bind the soil and rubbershreds for long term durability, while the rubbershreds served as a flexible filler material, without compromising the targeted strength and compressibility.

Keywords: Cement, rubbershreds, residual soil, pavement.

Introduction

Residual soils commonly distributed in tropical countries are well known as good backfill materials. However, the high fine contents mean that the soil has characteristics more like a cohesive material than a granular one. Typical features, such, as low strength and high compressibility are arguably the two most problematic characteristics of the material. Therefore, many of the unpaved roads built on these soils often end up damaged with the need for regular repair and maintenance, a condition made worse by the high rainfall intensity as well as monsoon seasons, not to mention shoddy workmanship. On the other hand, by stabilizing in situ soils to form road foundations and capping the surface with a thin layer of cemented crushed rock (i.e. 2-layer road system), savings of materials, costs and labor are possible while providing a satisfactory access road for the local community. Considering today's severe depletion of raw materials and alarming deterioration of environmental quality, it is timely to explore alternative construction methods and materials to fulfill the needs of the present without compromising those of future generation.

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Past researchers [1-3] have successfully demonstrated the incorporation of granulated rubber in soil stabilisation. On the other hand, the reuse of recycled wastes, like rubbershreds processed from used tires, inadvertently raised concerns over potential contamination and pollution, both of which could result in severe or irreversible environmental impact [4]. Such valid claims of possible detrimental effects on the environment were examined by Tatlisoz et al. [5], where an extensive literature survey on the environmental suitability of tire chips was carried out by the authors. It was revealed that despite the worst case scenarios of actual field conditions simulated in laboratory models, no significant threats could be identified from the relevant leaching tests.

Rubber is well recognized for possessing desirable qualities like durability, strength, resiliency and high frictional resistance [6]. These inherent properties make rubber a suitable inclusion in civil engineering works for enhanced performance. As reported by Hazarika et al. [7], recycled rubberchips and rubbershreds are not dissimilar to the ubiquitous geosynthetics used in a wide range of civil engineering applications, including drainage, leachate control, reinforcement, bearing capacity improvement, erosion control, thermal insulation, noise barriers and of course, soil stabilisation. Indeed, the reuse of these otherwise waste materials does not only help in preserving the environmental well-being, but also taking a step closer to sustainable construction and development at significant cost benefits.

Following is a description of the series of laboratory trials performed prior to the construction of a trial

road in a local oil palm plantation. The laboratory work included characterization of the soil, bender element test to assess the improved stiffness, as well as the unconfined compression test.

Materials and Methods

As the field application was intended for a treated road foundation of no more than 500 mm thick, disturbed samples were collected from within the depth for characterization purposes. The soil was found to be uniform for the depth, and the relevant properties are given in Table 1. The site was overlain with debris from past relaying and maintenance exercises. Hence the top 50 mm was initially scraped and removed to avoid such impurities in the retrieved soil samples (Figure 1).

The rubbershreds (RS) used in this study were provided by a used tire processing plant. The shreds were within the size of 0.425 mm - 12 mm in length, and the thickness was generally less than 2 mm (Figure 2). Referring to the classification system for processed rubber in ASTM D6270-98 [8], the rubbershreds were categorized as 'granulated rubber'. Ordinary Portland cement (C) was used as the binder of the soil and rubbershreds.

The test specimens were prepared by first mixing the soil, cement and rubbershreds at pre-determined quantities in a kitchen mixer. Pair of specimens with a range of water, cement and rubbershred contents were examined to identify the optimum mix ratios for the targeted performance (Table 2). The mixture was next transferred to a detachable steel mould (internal dimensions 100 mm x 50 mm x 30 mm), and compacted with a hydraulic press up to 20 kPa. Upon demoulding, the specimens were wrapped in cling film and stored in a humid chamber for curing.

Figure 1. The Proposed Trial Road Site-Overlain with Debris from Past Repair Works

Figure 2. Rubbershreds
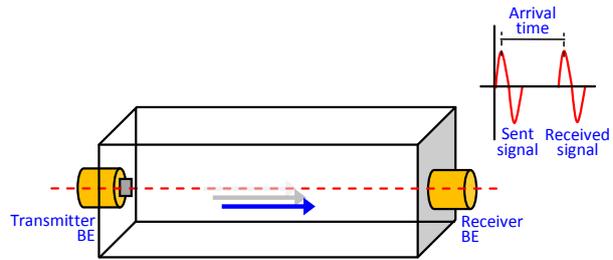
Figure 3. Bender Element Test

Table 1. Properties of the Soil

Original soil	SC: clayey sand
Specific gravity	2.73
Liquid limit, w_L	48.25 %
Plastic limit, w_P	23.68 %
Shrinkage limit, w_S	8.21 %
D_{10}	0.07 mm
D_{30}	0.22 mm
D_{50}	0.35 mm
D_{60}	0.48 mm
Mixed soil	***Shrinkage limit, w_S**
2R (2 % rubbershreds)	9.29 %
4C (4 % cement)	7.86 %
4C 2R (4 % cement and 2 % rubbershreds)	6.43 %
	*The stabilized material displayed reduced shrinkage: an advantage for field applications.

Then, bender element tests were conducted with the GDS BE (bender element) Test System, where P- (compression) and S- (shear or transverse) waves were sent through the specimens (Figure 3). By identifying the tip-to-tip travel distance and time of the waves respectively, the wave velocities (v_p and v_s) were simply derived by dividing distance with time. More details on bender element tests and the wave arrival time determination can be referred to in Chan [9]. Assuming the specimen to be an elastic, isotropic and homogeneous medium, the small strain stiffnesses of the material can be obtained as follows:

Bulk modulus, $\quad K = \rho v_p^2$ $\qquad\qquad\qquad$ (1)

Shear modulus, $\quad G_o = \rho v_s^2$ $\qquad\qquad\qquad$ (2)

In which, v_p is the P-wave velocity, v_s, the S-wave velocity, and ρ, the bulk density.

Table 2. Mix Ratios of the Test Specimens (a pair each)

Specimen	Cement, C (%)	Rubbershreds, RS (%)
Soil	0	0
4C	4	0
2RS	0	2
3RS	0	3
4RS	0	4
4C2RS	4	2

Note: C and RS percentages were calculated based on dry weight of soil.

A conventional unconfined compressive strength test apparatus was used to evaluate the strength of the specimens, with reference to the procedure pre-scribed in BS 1377 [10]. The same specimens used in the non-destructive bender element tests were subjected to the compression tests, eliminating any discrepancies that might arise from non-uniformity of the test specimens prepared.

Results, Analysis and Discussions

Compaction
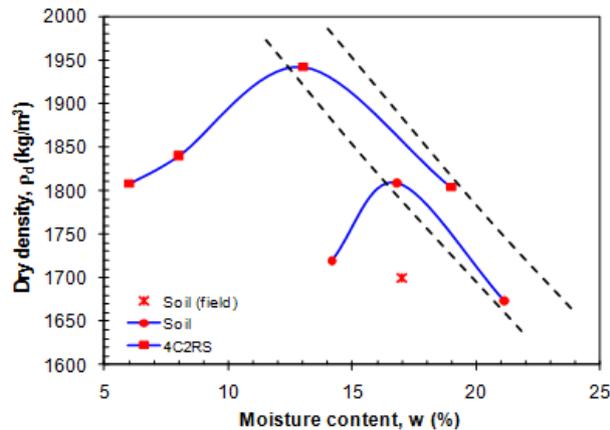
Figure 4. Relationship Between Density and Water Content of the Soil

Serving as a road foundation, the density of the treated soil layer is naturally of much concern. The compaction curve of the soil is shown in Figure 4, together with the field and remolded densities. The natural water content, w, of the soil was 17%, corresponding to a dry density, ρ_d, of about 1700 kg/m³. The compaction curve derived from standard procedure gave a maximum ρ_d of 1800 kg/m³ at approximately the same water content, suggesting an under-compacted soil layer on site. Probably due to the sandy nature of the soil, the maximum density was achieved with remnants of approximately 5% of air voids in the compacted soil mass.

The entrapped air within the compacted soil mass was undesirable for long term performance of the road foundation, as it can permit water infiltration and eventual loosening of the soil structure with increased permeability. By mixing the soil with 4% cement and 2% rubbershreds, there remained approximately 5% air voids in the soil matrix at optimum water content. Note that this is not much different from the compacted soil only specimen, indicating the impossibility of total air pockets elimination even with induced cementation. Besides, the corresponding increase in density of the treated soil was admittedly marginal, i.e. about 8% (Figure 4). This minor change in density can be attributed to the small dosage of cement added in the mixture, as well as the low density of rubbershreds.

It has been observed too, that additional 2.5-3.0% water was required to form the treated soil. This was inevitable for a couple of reasons: (1) to lubricate the additional surface area of the rubbershreds; (2) to provide water for the cement hydration process, which binds the soil particles and rubbershreds to form a strengthened matrix. It is worth noting here, that based on a preliminary soaking test conducted on the rubbershreds, the material was not found to have an affinity towards water, hence ruling out the need for additional water to accommodate absorption.

Looking at the compaction curve of 4C2RS, it is intuitive to target the maximum ρ_d compacted at optimum water content, w_{opt}, in field applications. However $w_{opt} = 13\%$ is lower than the soil's natural water content of 17%, suggesting prior partial drying of the in situ soil if these values are to be adopted and achieved on site. The tendency of the soil-cement-rubbershreds mixture to form non-uniform lumps under a low moisture environment was also noticed during the compaction test. As homogeneity of the mixture can hardly be expected with deprived water, especially with the onset of cement hydration, the increased density recorded can be misleading for practical purposes.

Effects of Cement and Rubbershreds on Strength

As the first step taken to examine the effect of rubbershreds addition on the soil, unconfined compression tests were carried out on specimens admixed with the rubber component only at 19.5% water content (based on the compaction test results, as discussed above). Figure 5 shows the results of the tests, where 2-4% of rubbershreds (based on dry weight of soil) were used to prepare the specimens. Note that the comparatively small percentages were in compliance with the light weight of the material.

The plots indicate that too much of rubbershreds added to the clay can significantly reduce the strength, i.e. 4RS specimen. More importantly, considering the similar strength values of specimens 2RS and 4RS, the rubbershred dosage was fixed at 2% for subsequent mixes, for the apparent reason of avoiding wastage. The benefits towards strength enhancement with rubbershreds addition is not unlike that of fibre inclusion, such as reported by Muntohar [11] who examined the strength of a clay soil stabilized with lime–rice husk ash–plastic fiber. It was suggested that the frictional contact between fibers and soil particles contributed to the strength increase.

In Figure 6, the stress-strain plots of various specimens were included. By comparing the soil only specimen (labeled as 'Soil') with that of 2RS, the rubber component clearly introduced ductility to the soil. This was accompanied by an approximately 50% of strength reduction too. However, when 4% of cement was mixed with the soil (specimen 4C), the strength was dramatically raised by almost 2.5 times. When 2% rubbershreds was added to the same mixture (specimen 4C2RS), a slight drop in the strength can be observed. This can be attributed to the flexibility of the rubbershreds. It should be noted that in spite of the slight drop in the unconfined compressive strength, q_u, the stiffness of the composite material remained largely unchanged. It can be deduced that the rubbershreds acted as a filler material, consequently reducing the amount of cement required to attain similar strengths without rubbershreds.

Figure 7 shows the specimens after compression tests. Comparing the first 2 photos, it can be seen that cement effectively hardened the soil, where the cemented specimen displayed a distinct failure plane during compression. On the other hand, a brittle failure mode was observed with the addition of rubbershreds alone to the soil. A combination of cement and rubbershreds resulted in a compromised failure mode: hardened, but with additional tensile resistance against brittle failure. Being slightly expanded post-compression, the soil-cement-rubbershreds specimen is notably less distorted compared to the soil only specimen (compare 'Soil' and '4C2RS' in Figure 7).

Referring to earlier discussions on the compacted densities of the mixture, further insights on the improved properties of the mixture can be acquired. The unchanged density of the soil-cement-rubbershreds mixture, compared to the compacted soil alone (Figure 4), was not reflective of the mixture's markedly improved strength (Figure 6). This can be explained by the induced bonding of cement added to the mixture. In application, the relatively unchanged density indicates a potential advantage in terms of subsidence control, due to self-weight of the treated soil layer.
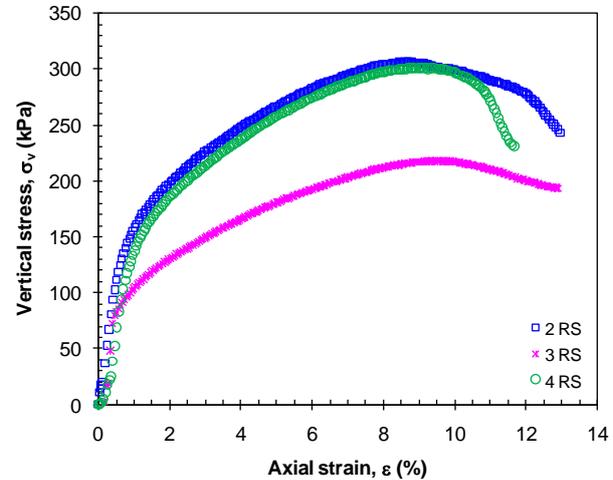
Figure 5. Unconfined Compression Test Results of Soil-Rubbershreds Specimens
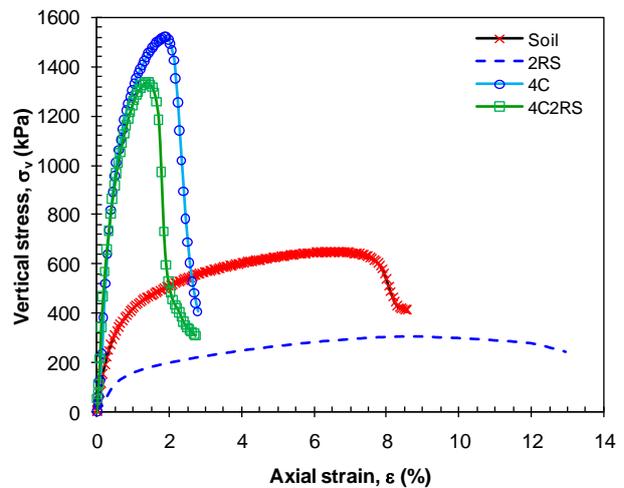
Figure 6. Comparison of the Stress-Strain Behaviour of Various Specimens
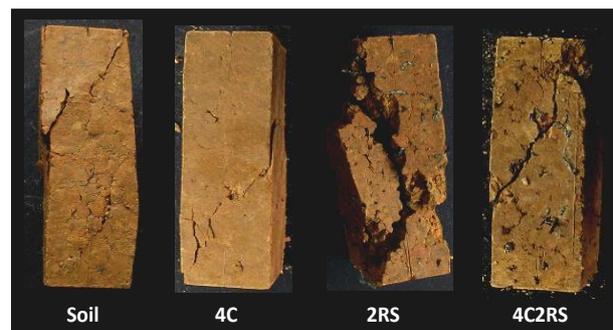
Figure. 7. Specimens after the Compression Tests

Effect of Mixing Water Content on Stiffness

Shown as P-wave or S-wave velocity (v_p and v_s respectively), the measured values over a period of 8 days for specimens with 4% cement and 2% rubbershred additions are given in Figure 8. The mixing water content (w) was varied between 6-13%, based on dry weight of the soil. Albeit the slight scatter in both plots, it can be clearly seen that stiffness of the specimens increased markedly within a day of mixing, and remained fairly unchanged for the rest of the curing period. Also, the variation in mixing water content did not appear to significantly affect the improved stiffness.

These observations are important for field applications, particularly (1) to determine the necessary resting period before the overlying or capping layer can be placed; (2) to identify the effect of surface water infiltration on the composite material at an early age, when the treated soil layer has yet to sufficiently mature.
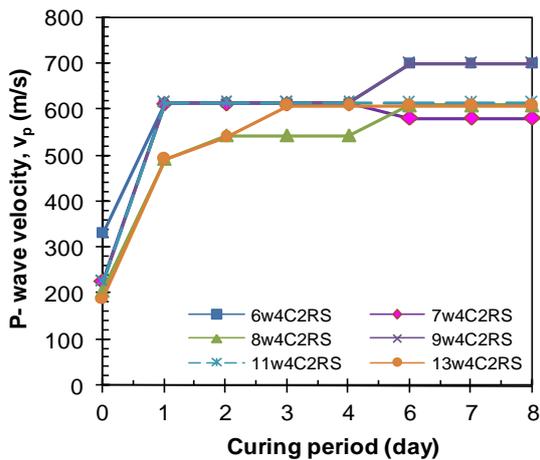
Figure 8(a). P-Wave Velocity (v_p) of the Various Specimens
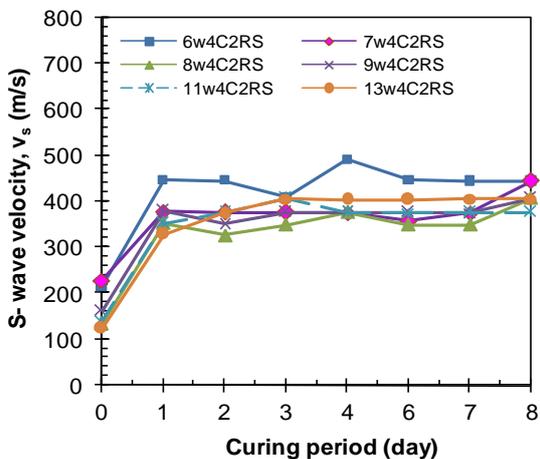
Figure 8(b). S-Wave Velocity (v_s) of the Various Specimens
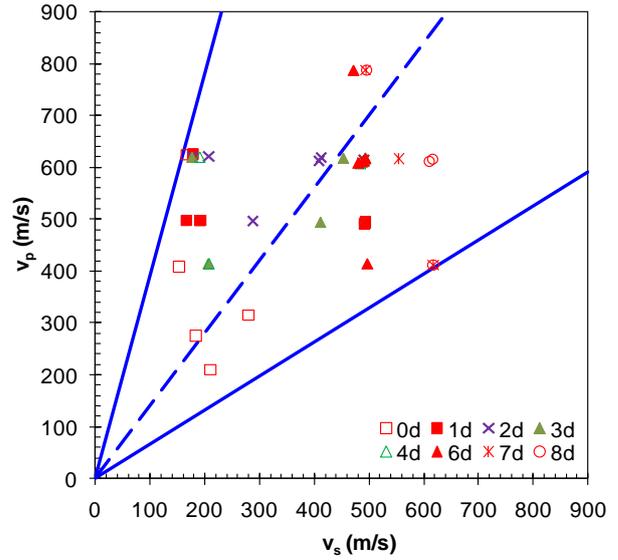
Figure 9. v_p - v_s plot

Figure 9 shows the compilation of all the wave velocity data points grouped according to the age of the specimens. v_p is generally reported to be 1.5-2.0 times that of v_s. By taking the average of the upper and lower limits for the data, it was established that v_p is approximately 1.4 times of v_s. The correlation is useful should only P-wave measurement is available, where v_s could be readily estimated. Of course, it is puzzling that some data points should fall below that of the line of equality (i.e. $v_p = v_s$). It is postulated that a plausible explanation is the poor contact between the bender element transducers and the specimen during measurement. As the wave velocities depend very much on the quality of signals captured for interpretation, which in turn depends on the good contact of the transducers and the material tested (among other factors influencing wave propagation through a confined medium), it was perceived to be the most probable cause of the discrepancy observed.

Conclusions

- While the soil-cement-rubbershreds mixture was shown to produce greater densities with lower water contents in the compaction test, it is deemed unsuitable for site applications, for the range was below that of the natural water content of the in situ soil.
- For field application, it is recommended that cement be introduced in liquid form, which corresponds to an additional 3% water, so as to facilitate more effective mixing and compaction of the materials.
- The compressive strength test results showed cement as the dominant strength enhancement factor. The rubbershreds mainly function as a flexible filler material, and compensate for the

rigidity and brittleness caused by cementation. This is considered a favorable characteristic for the proposed road foundation: enhanced durability, comfort and trafficability.

- Based on the stiffness check with bender elements, no more than 24 hours is necessary as the resting period for the treated soil. However care should be taken to prevent moisture loss during the period, such as by covering the treated surface layer from exposure to the elements. As in concrete and reports of premature drying of stabilized soils, shrinkage can occur, and the resulting strengths can be compromised. It is worth noting that subsequent field trial showed that 'crusting' (formation of a thin solidified layer) can take place, leaving the treated layer susceptible to surface damage.

Acknowledgment

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