GEOTECHNICAL CHARACTERISTICS OF BAUXITE RESIDUE SAND MIXED WITH CRUMBED RUBBER FROM RECYCLED CAR TIRES

Mohamed A. Shahin[1], Tyrone Mardesic[2], and Hamid R. Nikraz[3]

ABSTRACT

The re-use of waste materials is an essential step in creating a sustainable future, and research into the re-use of different by-products has often led to new materials that provide superior service or greater economy than those traditionally used. This paper aims to investigate the use of new mixtures of bauxite residue sand and crumbed rubber from recycled car tires, as fill material. In Australia alone, 20,000 tons of bauxite residue sand is produced daily as a by-product from the Aluminum industry and 20 million recycled car tires are annually disposed, leading to environmental health and hazard problems. In this paper, the geotechnical characteristics of the new mixtures are investigated under static and dynamic loading conditions. A series of laboratory experiments are conducted, including sieve analysis, compaction, permeability and static as well as repeated loading consolidated drained triaxial tests. In addition, numerical modeling using the finite element method is used to examine the feasibility of the new materials in two geotechnical engineering applications, including slope stability and pavement design. The results indicate that the bauxite residue sand-tire crumb mixtures have a good potential for use as lightweight fill material in geotechnical engineering applications.

Key words: Geotechnical properties, car tire crumbs, recycled materials, bauxite residue sand.

1. INTRODUCTION

Due to shortage of natural resources and increasing waste disposal costs, the re-use of waste and recycled materials is increasing worldwide and becoming more popular in civil engineering, especially for construction of highways (Edincliler *et al.* 2004). However, full understanding of the engineering behavior of these materials is essential so that they can be used safely in civil engineering applications. The literature indicates that the addition of shredded rubber from recycled car tires to sand enhances the engineering properties of the sand-tire mixtures. Furthermore, sand-tire mixtures are usually lightweight, which is a desirable property that leads to higher levels of stability in specific geotechnical engineering structures such as highway embankments over weak or compressible soils and backfill behind retaining walls. In addition, shredded rubber derived from recycled car tires is a safe waste material and do not show any likelihood of having adverse impacts on ground water quality (Humphrey *et al.* 1997; Liu *et al.* 2000).

The products of shredded rubber tires are usually referred as "tire chips" when they are between 12 to 50 mm in size, and are called "tire shreds" when they are more than 50 mm in size (Youwai and Bergado 2004). The geotechnical engineering properties of tire chips and tire shreds mixed with sand have been investigated by many researchers (*e.g.* Bergado *et al.* 2005; Dutta and Rao 2009; Edil and Bosscher 1994; Foose *et al.* 1996; Lee *et al.* 1999; Youwai and Bergado 2004). Research into sand-tire mixtures (*e.g.* Hataf and Rahimi 2006; Zornberg *et al.* 2004) indicates that adding an adequate amount of large-size tire chips or shreds of aspect ratio between 2 ~ 8 to sand can generally improve the shear strength characteristics of the mixture, even though compressibility increases. This is attributed to the fact that large-size tire pieces act as random reinforcement, which increases the shear strength capability of the sand-tire mixtures. However, the oriented reinforcement associated with the larger size of tire chips or shreds may develop potential planes of weakness parallel to reinforcement.

In Australia, 20 million used car tires are disposed annually and cause fire and environmental health hazard problems. Similarly, 20,000 tons of bauxite residue sand are produced daily by the Aluminum industry and cause stockpiling problems. In this paper, the geotechnical properties of new mixtures from two by-products, *i.e.* bauxite residue sand and shredded rubber of disposed car tires, are investigated in an attempt to obtain a potential lightweight structural fill that can be used as a cheaper alternative to conventional fill materials so as to reduce the disposing problems of the two by-products. The geotechnical engineering properties investigated include the compactive behavior, permeability, compressibility and shear strength characteristics under static and dynamic loading conditions. The suitability of the new mixtures as structural fill material for highway embankments and pavement structures is examined through two practical examples, *i.e.* slope stability analysis and pavement design, using the finite element method. The sizes of the shredded rubber used include tire grains of 4 mm and tire powder of 750 μm, and will be denoted "tire crumbs". It should be noted that the size of tire crumbs used are much smaller than those of tire chips or shreds examined elsewhere in the literature so as to limit the potential planes of weakness associated with the larger size of tire chips and shreds. This means that any improvement that tire crumbs will provide to the sand-tire mixtures will basically rely on increased direct contact area of tire rather than the reinforcement

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Manuscript received October 19, 2010; revised December 14, 2010; accepted February 18, 2011.

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effect. In addition, the workability of sand mixed with tire crumbs is much higher than that of sand mixed with tire chips or shreds and thus, sand-tire crumbs are more favorable from the practical point of view. To the authors' best knowledge there has been no research into the behavior of such small sizes of shredded rubber tires mixed with soil.

2. EXPERIMENTAL PROGRAM

2.1 Material Tested

The sand used in this study is a bauxite residue by-product of the Aluminum industry. It is poorly graded, medium grain sand classified as SP by the Unified Soil Classification System (USCS). It has a specific gravity of 3, which tends to be higher than that of other types of sands and this may be attributed to the high mineral content in the sand particles, permeability of 5.7×10^{-6} m/s, which seems to be lower than that of other types of sands but is still greater than the limit of good drainage material as considered by Fell *et al*. (1992), maximum dry unit weight of 18.0 kN/m^3, optimum moisture content of 17.8%, apparent cohesion of 10.8 kPa and friction angle of 41°. The above characteristics are in good agreement with those obtained by Jitsangiam and Nikraz (2010). The particle size distribution curve of the bauxite residue sand used is shown in Fig. 1 (which also includes the particle size distribution curves of the tire crumbs used) and an optical microscopy image of the sand particles is depicted in Fig. 2, which shows that the sand particles have rough angular shapes.

Two different sizes of rubber tire crumbs of aspect ratio one are used, including 4 mm tire grains and 750 μm tire powder. The grain size distribution curves of the tire grains and powder used are shown in Fig. 1, and photographs of samples of the tire grains and powder are shown in Fig. 3. These tire grains and powder are by-products of used car tires that are manufactured by a local company in which a series of shredders and magnets are used to produce a clean and consistent grade of rubber crumbs. The rubber tire crumbs used have a specific gravity of 1.1, which is lower than the typical values of 2 ~ 3 for most geotechnical materials. This significantly decreases the overall weight of the bauxite residue sand-tire mixtures. In this study, the bauxite residue sand is mixed with three different amounts (by weight) of tire grains (*i.e.* 10%, 30%, and 40%) and tire powder (*i.e.* 6%, 9%, and 12%).

2.2 Compaction

Stability and settlement of most geotechnical engineering structures, *e.g.* highway embankments, relies on soil compaction. In this study, a series of modified Proctor compaction tests are carried out on the bauxite residue sand-tire mixtures to obtain their maximum dry unit weights and corresponding optimum moisture contents. The tests are conducted in accordance with the Australian Standards AS 1289 (2007) and the results are shown in Fig. 4. It can be seen that the maximum dry unit weight of the bauxite residue sand-tire mixtures decreases with the increase of tire content, for both tire grains and tire powder with the tire powder being more effective at reducing the maximum dry unit weight than tire grains. These results indicate that sand- tire mixtures have a good potential for using as a lightweight fill.

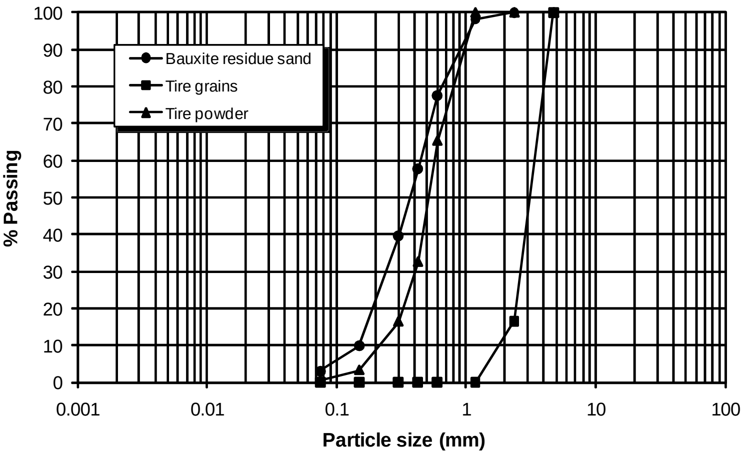


Fig. 1 Grain size distribution curves of the bauxite residue sand and tire crumbs

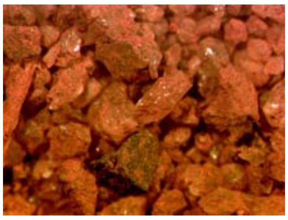


Fig. 2 Optical microscopy image of the bauxite residue sand magnified 30 times

Fig. 3 Photographs of the 4 mm tire grains (left) and 750 μm tire powder (right)

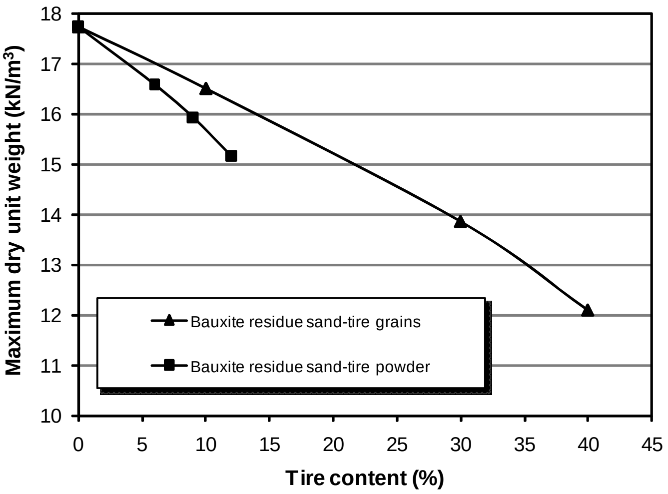


Fig. 4 Effect of tire content on the maximum dry unit weight of bauxite residue sand-tire mixtures

2.3 Permeability

Permeability is an important factor that significantly influences the behavior of fill under saturated conditions, and often dictates the suitability of fill for specific applications. This is because a well-drained fill prevents the development of excess pore water pressure during loading and also accelerates consolidation of underlying low permeability foundation soils by providing a drainage path (Cedergren 1989). According to Fell *et al.* (1992), a material that has permeability greater than 1×10^{-6} m/s is considered as a good drainage material. In this study, a series of falling head permeability tests are conducted on the bauxite residue sand-tire mixtures according to the Australian Standards AS 1289 (2007), and the results are shown in Fig. 5. It can be seen that there is a general trend of increasing permeability with the increase of tire content, for both tire grains and powder. The slight decrease in permeability between the 30% and 40% tire grain-sand mixtures may be attributed to the fact that as the amount of tire grains is increased beyond 30%, the tire grains block the water flow inside the sand-tire mixture and thus permeability decreases. It can also be seen that the permeability of all bauxite residue sand-tire mixtures used in this study are greater than 1×10^{-6} m/s, which indicates good drainage materials.

2.4 Compressibility and Shear Strength under Static Loading

The stability of geotechnical engineering structures depends mainly on the strength and deformation characteristics of the materials used. In this study, a series of strain-controlled consolidated drained triaxial tests under static loading is carried out on specimens of bauxite residue sand-tire mixtures of dimensions 35 mm in diameter and 75 mm in height. All tests are conducted in accordance with the procedures set out by Head (1998). All specimens are prepared to the optimum moisture content and then compacted in five layers in the split mould so as to achieve a minimum compaction equal to 95% of that obtained from the modified Proctor compaction test. At the start of each test, the specimens are brought to a degree of saturation of at least 95%, which is measured by checking the pore pressure parameter *B*. The specimens are subjected to confining pressures of 50, 100, and 250 kPa, and an axial stress is applied to failure at a strain rate of 0.25 mm/minute. The deviatoric stress-strain and volumetric strain behavior observed on the bauxite residue sand-tire mixtures at a confining pressure of 250 kPa are shown in Figs. 6 and 7. Similar behavior is obtained at lower confining pressures of 50 and 100 kPa.

It can be seen from Figs. 6(a) and 7(a) that the addition of tire crumbs (whether grains or powder) generally decreases the ultimate strength and stiffness (modulus of elasticity) of the sand-tire mixtures, and increases the deformation at failure. This can be attributed to the fact that the addition of tire grains or powder increases their direct area of contact, leading to higher compressibility. Although a decrease in ultimate shear strength and an increase in compressibility are not desirable, one practical implication of adding tire crumbs to the bauxite residue sand is to allow some geotechnical structures, *e.g.* embankments, to undergo larger strains without failure. Figures 6(a) and 7(a) also show an improvement in the strain hardening (ductility) behavior of the bauxite residue sand-tire mixtures, with decreased loss of post-peak shear strength.

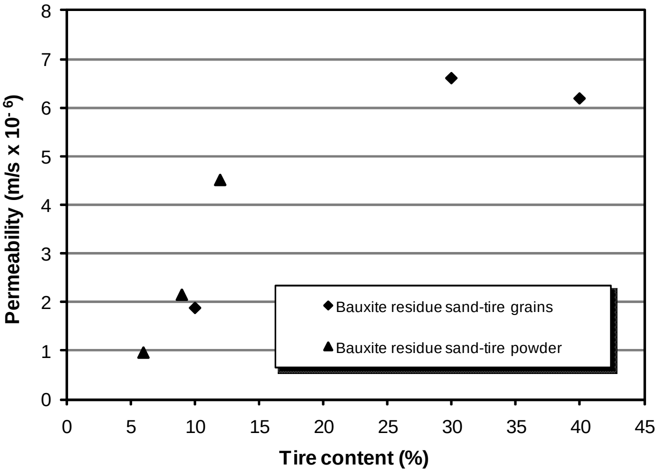
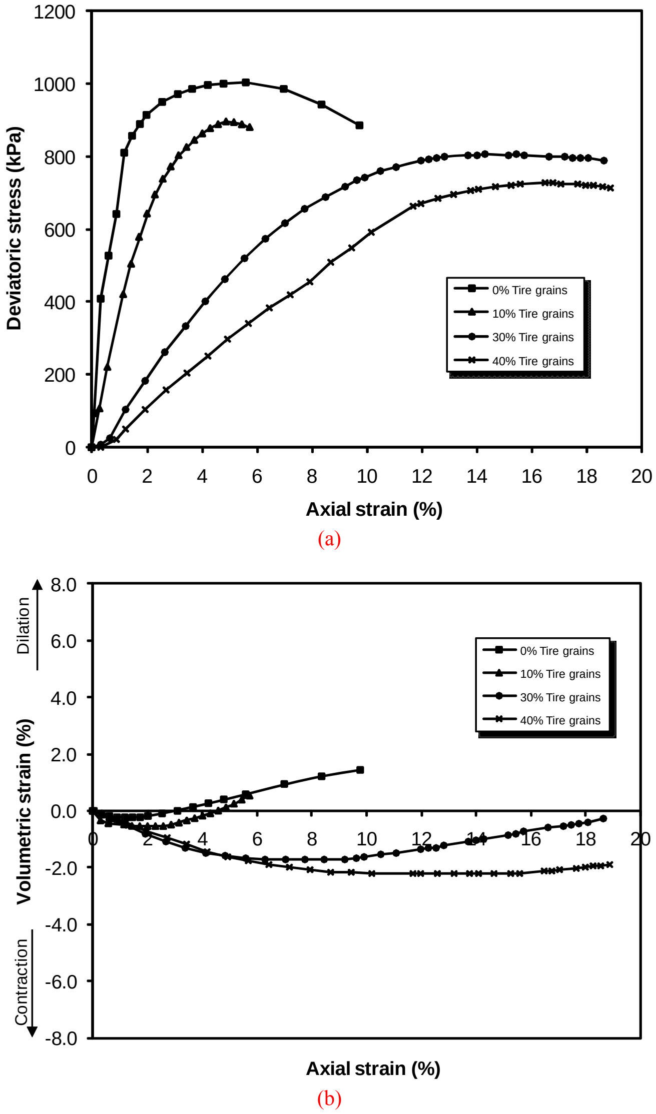


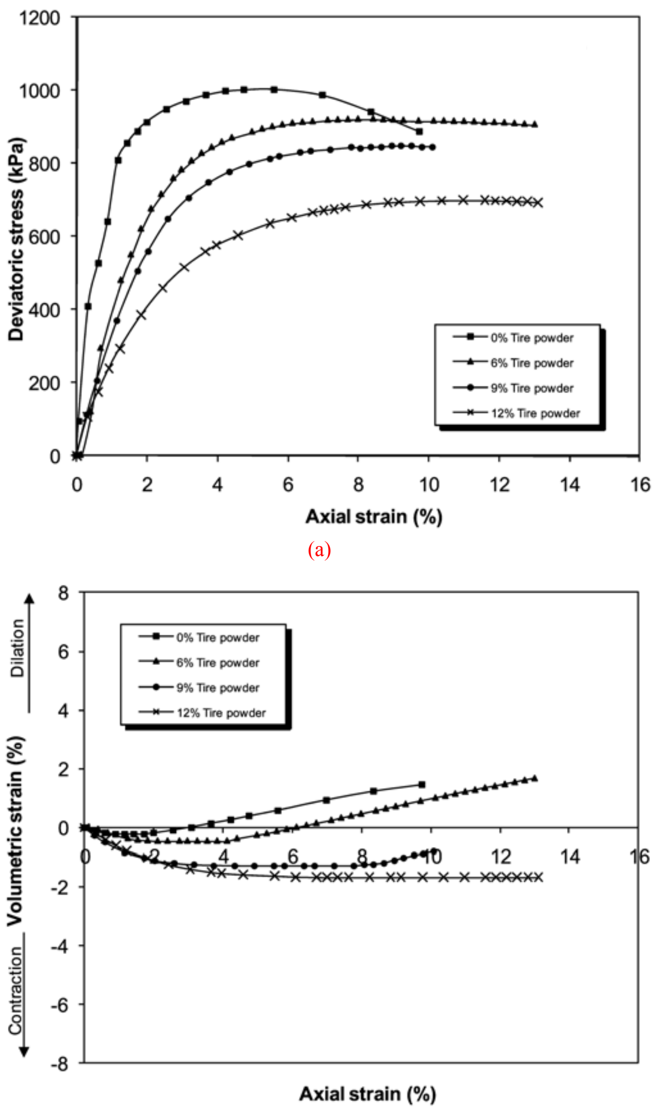
Fig. 5 **Effect of tire content on the permeability of bauxite residue sand-tire mixtures**



(a)

(b)

Fig. 6 **Results of the triaxial tests carried out on bauxite residue-sand tire grains at confining pressure of 250 kPa**



(a)

(b)

Fig. 7 Results of the triaxial tests carried out on bauxite residue-sand tire powder at confining pressure of 250 kPa

Figures 6(b) and 7(b) show the volumetric strain versus axial strain characteristics of the bauxite residue sand-tire mixtures. It can be seen that the volumetric strain changes from dilation towards overall compression as tire content increases. This indicates that the addition of tire grains or powder decreases soil dilatancy, which may not be a desirable property in some geotechnical engineering structures.

The shear strength parameters (*i.e.* apparent cohesion, *c*, and angle of friction, ϕ) of the bauxite residue sand-tire mixtures are calculated from the peak shear stress values obtained from the triaxial tests, and the results are shown in Fig. 8. It can be seen from Fig. 8(a) that the addition of tire grains increases the apparent cohesion but decreases friction. For example, the addition of 30% tire grains increases cohesion from 11 kPa (for sand without tire grains) to 30.6 kPa (for sand-tire grains mixture) and decreases the angle of friction from 41° (for sand without tire grains) to 35.5° (for sand-tire grains mixture). It can also be seen that the addition of more than 30% tire grains has a marginal impact on improving cohesion. On the other hand, Fig. 8(b) shows that the addition of 6% tire powder increases cohesion from 11 kPa (for sand without tire powder) to 14.5 kPa (for sand-tire powder mixture) and decreases angle of friction from 41° (for sand without tire powder) to 37.1° (for sand-tire powder mixture). Figure 8(b) also shows that adding more than 6% tire powder does not seem to have a significant impact on the shear strength parameters of the sand-tire mixture.

2.5 Compressibility and Shear Strength under Dynamic Loading

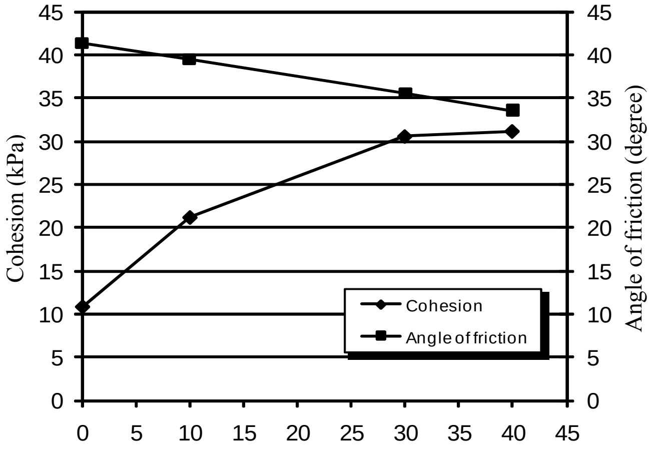
Geotechnical engineering structures built in earthquake prone areas or those subjected to dynamic loading such as road or railway construction require calculations of the dynamic stiffness and deformation characteristics of the materials used under cyclic loading conditions. In this study, a series of repeated loading triaxial tests are performed on the bauxite residue sand-tire mixtures in order to establish the relationships between the applied stress, and resilient modulus and permanent deformations. The triaxial testing system employed in this investigation is a pneumatic digital servo control testing machine, as shown in Fig. 9. The axial dynamic load is applied to the specimen by the top platen using a feedback-controlled high pressure air actuator, and various transducers are mounted in the system for measuring the axial load, confining pressure and axial strain. Axial deformations are measured by a pair of LVDTs attached to the top platen, which convert the mechanical movements into electronic signals via the Control and Data Acquisition System (CADS) that provides and displays the output on a personal computer screen. A series of tests are carried out on bauxite residue sand specimens (with and without tire crumbs) at confining pressures of 50, 100, and 250 kPa. The percentage of tire grains and powder used for the dynamic loading tests are chosen to be 30% and 6%, respectively. A cyclic deviator stress of sinusoidal shape is applied at frequencies of 0.5 and 2 Hz with a value equal to half the failure static deviator stress obtained in Section 2.4. The frequencies selected represent the range of conditions forming the majority of practical problems in geotechnical engineering. A seating load of 2 kPa is also maintained during the test to ensure that the actuator shaft remains in contact with the top loading platen. For each test conducted, 10,000 load cycles are applied. In the section that follows, only the results obtained from a frequency of 0.5 Hz are presented, as similar behavior is determined for a frequency of 2 Hz.

Figure 10 shows the results of the resilient modulus for the bauxite residue sand with and without tire crumbs at the confining pressure of 250 kPa. Similar behavior is obtained at lower confining pressures of 50 and 100 kPa. The resilient modulus, *RM*, is calculated as follows:

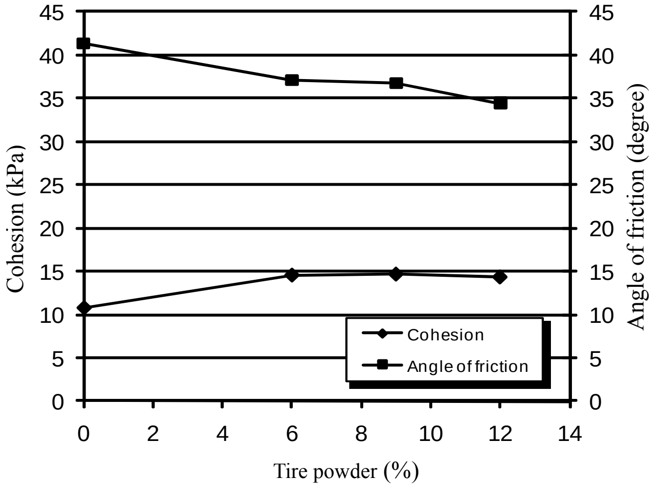
$$RM = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

where σ_d is the repeated deviator stress and ε_r is the recoverable axial strain. Figure 10 shows that adding tire crumbs (whether grains or powder) to bauxite residue sand decreases the resilient modulus of the sand, with the sand-tire grains mixture appearing to be more prone to decreasing resilient modulus than that of the sand-tire powder mixture.

In order to establish the relationship between the resilient modulus of the bauxite residue sand-tire mixtures and applied dynamic stresses, the *k*-θ model (Hicks and Monismith 1971) is used as follows:



(a) Tire grains



(b) Tire powder

Fig. 8 Effect of tire crumbs on shear strength parameters of bauxite residue sand-tire mixtures

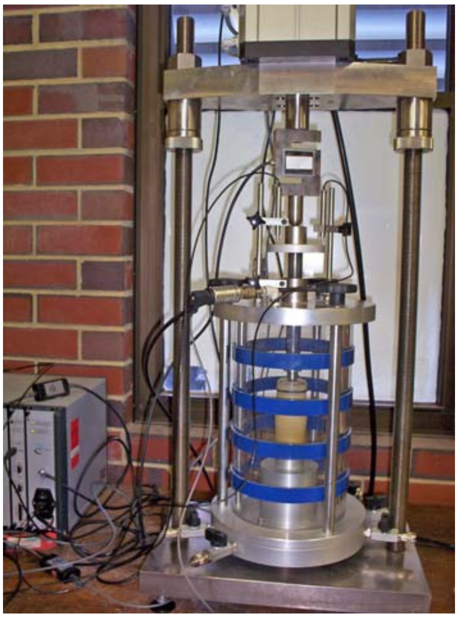


Fig. 9 Pneumatic dynamic loading triaxial apparatus

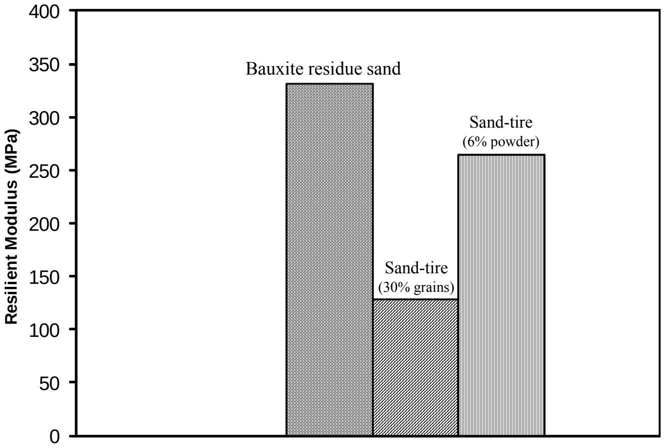


Fig. 10 Resilient modulus of the bauxite residue sand with and without tire crumbs

$$RM = k_1 \theta^{k_2} \tag{2}$$

where θ is the bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$), and k_1 and k_2 are regression analysis constants that need to be determined experimentally. The results of the regression analysis are shown in Fig. 11, which have led to the following representative k-θ models:

$$RM = 0.2793\ \theta^{0.87}\ \text{(for bauxite residue sand-tire grains)} \tag{3}$$

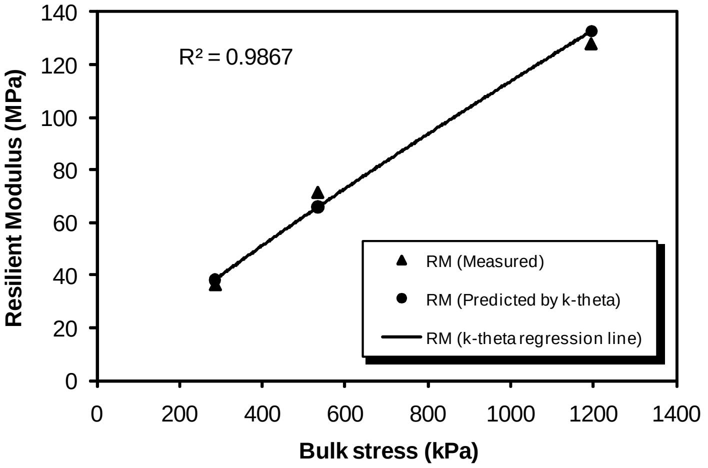
and

$$RM = 9.7087\ \theta^{0.47}\ \text{(for bauxite residue sand-tire powder)} \tag{4}$$

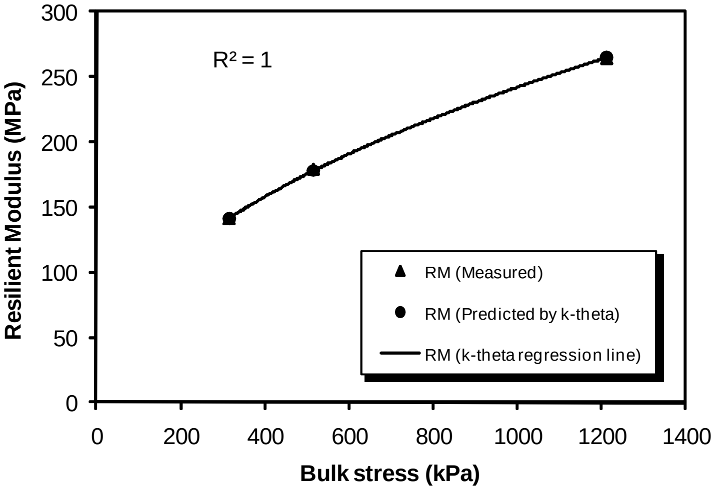
The deformation data of the tests conducted on the bauxite residue sand with and without tire crumbs at a confining pressure of 250 kPa are plotted in Fig. 12. Similar behavior is obtained at lower confining pressures of 50 and 100 kPa. It can be seen that the permanent (plastic) deformation of all samples increases rapidly up to 1,000 cycles, beyond which the deformation remains constant up to 10,000 cycles. The rapid increase in deformation at the initial 1,000 cycles is due to the considerable packing and sliding of particles (stabilization stage), resulting in significant settlement and formation of compact material compared to the initial arrangement. After 1,000 cycles, the material undergoes elastic shakedown and there is no further accumulation of permanent strain with increasing cycle number. It can also be seen that the bauxite residue sand-tire mixtures exhibit more permanent deformation with the number of cycles than that of the bauxite residue sand alone, and that the sand-tire mixture of 30% tire grains exhibits more deformation than that of the sand-tire mixture of 6% tire powder. The relationship between the axial deformation, ε_a, and number of cyclic loadings, N, shown in Fig. 12 may be expressed as follows:

$$\varepsilon_a = A\, N^B \tag{5}$$

where A and B are regression analysis constants determined from experiments and has led to the following models:



(a) Tire grains



(b) Tire powder

Fig. 11 Regression modeling of the resilient modulus of bauxite residue sand-tire crumbs

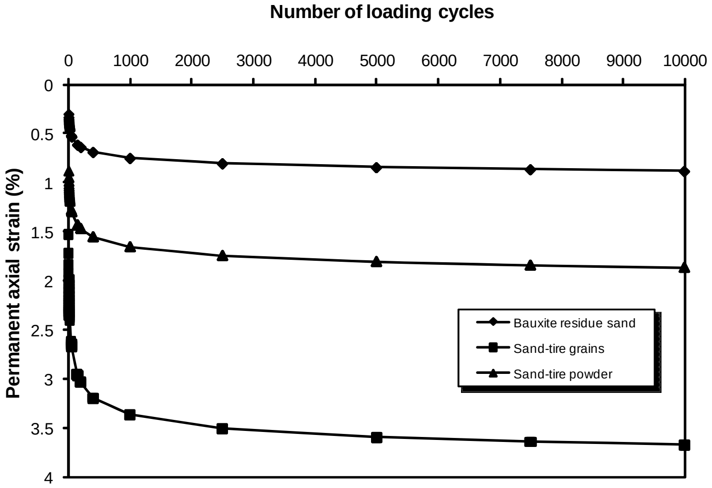


Fig. 12 Permanent axial strain due to cyclic loading of the bauxite residue sand with and without tire crumbs at confining pressure of 250 kPa

$$\varepsilon_a = 0.957\,N^{0.076}$$

(for bauxite residue sand-tire grains with $R^2 = 0.98$) (6)

and

$$\varepsilon_a = 1.9053\,N^{0.078}$$

(for bauxite residue sand-tire powder with $R^2 = 0.93$) (7)

3. PRACTICAL APPLICATIONS

In this section, the suitability of bauxite residue sand-tire mixtures in two geotechnical engineering applications is assessed by numerical modeling using the available finite element software package PLAXIS 2D Version 9.0 (PLAXIS 2008). The applications include static loading of slope stability analysis and dynamic loading of falling weight deflectometer used for pavement design. Despite the fact that the selected practical applications seem to be simplistic, they are rather informative and elucidate the suitability of the new mixtures in real situations.

For the slope stability analysis, embankments of varied heights of 5, 10, and 15 meters with slope angle of 30° are numerically simulated using 2D plane strain conditions. An example of the mesh discretization used for the 10 meters height slope is shown in Fig. 13, which utilizes 15-node triangular elements that provided a fourth-order interpolation for displacements and involved 12 Gauss points (stress points) for the numerical integration. At the left- and right-hand sides of the embankment, the displacements normal to the boundary are fixed, and the tangential displacements are kept free to allow for smooth movements. The bottom boundary is fully fixed to simulate the bedrock and the top boundary is fully free to move. An elasto-plastic constitutive model with Mohr-Coulomb failure criterion is assumed for the sand and sand-tire mixtures, and the slope stability soil parameters are given in Table 1. The *Phi-c reduction* process available in PLAXIS (2008) was used to calculate a global factor of safety for the slope at hand (an example of slope displacement vectors is depicted in Fig. 14) and the factor of safety results are shown in Fig. 15. It can be seen that for all cases, the factor of safety decreases with the increase of embankment height, as expected. It can also be seen from Fig. 15(a) that for all embankment heights, significant improvement in slope stability occurs with increasing tire grain content (especially at 30%). On the other hand, Fig. 15(b) shows that the addition of powder does not seem to make any significant improvement on slope stability and thus, will not be considered in the analysis that follows. In order to study the effects of slope angle on stability of embankments, additional numerical modeling is conducted and the results are shown in Fig. 16. It can be seen from Fig. 16(a) that for the minimum acceptable factor of safety of 1.5, the steepest allowed slope angle for embankment of bauxite residue sand alone and height ≥ 9 m is 50°, and for embankment heights up to 12 m is 45°. On the other hand, Fig. 16(b) demonstrates that for any embankment height ≤ 15 m, the steepest allowed slope for bauxite residue sand mixed with 30% tire grains is 65°. The increased slopes allowed for sand-tire grain embankments will have an immense economical benefit as it means lesser construction materials for a cheaper design, and smaller embankment widths for reduction in land purchase and the need for right-of- way acquisition. Overall, the above results indicate that the bauxite residue sand-tire grains can be used as an effective structural fill in slope stability problems.

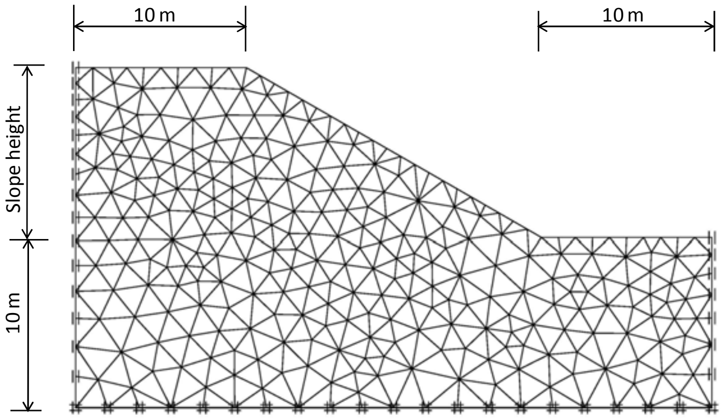


Fig. 13 Finite element mesh used in PLAXIS for the stability analysis of 10 m height embankment with slope angle of 30°

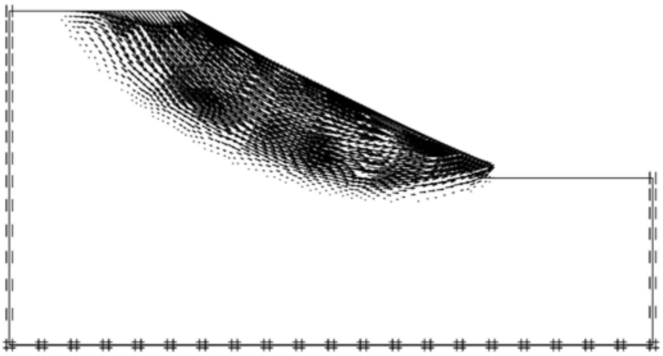
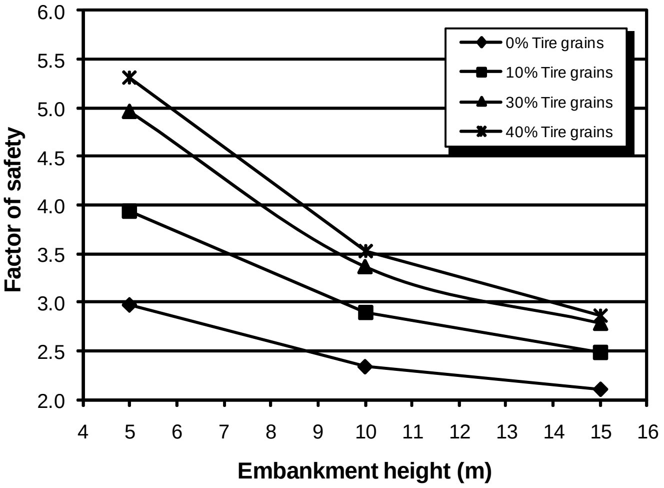


Fig. 14 Total displacement vectors computed by PLAXIS for embankment of 10 m height and slope angle of 30°

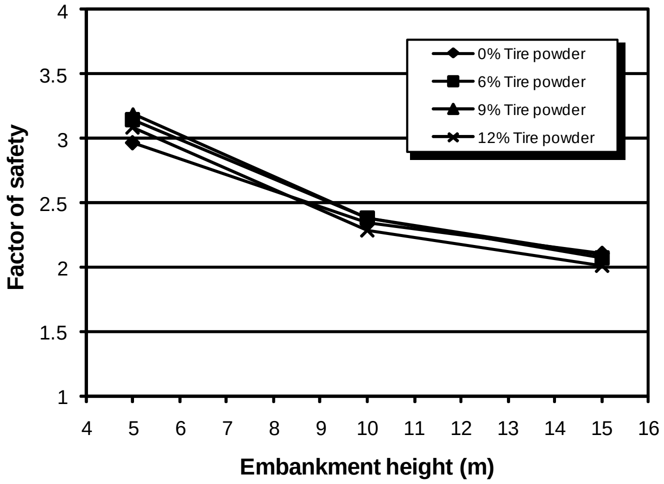
Table 1 Slope stability soil properties used in the finite element analysis

Parameter	Material						
	Sand alone	Sand with 10% tire grains	Sand with 30% tire grains	Sand with 40% tire grains	Sand with 6% tire powder	Sand with 9% tire powder	Sand with 12% tire powder
Unit weight, γ (kN/m^3)	17.7	16.5	13.8	12.1	16.6	15.9	15.2
Apparent cohesion, c (kPa)	10.8	21.2	30.6	31.2	14.6	14.5	14.3
Friction angle, ϕ (degree)	41.3	39.5	35.5	33.5	37.1	36.8	34.5

The dynamic loading example presented in this study is reported in PLAXIS (2008) and investigates the dynamic response of a multi-layer system due to a transient load pulse from a Falling Weight Deflectometer (FWD). FWD is a non-destructive test usually used for the evaluation of pavement structures. A three-layered pavement structure is considered which consists of asphalt (150 mm thick), subbase (250 mm thick) and soft subgrade. In the current study, the effects of using the bauxite residue sand (with and without tire grains) as a subbase material is investigated. The geometry of the pavement system is 16 m wide and 15.4 m deep, as shown in Fig. 17, and is simulated with an axisymmetric model using 15-noded triangular elements. As with the slope stability analysis, the displacements normal to the boundary at the left- and right-hand sides of the geometry are fixed, and the tangential displacements are kept free to allow for smooth movements. The bottom boundary is fully fixed and the top boundary is left fully free to move. Absorbent boundaries are applied at the bottom and right-hand boundary to allow for geometric damping but no material damping is considered. The constitutive parameters used for all pavement materials are given in Table 2. A typical FWD of distributed load with 0.15 m radius is applied to the pavement system which produces the load pulse shown in Fig. 18, and the results of the analysis are shown in Figs. 19 and 20. Figure 19 shows the ground vertical displacement versus dynamic loading time, whereas Fig. 20 depicts the vertical stress on top of the soft subgrade versus dynamic loading time.



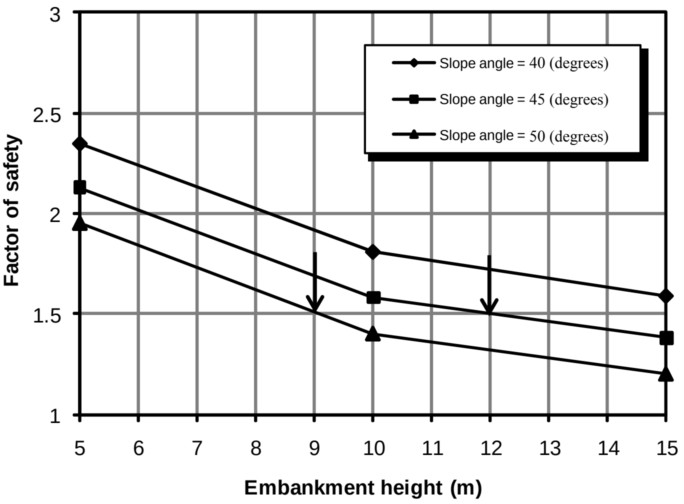
(a) Tire grains



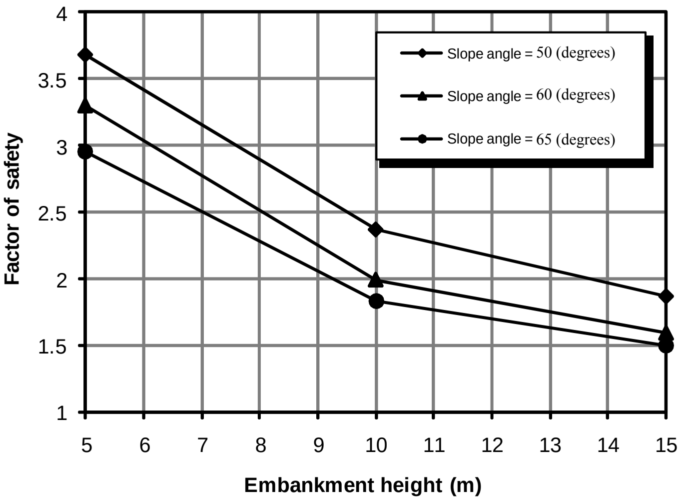
(b) Tire powder

Fig. 15 Stability analysis results for embankments of bauxite residue sand mixed with different amounts of tire crumbs

It can be seen from Fig. 19 that the pavement with the sand-tire grain subbase exhibits higher ground maximum deformation (*i.e.* displacement directly under the center of load) than that of the pavement with the sand alone subbase, as expected. This is of course attributed to the higher compressibility of the sand-tire grain subbase. The maximum vertical displacement for the pavement with sand alone is found to be 0.9 mm, while it is 1.3 mm for the pavement with the sand-tire grain subbase. On the



(a) Bauxite residue sand alone



(b) Bauxite residue sand mixed with 30% tire grains

Fig. 16 Effects of slope angle on stability of embankments

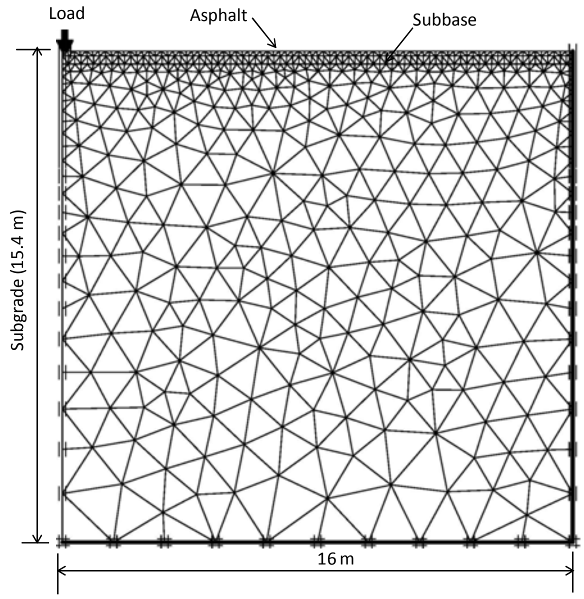


Fig. 17 Finite element mesh used in PLAXIS for pavement design application

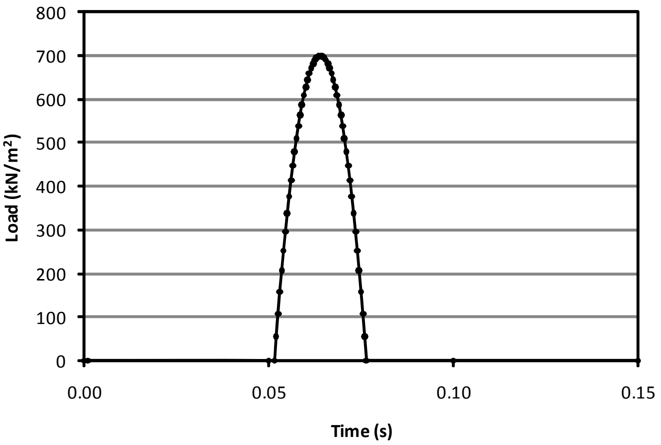


Fig. 18 Falling weight deflectometer pulse load curve

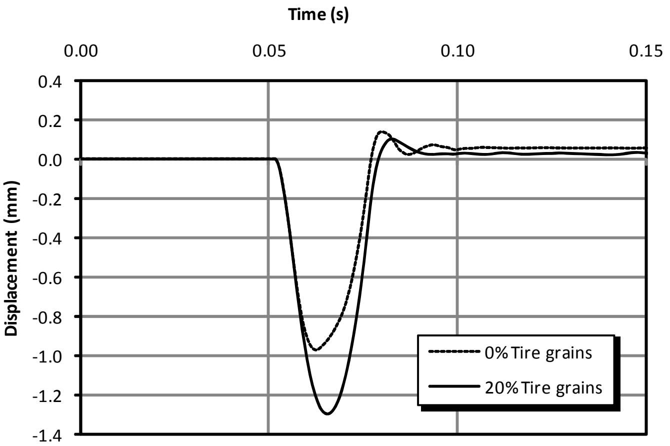


Fig. 19 Ground vertical displacement at the centre of deflectometer

other hand, Fig. 20 demonstrates that the pavement with the sand-tire grain subbase exhibits lower vertical maximum stress (*i.e.* vertical stress directly under the center of load) than that of the pavement with the sand alone subbase. The pavement with the sand-tire grain subbase is found to give a maximum vertical stress of 71 kPa compared to a maximum vertical stress of 87 kPa for the pavement with the sand alone subbase. It can also be seen that the residual stress of the pavement with the sand alone subbase is higher than that of the pavement with the sand-tire grain subbase. The practical implication of these results indicate that despite the higher compressibility obtained for the sand-tire pavement system, the lower vertical and residual stresses on top of the subgrade layer help to prevent the progressive shear failure that might occur at the subgrade surface due to repeated vehicle loads, particularly for subgrades of high clay content. The above results indicate the bauxite residue sand-tire grain mixtures have a potential of using as a lightweight subbase material for road construction.

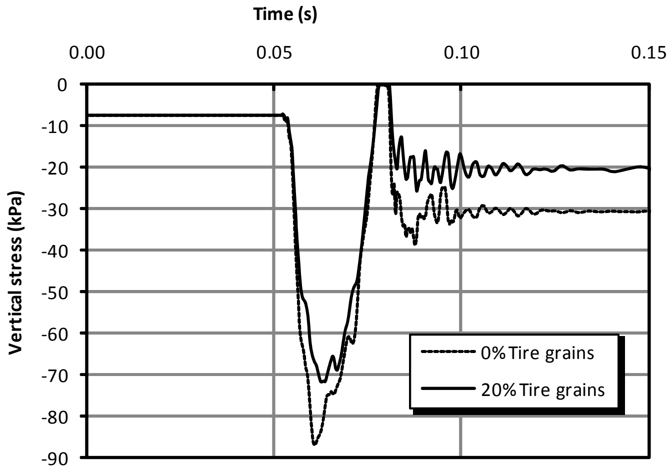


Fig. 20 **Vertical stress on top of subgrade at the centre of deflectometer**

Table 2 **Material properties used in the finite element simulations for pavement design**

Parameter	Material			
	Asphalt	Sand alone subbase	Sand with 20% tire grain subbase	Soft subgrade
Model	Elastic	Mohr-Coulomb	Mohr-Coulomb	Elastic
Resilient Modulus, *RM* (MPa)	1000	251	72	25
Poisson's ratio, ν	0.35	0.30	0.30	0.35
Unit weight, γ (kN/m^3)	23.0	17.7	15.0	15.0
Cohesion, *c* (kPa)	–	11.0	26.0	–
Friction angle, ϕ (degree)	–	41.5	37.0	–

4. SUMMARY AND CONCLUSIONS

The applicability of new mixtures of bauxite residue sand and rubber crumbs from recycled car tires was investigated for use in geotechnical engineering applications. An experimental testing program involving the addition of tire grains of size 4 mm and powder of size 750 μm to bauxite residue sand was undertaken and the geotechnical engineering properties of the new mixtures were evaluated. The experiments included sieve analysis, compaction, permeability and triaxial tests under static and dynamic loading conditions. Evaluation of the new mixtures as structural fill materials was further investigated through two practical applications, including slope stability analysis and pavement design, using the finite element method. The results obtained in this study led to the following conclusions:

1. Under the modified Proctor compaction, the unit weight of bauxite residue sand-tire mixtures decreases with the increase of tire content, and less tire powder content is required to achieve this reduction than tire grains.
2. Permeability of all bauxite residue sand-tire mixtures used in this study (*i.e.* 10%, 30%, and 40% tire grains and 6%, 9%, and 12% tire powder) remains above 1 × 10^{-6} m/s, which is generally considered as good drainage material.
3. Under static loading conditions, the addition of tire grains and powder to bauxite residue sand generally decreases material ultimate shear strength and stiffness, and increases material deformation at failure but also provides higher strain hardening (ductility) and decreases dilatancy.
4. Under dynamic loading conditions, the addition of tire grains and powder to bauxite residue sand decreases material resilient modulus and increases material permanent axial strain. However, because of the high damping capacity of the rubber tire grains, the mixture will be a good material for use as part of a vibration damping system for machine foundations or beneath railway track beds.
5. Adding 30% tire-grains to bauxite residue sand seems to lead to satisfactory geotechnical engineering properties for stability of embankments and is thus recommended. On the other hand, adding 6% to 12% tire powder does not seem to make any significant improvement to the stability of embankments.
6. Using the bauxite residue sand with 30% tire grains as a subbase material for pavement design appears to decrease the maximum and residual vertical stresses on top of subgrades and is thus desirable, although compressibility increases.

ACKNOWLEDGEMENTS

The authors would like to thank Sim Tire Cycle Pty Ltd. (Melbourne) for providing the tire crumbs used in this work. The authors would like also to thank Mr. Richard Loh for his assistance in conducting the laboratory tests.

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