Small- to Large-Strain Shear Modulus and Damping Ratio of Sand-Tyre Crumb Mixtures

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Abstract: Utilizing rubber tyres in vibration mitigation can be a viable approach of resolving the chronic problems associated with disposal of waste tyres. However, the dynamic properties of sand-tyre crumb mixtures (STCM) are essential for the design of a vibration isolation system. In this study, the dynamic properties of STCM in terms of shear modulus and damping ratio are presented against the shear strain. The modulus and damping ratio of STCM for small to large shear strain were measured using Torsional resonant column tests and cyclic triaxial tests, for two composition of tyre crumbs (50% and 75%) and three different confining pressure (50, 100, and 200 kPa). The results showed that, shear modulus and the damping ratio of the mixtures are strongly influenced by the percentage of rubber inclusion. Shear modulus decreased with an increase in tyre crumb inclusion for all the confining pressure, whereas the damping ratio increases with the increase in rubber content in STCM. For any percentage of tyre crumbs inclusion, the shear modulus increases and damping ratio decrease with increasing confining pressure. These results are useful to understand the dynamic response of STCM and further used in model studies to design a low cost isolation system.

INTRODUCTION

Dynamic soil properties are important parameters for the analysis and design of structures required to resist dynamic loads such as earthquake shaking, machinery vibrations, blast forces, traffic loading, etc. Each one of the above events subjects the soil-structure system to very different amplitudes and frequencies and requires the soil dynamic properties for a wide range of load amplitudes and frequencies. The mechanical behaviour of soils is determined by effective stresses, void ratio, water content, and several other parameters such as strain level and stress or strain path. All these factors are equally important under either static or dynamic loading conditions. Then the features that distinguish the dynamic from the static problems are the speed of loading and load repetitions. In the analysis of most soil dynamic problems, determination of shear modulus and damping ratio as a function of shear strain amplitude is a key parameter to specify dynamic properties or to estimate the stiffness and energy absorption capacity (Nakhaei et al., 2012).

Over the past two decades, many studies were conducted to determine the physical and mechanical properties of rubber-soil mixtures by numerous researchers, to use rubber-soil mixtures as alternate construction material or lightweight material in civil engineering projects. The parameters considered in their study were, shear strength, compressibility, permeability, bearing capacity, shear modulus and damping ratio (Ahmed, 1993; Edil and Bosscher, 1994; Lee et al., 1999; Edincliler et al., 2004; Foose et al., 1996; Hataf and Rahimi, 2005; Feng and Sutter, 2000; Nakhaei et al., 2012; Anastasios et al., 2011). The authors of this paper were also investigated the static properties (shear strength and energy absorption capacity) of Sand Tyre Crumb Mixtures (STCM). The shear strength and energy absorption capacity of STCM increases upto certain extent of tyre crumbs in the mix, thereafter it started decreasing with further increase in the rubber. Also, it was noted that the static properties of STCM were size dependent (Anbazhagan and Manohar, 2015). In addition, rubber-soil mixtures have been proposed as isolation system through numerical studies to modify the seismic response of superstructures, especially suited for developing countries (Tsang, 2008; Tsang et al., 2012).

Regardless of immense work performed by various researchers to determine dynamic properties of rubber-soil mixtures, the authors couldn't able to find the detailed study of dynamic properties covering all the strain range (0.0001% to 10%). Many of the earlier studies were carried out for either low strain values (0.0001 to 0.1%) or high strain values (0.1% to 10%). Therefore, such a detailed study on STCM covering all the strain range (0.0001% to 10%) may be useful for selecting the modulus and damping values associated with field events (machine foundations, motion characteristics, and earthquake motion). Also obtaining the shear modulus and damping value for the selected optimum size of tyre crumbs from static tests, considering the size effect, which is recommended by many researchers (Promputthangkoon and Hyde, 2008), will also help to enhance the mechanical properties of STCM, which are also of prime concern in many engineering projects along with dynamic properties.

Additionally, the utilization of waste tyres as an isolation material can provide an alternative way to consume the large dumps of scrap tyres all over the world. On an average, scrap tyres are generated one per capita annually in many of the countries (Edil & Bosscher, 1994), in particular developed countries, resulting in significant disposal problems. The use of waste tyres in geotechnical application may be feasible way of utilizing scrap/waste tyres. Reuse of scrap tyres would not only provide a way of disposing them, but also helps to solve some economic and technical problems for the sustainable environment.

In this study, the small to large-strain dynamic properties of Sand-Tyre Crumb Mixtures (STCM) in terms of shear modulus and damping ratio are presented against the shear strain. Torsional resonant column tests were performed to measure the modulus and damping ratio of the small strain rate of 0.0001% to 0.1%. The modulus and damping values at a large strain rate (0.1% to 10%) were measured through cyclic triaxial test. In this study, both torsional resonant column tests and cyclic triaxial tests are performed on dry, dense specimen of STCM, with the samples diameter and height was 100 and 200 mm, respectively. Considering the high permeability of granular soil-rubber mixtures exhibit as well as the main applications of the aforementioned materials, the specimens of this study were examined in dry conditions and high relative density (Anastasios et al., 2011). The tyre crumbs used in STCM were selected from seven different size ranges, varying from 1.00 mm to 20.00 mm by carrying static triaxial test. The tyre crumb size, which gave highest shear strength compared to other sizes is considered as optimum size, and further used in dynamic studies. Specimens were prepared using two different percentages of sand and tyre crumbs in STCM (50% and 75% tire crumbs by volume), and varying confining pressure (50, 100 and 200 kPa). The torque amplitude was increased with each test to measure the modulus and damping ratio at different strain level in resonant column test. The experimental results indicate that the shear modulus and the damping ratio of the mixtures are strongly influenced by the percentage of rubber inclusion. Shear modulus decreased with an increase in tyre crumb inclusion for all the confining pressure, whereas the damping ratio increases with the increase in rubber content in STCM. For any percentage of tyre crumbs inclusion, the shear modulus increases and damping ratio decrease with increasing confining pressure. These results are useful to understand the dynamic response of STCM.

EXPERIMENTAL PROGRAM

In this section, a large and extensive experimental program was undertaken to investigate the shear modulus and damping ratio at varying strain level for sand and Sand-Tyre Crumb Mixture (STCM). The detailed experimental program is explained in following sections.

Materials Used

In the present study, the locally available sand and industry's produced scrap tyres from Mumbai (India) were used. The soil used in the present study was granular in nature, passing through a 4.75 mm sieve. The grain size of sand varied between 0.075 mm and 4.75 mm, and its distribution curve is shown in Figure 1. The specific gravity of the sand is 2.65, estimated as per ASTM D854 (2010). The sand is classified as uniformly graded sand according to the unified classification system, ASTM D2487 (2011). Other details of sand are presented in Table 1. Tyre crumb were prepared with special machinery where scrap tyres were crushed into pieces and powdered after removing steel belting. The processed tyre crumbs obtained from local industry were sieved into groups of seven different sizes, 2.00 – 1.00 mm (passing the 2.0 mm sieve and retained on 1.00 mm sieve, designated as A), 4.75 – 2.00 mm (B), 5.60 – 4.75 mm (C), 8.00 – 5.60 mm (D), 9.50 – 8.00 mm (E), 12.50 – 9.50 mm (F), and 20.00 mm – 12.50 mm (G). Each group of tyre crumbs is called by alphabet A to G, where A corresponds to 1 mm to 2 mm and G corresponds to 20.00 mm to 12.50 mm. The specific gravity and water absorption values of tyre crumbs are determined in accordance with ASTM D854 (2010) and ASTM C128 (2007), except the specimens were air dried rather than oven dried in the beginning of the test. The obtained specific gravity and water absorption were found to be 1.14 and 3.85.

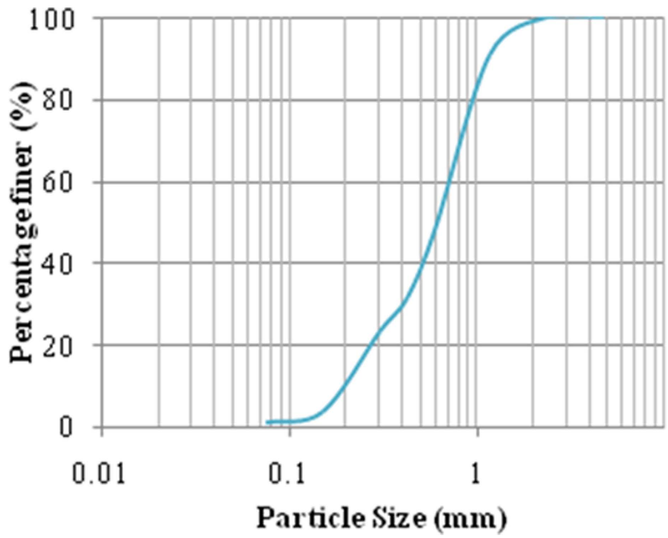

FIG. 1. Particle size distribution curve.

Table 1. Properties of sand used in this study

Description	Value
Effective size, D_{10}	0.2 mm
D_{30}	0.4 mm
Mean size, D_{50}	0.6 mm
D_{60}	0.71 mm
Uniformity coefficient (*Cu*)	3.50
Curvature coefficient (*Cc*)	1.14
Specific Gravity	2.65
Maximum dry density	1.786 g/cc
Minimum dry density	1.434 g/cc
Relative density adopted	80 %
Relative density adopted	35^{o}

Sample Preparation

The amount of sand and tyre crumb required for each percentage composition was estimated. Tyre crumb specimens were prepared by hand mixing with dry sand. Then dry sand-tyre crumbs were transferred into the mould in layers with uniform mix to avoid segregation during the sample preparation. For 50% STCM maximum care was taken to avoid segregation, anyhow for higher rubber content i.e. for 75% STCM, fully segregation was not avoided due to compaction. The compaction was achieved through a metal rod tamper, with uniform number of blows for each layer of STCM. The numbers of blows were slightly increased for 75% STCM to achieve the required density of STCM.

Testing Procedure

The Unconsolidated Undrained triaxial tests were carried out on sample size of 50 x 100 mm for crumb sizes A to D, and 100 x 200 mm for crumb size of E to G for the respective densities of STCM and for effective confining pressures of 20, 60 and 100 kPa to select the optimum size of tyre crumb. The samples were tested according to ASTM-D2850 (2007).

The dynamic properties were tested from the GCTS TSH-200 Resonant Column/Torsional Shear Testing system combines the features of resonant column/torsional shear devices and cyclic triaxial testing devices into one system. The dynamic properties at low strains were performed on fixed-free type longitudinal resonant column apparatus. A harmonic torsional excitation is applied to the top of the specimen by an electromagnetic loading system. The resonant column tests were performed on sample sizes of 100 mm diameter and 200 mm height for three confining pressure of 50, 100 and 200 kPa with ASTM D4015-07 specifications. The torque amplitude was increased with each test to measure the modulus and damping ratio at different strain level in resonant column test.

Cyclic triaxial test were performed on same sample size of 100 x 200 mm, with three confing pressure with ASTM D3999-11 specifications. In each test, hundred cycles with same deviator stress amplitude were applied on the specimen under stress controlled condition and 1 Hz frequency. In every cycle, thirty two data sets were obtained and saved by computer program.

TEST RESULTS

Influence of Tyre Crumb Size

To study the effect of crumb size on shear properties of STCM, a series of UU tests was carried out. Shear strength of STCM increases with increasing tyre crumb size from A to F, and it decreases thereafter (G). The optimum percentage mix of tyre crumbs for enhanced shear strength of STCM varies for different sizes of crumbs (A to G). In this study, the shear properties of sand were increased with the addition of tyre crumbs, which might be due to the influence of tyre crumb length, aspect ratio (length/diameter), stiffness of tyre crumbs, orientation of tyre crumbs, sand friction angle and confining stress (Gray and Ohashi, 1983). The results demonstrated that the crumb size tended to be more effective in increasing the shear properties of STCM. Considering all the crumb sizes, crumb size F provides comparatively higher energy absorption capacity and stiffness. The complete details can be found in Manohar et al., (2014). Hence crumb size F is considered as optimum size and further used to carry dynamic studies with higher rubber content.

Discussion on Shear Modulus

The shear modulus-shear strain curves for the 50% STCM and 75% STCM are presented in Figure 2 and Figure 3, for the confining pressure of 50, 100 and 200 kPa. In both the figures, the shear modulus value upto 0.1% were obtained from resonant column test. After 0.1% of shear strain, the modulus values were obtained from cyclic triaxial test. In following figures, results of both the test have been combined and presented. The results indicated that, with the addition of tyre crumbs to sand, the mixture becomes softer and the shear modulus decreases. But, with the increase in confining pressure, shear modulus value increased.

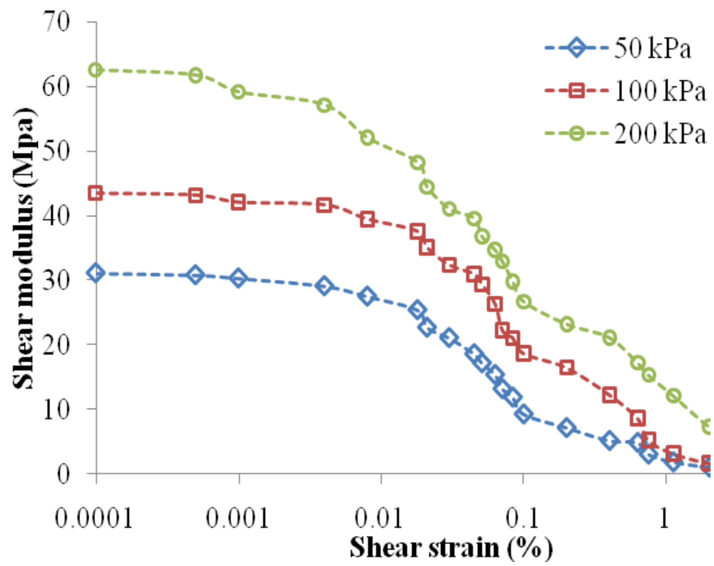

FIG. 2. Shear modulus degradation curve for 50% STCM with different confining pressure.

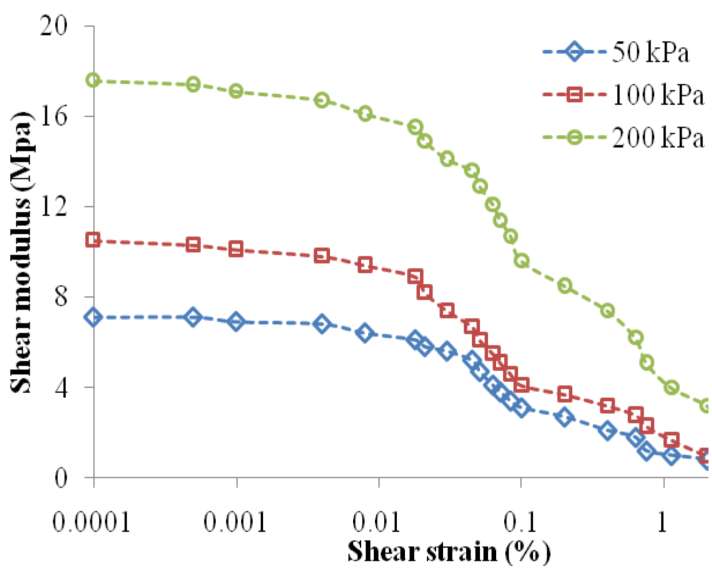

FIG. 3. Shear modulus degradation curve for 75% STCM with different confining pressure.

Figure 4 shows that, at a constant confining pressure, with the increase in rubber content to sand, shear modulus value decreases. The same trend is observed for all the confining pressure considered in this case. This trend was predictable, due to decrease in stiffness of STCM with increase in rubber percentage in the mix. The results also indicated that, with the increase in the rubber percentage, the effect of confining pressure on shear modulus decreases. This result coincides with the results obtained from Feng and Sutter, (2000) and Nakhaei et al., (2012).

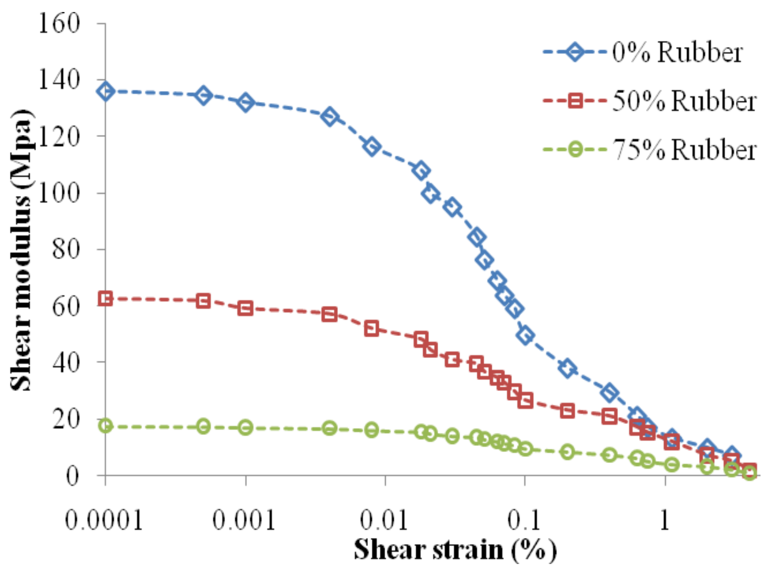

FIG. 4. Shear modulus degradation curve for different percentage of rubber at 200 kPa.

Discussion on Damping Ratio

The damping ratio-shear strain curve for 50% and 75% STCM are presented in Figure 5 and Figure 6 for the confining pressure of 50, 100 and 200 kPa. The damping ratio values shown in plot upto 0.1% strain were obtained from resonant column test, and for further strain (greater than 0.1% strain) damping ratio values were obtained from cyclic triaxial test. In Figure 5, 6 and 7, results of both the tests are combined and presented. The results showed that, with an increase in rubber inclusion, damping ratio increases. The damping ratio-shear strain curves, for 50% and 75% STCM showed that, with an increase in the confining pressure the damping ratio decreases, which matches with the results of Feng and Sutter (2000). For STCM, damping ratio decreases with an increase in confining pressure. The explanation of this behaviour is that, with an increase in intergranular friction which is due to an increase in confining pressure, plastic strain decreases, and causes damping ratio to decrease (Nakhaei et al., 2012).

Figure 7, shows the variation of damping ratio verses the shear strain for different percentage of rubber content in STCM for the confining pressure of 50 kPa. The effect of rubber inclusion on damping ratio of STCM can be clearly seen from this plot. Here the damping ratio increases with increase in rubber content. Compared to normal soil (0% rubber), the damping ratio increased by two times for 75% rubber content in STCM.

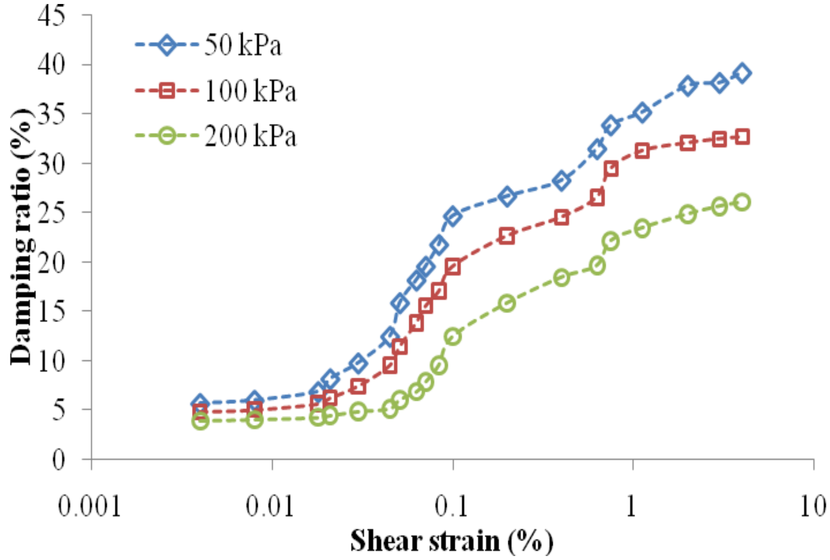

FIG. 5. Damping ratio verses shear strain for 50% STCM, with the variation of confining pressure of 50, 100 and 200 KPa.

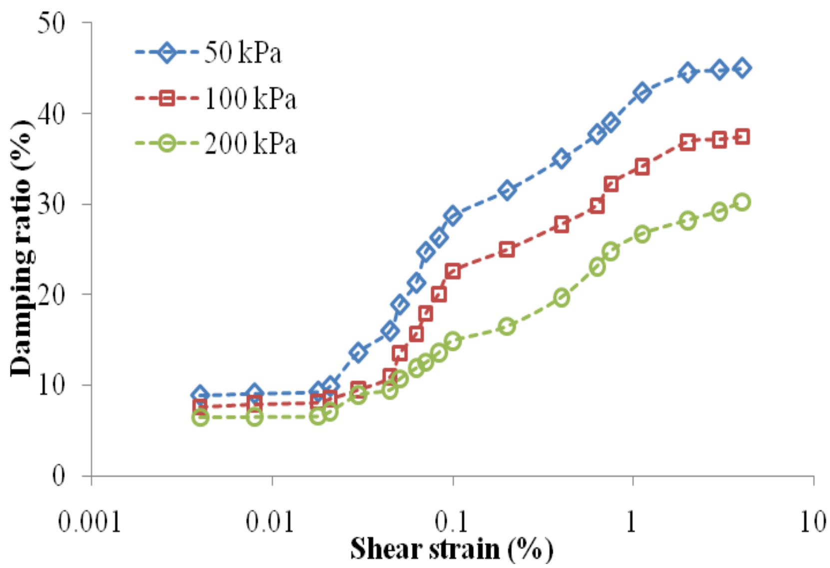

FIG. 6. Damping ratio verses shear strain for 75% STCM, with the variation of confining pressure of 50, 100 and 200 KPa.

SUMMARY AND CONCLUSIONS

This paper presents the results of resonant column test and cyclic triaxial tests on sand and sand-tyre crumb mixtures (STCM). In this study, the dynamic properties of STCM in terms of shear modulus and damping ratio are presented against the small to large shear strain values. The dynamic studies were carried for two compositions of tyre crumbs (50% and 75%) and three different confining pressure (50, 100 and 200 kPa). The tire crumbs used in STCM were selected from seven different size ranges, varying from 1.00 mm to 20.00 mm by carrying static triaxial test.

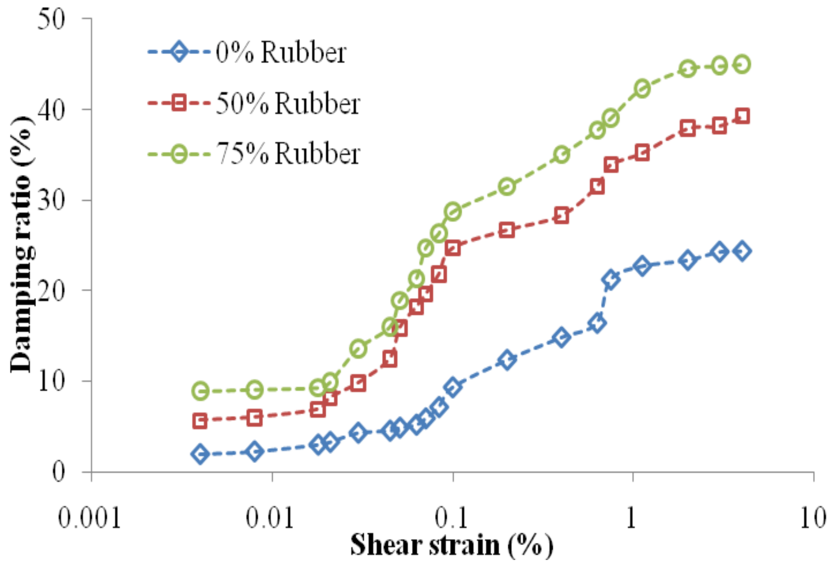

FIG. 7. Damping ratio verses shear strain for different percentage of rubber in STCM, for the confining pressure of 50KPa.

The experimental results indicate that the shear modulus and the damping ratio of the mixtures are strongly influenced by the percentage of rubber inclusion. Shear modulus decreased with an increase in tire crumb inclusion for all the confining pressure, whereas the damping ratio increases with the increase in rubber content in STCM. For any percentage of tyre crumbs inclusion, the shear modulus increases and damping ratio decrease with increasing confining pressure. These results are useful to understand the dynamic response of STCM and further used in model studies to design a low cost isolation system.

REFERENCES

Ahmed, I. (1993). "Laboratory study on properties of Rubber-Soils." Purdue University, Indiana, *Joint Highway Research Project*, Report No. FHWA/IN/JHRP-93/4, p. 384.

Anastasios, A., Kostas, S., and Kyriazia, P. (2011). "Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures." *Geotechnical and Geol Engineering*, DOI 10.1007/s10706-011-9473-2.

Anbazhagan, P., and Manohar, D. R. (2015). “Energy absorption capacity and shear strength characteristics of waste tire crumbs and sand mixtures.” *International journal of Geotechnical Earthquake Engineering*, 6(1), 30-51, January-June 2015.

American Society for Testing and Materials (ASTM). (2011). “Standard Practise for Classification of Soils for Engineering Purposes (Unified Soil Classification System).” ASTM D 2487-11.

American Society for Testing and Materials (ASTM). (2010). “Standard Test Methods for Specific Gravity of Soils by Water Pycnometer”, ASTM D 854-10.

American Society for Testing and Materials (ASTM). (2007). “Standard Test Methods for Density, Relative Density and Absorption of Fine Aggregate”, ASTM C 128-07.

American Society for Testing and Materials (ASTM). (2007). “Standard Test Methods for Unconsolidated Undrained Triaxial Compression Test.” ASTM D 2850-07.

American Society for Testing and Materials (ASTM). (2007). “Standard test methods for modulus and damping of soils by resonant column method.” ASTM D 4015-07.

American Society for Testing and Materials (ASTM). (2011). “Standard test methods for the determination of the modulus and damping properties of soils using the cyclic triaxial apparatus.” ASTM D 3999-11.

Edil, T. B., and Bosscher, P. J. (1994). “Engineering Properties of Tire Chips and Soil Mixtures.” *Geotechnical Testing Journal*, GTJODJ, Vol. 17 (04), 453-464.

Edincliler, A., Baykal, G., and Dengili, K. (2004). “Determination of static and dynamic behavior of recycled materials for highways.” *Resources, Conservation and Recycling*, 42 (2004) 223-237.

Feng, Zheng-Yi., and Sutter, G. Kevin. (2000). “Dynamic properties of granular rubber/sand mixtures.” *Geotechnical Testing Journal*, GTJODJ, Vol. 23, No. 3, 338-344.

Foose, G. J., Benson, C. H., and Bosscher, P. J. (1996). “Sand Reinforced with Shredded Waste Tires.” *Journal of Geotechnical Engineering*, Vol. 122 (9).

Gray, D. H., and Ohashi, H. (1983) “Mechanics of Fiber Reinforcement in Sand.” *Journal of Geotechnical Engineering*, Vol. 109, No. 3, March 1983.

Hataf, N., and Rahimi, M.M. (2005). “Experimental investigation of bearing capacity of sand reinforced with randomly distributed tire shreds.” *Construction and Building Materials*, 20 (2006), 910-916.

Lee, J. H., Salgado, R., Bernal, A., and Lovell, C. W. (1999). “Shredded Tires and Rubber-Sand as Lightweight Backfill.” *Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 2, February, 1999.

Manohar, D. R., Anbazhagan, P., Neaz Sheikh, M., and Hing-Ho Tsang. (2014). “Effects of geosynthetic reinforcement on the mechanical behaviour of composite materials for vibration isolation.” *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, 9-12 December, Byron Bay, Australia.

Nakhaei, A., Marandi, S.M., Sani Kermani, S., and Bagheripour. (2012). “Dynamic properties of granular soils mixed with granulated rubber.” *Soil Dynamics and Earthquake Engineering*, 43 (2012), 124-132.

Promputthangkoon, P., and Hyde, A. F. L. (2008). “Compressibility and liquefaction potential of rubber composite soils.” *Proceedings of the international workshop on*

Scrap Tire Derived Geomaterials - Opportunities and Challenges - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 161-170.

Tsang, H.H. (2008). Seismic Isolation by Rubber-Soil Mixtures for Developing Countries. *Earthquake Engineering and Structural Dynamics*, 37(2):283-303.

Tsang, H.H., Lo, S.H., Xu, X., and Sheikh, M.N. (2012). Seismic Isolation for Low-to-Medium-Rise Buildings using Granulated Rubber-Soil Mixtures: Numerical Study. *Earthquake Engineering and Structural Dynamics*, 41(14):2009-2024.