Energy Absorption Capacity and Shear Strength Characteristics of Waste Tire Crumbs and Sand Mixtures

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ABSTRACT

The primary objective of the study is to estimate the energy absorption (EA) capacity, brittleness index (ductility) and stiffness characteristics of Sand-Tire Crumb Mixtures (STCM) using direct shear test and Unconsolidated Undrained (UU) triaxial test for the effective reuse of waste tire crumbs as isolation materials. The properties considered include, strength and deformation characteristics of a STCM. A relatively uniform sand and readily available tire crumb grouped into four size has been selected to generate STCM. Experimental studies have been carried out on STCM with constant density of 1.54 g/cc. Stress-strain curve obtained from UU test has been used to estimate EA. The experimental results show that peak strength, EA and stiffness increases with increasing percentage of tire crumbs up to 25% and starts decreasing thereafter. Among the tested tire crumb sizes, crumb size IV provide the maximum EA without compromising on strength compared to other tire crumb sizes.

Keywords: *Brittleness Index, Energy Absorption, Sand-Tire Crumb Mixtures, Shear Strength*

INTRODUCTION

Urban agglomeration and population growth results in increasing automobile industries and in turn increase the disposal of waste products from these industries, including scrap tires (WRAP, 2007; RMA, 2009; RRI, 2009). Most of the wastes generated from automobile industries are reusable without affecting surrounding environment except vehicle tires. On an average, scrap tires are generated one per capita annually in many of the countries (Edil & Bosscher, 1994), particularly in developing countries facing significant disposal problem. It is estimated that, 13.5 million tons of tires (United States 4.4 million tons) are scrapped each year (Genan, 2012). In

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Canada, it is about 28 million scrap tires (Dickson et al., 2001), and in Europe, approximately 5.5 million tons (ETRMA, 2010) are stockpiled. In Korea, approximately 20 million tires are removed every year (Yoon et al., 2008). In India, it is estimated that at the end of 2010, 112 million tires are scrapped (Rao & Dutta, 2006). These tires cannot be deposited in landfills as they occupy large space, gives an ugly view and forms ideal breeding places for mosquitoes and other insects (Masad et al., 1996). It becomes harder and also expensive to dispose them safely without any threat to human health and the environment in many regions of the world due to the possibility of fire and health hazards. This situation has produced a need to find new beneficial ways of recycling waste tires. Current beneficial way of recycling waste tires, includes tire-derived fuel for energy generation, tire retreading applications, highway crash barriers, breakwaters, reefs and crumb rubber asphalt pavement (Lee et al., 1999). These reuse and recovery effort has reduced the amount of landfills by consuming 89% of waste tires in the United States (RMA, 2009), and around 90% in European Countries (ETRMA, 2010). But, some of the current uses of recycling waste tires has negative impact on environment. Though current reuse and recovery effort has slightly reduced the amount of landfills, but still there is a need for developing additional practice for the reuse of scrap tires. One of the applications is to reuse tire in civil engineering as an alternate material in construction projects. Over the last few years, recycling of waste materials as construction materials has been considered important to improve geotechnical properties of soil and to solve economical and technical problems for a sustainable environment. Geomaterials derived from scrap tire are used in several geotechnical applications and related papers can be found in Hazarika & Yasuhara (2008). Tire crumbs were widely used as light weight materials for backfill in embankment construction due to a shortage of natural resources and increase in waste disposal cost (Edincliler et al., 2010).

Significant reduction in loss of lives due to earthquake can be achieved by implementing safe seismic construction procedures. But the existing safe seismic methods need an extra 15-25% cost of the project, which cannot be afforded by the common man in the developing countries. A developing country is one where the buildings are predominantly non-engineered and building codes are not implemented effectively (Charleson & Fyfe, 2001). Many earthquakes that have occurred in the recent past have shown high potential of loss of lives and property under moderate to high level of shaking. The risk to life is further increased due to increase in the population density in cities in developing countries. This led to finding new beneficial ways of increasing safety of the house of the common man without increasing cost of construction in the developing countries. Any innovative system can be widely adopted in developing countries, if it is a cost effective technology (Tsang, 2008; Tsang et al., 2012).

One promising approach in waste tire utilization is vibration reduction and seismic isolation of building taking into account the high damping behavior in rubber (Hazarika, 2008; Hazarika et al., 2008; Tsang, 2008; Tsang et al., 2012). However, systematic studies of the static and dynamic properties of Sand-Tire Crumb Mixtures (STCM) are limited. The objective of the present study is to assess the energy absorption capacity and shear strength characteristics of STCM considering different size of tire crumbs and percentage of mixing. Shear and Unconsolidated Undrained (UU) triaxial tests have been carried out on STCM samples for different normal and confining pressure. Peak strength, ultimate strength, ductility and the energy absorption of STCM are presented in this paper for tire crumbs size of *I*, *II*, *III* and *IV* and for tire crumbs amount of 0%, 10%, 15%, 20%, 25%, and 30% of total volume of the sample. This study identifies the optimum size and percentage of mix among tested samples, considering static properties and energy absorption capacity. Selected STCM mix can be used to estimated dynamic properties in future, through which one can select to design an isolation system for low to medium rise buildings.

BACKGROUND

Composites of raw materials in tire have unique properties such as flexibility, strength, resiliency, and high frictional resistance (Ahmed, 1993). The properties mentioned above are altered after use in the vehicle (i.e. scraped tires), however a considerable amount of above properties still remain in the waste tires. If tires are used as construction material, one can exploit above unique properties in beneficial ways (Ahmed, 1993). Exploiting the inherent properties not only helps in effective disposal of waste tires, but also solves some technical problems in geotechnical engineering. It is necessary to consider any possible implications of waste tires on subsurface environment, such as ground water contamination before they are used in geotechnical engineering projects. Young et al., (2003), conducted column tests to simulate field conditions where tire shreds are placed above and below the water table. Initial test results showed that the placement of tire above water table had no or little environmental impact on surroundings. However, placement of tire shreds below water table had a negative impact, if there is no proper drainage condition, as it leads to pond effect. Recent research on tire alone or tire-soil mix on ground water showed a higher concentration of iron and manganese, but human health concerns are minimal (Edil, 2008). This review indicates the significant research that has evolved over the last 25 years. Tires placed in surface water have shown to be toxic and this practice should be abandoned (Edil, 2008). The experimental studies regarding the shear strength of scrap tires are summarized in Table 1.

From the above literature review it can be concluded that parameters influencing shear strength and compressibility characteristics were rubber size, sand matrix unit weight, rubber content, aspect ratio, normal stress, and confining pressure. However, many studies carried out to find the shear strength of the sand - tire mix were conducted by considering one particular size of rubber or varying sizes of tire shreds and tire chips. Only few studies have been carried out to investigate the shear strength behavior of sand tire-crumb mixtures (STCM), in those studies the detailed investigation of the effect of different tire-crumb sizes and tire-crumb content on shear strength of rubber-sand is very limited, which is recommended by many researchers (Promputthangkoon & Hyde, 2008). This paper presents the experimental investigation carried out to determine the shear strength characteristics and energy absorption capacity of STCM for every 5% variation in tire crumbs up to 30% STCM for four different sizes (*I* to *IV*).

EXPERIMENTAL MATERIALS AND TESTING PROCEDURE

Material Characterization

In the present study, the locally available sand and industry's produced scrap tires were used. The soil particles used in the present study were 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 (2003). Other details of sand are presented in Table 2. Tire crumb were prepared with special machinery where scrap tires were crushed into pieces and powdered after removing steel belting. The processed tire crumbs are obtained from local industry were sieved into groups of four different sizes, 8 mm - 5.6 mm (passing the 8 mm sieve and retained on 5.6 mm), 5.6 mm - 4.75 mm, 4.75 mm - 2 mm, and 2 mm - 1 mm. Each group of tire crumbs is called by roman letter *I* to *IV*, where *I* corresponds to 1 mm to 2 mm and *IV* corresponds to 5.6 mm to 8 mm. The specific gravity and water absorption values of tire crumbs are determined in

Table 1. Summary of shear strength character obtained by different researchers

Reference	Testing Method	Materials	Unit weight KN/m3 /RD (%)	Remarks
Arroyo et al., (2008)	Large scale direct shear 1000 x 1000 mm and 300 x 300 mm	10 mm TDA 30 mm TDA 50 mm TDA 65 mm TDA 100 mm TDA	10.81 11.96 12.54 14.11 11.37	• To minimize the risk of self combustion large size tire aggregates were favored • Results showed no evidence of size effect on shear resistance
Edil & Bosscher (1994)	Large scale direct shear 152.4 mm x305 mm	100% S+0% TC 96% S+4% TC 91.2% S+8.8% TC 85% S+15% TC 75% S+25% TC	17.0 17.1 16.8 16.6 16.0	• TC size used: 25x50 mm, 50x75 mm &100x450 mm. • SS of the matrix increases with increase in tire chips percentage
Foose et al. (1996)	Large scale direct shear, 280 mm dia & 300 mm high	90% S+10% TS 70% S+30% TS	16.8&14.7 14.7&16.8	• TS size used: up to 5 cm, 5-10 cm & 10-15 cm. • Initial friction angle of sand matrix is twice of the friction angle of sand. • The influence of shred length was barely assessed.
Humphery, (2008)	Triaxial tests	Only rubber	6.1 to 6.9	• Triaxial test carried out for < 25 mm tire shreds • Direct shear test carried out for < 75 mm tire shreds • Shear strength is not affected by tire derived aggregate size
Kawata et al., (2008)	Undrained and drained triaxial tests	100% S 90% S+10% TC 80% S+20% TC 70% S+30% TC 50% S+50% TC 30% S+70% TC 100% TC	15.43 14.75 13.48 12.10 9.70 7.21 4.33	• Tire chips used in this study were 2 mm in diameter • Samples containing tire chips showed decrease in strength and friction angle
Masad et al., (1996)	Triaxial test, 71.1 mm x 147.3 mm	100% S 50% S+50% TC 100% TC	90% 90% 90%	• Max size of TC used to be 4.75 mm. • No improvement in SS with the addition of tire crumbs. • SS increases with increase in confining pressure.
Mahmoud, (2004)	Small scale direct shear	100% S 90% S+10% GR 85% S+15% GR 80% S+20% GR 50% S+50% GR 30% S+70% GR 100% GR	14&14.5 12.9&13.5 12.3&13.0 10.9&12.4 7.7&8.0 6.4&6.7 4.7&5.1	• GR size ranges from 1-8 mm. • Factors influencing SS were normal stress, mixture unit weight and rubber content. • Peak failure shifts with increase in value of axial strain. • Dilation characteristics were also observed.

continued on following page

Table 1. Continued

Reference	Testing Method	Materials	Unit weight KN/m3 /RD (%)	Remarks
Edincliler, (2008)	Large scale direct shear 300 x 300 x 300 mm	100% S 95% S+5% TB 90% S+10% TB 80% S+20% TB 70% S+30% TB 100% TB	15.3 15.19 14.89 14.22 13.56 5.1	• TB whose length varies from 2 – 40 mm and thickness 1- 4 mm • Shear strength decreases with addition of tire buffings
Edincliler et al., (2010)	Large scale direct shear 300 x 300 mm	100% TC 100% S 95%S+5%TC 90%S+10%TC 80%S+20%TC 70%S+30%TC	5.4 13.78 13.38 13.02 12.38 11.85	• Dimension of TC were between 1 and 3 mm • Maximum shear strength value was obtained at 20% TC to sand. • Processing technique of used tires is most significant characteristics influencing SS.
Neaz et al., 2012	Triaxial test, 38 mm dia x 76 mm height	100% S 90%S+10%TC 80%S+20%TC 70%S+30%TC 60%S+40%TC	Void ratio -0.63 and poorly graded sand	• Tests were carried on two different sizes of TC. • TC mixture with sand shows a reduction of shear strength.
Promputthangkoon & Hyde (2008)	Cyclic triaxial test	100% S 99% S+1% TC 97.5% S+2.5% TC 95% S+5% TC 85% S+15% TC	0.678 0.681 0.675 0.676 0.677	• Authors strongly recommend that further studies on factors such as size, shape, and material properties are required.

Note: GR-Granulated rubber, S-Sand, SS-Shear strength, TB- Tire buffing, TDA- Tire derived aggregate,TC- Tire chips, TS-Tire shreds

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, which are comparable with the findings of Mahmoud (2004), and Bosscher et al., (1997).

Sample Preparation and Testing Procedure

In this study, STCM samples were prepared by considering constant density of 1.54 g/cc and a void ratio of 0.69. The density of STCM is close to the mean dry density of sand. STCM mix has been prepared for 10%, 15%, 20%, 25% and 30% tire crumbs by volume. Tire crumb specimens were prepared by hand mixing using required amount of sand and tire crumbs for each percentage. The STCM were transferred into the mould in layers with uniform mix, such that segregation would not occur during the sample preparation. Typical photographs of STCM sample preparation for direct shear test and UU triaxial test is shown in Figure 2 and 3.

Small direct shear test apparatus with rectangular mould having a size of 60 mm x 60 mm and thickness of 30 mm was used to perform shear test on the STCM samples. Tests have been carried out as per ASTM-D5321 (2008) for three normal stresses of 50, 100 and 150 kPa, at a constant strain rate of 0.25 mm/min. Tests were carried out on the samples containing of pure sand, and five STCM, i.e., 10%, 15%, 20%, 25% and 30% rubber by volume. Similarly the static triaxial test was carried out as per ASTM-D2850 (2007) with a sample size of 38 mm in

Figure 1. Particle size distribution curve of sand used for the study

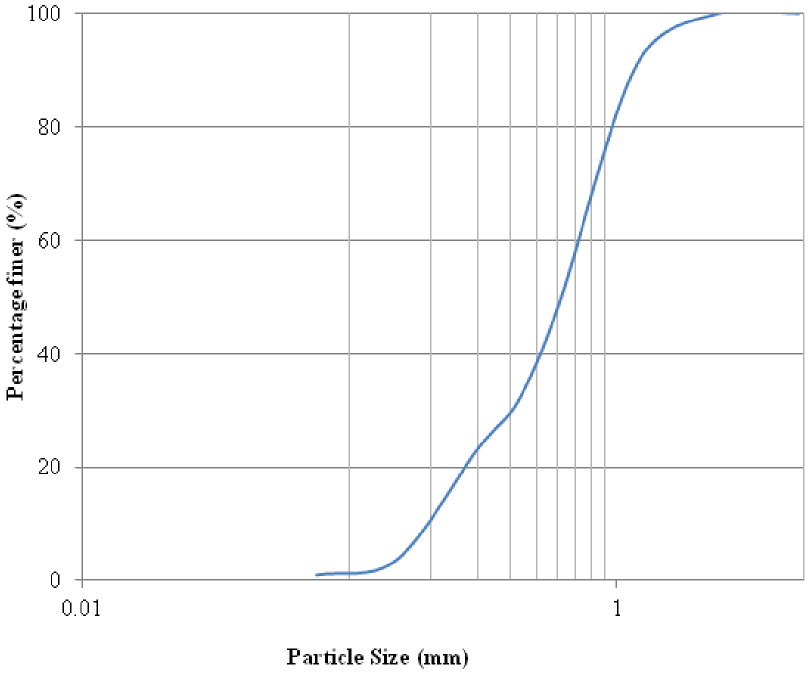


Table 2. Properties of sand used in the study

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	3.50
Curvature coefficient	1.14
Specific Gravity	2.65
Maximum dry density	1.786 g/cc
Minimum dry density	1.434 g/cc
Relative density adopted	70%
Friction angle	33°

diameter and 76 mm in height for effective confining pressures of 20, 60 and 100 kPa at constant strain rate of 1.25 mm/min. To achieve a similar density at different percentage of tire crumbs, the samples are compacted by different compaction enegry, i.e. for lower percentage of rubber samples were poured in 2 to 3 layers, and for a higher percentage of rubber STCM samples were poured into mould in 4 to 5 layers and compacted.

Figure 2. Typical photographs of STCM sample preparation for direct shear test

RESULTS AND DISCUSSION

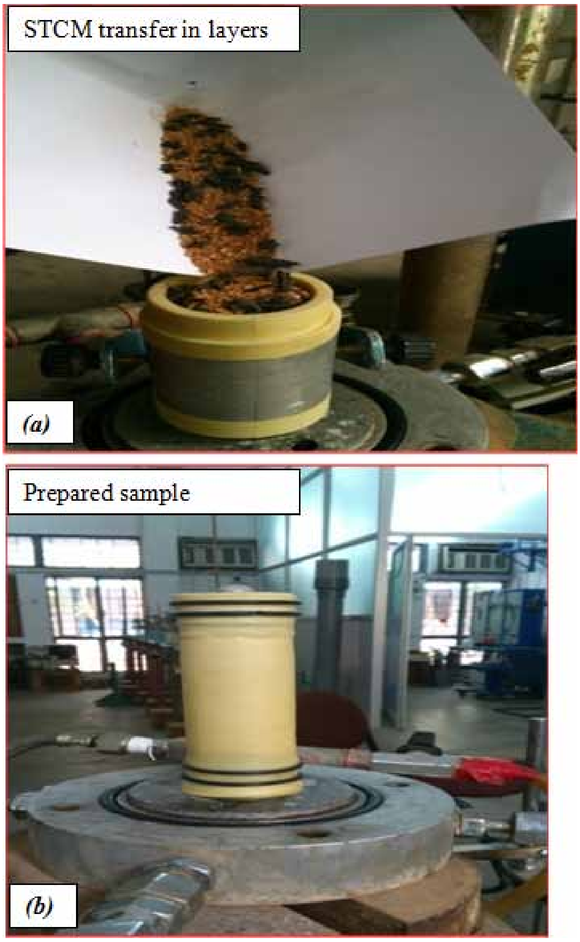
In this section, the results of the laboratory tests are presented with discussion highlighting the effects of various parameters. The shear strength is investigated through direct shear test and energy absorption through Unconsolidated Undrained (UU) triaxial test. The presentation of all the figures would have made the paper lengthy, so only selected are presented.

Direct Shear Test

Influence of Percentage of Tire Crumbs

Typical stress-strain plot from direct shear test for tire crumb size of *IV* are shown in Figure 4 for all five percentages of tire crumbs and normal stress of 100 kPa. It can be noticed from Figure 4 that for all STCM, a clear peak shear stress is observed, and shear stress increases with the increase in percentage of tire crumbs up to 25%, then it starts decreasing thereafter. However, the shear strain corresponding to peak shear stress increases with the increasing tire crumbs content. The shear strain at failure was also found to increase with increase in tire crumbs. Adding 10-

Figure 3. Typical photographs of STCM sample preparation for triaxial test



25% of crumbs to sand particles enhances the shear strength in comparison to clean sand. The sand is loose and capable of accommodating more particles of tire crumbs. The voids created by sand grains are occupied by the rubber, rubber particles act as reinforcement for the sand upto 25% STCM, thereafter (for greater than 25% tire crumbs) with the increase in the rubber content and with the limitation of sand, the voids created in STCM will be more, thus reducing the shear strength properties of STCM. Thus, compared to clean sand, the strength of composite materials is enhanced upto 25% STCM and decreases thereafter. Variation of volumetric strain against shear strain for crumb size *IV* with different percentage of rubber at a normal stress of 100 kPa is shown in Figure 5. It can be observed from Figure 5 that for a given normal stress, volumetric strain increases with increase in shear strain for sand. However, initial compression and dilation upon shearing at higher shear strain has been observed for STCM. This behaviour increases with increasing rubber content for all sizes of tire crumb.

Here, with the addition of tire crumbs, peak shear stress increases and volumetric strain decreases for all sizes of STCM. In any plane for shearing to take place, the sand particles must either climb over or shear through the tire crumbs. However, tire crumbs are deformable and

Figure 4. Typical plot of the variation of peak shear stress for crumb size IV with different percentage of STCM and normal stress of 100 kPa

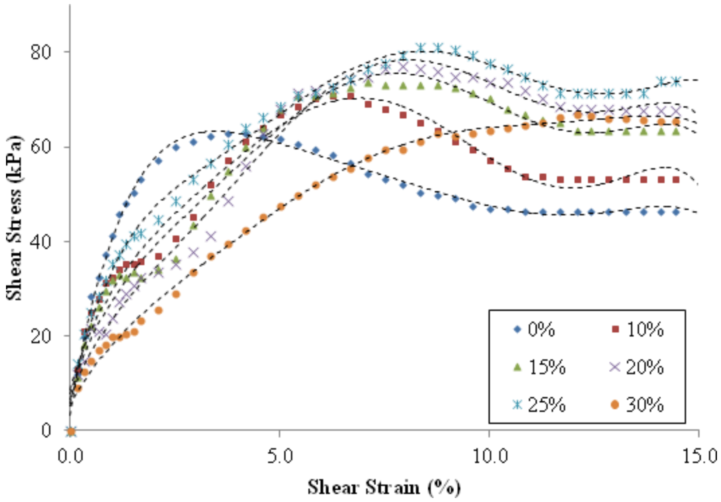
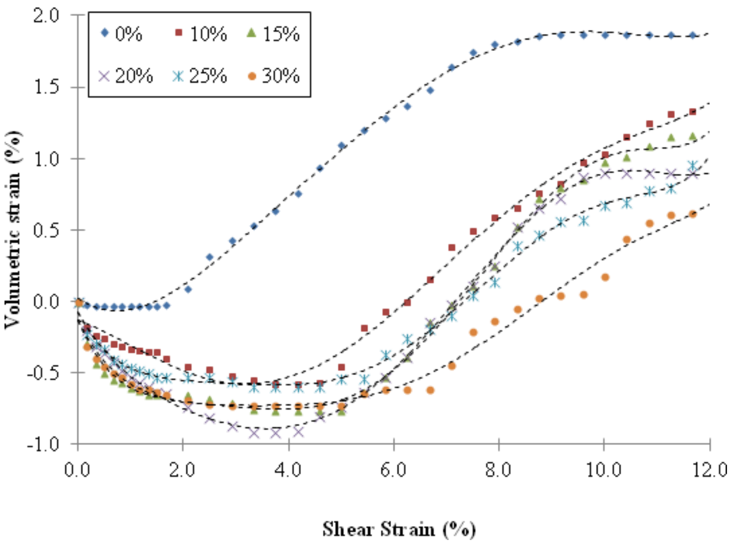


Figure 5. Typical plot of the variation of shear strain corresponding to peak shear stress for crumb size IV with different percentage of STCM and normal stress of 100 kPa



thus reduce the possibility of particle movements around rubber during shearing. The path of least resistance will determine shear strength. When normal stresses are applied in the shear tests, sand particles penetrate into rubber, resulting in decreased volumetric strain. Under low to moderate normal stresses, sand particles might be forced to move around tire crumbs during shearing from their initial penetration into rubber to some extent, resulting in increased dilatancy (Lee et al., 1999; Foose et al., 1996).

Influence of Normal Stress

Figure 6 shows a typical plot of shear stress versus normal stress for crumb size *IV* with different percentage of rubber. For different applied normal stresses, shear resistance of STCM were higher than that of pure sand, but the increasing trend maintains up to 25% of rubber, beyond which the shear resistance decreases. The Mohr-Coulomb envelopes obtained from all samples of different sizes are almost linear. The linear behaviour is due to small grain sizes of rubber particles, which were distributed randomly in the mixture to form a continuum material with a granular behaviour (Mahmoud, 2004).

Influence of Tire Crumb Size

Many researchers have reported the influence of different size of tire chips on shear strength (see Table 1). In order to understand the effect of smaller size tire crumbs on shear strength, results obtained from the direct shear test are plotted. Figure 7 shows frictional angle estimated for different percentage and size of tire crumbs. It is observed from Figure 7 that by adding rubber crumbs up to 25% will increase friction angle and then the trend starts reversing with further addition of tire crumbs. The friction angle in the present study varies from 33° to 44° for sand with 25% rubber mix for the crumb size of *IV*. Shear strength for crumb size *IV* and *I* in STCM's are higher when compared to *III* and *II*, this increase might be due to the grains of similar sizes which enhances shear strength filling more voids for the mix *I* and for crumb size *IV*, rubber grains acts as reinforcement for sand. *II* and *III* crumbs are of medium size range that neither fills the voids nor acts as reinforcement and cause strength to decrease compared to other crumb sizes (*I* and *IV*). Shear strength of STCM is based on pressure imposed from sand grains to the tire crumbs due to application of normal stress and the friction mobilized between sand-rubber, rubber-rubber, and sand-sand (Mahmoud, 2004).

Figure 6. Typical plot of the variation of shear stress with normal stress for crumb size IV with different percentage of rubber mix

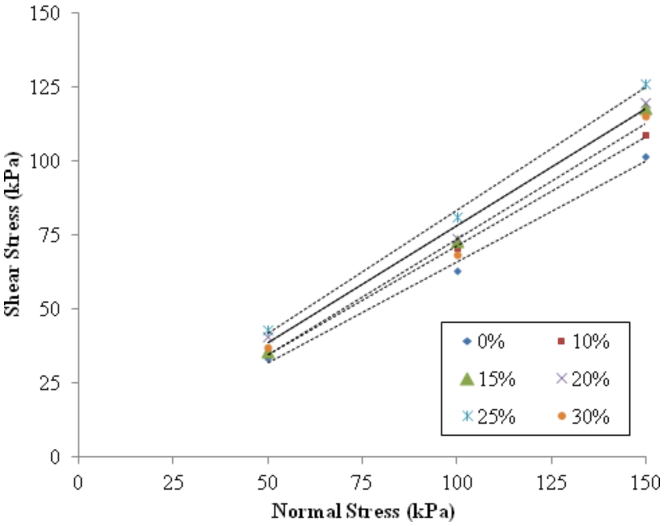
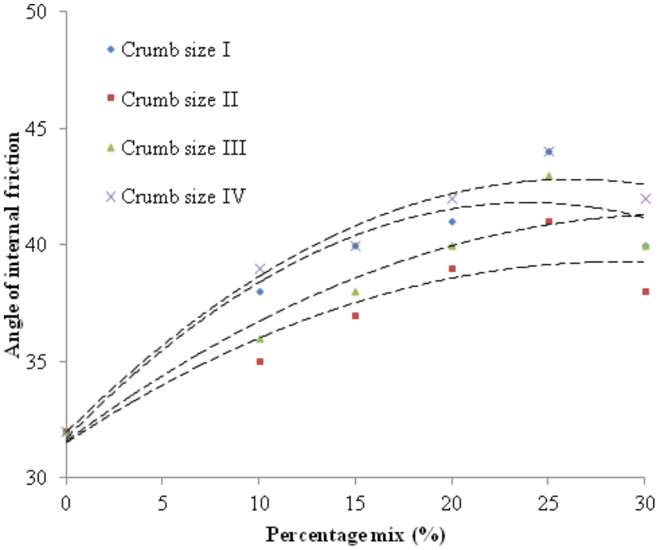


Figure 7. Variation of friction angle for different rubber sizes and proportion of mix



Unconsolidated Undrained (UU) Test

STCM samples are also tested in triaxial UU condition. The stress-strain response, the deviatoric stress at failure (q_f) and the ultimate stress (q_{ult}) are obtained for all the combinations. Typical trends of stress-strain curves obtained from UU triaxial tests on STCM size *IV* for confining pressure of 100 kPa is shown in Figure 8. The influence of rubber content can be noticed by significant change in the stress-strain behaviour. These results are used to estimate the peak strength, ultimate behaviour, stiffness and ductility, which are presented below.

Failure and Ultimate Strength

In addition, of tire crumbs to sand, the stress-strain response of the composite mix exhibit increase in deviatoric stress, which in turn increase value of failure and ultimate strength. The effects of confining pressure on deviatoric stress (q_f) at failure and on ultimate deviatoric stress (q_{ult}) for crumb size *IV* are presented in Figures 9 and 10. It can be noticed from the figure that the increase in rubber percentage results in an increase of q_f and q_{ult} up to 25% of rubber, beyond which the trend starts reversing. As expected, the values obtained for crumb size *II* and *III* were slightly lower, but the trends remain similar. The effect of confining pressure is clearly indicated in the strength envelopes shown in Figure 10.

Secant Modulus

Figure 11 illustrates the typical variation of the secant modulus (E) verses percentage of STCM for crumb size of *IV* with different confining pressure. It can be observed from the plot, that the E values increases with the increasing rubber content up to 15% by volume, thereafter it remains constant up to 25% mix, followed by a decreasing trend thereafter. However, the E value increases with increasing in confining pressure, this is in agreement with the trends reported by Ahmed (1993). A similar trend has been observed for other sizes of tire crumb mix, but E values

Figure 8. Typical plot of Stress-strain curve for confining pressure of 100 kPa for rubber size IV

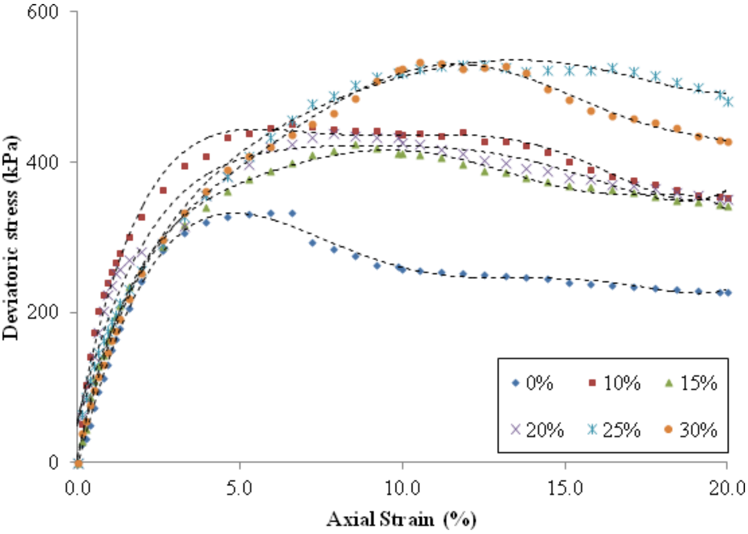
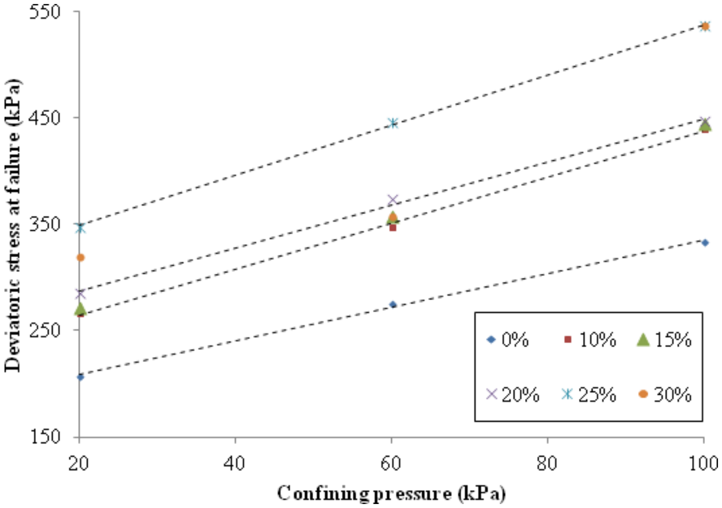


Figure 9. Effect of STCM for crumb size IV on deviatoric stress at failure for different composition



obtained for *II* and *III* crumb size are slightly lower compared to other sizes. Initial increasing in E up to 15% is attributed by addition of tire crumbs in effective composition, then balance amount of crumb and sand makes E stable up to 25% and after that the value of E reduces due to the domination of crumbs.

Ductility

The unique advantage of scrap tire crumb when compared to any other waste materials is the improvement of ductility as a composite engineering material. The measure of this behaviour

Figure 10. Effect of STCM for crumb size IV on ultimate deviatoric stress for different composition

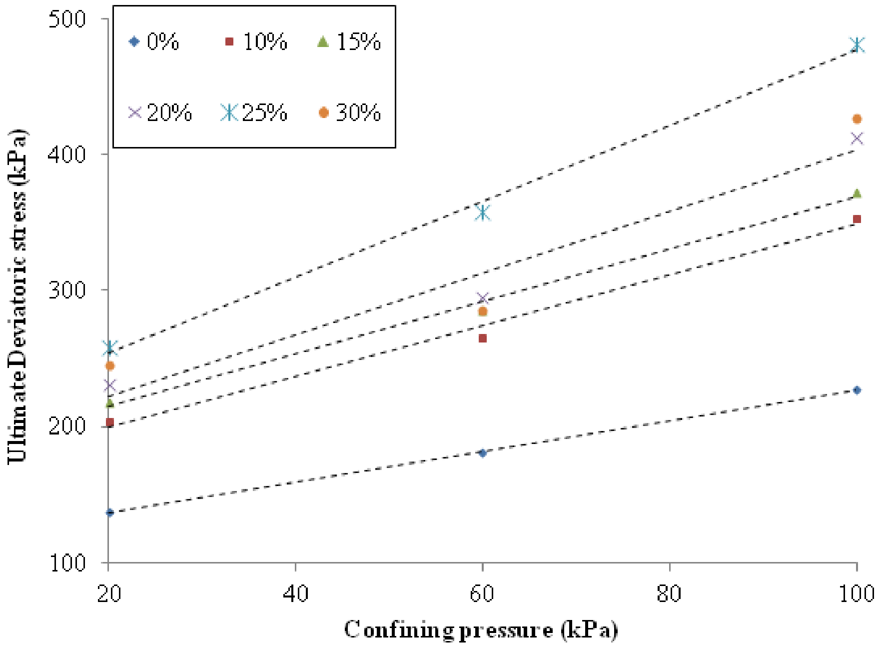


Figure 11. Typical plot of modulus of elasticity verses percentage of mix for crumb size IV

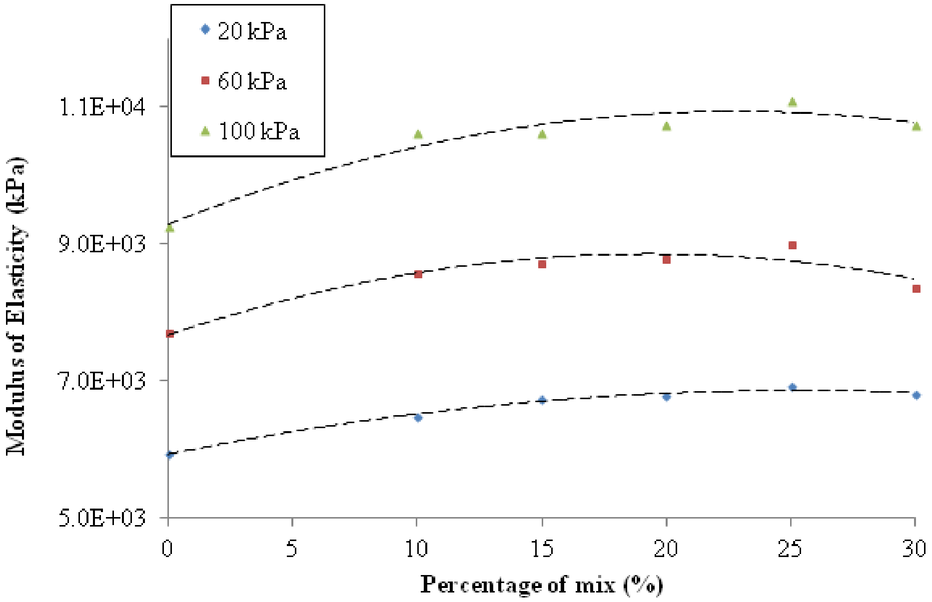
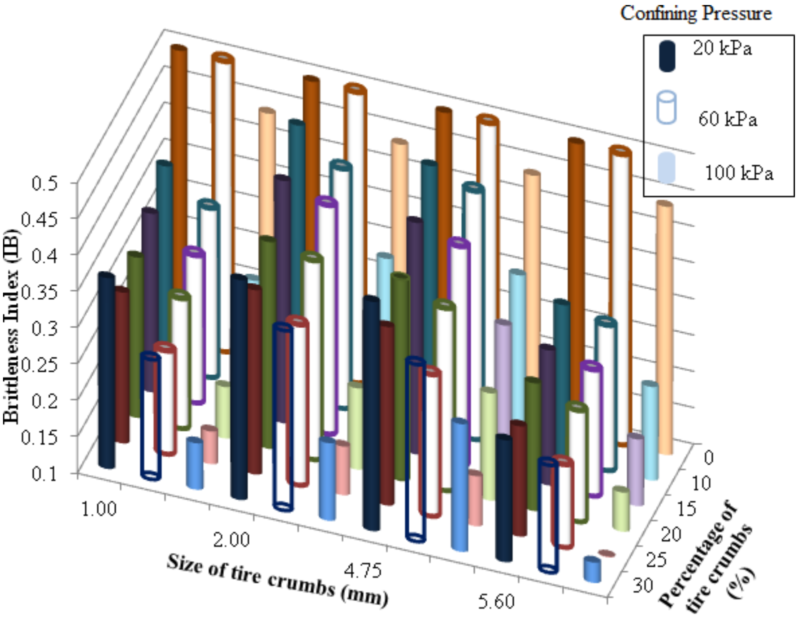


Figure 12. Influence of tire crumb size and composition of tire crumbs on the brittleness index for the confining pressure of: 20 kPa, 60 kPa, and 100 kPa



can be given by the brittleness index (I_B). I_B is a function of q_f and q_{ult} and estimated by using the relation:

$$I_B = \frac{q_f}{q_{ult}} - 1 \tag{1}$$

where, q_f and q_{ult} are the failure and the ultimate deviatoric stress. As the brittleness index approaches zero, failure mechanism becomes more ductile. In Figure 12 solid cylinder with dark colours indicate the variation of I_B of STCM with different size and percentage of the mix for a confining pressure of 20 kPa. While hollow cylinder and the cylinder with lighter colours indicate variations of I_B for confining pressures of 60 and 100 kPa. This study shows that I_B of sand decreases with the increasing percentage of rubber up to 25%, thereafter it starts increasing. Brittleness index decreases with increase in confining pressure. The values of I_B for crumb size *II* and *III* are greater than the other two sizes for all the confining pressure. These results are also summarized in the Table 3. In future stress-strain plot of STCM will be used to estimate the energy absorption capacity.

Energy Absorption Capacity

Energy absorption capacity of STCM plays a very important role in the application of seismic isolation. Several static strength related studies were carried out on STCM, but very limited results are available on energy absorption capacity. The area under the stress-strain curve up to

Table 3. Ductility and energy absorption values of sand and STCM

Material	Confining Pressure (kPa)	Brittleness Index, I_B				Energy Absorption ED(kJ/m^3)			
		I	II	III	IV	I	II	III	IV
Sand	20	0.519				30.4			
	60	0.504				40.1			
	100	0.442				48.7			
Sand+10% Rubber	20	0.376	0.475	0.462	0.313	36.8	31.4	34.1	40.9
	60	0.333	0.430	0.442	0.300	48.9	42.8	45.0	50.6
	100	0.247	0.320	0.340	0.229	71.6	60.8	67.2	72.8
Sand+15% Rubber	20	0.346	0.434	0.419	0.286	38.3	32.7	36.8	43.3
	60	0.303	0.415	0.401	0.274	51.3	44.2	47.1	57.8
	100	0.210	0.278	0.306	0.192	75.2	62.4	68.6	77.1
Sand+20% Rubber	20	0.321	0.385	0.376	0.276	38.8	35.1	41.1	47.0
	60	0.279	0.374	0.351	0.253	53.5	48.4	50.3	63.4
	100	0.171	0.212	0.248	0.154	75.1	65.1	70.6	80.8
Sand+25% Rubber	20	0.308	0.354	0.346	0.252	46.6	40.7	46.4	51.8
	60	0.242	0.321	0.295	0.214	61.7	55.6	60.4	70.9
	100	0.145	0.167	0.169	0.101	79.3	70.7	76.6	86.9
Sand+30% Rubber	20	0.363	0.403	0.416	0.268	36.7	33.9	37.6	45.1
	60	0.265	0.348	0.344	0.248	54.2	47.9	49.0	61.1
	100	0.164	0.207	0.276	0.128	71.3	64.5	67.2	82.7

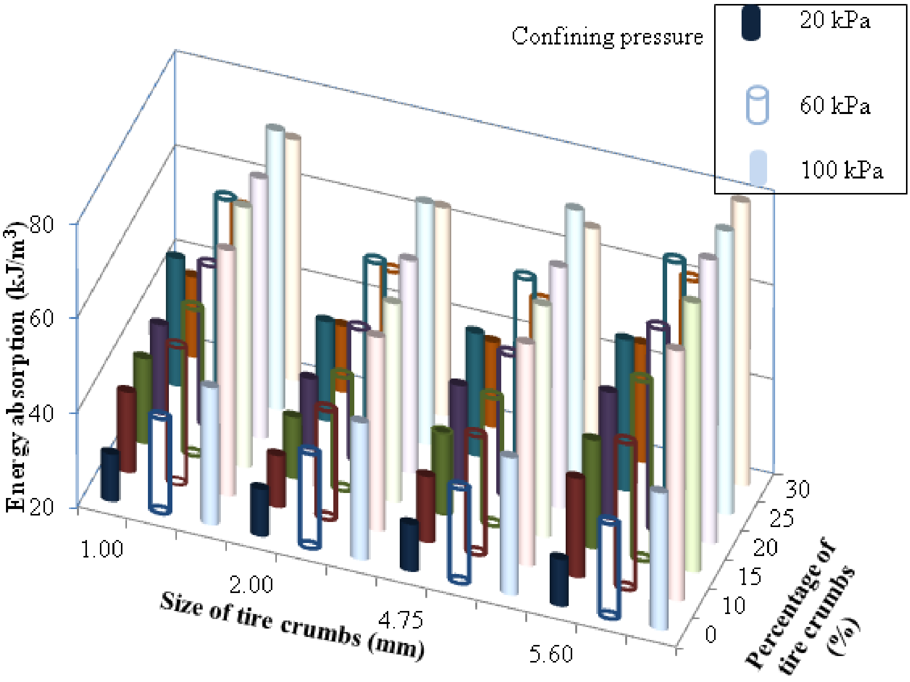
a given value of strain is the total mechanical energy per unit volume consumed by the material while straining it to that value (Roylance, 2001). This is given by:

$$EA = \int_{0}^{\in} \sigma\left(\in\right) d \in \tag{2}$$

where $\sigma\left(\in\right)$ is the stress as a function of the strain. The energy absorption capacity (toughness) of the mix is determined by the area traced out by the stress-strain curve obtained from UU tests. The area up to yield point is termed modulus of resilience and total area up to fracture is termed as modulus of toughness. Energy absorption capacity for different size and the amount of crumbs under three confining pressure is shown in Figure 13 as the 3-D plot. In Figure 13 solid cylinder with dark colors indicate the variation of energy absorption capacity of STCM with different size and percentage of the mix for a confining pressure of 20 kPa. For confining pressure of 60 and 100 kPa, variation in energy absorption capacity is indicated by hollow cylinder and the cylinder with lighter colors in Figure 13. It is seen from the Figure 13 that the energy absorption capacity increases with the increasing rubber content up to 25%, which is due to the increase in inherent damping of raw materials, and starts decreasing thereafter. The energy absorption of a particular percentage mix increases with an increase in the confining pressure. The same trend is observed in composite for all sizes of tire crumbs and slightly lower values for mixtures *II* and *III* tire crumbs.

Figure 14 shows the typical variation of stiffness (secant modulus) and energy absorption capacity of STCM for rubber size of *IV*. In Figure 14, dotted lines with hollow symbol indicate energy absorption capacity and solid lines with solid symbol indicates initial stiffness. It can be

Figure 13. Influence of tire crumb size and composition of tire crumbs on energy absorption capacity for confining pressure of: 20 kPa, 60 kPa, and 100 kPa

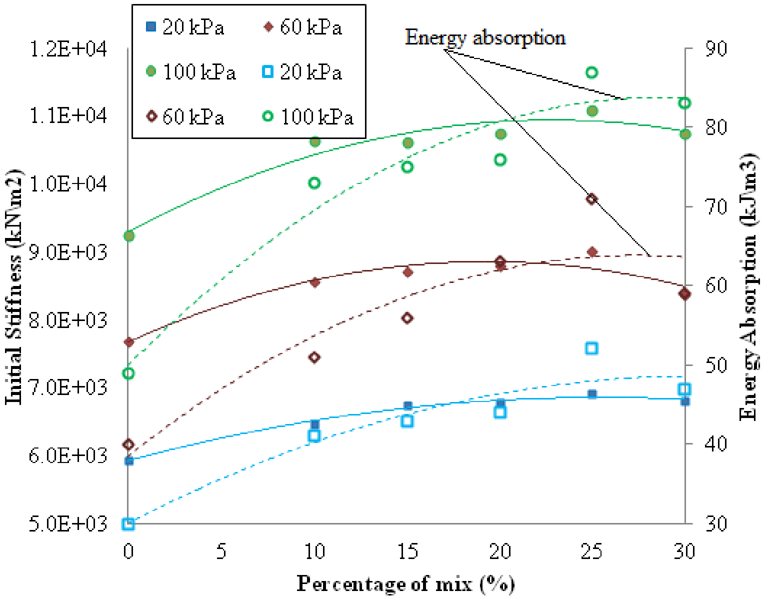


clearly seen from Figure 14, stiffness values increase with increasing in rubber content up to 15% by volume, thereafter it remains constant up to 25% and decrease slightly beyond 25%. However the initial stiffness values of STCM above 25% to 30% is greater than clean sand. Energy absorption capacity of STCM is about 40% to 70% when compared to clean sand. Also energy absorption capacity increases due to the addition of crumbs to sand up to 25% and decreases thereafter. The observed results are in general agreement with the results from other authors (Edincliler et al., 2010 and Mahmoud, 2004), but the findings of the current study contradict the finding of Masad et al (1996), Youwai & Bergado (2003) and Neaz et al (2012). This may be attributed that Masad et al (1996) and Youwai & Bergado (2003) used tire chips and higher tire content (50% and 30%) and Neaz et al. (2012) used similar crumbs with poorly graded sand, also the void ratio of STCM was different from this study. More testing is needed to understand the effect of void ratio and gradation of sand in the shear strength behaviour of STCM.

Stiffness and Energy Absorption

In this study, a practical equation has been developed for quantitative prediction of stiffness and energy absorption of STCM. The experimental data obtained from UU test has been further used to derive practical equations to predict stiffness and energy absorption. Regression analysis is a statistical tool for the investigation of relationships between variables (Alan, 1992). In this study, multiple regression analysis, which is an extension of simple linear regression in which more than one independent variable (crumb size (X_1), crumb content (X_2) and confining stress (X_3)) are varied to predict the dependent variable (Energy absorption (EA) capacity and stiffness (Y)). The most common empirical models fit the experimental data are either simple linear or more

Figure 14. Typical plot of variation of secant modulus and energy absorption capacity for crumb size IV and different proportion mix



complex quadratic or cubic model. The second order model is widely used in regression model due to its flexibility and considerable practical experience. Additional details about multiple regression analysis used in present work can be found in Myers & Montgomery, (1995). The regression equation to energy absorption capacity (dependent variable) as a function of size, content and confining pressure is given below:

$$EA = 44.71 + 2.43x_1 + 6.60x_2 + 15.3x_3 + 11.35x_1^2 \\ -3.59x_2^2 + 2.67x_3^2 + 1.68x_1x_2 - 0.033x_1x_3 + 1.54x_2x_3 \qquad (3)$$

Similarly the prediction of stiffness is given by following equation:

$$Y = 8109.67 + 62.42x_1 + 357.62x_2 + 1825.49x_3 + 576.1x_1^2 \\ -173.51x_2^2 - 119.83x_3^2 - 35.12x_1x_2 + 31.39x_1x_3 + 70.58x_2x_3 \qquad (4)$$

where x_1 = crumb size in mm, x_2 = crumb content in percentage and x_3 = confining stress in kPa. These models have R^2 value of 0.912 for energy absorption (Equation 3) and 0.998 for stiffness (Equation 4). These R^2 values are almost close to unity, indicates a better fit to the data. Also, the higher the value of R^2, the greater will be the relationship between dependent and independent variables. Figure 15 shows a predicted energy absorption capacity of STCM by the proposed model with UU test results for tire crumb size of *I* to *IV* and confining pressure of 100 kPa. Similarly, Figure 16 shows a predicted stiffness (secant modulus) of STCM by the proposed model with experimental data for tire crumb size of *I* to *IV* and confining pressure of 100 kPa.

Figure 15. Typical comparison of predicted energy absorption capacity with measured data for different crumb sizes at confining pressure of 100 kPa

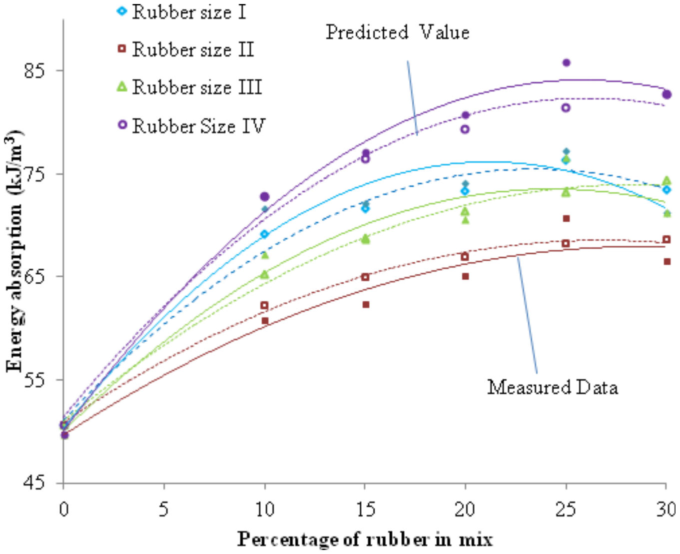
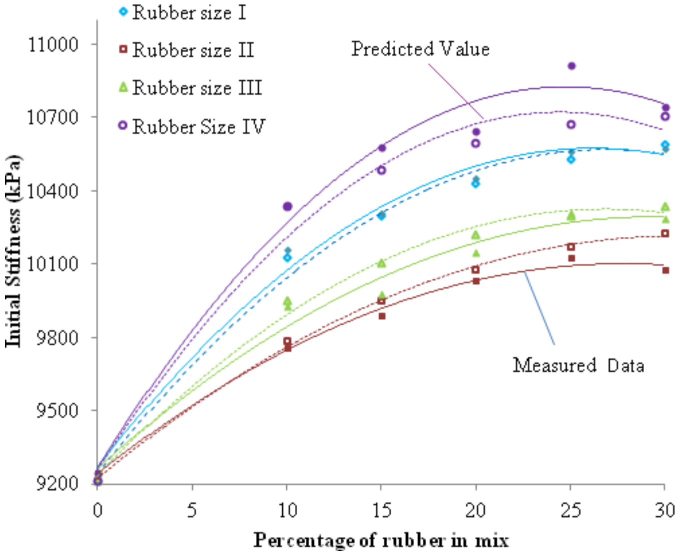


Figure 16. Typical comparison of predicted stiffness (secant modulus) with measured data for different crumb sizes at confining pressure of 100 kPa



In both the Figures the solid symbol indicates the measured values obtained from experimental studies and the solid line is a best fit trend line, hollow symbol are predicted values using above equations and dotted lines are best fit for predicted values. A good match between actual and predicted values can be noticed from the figures. The developed model is also checked for model adequacy and hypothesis testing. None of the developed models revealed any model inadequacy ensuring adequate approximation of the engineering behavior of STCM. The regression equations can be used directly to predict stiffness and energy absorption of STCM in future works.

SUMMARY AND CONCLUSION

A series of direct shear and triaxial tests (UU) on STCM's have been carried out for different sizes, composition of mix and for different confining pressure with constant density of 1.54 g/cc. Stress-strain curve obtained from UU test for different confining pressure has been used to estimate energy absorption, brittleness index and stiffness characteristics. Based on the results obtained from the experimental studies, the following conclusions can be drawn:

1. It is noticed in the study that the parameters influencing strength characteristics, energy absorption and brittleness index are tire crumb size, percentage of tire crumb, normal stress and confining pressure;
2. Tire crumb mixtures exhibit a significant increase in peak and ultimate strength. Also, addition of tire crumbs consistently improved internal friction angle;
3. The shear enhancement by adding rubber crumbs increases with the percentage of rubber and starts decreasing after 25% rubber by volume. This trend is observed for all sizes of tire crumbs from the direct shear test;
4. The strength characteristics of sand were increased by the inclusion of rubber, which in turn increase the energy absorption capacity and ductility. This trend is observed for all sizes of tire crumbs from UU test;
5. Maximum energy absorption and friction angle of STCM is observed for the crumb size of *IV* when compared to *I*, *III* and *II*;
6. Stiffness value remains constant beyond 15% STCM, whereas energy absorption capacity increases. The increase in stiffness up to 15% is controlled by more percentage of sand, beyond which it is controlled by the higher percentage of rubber;
7. The regression equation to predict energy absorption capacity and initial stiffness of STCM was proposed using available results.

It can be concluded from this study that the addition of waste tire crumbs to sand increases the energy absorption capacity and ductility by about 40 to 70%. These test results can be used for effective selection of tire crumb size for dynamic studies in future, through which one can select suitable STCM for vibration isolation. Identified STCM mix can be further used to develop shear modulus reduction and damping curves. Also, this optimum mix can be placed around the isolated footing and dynamic response and energy absorption may be estimated in the future, so that STCM can be used as vibration isolation material in low to medium rise buildings.

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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.

Alan O Sykes. (1992). *An introduction to regression analysis*. University of Chicago, The law school.

Arroyo, M., Estaire, J., Sanmartin, I., & Lloret, A. (2008). Size effect on tire derived aggregate mechanical properties. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 151-160.

ASTM. (2003). Standard Practise for Classification of Soils for Engineering Purposes. Unified Soil Classification System. ASTM D2487.

ASTM. (2007). Standard Test Methods for Density, Relative Density and Absorption of Fine Aggregate. ASTM C128.

ASTM. (2007). Standard Test Methods for Unconsolidated Undrained Triaxial Compression Test. ASTM D2850.

ASTM. (2008). Standard Test Methods for Determining Coefficient of Soil and Geosynthetic or Geosynthetic Friction by Direct Shear method. ASTM D5321.

ASTM. (2010). Standard Test Methods for Specific Gravity of Soils by Water Pycnometer. ASTM D854.

Bosscher, P. J., Edil, T. B., & Kuraoka, S. (1997). Design of highway embankments using tire chips. *Journal of Geotechnical and Geoenvironmental Engineering*, *123*(4), 295–304. doi:10.1061/(ASCE)1090-0241(1997)123:4(295)

Charleson, A. W., & Fyfe, G. D. (2001). Earthquake building damage in developing countries: A review of recent reconnaissance reports. Bulletin of the New Zealand society for earthquake engineering, Vol. 34, No. 2, June 2001.

Dickson, T. H., Dwyer, D. F., & Humphrey, D. N. (2001). *Prototypes tire-shred embankment construction. Transportation research record 1755, TRB* (pp. 160–167). Washington, DC: National research council.

Edil, T. B. (2008). A Review of Environmental Impacts and Environmental applications of Shredded Scrap Tires. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 151-160.

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

Edincliler, A. (2008). Using waste tire-soil mixtures for embankment constructions. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials -Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 319-328.

Edincliler, A., Baykal, G., & Saygili, A. (2010). Influence of different Processing Techniques on the Mechanical properties of used tires in Embankment Construction. *Waste Management (New York, N.Y.)*, *30*(6), 1073–1080. doi:10.1016/j.wasman.2009.09.031 PMID:20060280

ETRMA. (2010). *End of life tyres- a valuable resource with a wealth of potential*. Report 2010, European Tyre and Rubber Manufactures Association, Brussel.

Foose, G. J., Benson, C. H., & Bosscher, P. J. (1996). Sand Reinforced with Shredded Waste Tires. *Journal of Geotechnical Engineering*, *122*(9), 760–767. doi:10.1061/(ASCE)0733-9410(1996)122:9(760)

Genan Business & Development A/S. (2012). http://www.genan.eu/tyres-2.aspx Accessed 10 November 2012. Jegindovej 16. DK-8800 Viborg Denmark.

Hazarika, H. (2008). Structural stability and flexibility during earthquakes using tyres (SAFETY) – A novel application for seismic disaster mitigation. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 115-125.

Hazarika, H., & Yasuhara, K. (2007). Scrap tire derived geomaterials – oppurtunities and challenges. *Proceedings of the international workshop (IW-TDGM 2007)*, 23-24 March 2007, Yokosuka, Japan.

Hazarika, H., Yasuhara, K., Karmokar, A. K., & Mitarai, Y. (2008). Shake table test on liquefaction prevention using tire chips and sand mixture. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 215-222.

Humphery, D. N. (2008). Tire derived aggregate as light weight fill for embankments and retaining wall. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 59-81.

Kawata, S., Hyodo, M., Orense, R. P., & Yamada, S. (2008). Undrained and drained shear behavior of sand and tire chips composite material. *Proceedings of the international workshop on Scrap Tire Derived Geomaterials - Opportunities and Challenges* - Hazarika and Yasuhara (eds) ©2008 Taylor and Francis Group, London, pp 277-283.

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

Mahmoud, G. (2004). Shear Strength Characteristics of Sand-Mixed with Granular Rubber. *Geotechnical and Geological Engineering*, *22*, 401–416. doi:10.1023/B:GEGE.0000025035.74092.6c

Masad, E., Taha, R., Ho, C., & Papagiannakis, T. (1996, September). Engineering Properties of Tire/Soil Mixtures as a Lightweight Fill Material. *Geotechnical Testing Journal*. *GTJODJ*, *19*(3), 297–304.

Myers, R. H., & Montgomery, D. C. (1995). *Response Surface Methodology: Process and product optimization using designed experiments*. New York: Wiley.

Neaz Sheikh, M., Mashiri, M. H., Vinod, J. S., & Tsang, H.-H. (2012). Shear and Compressibility Behaviours of Sand-Tyre Crumb Mixtures. *Journal of Materials in Civil Engineering*, *25*(10), 1366–1374. doi:10.1061/(ASCE)MT.1943-5533.0000696

Promputthangkoon, P., & 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.

Rao, G. V., & Dutta, R. K. (2006). Compressibility and strength behaviour of sand–tyre chip mixtures. *Geotechnical and Geological Engineering*, *24*(3), 711–724. doi:10.1007/s10706-004-4006-x

Recycling Research Institute RRI. (2009). http://www.scraptiresnews.com

Roylance, D. (2001). *Stress-Strain Curves*. Cambridge: Department of Materials Science and Engineering Massachusetts Institute of Technology.

Rubber Manufactures Association RMA. (2009). http://www.rma.org

Tsang, H. H. (2008). Seismic Isolation by Rubber-Soil Mixtures for Developing Countries. *Earthquake Engineering & Structural Dynamics*, *37*(2), 283–303. doi:10.1002/eqe.756

Tsang, H. H., Lo, S. H., Xu, X., & Sheikh, M. N. (2012). Seismic Isolation for Low-to-Medium-Rise Buildings using Granulated Rubber-Soil Mixtures: Numerical Study. *Earthquake Engineering & Structural Dynamics*, *41*(14), 2009–2024. doi:10.1002/eqe.2171

Waste and Resources Action Program WRAP. (2007). Tyres re-use and recycling. http://www.wrap.org.uk

Yoon, Y. W., Heo, S. B., & Kim, K. S. (2008). Geotechnical performance of waste tires for soil reinforcement from chamber tests. *Goetext. Geomembr*, *26*(1), 100–107. doi:10.1016/j.geotexmem.2006.10.004

Young, H., Sellasie, K., Zeroka, D., & Sabnis, G. (2003). Physical and Chemical properties of Recycled Tire Shreds for use in Construction. *Journal of Environmental Engineering*, *129*(10).

Youwai, S., & Dennes, T. (2003). Strength and Deformation Characteristics of Shredded Rubber Tire-Sand Mixtures. *Canadian Geotechnical Journal*, *40*(2), 254–264. doi:10.1139/t02-104