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Influence of size of granulated rubber and tyre chips on the shear strength characteristics of sand–rubber mix

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ABSTRACT

Use of scrap tyres in isolation systems for seismic damping, requires a knowledge of the engineering properties of sand–rubber mixtures (SRM). The primary objective of this study is to assess the influence of granulated rubber and tyre chips size and the gradation of sand on the strength behaviour of SRM by carrying out large-scale direct shear tests. A large direct shear test has been carried out on SRM considering different granulated rubber and tyre chip sizes and compositions. The following properties were investigated to know the effect of granulated rubber on dry sand; peak shear stress, cohesion, friction angle, secant modulus and volumetric strain. From the experiments, it was determined that the major factors influencing the above-mentioned properties were granulated rubber and tyre chip sizes, percentage of rubber in SRM and the normal stress applied. It was observed that the peak strength was significantly increased with increasing granulated rubber size up to rubber size VI (passing 12.5 mm and retained on 9.5 mm), and by adding granulated rubber up to 30%. This study shows that granulated rubber size VI gives maximum shear strength values at 30% rubber content. It was also found that more uniformly graded sand gives an improved value of shear strength with the inclusion of granulated rubber when compared to poorly graded sand.

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KEYWORDS

Friction angle; sand–rubber mixture; secant modulus; shear strength

1. Introduction

Every year, approximately a million tons of scrap tyres are generated in India. This figure is increasing dramatically with the increase in the number of vehicles due to the upgradation in living standards. As per the records of Automan (1999), annual tyre production in India is expected to grow at a rate of 8%, cumulatively. As there is no governmental agency monitoring the generation of scrap tyres in India, the best estimate of waste tyres can only be made from the tyre production. The growing population around the world has resulted in hundreds of millions of scrap tyres, which are disposed of every year (WRAP 2007, RMA 2009, RRI 2009). It is estimated that 1.5 billion waste tyres are generated in the world annually, out of which 40% is contributed from upcoming markets like India, China, South America, Eastern Europe and South Africa. Also, the supply of this scrap material can be assumed to increase with increase in automobile sales. In India, waste tyres are used for applications in tyre retreading, as a fuel in kilns, producing belts for motor shafts, etc., but all these applications constitute only a fraction of the potential utilisation of the amount of scrap tyres produced. Some of the current uses of recycling have a negative impact on the environment. It becomes harder and also expensive to dispose them safely without any threat to human health and the surrounding environment in many regions of the world, due to the possibility of fire and health hazards. Over the last few years, recycling of waste tyres as construction materials (light weight backfill material, thermal insulation and drainage layer) have been considered important to solve the economic and technical problems for a sustainable environment (Bosscher *et al.* 1992, Humphrey and Manion 1992, Humphrey 1998, Tweedie *et al.* 1998, Strenk *et al.* 2007, Tandon *et al.* 2007, Edincliler *et al.* 2010). The waste tyres, which are shredded into tyre crumbs/chips/granulated rubber, are mixed with sand, which can be used for vibration isolation. This may result in the effective utilisation of abundantly available waste tyres and also helps to develop a low-cost isolation/damping system. Geomaterials derived from scrap tyres are used in several geotechnical applications and bibliographic references to related papers can be found in Hazarika and Yasuhara (2008).

The use of waste/scrap tyres in vibration reduction and seismic isolation of buildings is a promising approach, taking into account the high damping behaviour in the waste tyres (Hazarika 2008, Tsang 2008,

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Tsang *et al.* 2012). Several numerical schemes and model tests were studied by many researchers; however, systematic studies of the static properties of sand–rubber mixtures (SRM) considering the different sizes of shredded/scrap tyres are limited. The objective of the study is to assess the shear strength characteristics of SRM considering different sizes of granulated rubber, tyre chips and percentage of mixing. A number of large-scale direct shear tests were conducted on mixtures of dry sand and SRM at three different normal stresses, i.e. at 16, 32 and 80 kPa. Peak shear stress, cohesion, angle of internal friction, secant modulus and volumetric strain for the SRM are analysed for granulated rubber sizes ranging from I to VI, tyre chips size VII and rubber proportions up to which, the shear strength parameters improved (i.e. 10–35% rubber by volume). The factors evaluated during the tests were rubber content, rubber size and the normal stress. This study prescribes the optimum size and percentage of the mix among tested samples, considering static properties for further studies.

2. Background

Aggregates derived from waste tyres can be used with soil in civil engineering applications (ASTM-D6270-08). Sunthonpagasit and Duffey (2004) pointed out that, of all scrap tyre products, crumb/granulated rubber was investigated the least in terms of production and markets. Even though tyres are combustible materials, there is no harm in using them in the buried condition (Yeo, 2007). Due to their low unit weight, high strength and surplus availability, waste tyres are used as lightweight fill material for embankment construction on weak, compressible soils (Bernal *et al.* 1997, Humphrey 2007). It has been reported in previous studies that sand reinforced with tyre chips can provide higher shear strength than sand itself, with friction angles as large as 65.8° being obtained for mixtures of dense sand containing 30% tyre chips by volume. The corresponding friction angle of sand alone was only 34.8° (Ahmed 1993, Ahmed and Lovell 1993, Edil and Bosscher 1994). Foose *et al.* (1996) studied the feasibility of the application of shredded waste tyres to reinforce sand. Large-scale direct shear tests were conducted on mixtures of dry sand and tyre shreds. The authors investigated the influence of the following factors affecting the shear strength: sand matrix unit weight, shred content, shred length, shred orientation and normal stress. They concluded that the shred content and sand matrix unit weight were the most important factors affecting the shear strength of the mixture. Edil and Bosscher (1994) and Humphrey and Manion (1992), have evaluated that tyre shreds and soil–tyre shred mixtures undergo significant compression at low normal stresses. However, most of the compression that occurs is plastic, i.e. the compressibility decreases substantially once the tyre shreds have experienced one load application. Hence, preloading can be done to mitigate plastic compression, once the fill has been constructed. Compressibility also reduces on providing confinement. Bosscher et a1. (1992) and Humphrey and Manion (1992) reported that a vertical stress imposed by a 1 m thick soil layer will significantly reduce compressibility and deflections of overlying pavements. This result was obtained in both laboratory tests and finite element modelling, and is consistent with field observations made by Bosscher *et al.* (1992). Bosscher *et al.* (1992), Ahmed and Lovell (1993) and Humphrey and Manion (1992) reported that tyre shreds and soil–tyre shred mixtures can be compacted using common compaction procedures. It was also found that unit weight is primarily controlled by the soil content in the mixture. On the other hand, vibratory compaction effort and moulding water content appear to have no significant effect. Rao and Dutta (2006) demonstrated that sand–tyre chip mixtures up to 20% could be a potential material for highway construction and embankment construction up to around 10 m height. It has been observed that the optimum size and sand–tyre crumb ratio should be determined experimentally, as the shape and size of the scrap tyres is a factor of the numerous processing techniques and machinery used in production (Edincliler *et al.* 2010). Edil and Bosscher (1993) observed that the addition of 10% tyre shreds by volume in a random arrangement in the dense outwash sand caused a significant increase in shear strength. They reported that the orientation of shreds is an important factor in contributing to the shear strength. They also found that, placing tyre shreds vertically instead of randomly caused a higher strength on a plane perpendicular to the shreds.

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–tyre mix were conducted by considering one particular size of rubber or varying sizes of tyre shreds/chips. Only few studies have been carried out to investigate the shear strength behaviour of sand–granulated rubber mix. Even in those studies the investigation of the effect of different granulated rubber sizes and rubber content on shear strength of rubber–sand is very limited in terms of details, whereas detailed study has been recommended by Promputthangkoon and Hyde (2008). In the present study, shear and volumetric behaviour of SRM for different rubber sizes and content by volume of the mix have been analysed based on the data obtained from the large-scale direct shear tests. Also, the effect of gradation of sand on the shear behaviour of SRM has been analysed.

3. Materials and experimental set-up

3.1. Sand

In this study, two different gradation of sand were considered. The influence of granulated rubber and tyre chips size on shear strength properties of SRM considering seven different rubber sizes was studied by using well-graded/uniformly graded sand. The well-graded sand is named Sand-A, while the poorly graded sand is named Sand-B. The sand used in the present study was locally available and was relatively uniform, passing through a 4.75 mm sieve and retaining on 0.075 mm sieve. The specific gravity of Sand-A was found to be 2.65, as per ASTM D854 (2010). The Sand-A is classified as well-graded sand as per Unified Soil Classification System (UCS), ASTM-D2487 (2003). Sand-B is classified as poorly graded sand (with Cc < 1, refer to Table 1) as per the UCS, passing through a 2.00 mm sieve and retaining on 0.075 mm sieve. The primary properties such as grain size distribution, maximum and minimum dry density, specific gravity, coefficient of curvature and uniformity coefficient of each category of sand were determined. The physical properties of Sand-A and -B are given in Table 1, and the particle size distribution curve is shown in Figure 1. Sand-B is poorly graded and is used in further studies on the gradation of sand.

3.2. Granulated rubber

As per ASTM D6270 (2008), particulate rubber composed of non-spherical particles with size ranges from 425 µm to 12 mm is referred to as granulated rubber. Scrap tyre pieces between 12 and 50 mm are referred to as tyre chips. In the present study, rubbers are grouped into different groups based on particle size, group I (passing 2 mm sieve – and retained on 1 mm sieve), group II (4.75 mm–2 mm), group III (4.75 mm–5.6 mm), group IV (5.6 mm–8 mm), group V (8 mm–9.5 mm), group VI (12.5 mm–9.5 mm) and group VII (20 mm–12.5 mm). Of these, six groups (I–VI) can be called granulated rubber and group VII is called tyre chips. These rubbers were procured from the local industry, which were prepared with special machinery by removing the steel belting from scrap tyres, then crushing into pieces and powdered. The procured rubber grains were angular and had rough sides. These were sieved and separated into groups (I–VII) as per particle sizes described above. The average value of water absorption of rubber is 3.85 according to ASTM-C128 2007). The specific gravity of rubber grains was found to be 1.11 (I), 1.13 (II), 1.14 (III), 1.14 (IV), 1.16 (V), 1.17 (VI) and 1.16 (VII) based on ASTM-D854 (2010) procedures, according to rubber sizes mentioned above. The average value of specific gravity of considered rubber sizes was found to be 1.14. Similarly, the densities of granulated rubber/tyre chips as per above-quoted respective sizes were 4.7, 5.4, 6.2, 6.45, 6.71, 6.9 and 6.6 kN/m^3. Figure 2 depicts a typical rubber sample for rubber size III.

Table 1. Specifications of sand.

Description	Sand-A	Sand-B
Effective size, D_{10}	0.2 mm	0.18 mm
D_{30}	0.4 mm	0.28 mm
Mean size, D_{50}	0.6 mm	0.50 mm
D_{60}	0.71 mm	0.60 mm
Uniformity coefficient	3.55	3.33
Curvature coefficient	1.13	0.726
Specific Gravity	2.65	2.64
Maximum dry density	1.786 g/cc	1.671 g/cc
Minimum dry density	1.434 g/cc	1.354 g/cc
Relative density adopted	80%	80%
Friction angle	35.17°	41.09°

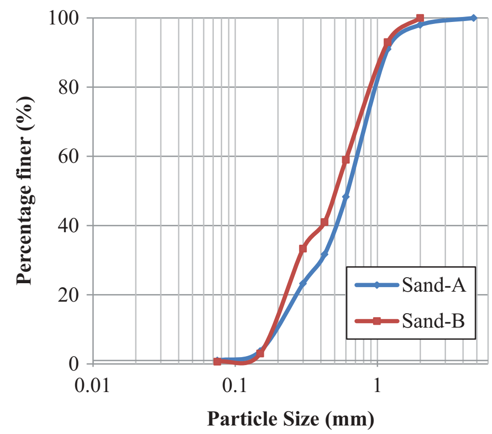

Figure 1. The particle size distribution curve of Sand-A and -B used for this study.

3.3. Direct shear apparatus

The shear strength of the sand and SRM was measured by direct shear using a large-scale direct shear apparatus. The selected rubber sizes exceeded the maximum particle size limit, i.e. 1/10th of the standard direct shear box (ASTM-D3080 2011), hence the large-scale

Figure 2. Typical granulated rubber sample for rubber size III.

direct shear apparatus was used here. Also, large-scale direct shear equipment provides conservative results for shear strength (Xiao *et al.* 2013). The shear box consists of two equal halves. The dimensions of shear box are 300 mm × 300 mm × 230 mm, and each half-box are 300 mm × 300 mm × 115 mm. The tests were carried at the constant horizontal displacement rate of 1 mm/min. Both the boxes are made of strong structural steel having wall thickness of 25.4 mm to bear large horizontal and vertical loads. The vertical load was applied through a lever. The vertical displacement was measured with the help of a dial gauge of least count 0.001 mm to determine the volumetric strain variation. The horizontal displacement was provided in the lower shear box through the larger box with the help of a mechanical shaft through an electrical motor. Maximum horizontal displacement up to 12% of strain was measured.

4. Specimen preparation and testing

In this study, SRM samples were prepared for their respective unit weight. Figure 3 shows the variation of unit weight for different rubber sizes and contents. SRM mix has been

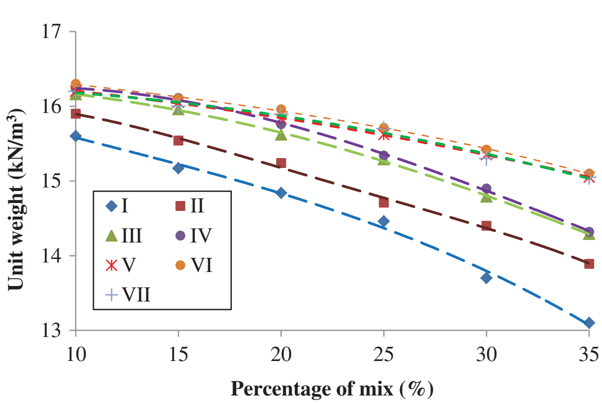

Figure 3. Unit weight plot for different rubber sizes and rubber content.

prepared for 10%, 15%, 20%, 25%, 30% and 35% rubber by volume (volume of the rubber/total volume of the specimen). Granulated rubbers and tyre chip were mixed with sand on volumetric basis, because volumetric specification would be easier to implement in the field. However, sample preparation in the laboratory was performed using measurement of weight instead of volume. Thus, the volume has been calculated by known weight and specific gravity (Foose 1993). SRM specimens were prepared by hand mixing using required amount of sand and rubber for each percentage. The SRM samples were transferred into the direct shear box in layers and special care was taken that the rubber does not segregate. After placing each layer, slight compaction was done and care was taken to ensure that the failure plane/shear plane characterised by the shear boxes came in the centre of the compacted layer. The tests were carried out at three different normal stresses, i.e. 16, 32 and 80 kPa at a constant strain rate of 1 mm/min and a strain level up to 12%. Low- to medium-range normal stresses are selected in this study to know the effect of normal stress on compressibility of SRM similar to (Humphery and Manion 1992, Edil and Bosscher 1994). Edil and Bosscher (1994) and Humphery and Manion (1992) demonstrated that tyre shred–soil mixtures are highly compressible at low normal pressures. In order to account for this compressible behaviour of sand–granular mix, low- to medium-range normal stresses were selected.

5. Results and discussion

Shear strength characteristics and volumetric characteristics of the composite materials were examined with respect to the size of granulated rubber and tyre chips, the percentage of rubber and the applied normal stress on the samples in the large-scale direct shear test. The influences of granulated rubber and tyre chips on the cohesion and friction angle of sand were analysed considering varying sizes and contents of rubber. Additionally the influence of change in sand gradation on the shear properties was also studied for rubber sizes I and II. The dilation behaviour of the SRM sample on the increase in rubber content was analysed. In this section, the results of the laboratory tests are presented with a discussion highlighting the effects of the various parameters.

5.1. *Influence of granulated rubber content*

5.1.1. *On stress–strain behaviour*

Typical stress–strain plot from large-scale direct shear test for granulated rubber size of VI for all six percentages of granulated rubber and normal stress of 80 kPa is shown in Figure 4. It can be observed from Figure 4

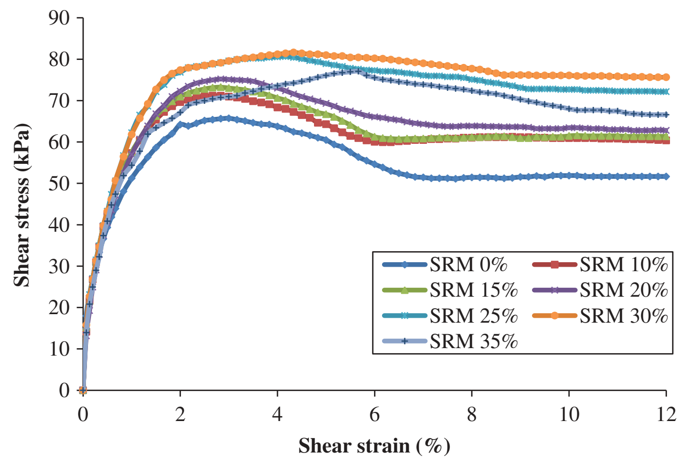

Figure 4. Typical stress–strain plot for granulated rubber size VI at normal stress 80 kPa for various percentage of rubber.

that for all SRM, a clear summit in stress is observed. The peak shear stress values were used for the determination of shear strength of each sample. The shear stress increases with an increase in the rubber content up to 30%, with no further increase thereafter. But the value of shear stress at all percentages is found to be greater than the shear stress for sand only, i.e. at 0% rubber content. However, the shear strain corresponding to peak shear stress increases with the increasing rubber content. The shear strain at failure was also found to increase, especially at a higher percentage of rubber. Granulated rubber addition to sand increases the initial slope of the stress–strain curve, which indicates that SRM will have more strength at small strain values. Adding 10–30% of rubber to sand particles enhances the shear strength in comparison to clean sand, which may be because of two reasons. First, the sand is capable of accommodating more particles of rubber sizes I and II due to similar grain sizes. The voids created by rubber grains are occupied by the sand for rubber sizes I and II, and for other rubber sizes (III–VII) rubber particles act as reinforcement for the sand. With the increase in the length of rubber the shear strength of SRM increases up to rubber size VI, thereafter it starts decreasing for larger rubber size VII. This decrease in strength might be due to decrease in the density of SRM for rubber size VII than VI. Thus, compared to clean sand, the strength of composite materials is enhanced. Second, the addition of more rubber results in creating more voids in SRM, which starts adversely affecting its strength. The decrease in peak stress observed at higher rubber content is due to increase in the quantity of rubber in failure plane and the rubber–rubber particle friction will have a larger influence (Mavroulidou *et al.* 2009). This behaviour is observed in almost all tyre sizes. Influence of percentage of granulated rubber on the shear strain corresponding to peak shear stress at different normal stresses for rubber size VI is shown in Figure 5. The shear strain corresponding to peak shear stress shows a linear relationship with the normal stress. Also, the slope of the shear strain–normal stress curve increases with increase in the amount of rubber in SRM.

5.1.2. Volumetric strain

Typical plot of the variation of volumetric strain with shear strain for rubber size VI at a normal stress of 80 kPa is shown in Figure 6. It can be observed from Figure 6 that there is an initial compression and then expansion, i.e. dilation with increase in horizontal displacement. The volumetric strain increases with increase in shearing strain for all the rubber contents. The dilation behaviour decreases with the increase in tyre content. Similar behaviour was noted by Lee *et al.* (1999). This reduction in dilation by adding granulated rubber is

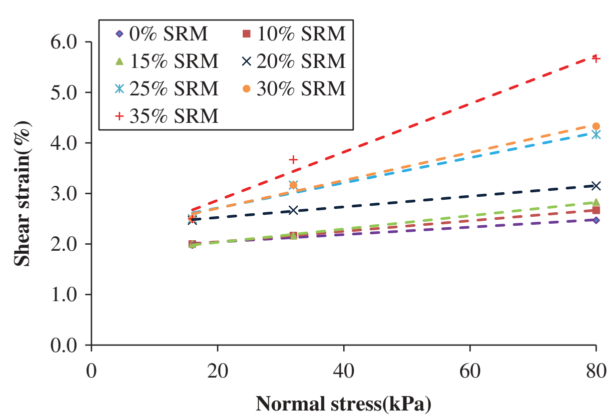

Figure 5. Typical plot of the variation of shear strain corresponding to peak shear stress for rubber size VI, with different percentage of rubber in SRM and normal stress.

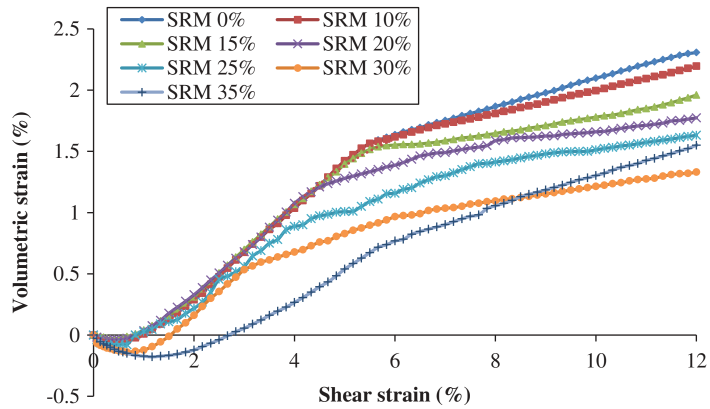

Figure 6. Typical plot for variation of volumetric strain with shear strain for granulated rubber size VI at normal stress 80 kPa for various rubber percentage.

observed for almost all rubber sizes. For the considered rubber sizes, there was no clear relationship between volumetric strains with varying rubber sizes. The decrease in volumetric strain with the increase in rubber content is due to the deformable behaviour of the rubber. When normal stresses are applied, the sand particles penetrate in the rubber particles and provide resistance against shearing results in increasing the shear strength, and with the increase in rubber content the compressibility of SRM particles increases.

Here with the addition of granulated rubber and tyre chips, peak shear stress increases and volumetric strain decreases for all sizes of SRM. In any plane for shearing to takes place, the sand particles must either climb over or shear through the granulated rubber/tyre chips. However, granulated rubber/tyre chips are deformable and thus reduce the possibility of particle movements around rubber during shearing. The path of least resistance will determine the shear strength of the mix. When normal stresses are applied in the shear tests, sand particles penetrate into rubber, resulting in decreased volumetric strain (Foose *et al.* 1996, Lee *et al.* 1999).

5.2. Influence of rubber size

5.2.1. On peak shear strength

Many researchers have reported that the difference in chips/crumb/granulated rubber sizes may result in different stiffness. To study the effect of rubber size on shear properties of SRM, a series of direct shear tests was carried out. Figure 7 represents the variation of peak shear stress with percentage rubber content for different rubber sizes at a normal stress of 80 kPa. In this study, the shear properties of sand were increased with the addition of granulated rubber and tyre chips, which might be due to the combined effect of rubber length, aspect ratio (length/diameter), stiffness of rubber, orientation of rubber, sand friction angle, and normal stress (Gray and Ohashi 1983). For a given size of the granulated rubber, the peak shear strength increases with increase in the percentage of rubber in

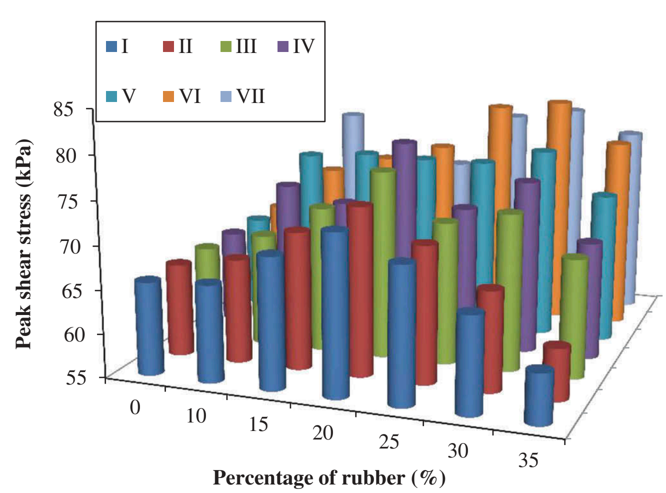

Figure 7. Plot for the variation of peak shear strength with varying rubber sizes and rubber content at normal stress 80 kPa.

the mixture up to a certain value and thereafter decreases. Thus, there is an optimum ratio of rubber to sand that results in the highest peak shear strength. This optimum percentage also generally increases with the increase in size of the granulated rubber, except in case of size VII (tyre chips), where a slight reduction is observed. From Figure 7, it can be seen that with the increase in rubber size up to VI, the peak shear stress increases for a corresponding percentage of rubber content up to 30%. This increase in strength with increase in size for corresponding percentage is due to the reinforcement effect of larger rubber particles, which have a greater interlocking capacity. But the shear strength slightly decreases for rubber size VII. From overall observation, it was noted that for rubber size I, II, III and IV, 20% rubber content was found to be optimum, and for rubber size V, VI and VII, 30% rubber content was determined to be optimum, giving the maximum shear strength (see Figure 7). However, it was found that granulated rubber size VI with 30% rubber content giving the highest increase in the shear strength at all the normal stresses compared to other sizes of granulated rubber and tyre chips.

5.2.2. On friction angle

In order to determine the influence of granulated rubber and tyre chips size on shearing properties, results obtained from direct shear tests were plotted between the angle of internal friction and percentage of rubber. Figure 8 shows a plot for variation of angle of internal friction with a percentage of the rubber for different granulated rubber and tyre chips sizes. From Figure 8, it can be observed that the friction angle increases with increase in rubber content up to some percentage and then decreases. The peak friction angle for rubber size I, II, III and IV is observed at 20% rubber content by volume, whereas for size V, VI and VII it is observed at 30% rubber content. The maximum friction angle among all rubber sizes is obtained for granulated rubber size VI at 30% rubber content, in which friction angle varied from 35° to 41°. Shear strength of SRM is based on pressure imposed from sand grains to the rubber due to application of normal stress and the friction mobilised between sand–rubber, rubber–rubber and sand–sand (Mahmoud 2004). Figure 9 depicts the plot for friction angles for different granulated rubber sizes and tyre chips at their optimum rubber content giving maximum shear strength parameters. In Figure 9, it can be observed from the general trend that the friction angle increases with increase in rubber size up to VI and then decreases. The initial increase in friction angle is due to the inclusion of rubber, which are angular in nature. The angularity of rubber contributes to increasing the friction angle by interlocking with sand particles. The increase in the angle of internal friction is due to failure in the shearing zone. In the shearing zone, the rubber particles are distributed and oriented randomly at the shearing surface. As shearing starts, the rubber particles mixed with sand either slide or resist the shearing against cut off, which results in an increased shearing force (Attom 2006). At higher rubber percentages, the friction angle decreases as the quantity of rubber is more than sand in the shear zone, causing the sand–sand and sand–tyre interface friction to reduce, resulting in the reduction of friction angle and hence reducing shear strength.

5.2.3. On cohesion

Figure 10 shows the plot for variation of cohesion values with different percentage of rubber by volume and rubber sizes. From Figure 10, it can be noted that the cohesion values increase significantly with addition of rubber to sand, the increase in cohesion with further increase in rubber content by volume is

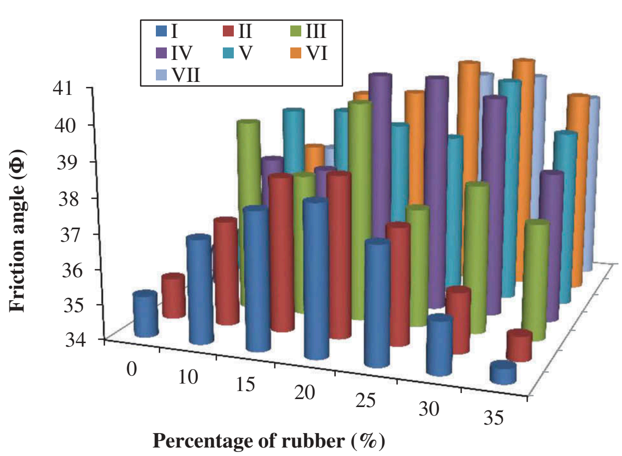

Figure 8. Plot for variation of friction angle with different size and percentage of rubber.

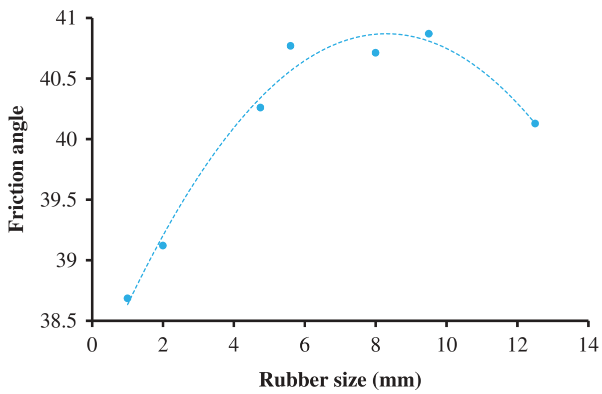

Figure 9. Plot for variation of friction angle at optimum rubber content with different rubber sizes.

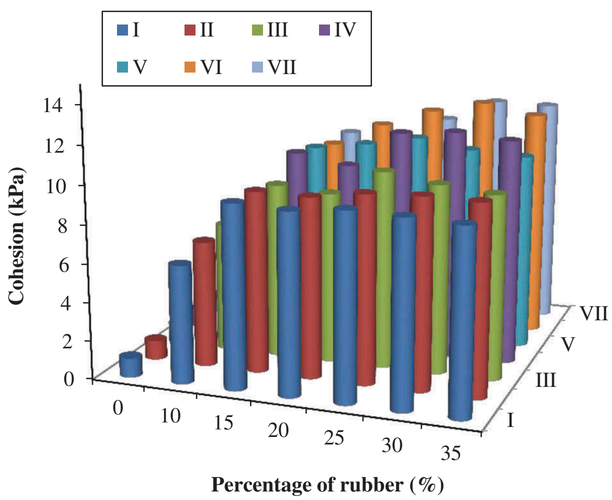

Figure 10. Plot for variation of cohesion for different rubber sizes and content.

not much significant, even though the values of cohesion increase slightly with increase in rubber content in the SRM. The cohesion value varies from 6.16 to 12.45 kPa with the inclusion of rubber to sand. The variation of cohesion for sand is 1.1 kPa. The variation of cohesion for different sizes of rubber in the SRM is not much significant. But the value of cohesion varies slightly with an increase in size of rubber. It can also be observed from previous plots that cohesion does not always give the highest shear strength parameters as in this case friction governs. Here the maximum value of cohesion is obtained for rubber size VI at 30% rubber content by volume. The cohesion values for rubber size VI range from 6.36 to 12.45 kPa. The increase in cohesion value for rubber size VI on the addition of rubber content from 10% to 35% is observed at almost twice the initial value for 10% SRM. As larger size rubber particles have good interlocking capacity, resulting in an increase in the cohesion with an increase in rubber particle size. The findings of the current study predicts well with the reported cohesion by Humphrey *et al.* (1993).

5.3. Influence of normal stress on shear strength

Figure 11 shows the typical plot of peak shear stress vs. Normal stress at different percentage of granulated rubber of size VI at three normal stresses, i.e. at 16, 32 and 80 kPa. For different applied normal stresses, shear resistance of SRM were higher than that of pure sand, but the increasing trend is maintained only up to 30% of rubber, beyond which the shear resistance decreases. The maximum shear strength was obtained at 30% rubber content at all the normal stresses. Increase in shear strength at different normal stresses has been observed at different rates, i.e. 16% for 16 kPa, 24.21% for 32 kPa and 49.12% for 80 kPa. The Mohr–Coulomb envelopes obtained from all samples of different sizes are almost linear. With the increase in normal stress, shear strength increases, as with increase in overburden pressure the voids of the SRM sample reduces, which increases the interlocking capacity of sand granules and rubber. These results are similar to the findings of Marto *et al.* (2013). Also, it can be stated that the addition of granulated rubber/tyre chips in optimum size and ratio improves the shear properties of the sand (Zornberg *et al.* 2004).

5.4. Secant/elastic modulus

The elastic modulus, E, of a substance is a measure of its stiffness. Elastic modulus can be defined as either tangent modulus or secant modulus. In the present study secant modulus is determined from the slope of

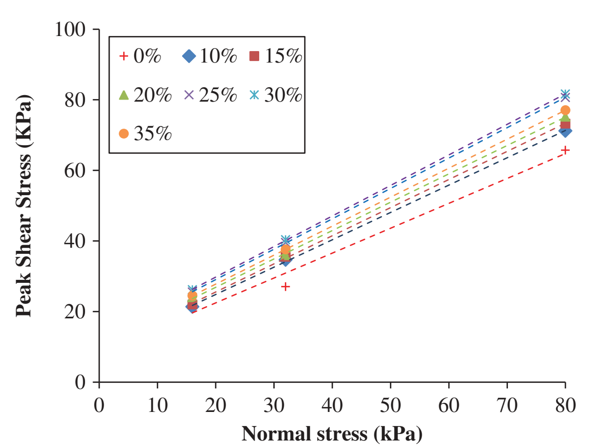

Figure 11. Typical plot for variation of shear stress with normal stress for SRM sample with granulated rubber size of VI, for different percentage rubber content.

the stress–strain curve up to an elastic limit. Figure 12 depicts the plot for variation of elastic modulus with percentage of rubber content, for SRM sample with different rubber sizes at a normal stress of 80 kPa. It can be observed from Figure 12 that on addition of granulated rubber/tyre chips, the secant modulus value increases initially and remains almost constant up to the optimum percentage content for respective sizes and then it starts to decrease. It is also observed that the modulus values are quite high at the optimum rubber content for the respective sizes due to increase in stress–strain characteristics. The values of elastic modulus are quite high for higher rubber sizes (i.e. VI and VII), but the maximum value is obtained at 30% SRM for rubber size VI. The decrease in E value after optimum rubber content is due to the greater influence of rubber–rubber interface, which results in a decrease in the shear strength.

5.5. Influence of change in gradation of sand

The results obtained from the present study are in general agreement with results from other authors (Mahmoud 2004, Ghazavi and Sakhi 2005, Attom 2006, Edincliler *et al.* 2010), but the findings of the current study contradict the finding of Masad *et al.* (1996), Youwai and Bergado. (2003), and Neaz Sheikh *et al.* (2013). This may be attributed to the fact that Masad *et al.* (1996) and Youwai and Bergado. (2003) used tyre chips and higher tyre content (50% and 30%), and Neaz Sheikh *et al.* (2013) and Masad *et al.* (1996) used a similar rubber with poorly graded sand. In order to know the influence of gradation of sand on shear properties of SRM, direct shear tests were carried out for two rubber sizes I and II by considering poorly graded sand. The poorly graded sand (Sand-B) has similar specific gravity, but the gradation were different from those of Sand-A. Here rubber size I and II are selected for testing with poorly graded sand, because the considered rubber sizes are in the same size range as considered by Neaz Sheikh *et al.* (2013) and Masad *et al.* (1996). Table 1 shows the specifications of the poorly graded Sand-B. SRM mix using Sand-B was prepared similarly to Sand-A and densities of SRM Sand-B samples are maintained similar to those of Sand-A.

5.5.1. On shear strength properties

Significant changes in shear strength properties were observed in SRM, with Sand-B for rubber sizes I and II compared to SRM with Sand-A. Figure 13(a,b) shows the comparison of plots of stress–strain diagram for SRM sample reinforced with rubber size I at a normal stress of 80 kPa for different percentages of granulated rubber for sand A and B, respectively. For Sand-A reinforced with rubber size I, increase in shear strength is due to gradation of Sand-A. The shear strength increases with increase in percentage of the rubber up to 20% SRM by volume, thereafter the trend starts reversing (i.e. shear strength values decrease) due to increase in percentage of rubber in SRM. However, for Sand-B, reinforced with rubber size I, shear strength decreases with inclusion of rubber. This might be due to difference in the gradation of Sand-B compared to Sand-A. By addition of rubber particles to Sand-B, the shear strength decreases, but the shear strains at failure increases with the addition of rubber; this is comparable with Masad *et al.* (1996) and Neaz Sheikh *et al.* (2013). Similarly, Figure14(a,b) shows the comparison of plots of stress–strain diagram for SRM sample reinforced with rubber size II at normal stress of 80 kPa, for different percentages of rubber for Sand-A and –B, respectively. Like rubber size I, a similar trend is observed for rubber size II also. For Sand-A, which is reinforced by rubber size II, the shear strength increases with increase in rubber content up to 20%

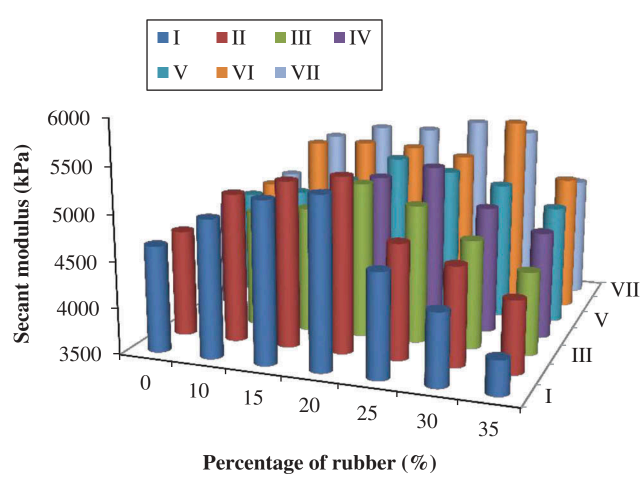

Figure 12. Typical plot for variation of secant/elastic modulus with different sizes and percentage of rubber in SRM.

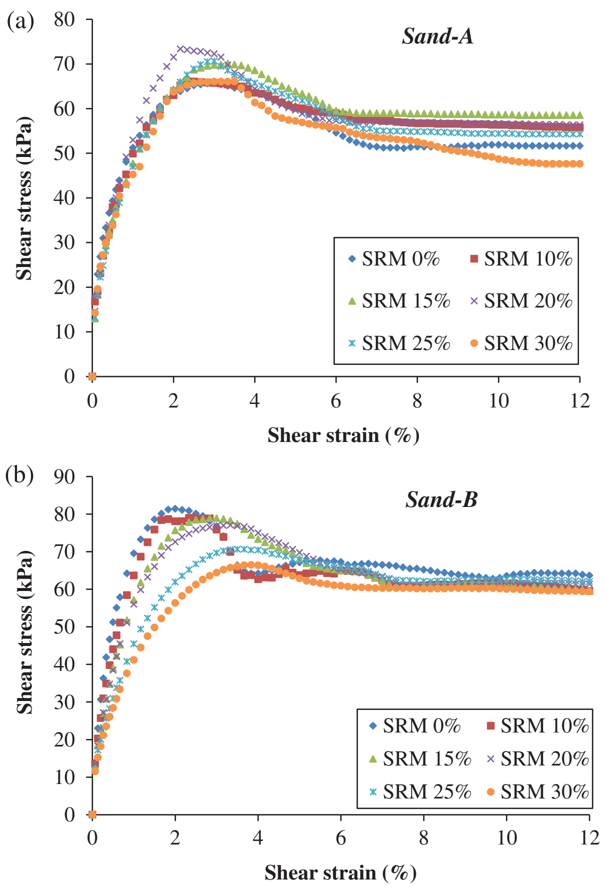

Figure 13. Stress–strain curve for SRM sample reinforced with rubber size I, at different percentage and rubber content at normal stress of 80 kPa (a) for Sand-A and (b) for Sand-B.

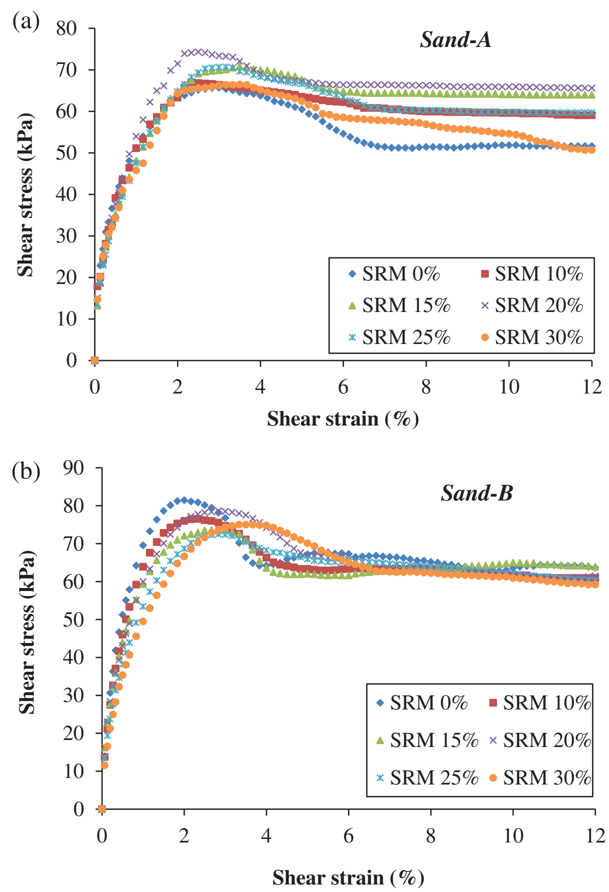

Figure 14. Stress–strain curve for SRM sample reinforced with granulated rubber size II, at different percentage of rubber content at normal stress of 80 kPa (a) for Sand-A and (b) for Sand-B.

SRM by volume, thereafter it starts decreasing with the addition of rubber particles. For Sand-B, with the inclusion of rubber, the shear strength starts decreasing, and it further decreases with increasing in rubber content in the SRM. From the figures it can be observed that with change in sand gradation, the stress–strain curve becomes steeper, and the values of peak stress also change with sand gradation. This behaviour is observed due to changes in the gradation of the sand. With the inclusion of poorly graded sand, the same shear strength trend is observed similar to earlier studies, but the values were slightly higher in this study, which could be due to changes in sand particle size compared to previous studies.

Figure 15 represents the variation of peak shear strength with a percentage of rubber content for rubber sizes I and II for Sand-A and Sand-B at a normal stress of 80 kPa. In Figure 15, dotted lines with hollow symbol indicate the variation of peak shear strength for Sand-B and solid lines with solid symbol indicate peak shear strength for Sand-A. In this study, shear properties of Sand-B alone is greater than Sand-A, which results in higher peak shear strength for Sand-B compared to Sand-A. With the inclusion of rubber to sand, the peak shear strength of SRM increases for Sand-A up to a certain content, then starts decreasing, while with the addition of rubber content to Sand-B the peak shear strength keeps on decreasing. But with the increase in rubber size, the shear strength increases for both the sand types considered in this study. Thus gradation of sand is one of the important parameters in SRM along with rubber size, length and aspect ratio, which control the shear strength of SRM.

Figure 16 shows the plots for the variation of friction angle with different rubber sizes, percentage of mix and sand type (A and B). In Figure 16, dotted lines with hollow symbol indicate the variation of friction angle for Sand-B and solid lines with solid symbol indicates friction angle for Sand-A. For SRM samples with Sand-B, it was observed that for rubber size I and II the overall variation in friction angle showed reducing trend with increase in rubber content. But it can also be observed that the corresponding friction angles for SRM samples with Sand-B is higher than that of older samples for almost all corresponding rubber

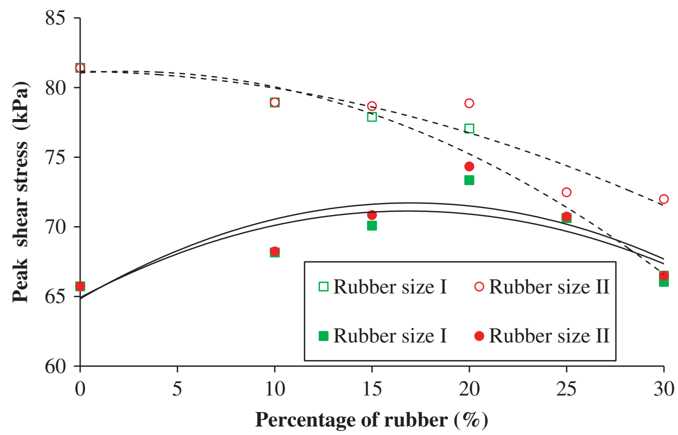

Figure 15. Plots for variation of peak shear stress with rubber content for SRM sample with rubber sizes of I and II for Sand-A and Sand-B.

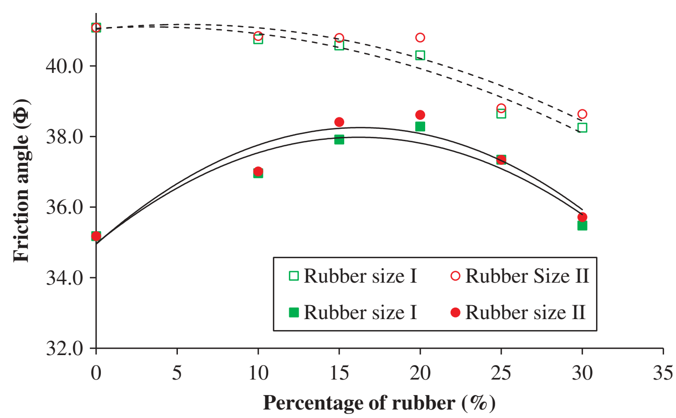

Figure 16. Plots for variation of friction angle with rubber content for SRM sample with rubber sizes of I and II for Sand-A and Sand-B.

percentages. But for the Sand-A, the friction angle increases with increase in rubber content up to 20% SRM, thereafter it starts decreasing for both rubber sizes (I and II) considered herein. The mechanism for increase in friction angle with rubber content is explained in earlier sections.

Even though the specific gravity of both Sand-A and -B are almost similar, however, their strength properties are different. This is due to the change in gradation of sands (refer to Figure 1). Thus, the gradation of sand used is one of the key parameters that control the shear strength of SRM along with the size of granulated rubber, percentage of rubber in SRM and normal stress. From the results of static tests on the shear characteristics of SRM considering different rubber sizes, one can select the optimum rubber size for further studies through which one can select the better composition of SRM for vibration isolation.

6. Conclusion

In this study the influence of granulated rubber sizes and tyre chips on the strength behaviour of SRM was investigated. In the first part, direct shear tests were carried out to know the influence of rubber size (I–VII) on shear properties of SRM considering seven different rubber sizes and composition (10–35% SRM by volume), where information is not readily available in the literature. In the second part of this study, large-scale direct shear tests are performed by considering different gradation of sand on rubber size I (passing 2 mm sieve – and retained on 1 mm sieve) and II (4.75 mm – 2.00 mm) to evaluate the shear strength of SRM. This study shows that inclusion of rubber to the sand can alter the shear strength, cohesion, friction angle and volumetric strain. Three factors were found to be significantly affecting the shear strength of SRM, namely rubber size, rubber content and normal stress. The following conclusions are drawn from this study based on the results obtained on SRM through large-scale direct shear test.

(1) The optimum percentage content of rubber, which gives maximum shear strength in the SRM sample with rubber size I, II, III and IV is 20% by volume. Whereas for other rubber sizes V, VI and VII, the optimum content of rubber is found to be 30% by volume.

(2) Granulated rubber size VI (passing 12.5 mm – retained on 9.5 mm) percentage ratio 30% by volume, is found to be the optimum size and rubber content, which gives maximum shear strength with high cohesion and angle of friction values among all the rubber sizes considered in this study.
(3) Using the granulated rubber with optimal size and content, the values of cohesion increases from 1.1 to 12.45 kPa, and the angle of friction from 35° to 41° for Sand-A.
(4) The normal stress is also an important factor affecting the increase in strength of soil–rubber matrix. The shear strength of SRM increases with increase in normal stress for all particle sizes and percentage content.
(5) The volumetric strain is observed to decrease with increasing rubber content for most of the rubber sizes which is similar to previous studies.
(6) The elastic/secant modulus increases with increase in rubber content up to an optimum percentage and then decreases for all rubber sizes.
(7) Poorly graded sand has a higher shear strength when compared to uniformly graded sand, which critically affects the shear strength of the SRM.
(8) Uniformly graded sand (Sand-A) shows that the addition of rubber to the sand increases the shear strength parameters for the selected two rubber sizes. Whereas poorly graded sand (Sand-B) shows that the addition of rubber to sand decreases the shear strength parameters.

The above results are useful in determining the optimum size and rubber content for suitable applications. Also, it helps in selecting the suitable rubber sizes for dynamic studies through which one can select the suitable SRM sample for vibration isolation in the future.

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Disclosure statement

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