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ORIGINAL PAPER

Direct Shear Tests on Waste Tires–Sand Mixtures

Ali Firat Cabalar

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Abstract Waste tires are used in some engineering applications and thereby reduce the potential impact on the environment, for example, as lightweight materials in geotechnical engineering projects. This paper presents a brief literature review on geotechnical applications of processed waste tires, and a laboratory study on the effect of tire shreds on the physical properties of two different sands (fine angular sand and coarse rotund sand). Each type of sand was mixed four different percentages of rubber particles; 5, 10, 20 and 50% by dry weight. Direct shear tests were employed to investigate the effect of rubber particles on the shear strength of sands and internal friction angle. The addition of shredded waste rubber particles slightly decreased both the internal angle of friction and the shear strengths of the sands within the tested stress and strain levels. Additionally, a prediction model using stepwise regression (SR) method is proposed to calculate the shear strength of sands with the increasing rubber content. The performance of accuracies of proposed SR models are quite satisfactory. The proposed SR models are presented as relatively simple explicit mathematical functions for further use by researchers.

A. F. Cabalar (✉)
Department of Civil Engineering, University of Gaziantep, 27310 Gaziantep, Turkey
e-mail: cabalar@gantep.edu.tr; a_cabalar@yahoo.com

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1 Introduction

Increase in the number of waste tires results in an environmental problem in many regions of the world. For example, Masad et al. (1996) stated that there are 279×10^6 discarded tires and over 2×10^{12} tires in stockpiles every year in the United States alone. There are about 28 million tires stockpiled in Canada (Dickson et al. 2001). Every year about 3 million tons of used tires (part worn + end of life tires) are generated in Europe, of which 2.4 million tons are end-of-life tires for which value recovery has to be maximized. This amounts to approximately 200 million units. Such wastes cannot generally be deposited in landfills since they require large spaces. Large quantities of waste tires discarded each year can be beneficially used in geotechnical and geoenvironmental applications (Edincliler 2008).

As the rubber tires do not easily decompose, engineers studying the physical properties of sand–shredded tire mixes have concluded that this mix can be used in many engineering projects. Civil engineering applications for scrap tires include lightweight fill, conventional fill, insulation layer, retaining wall and bridge abutment, and drainage applications (Young et al. 2003). Ahmed (1993), Masad et al. (1996) used triaxial testing apparatus to study the shear strength properties of waste tire particles in various size and shapes. Ahmed (1993) said that a sand can be strengthened by tire chips. He reported that adding tire chips increases the shear strength of sand, with angle of friction up to 65° obtained for dense sand with 30% tire chips. Masad et al. (1996) concluded that the shreded tires and Ottowa sand mixtures have a potential to be used as a lightweight fill material in highway embankments over compressible soils.

Tire shreds have been used as lightweight fill material in many embankments and retaining structures (Bosscher et al. 1997; Tweedie et al. 1998; Humphrey et al. 1998; Lee et al. 1999; Dickson et al. 2001; Zornberg et al. 2004). These studies show that the use of tire shred–soil mixtures have lower compressibility and higher shear strength and thus perform better than only tire shreds. Embankments constructed with soil–tire chip mixtures can potentially have steeper slopes because the backfill has higher shear strength and lower unit weight. Steeper side slopes decrease the volume of material needed. Also, because of using lightweight material, settlement of underlying soil is reduced (Tatlisoz et al. 1998). Edil and Bosscher (1994) reported that placing tire shreds in sand vertically led to a higher shear strength on the plane perpendicular to the shred.

Objective of the present study is to investigate the shear strength behavior of sand–rubber mixes under specific loading and strain conditions (up to around 17%). Direct shear tests were conducted. Two different types of sand were selected based on their size and shape. The two sands were mixed with four different percentages of shredded tires: 5, 10, 20 and 50% by dry weight. The shear strength of the sand was calculated before and after addition of the rubber particles.

2 Experimental Study

2.1 Materials and Methods

Two different gradations and shapes of sand were used during the experimental study, Leighton Buzzard Sand fraction B and local sand from Ceyhan Region. The Leighton Buzzard Sand fraction B used in the experiments was supplied by the David Ball Group, Cambridge, UK, confirming to BS 1881-131:1998. Their specific gravities were found to be 2.65 and 2.60. The specific gravity of rubber ranges from 1.02 to 1.36, depending on the amount of glass belting or steel wire in the tire (Edil and Bosscher 1994; ASTM 1998). Figure 1 shows the sieve analysis of the sand particles. From the Fig. 1, it is seen that the Ceyhan Sand is finer than Leighton Buzzard Sand. Figures 2, 3 and 4 show the SEM pictures of the geomaterials as well as the rubber particles used in the experimental study. As can be seen, Ceyhan Sand has an angular shape, Leighton Buzzard Sand has an rounded shape, and rubber particles are flaky.

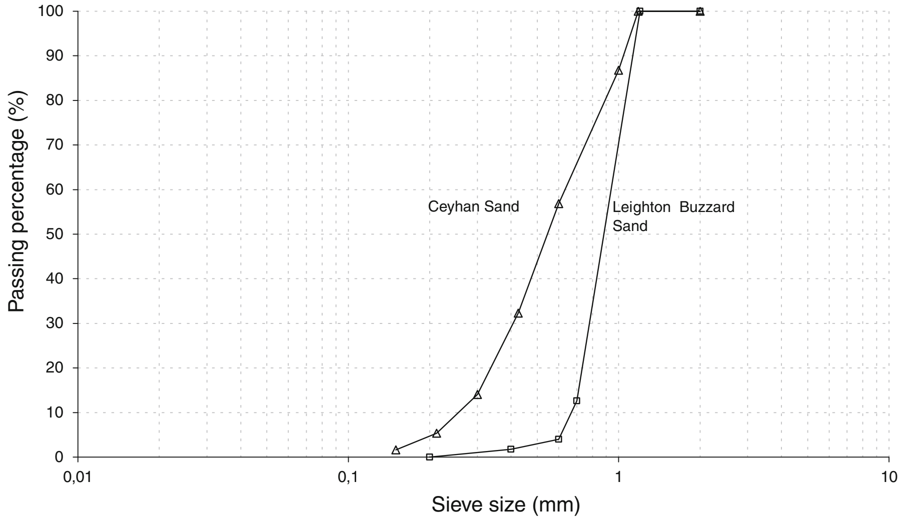
Leighton Buzzard Sand fraction B (coarse) and Ceyhan Sand (fine) were mixed with rubber particles at various percentages. The percentage of rubber particles meant in this study refers to the dry weight of rubber relative to the total dry weight of the mixture. Four fines percentages for each sand were considered without any compaction; namely 5, 10, 20, 50% and then compared with the clean sands.

The direct shear test was conducted in accordance with American Standrads for Testing and Materials D-3080 (ASTM 1985).

3 Analysis and Discussion of the Results

The shear strength of the sands with rubber particles was measured by conducting direct shear test at 28, 42 and 68 kPa normal stresses. As two examples, Figs. 5 and 6 present the shear stress–strain curves for clean sand and sand with various rubber particles (5, 10, 20 and 50%) at 68 and 28 kPa vertical stresses for Ceyhan Sand and Leighton Buzzard Sand, respectively. Increasing the percentage of the rubber particles content decreased the shear stress of both sands within the measured strain level (up to 18%). The same test was conducted on two type of sand adding the same amount of rubber particles at three vertical stresses. As an overall view, Fig. 7 shows the variation of maximum shear stress (τ_{max}) with rubber content. It is observed in the figure that the shear strength of mixtures does not change significantly for the Leighton Buzzard Sand, but for the Ceyhan Sand up to a particular rubber content (around 10%), then stay relatively constant. The rubber particle addition to sand slightly decreased the internal friction angle.

Fig. 1 Grain size distribution of two types of sand



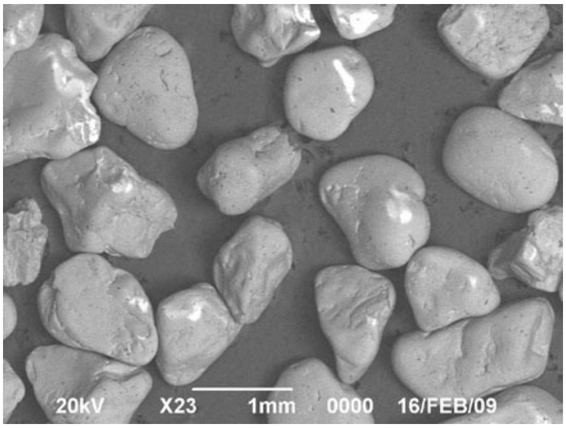


Fig. 2 Scanning electron micrograph of the Leighton Buzzard Sand

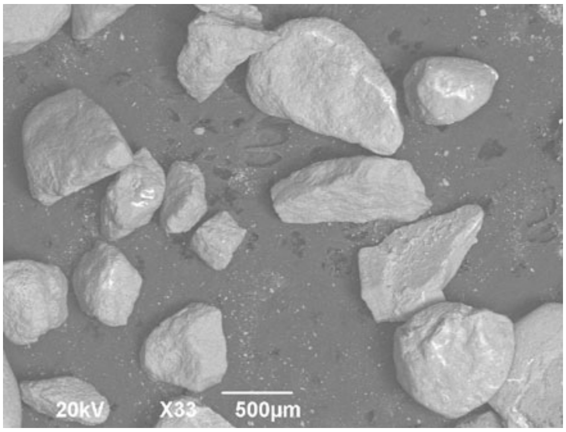


Fig. 3 Scanning electron micrograph of the Ceyhan Sand

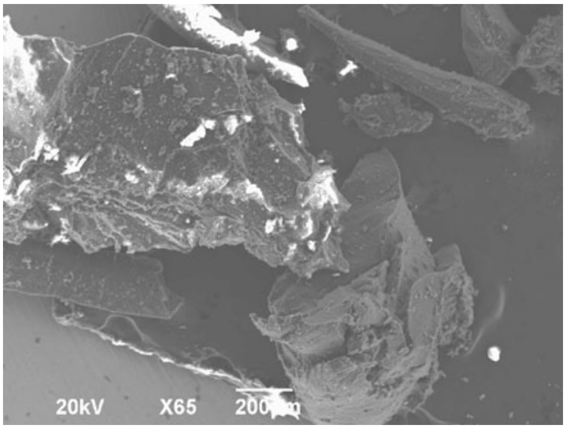


Fig. 4 Scanning electron micrograph of the Rubber Particles

As can be seen from the Fig. 8, amount of decrease in internal friction angle for Ceyhan Sand is higher than that of the Leighton Buzzard Sand, which could be because of the particle shape and size properties of both sands. Unit weights of the samples are presented in Table 1.

4 Development of Prediction Model

As dealing with large number of independent variables, it is necessary to determine the best combination of these variables to estimate the dependent variable. Modeling by Stepwise Regression (SR) is a robust tool for selection of the best subset models

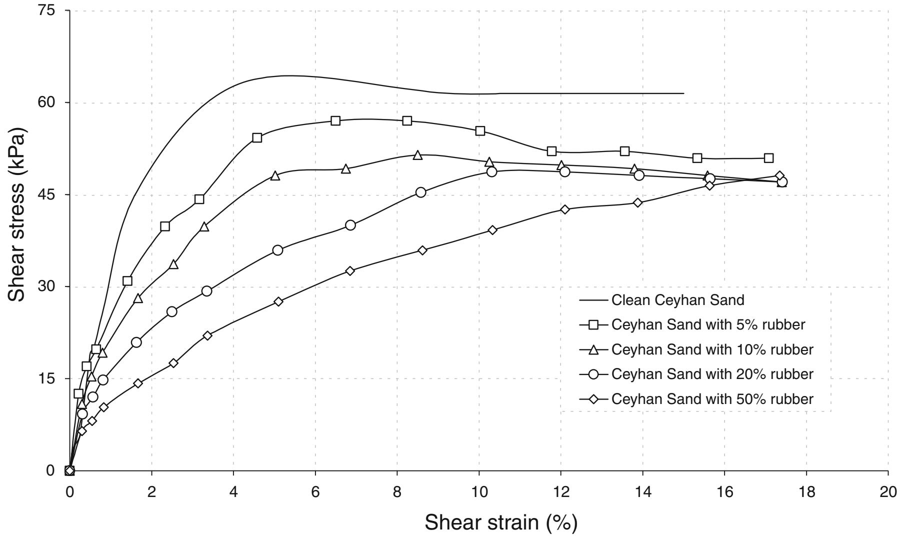


Fig. 5 Shear stress–shear strain curves for Ceyhan Sands with various mix ratios at vertical stress of 68 kPa

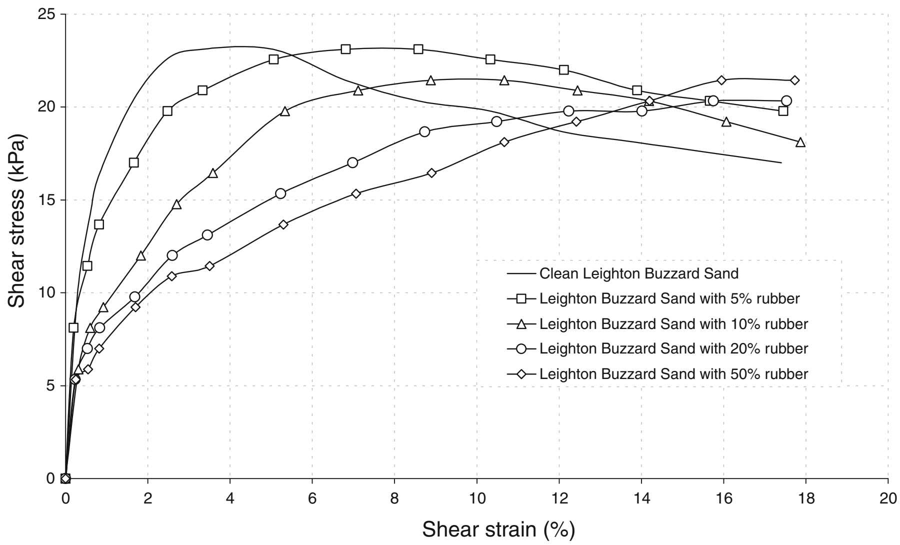


Fig. 6 Shear stress–shear strain curves for Leighton Buzzard Sands with various mix ratios at vertical stress of 28 kPa

(Campbell 2001). Subset models' determination is based on deleting or adding the variable(s) with the greatest impact on the residual sum of squares. The selection of variables may be using three ways; forward, backward or a combination of them. In the first one, the subset models are selected by adding one variable at a time to the previously selected subset. In each successive step, the variable in the subset of variables is added to the subset. Without an ending rule, forward selection longs until all variables are included to the model. However, backward stepwise method chooses the subset models by commencing with the full model and then eliminating at each step the one variable whose deletion will cause the residual sum of squares to increase the least and continues until the subset model contains only one variable (Rawlings 1998).

In both forward and backward methods, it should be noted that the influence of deleting or adding a variable on the contributions of other variables into the model is not being taken into account. Hence stepwise regression is a forward selection process that re-evaluates in each step the significance of all previously included variables. If the partial sums of squares for a previously considered variables do not have a minimum requirement to stay in the model,

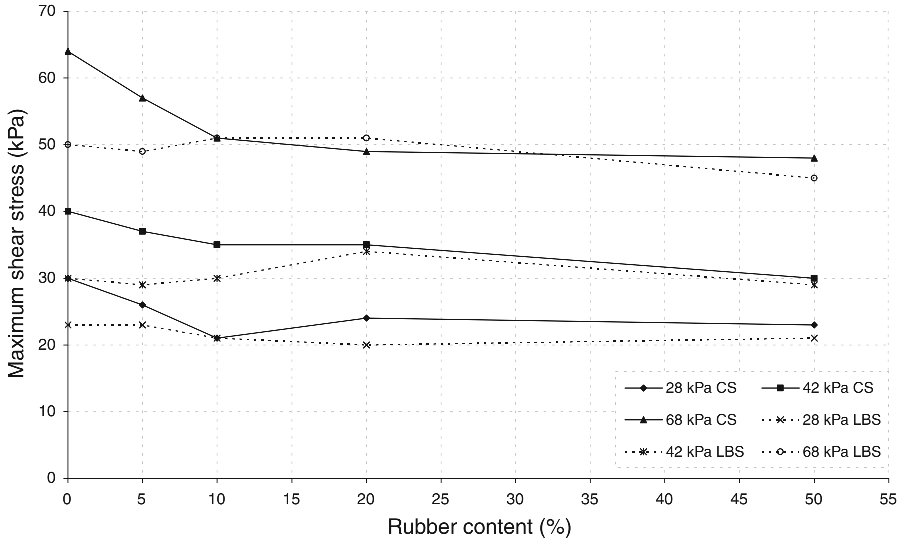


Fig. 7 Effect of rubber particles on the maximum shear stress for both sands (*CS* Ceyhan Sand, *LBS* Leighton Buzzard Sand)

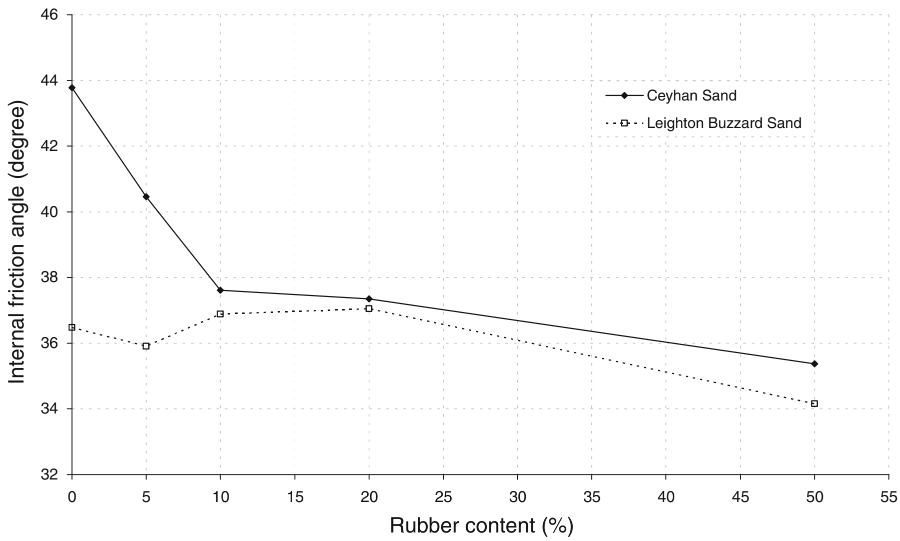


Fig. 8 Effect of rubber particles on the internal angle of friction for both sands

Table 1 Unit weights of the samples with various mix ratios

Type of sand	Waste tires content (%)				
	0 (kN/m^3)	5 (kN/m^3)	10 (kN/m^3)	20 (kN/m^3)	50 (kN/m^3)
Leighton Buzzard	17.05	16.58	16.27	15.51	15.10
Ceyhan	17.17	16.99	16.52	15.95	14.96

the selection way changes to backward one and variables are dropped one at a time by all remaining variables have the minimum requirement. Stepwise selection of variables needs more computing than forward or backward way but, it has an advantage in potential subset models evaluated before the model for each subset size is fixed. It seems to be reasonable that the stepwise selection have a significant chance of choosing the best subsets in the sample data, however selection of the best subset for each subset size is not under guarantee. Stepwise selection of variables uses both the forward and backward elimination criteria to stop the rule. The variable selection process ends when all variables in the model have the requirements to stay and no variables outside the model have the requirement to enter (Rawlings 1998).

This paper also aims to propose a single empirical formulation of shear stress (τ) of sand–rubber mixtures using SR. Therefore an extensive experimental program has been performed on various sand–rubber mixtures. The details of the experimental study including the ranges of parameters have been already given previous sections. Shear stress values have been modeled as a function of rubber content in percentage, normal stress, and horizontal strain, and then the following equations have been obtained for Ceyhan Sand and Leighton Buzzard Sand, respectively.

$$\tau_{CS} = 11 + 0.404 * \sigma * \varepsilon^{1/2} - 0.357 * (RC)^{1/2} * \sigma^{1/2} - 0.0067 * \varepsilon * \sigma^{1/2}$$

$$\tau_{LBS} = 16 + 0.14 * \sigma * \varepsilon^{1/2} - 1.45 * (RC)^{1/2} * (1/\varepsilon^{1/2})$$

where τ_{CS}, shear stress for Ceyhan Sand (kPa); τ_{LBS}, shear stress for Leighton Buzzard Sand (kPa); σ, normal stress (kPa); ε, horizontal strain (%); RC rubber content (%).

The SR results versus actual test results for all the models are presented in Figs. 9 and 10 for Ceyhan Sand and Leighton Buzzard Sand, respectively. Typical results for comparison between SR and test results are observed to very close as presented in Figs. 11 and 12 for shear stress. The formulas are developed using the horizontal strain measurements in direct shear testing.

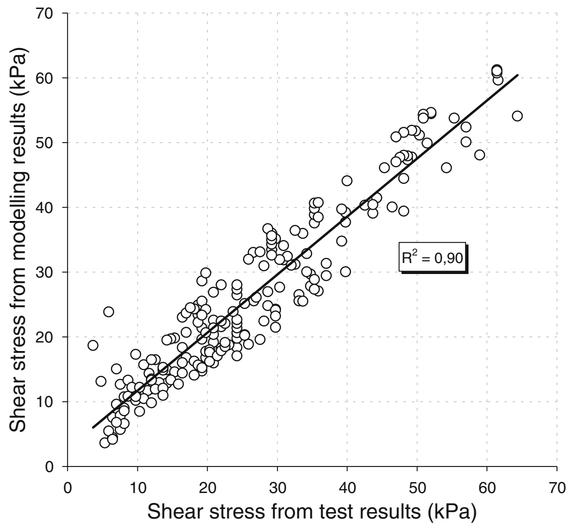


Fig. 9 Modelling versus test results for the Ceyhan Sand

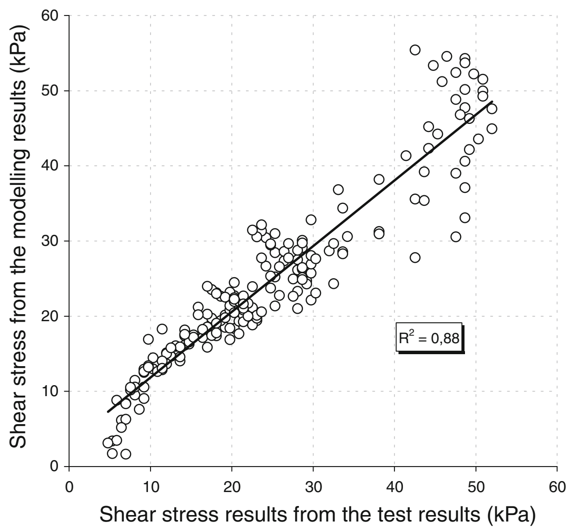


Fig. 10 Modelling versus test results for the Leighton Buzzard Sand

5 Conclusions

This paper investigates the potential use of waste tires for geotechnical applications. The processed waste tires (rubber particles) with low unit weight, widespread availability and low cost can be used as lightweight fill for embankment constructed on weak foundation soils and retaining wall backfill. From the tests conducted on two different gradations of sand mixed with four different percentages of rubber contents, the increase in the percent of rubber content slightly decreased both the angle of internal friction and the shear strength of the sand.

Ten percent rubber content seems to be the one where the behaviour of both sand starts to change. Maximum shear stress values for the rubber contents less than 10% reduces, those more than 10% relatively stays constant by adding rubber. Internal friction angle for the Ceyhan Sand decreases until 10% rubber content, and then stays relatively constant. However, internal friction angle for the Ceyhan Sand does not change significantly. A prediction

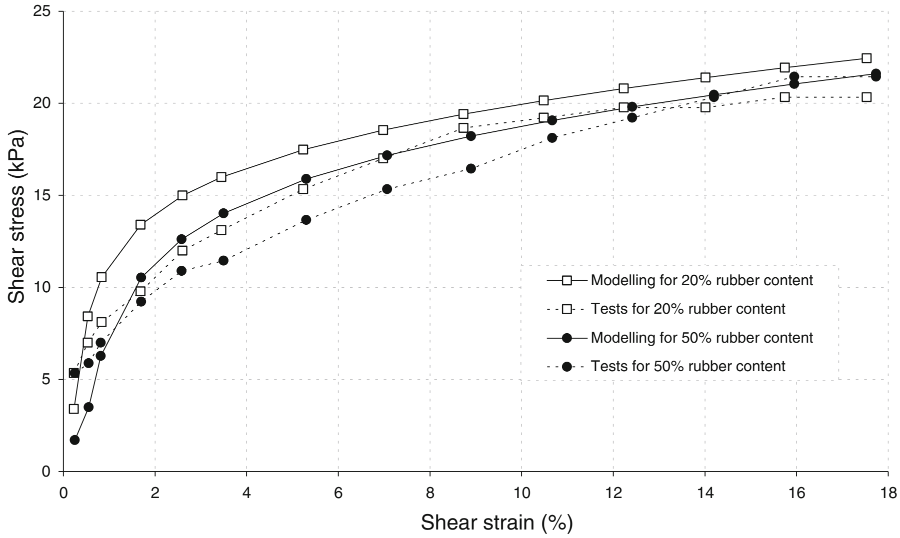


Fig. 11 Comparison for the Leighton Buzzard Sand under 28 kPa vertical stress

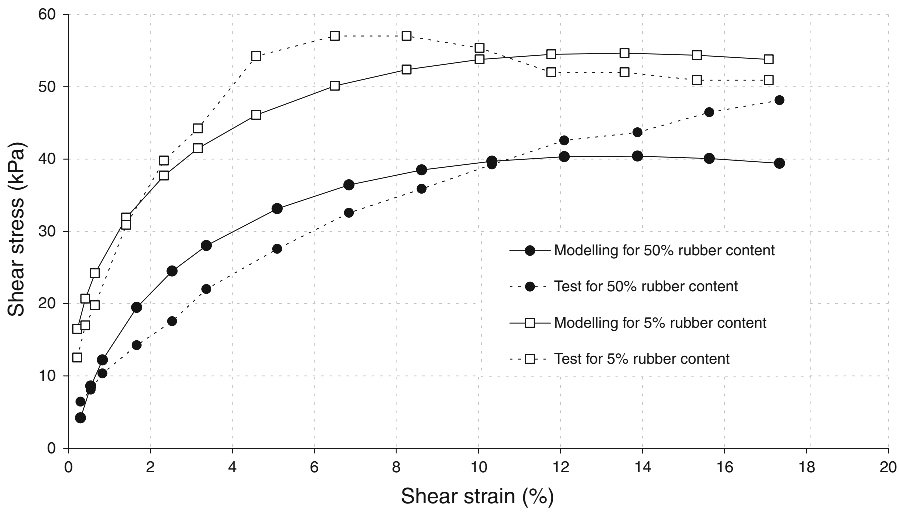


Fig. 12 Comparison for the Ceyhan Sand under 68 kPa vertical stress

model was developed to calculate the value of shear strength of sand–rubber mix. The accuracy of the prediction model is reasonable and calculate the shear strength with a correlation value of $R^2 = 0.90$ and $R^2 = 0.88$ for Ceyhan Sand and Leighton Buzzard Sand–rubber mixtures. The outcomes of this study are quite satisfactory which may serve SR approach to be widely used in geotechnical engineering applications.

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