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Experimental study on behavior of soil-waste tire mixtures

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Abstract. Waste tires are extensively being used in civil engineering applications to improve flexibility and elastic properties of the base foundation material. Moreover, by using pure tires or soil-tire mixtures, rubber stockpiles, which cause lots of environmental contaminations, are being consumed. The objective of this research is to study the strength and elastic modulus variations of sands when combined with rubber materials in different sizes and percentages. Triaxial experiments were performed on various sand-rubber mixtures using static triaxial apparatus. Samples were constructed at the maximum dry density and optimum moisture content to consider engineering applications in dry regions. The results show that rubber content and rubber-sand particle size ratio, $D_{50,r}/D_{50,s}$, significantly affect the mixture behavior in the manner which increase in the former and decrease in the latter, leading to a more softening behavior. Furthermore, specific combination of sand and rubber, which may improve the elastic properties of the mixture, is proposed as a flexible base layer.

1. Introduction

Large amounts of waste tires are produced annually which are either stockpiled in empty lots or dumped in landfills. Severe geo-environmental problems may occur in tire stockpiles, such as collection of rainwater, providing breeding ground for mosquitoes. On the other hand, stockpiled tires can be utilized in many civil engineering projects to improve mechanical properties of problematic soils.

Based on tire properties (e.g., unit weight, high hydraulic conductibility, and high elastic deformability), soil-tire mixtures have been used in civil engineering applications such as lightweight material in retaining wall backfills [1-11], slope stabilizer, drainage system, landfill leachate collection material, highway crash barrier, sound barrier fill, pavement frost barrier, rubber asphalt pavement [8,12], fuel-supplement [10], reinforcement layer [8], and soil improvement material [13].

According to studies performed by various researchers, major parameters affecting soil-rubber mixtures are tire content and rubber-sand particle size ratio, $D_{50,r}/D_{50,s}$. Some ranges of D_r/D_s have been reported in previous pieces of research such as $D_r/D_s \approx 0.25$ [14], $D_r/D_s \approx 0.8 - 1.1$ [15,16], $D_r/D_s \approx 4$ [17], $D_r/D_s \approx 5$ [18], $D_r/D_s \approx 10$ [19,20], $D_r/D_s \approx 20$ [7,10,21], $D_r/D_s \approx 100$ [6], $D_r/D_s >> 100$ [4,8,9].

Lee et al. [6] and Masad et al. [7] carried out triaxial tests on tire chips having particle sizes from 2 to 51 mm. Yang et al. [21] investigated the shear strength of soil-rubber mixtures using direct shear and triaxial apparatus. Bergado et al. [22], Zornberg et al. [4], and Youwai and Bergado [20] also examined strength

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characteristics of mixtures of different shape and size and different tire contents by triaxial apparatus and concluded that maximum shear strength is obtained in the mixture having about 35% rubber by weight. Gotteland et al. [23] also reported 34% rubber as the optimum value at the confining pressures under 100 kPa. Mixtures containing soil and rubber of 10 to 20 mm were experimented by triaxial tests by Rao and Dutta [24], and it was concluded that up to 20% of tire could be useful in highway construction. Rahman and Erlingsson [25], Pasten et al. [26], Perez et al. [27], and Wichtmann et al. [28] carried out various numerical analyses to evaluate stress-strain relationship of pure soils using finite element method and mathematical models.

In this research, authors tried to investigate static stress-strain behavior of soil-granular tire mixtures having various rubber contents and rubber-soil particle size ratios. The experimental program involves static triaxial tests on mixtures with tire content ranging from 0% (pure sand) to 25% by sand volume. In addition to general behavior evaluation, the specific contribution of this research to the field of composite materials is introducing mixture which improves the flexibility of pavements and machine foundations. In other words, granular rubber amount and rubber-soil particle size ratio, which can change the mixture behavior from sand-like to rubber-like behavior and may cause the mixture to behave as almost linear elastic material, are identified.

2. Materials and methods

Two types of sandy soil, S161 and S131, with different grain size distributions with mean grain sizes of 0.26 and 0.79 mm, were used in the laboratory experiments. Moreover, two different sizes of granular rubber having $G_s = 1.1$ were used, R1 and R2, with the maximum grain size of 5 mm and 1 mm, respectively. Particle size distribution diagrams of sands S161 and S131 and granular rubbers are shown in Figure 1.

2.1. Soil-rubber mixture

Mixture groups S161/R1, S131/R1, and S131/R2 were constructed using sand with 0%, 10%, and 15% of granular rubber by sand volume. Special focus was directed on the mixture group S131/R2 by preparing a mixture having 25% rubber content by sand volume.

2.2. Testing equipment

Triaxial Digital Tritest machine manufactured by Engineering Laboratory Equipment (ELE) was employed for all triaxial experiments on samples with 70 mm diameter and 140 mm high. To record the load, deformation, and inner and outer specimen pressures, an automatic data logger system was used. Using Linear Variable Differential Transformers (LVDTs) with a displacement range of about 40 mm and load cell with a capacity of 20 KN, axial strains and axial load were measured, respectively. Cell pressure and pore pressure were also recorded by using two pressure transducers connected to data logger system.

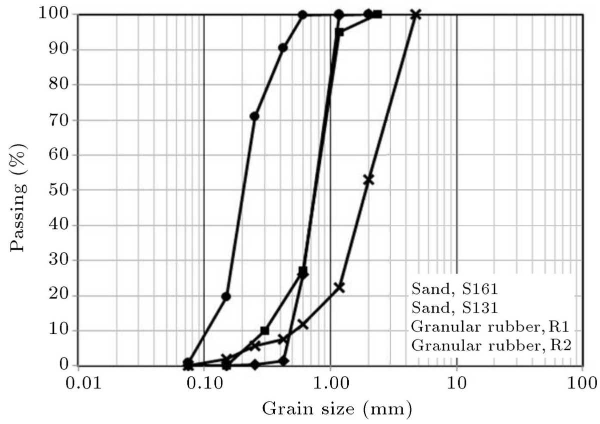

Figure 1. Particle-size distribution curves of sand and rubber.

2.3. Specimen preparation

After mixing the appropriate amount of dry sand and rubber ranging from 0% (pure sand) to 25% by sand volume, water was added to the mixture and the mixed materials were then compacted in five layers providing almost maximum dry density at optimum water content. Table 1 shows compaction characteristics of mixtures derived from compaction experiments. Compaction was performed using a metal rod tamper and wet tamping procedure following the under-compaction method [17]. All specimens were prepared in the same manner and at about the same compaction energy.

2.4. Testing program

Nine wet specimens of two pure sands and seven sand-rubber mixtures (rubber content in a range of 10-25% by sand volume) were investigated in static triaxial apparatus. After sample preparation, the triaxial cell was filled with water, and water pressure was then raised to about 30 kPa. Without conducting the saturation process, the cell water was pressurized to designated confining pressure. In the next step, consolidation was performed by applying the confining pressure to the sample and waiting for about 15 minutes while drainage valve was open. Finally, axial load was applied by the rate of approximately 0.5 mm/min with closed drainage valve. The final stage was continued until the axial strain reached 20% or failure occurred. Table 2 demonstrates all designated experiments in three groups of different sand type and rubber material. Rubber percentage and ratio of mean grain size of sand versus rubber, $D_{50,r}/D_{50,s}$, are also illustrated as changing parameters of static tests.

Table 1. Results of compaction tests.

No.	Mixture group	Compaction values	Rubber content by sand volume (%)			
			0	10	15	25
1	S161/R1	ω_{opt} (%)	14	17.5	18	
		$\gamma_{\max}$ (kN/m^3)	16.5	16.1	15.9	
2	S131/R1	ω_{opt} (%)	15.5	19	19.5	
		$\gamma_{\max}$ (kN/m^3)	15.6	15	14.8	
3	S131/R2	ω_{opt} (%)	15.5	19	19.5	20.5
		$\gamma_{\max}$ (kN/m^3)	15.6	14	13.8	13

Table 2. Scope of triaxial testing program.

No.	Mixture group	$D_{50,r}/D_{50,s}$	Rubber percentage
1	S161/R1	12:1	0%, 10%, 15%
2	S131/R1	3:1	0%, 10%, 15%
3	S131/R2	1:1.5	0%, 10%, 15%, 25%

3. Results and discussions

3.1. Effect of rubber inclusion on strength behavior of mixtures

Figure 2(a), (b), and (c) show the influence of rubber percentage on strength properties of mixtures. Pure sand specimens exhibit well-defined peak shear strength as they are dense samples. According to diagrams, adding tire results in softer behavior and less peak deviatoric stress specifically as $D_{50,r}/D_{50,s}$ decreases (Figure 3). This trend was observed in all mixtures except for one mixture, S131/R2-85/15 in which peak deviatoric strength depends on strain level (Figures 2(c) and 3). Generally, contribution of granular rubber can significantly change the mixture behavior which is more severe as $D_{50,r}/D_{50,s}$ reaches unity. Based on stress-strain curves, all samples exhibit elastoplastic behavior except for mixture S131/R2-85/15 which behaves approximately bilinear elastic. In other words, mixture behavior can be represented by almost two lines with different slopes indicating two distinct values of mixture modulus in which the secondary modulus is dominant in all axial strains except for those less than about 1%. Special considerations, including unloading the sample, are needed to investigate the elastic behavior of the mentioned mixture more precisely.

Another effect of increasing tire content on mixture behavior is initial modulus reduction. In other words, in the area of low strains, up to 5%, mixtures of each group behave almost linearly, and increase in tire content results in less initial tangent modulus, as shown in Figure 4. This trend was observed in all samples.

3.2. Effect of rubber-sand particle size ratio on strength behavior of mixtures

Figure 5(a) and (b) demonstrate the effect of $D_{50,r}/D_{50,s}$ on stress-strain behavior of mixtures. As previously stated, strength of the mixtures decreases by reduction of $D_{50,r}/D_{50,s}$, when rubber content is constant. In other words, lower value of $D_{50,r}/D_{50,s}$ means more rubber to rubber interfaces, and mixture behavior is then controlled by rubber part of the mixture. All specimens experience the same trend except for S131/R2-85/15, as previously mentioned.

3.3. Effect of rubber content on strength behavior of mixture S131/R2-85/15

Analysis of the presented results of nine static triaxial tests leads to some reasonable trends and one different result obtained for mixture S131/R2-85/15. Therefore, special focus was considered to investigate the effect of both $D_{50,r}/D_{50,s}$ and rubber content on stress-strain behavior of this mixture. It seems the parameter which plays a key role in the mentioned mixture behavior is $D_{50,r}/D_{50,s}$ which is less than unity. Moreover, 15% of rubber content is also required for the mixture to exhibit different strength characteristics, since mixture S131/R2-90/10 with $D_{50,r}/D_{50,s} < 1$ and 10% of rubber content follows the general strength trend. Therefore, it can be concluded that in the mixtures having $D_{50,r}/D_{50,s} = 1 : 1.5$ or 0.67, 15% of rubber content by sand volume is a threshold value beyond which sand-rubber mixture behavior transforms from elastoplastic behavior to approximately linear elastic behavior.

To better explore the minimum rubber con-

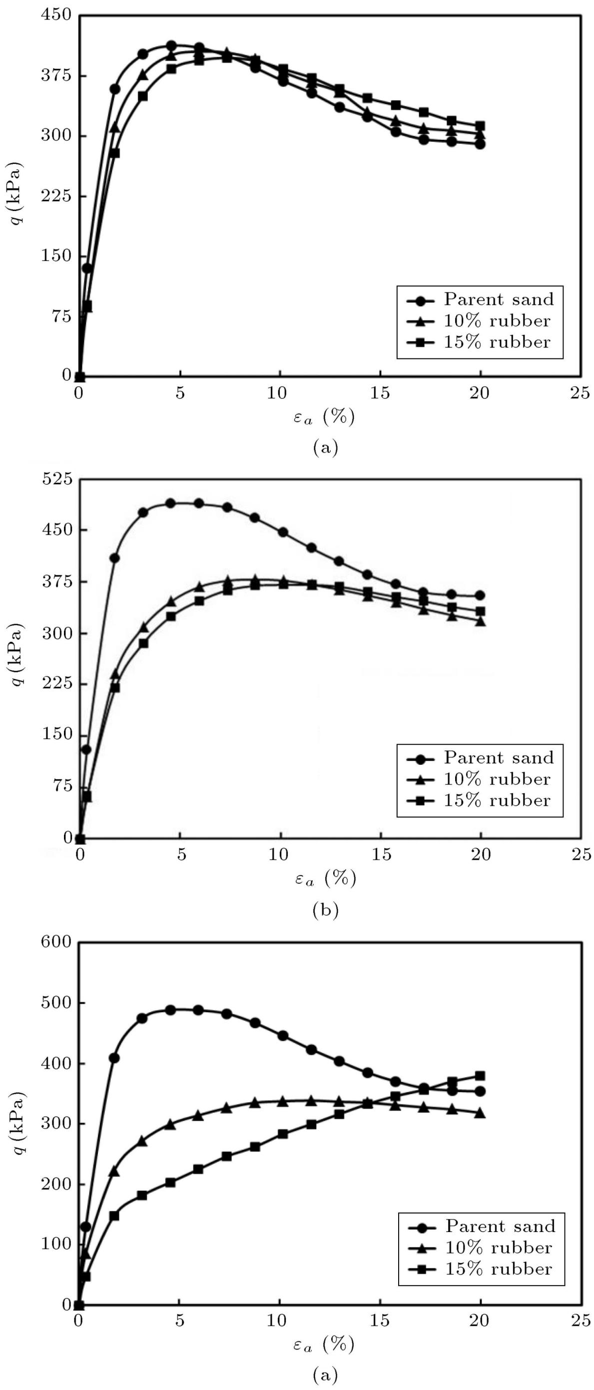

Figure 2. Rubber content influence on strength behavior of mixtures with $D_{50,r}/D_{50,s}$: (a) 12:1, (b) 3:1, and (c) 1:1.5.

tent of mixture which results in approximately linear elastic behavior, another triaxial experiment with $D_{50,r}/D_{50,s} = 0.67$ and 25% of rubber content by sand volume was considered to investigate the behavior of sand-rubber mixtures when rubber content exceeds 15%, namely S131/R2-75/25. Figure 6 presents all stress-strain diagrams of the mixture group S131/R2. Based on Figure 6, it can be concluded that in mixtures having $D_{50,r}/D_{50,s} = 0.67$ and rubber content less

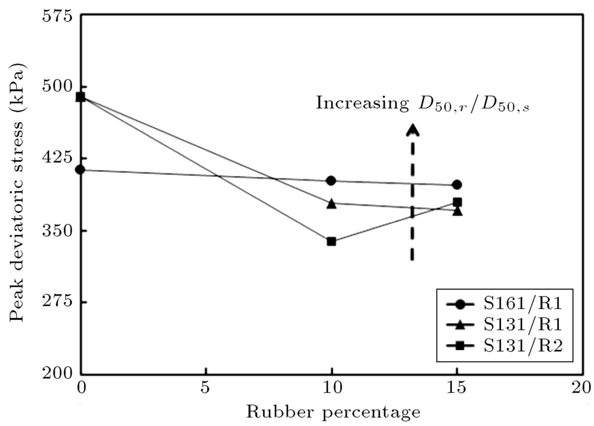

Figure 3. Effect of rubber content and $D_{50,r}/D_{50,s}$ on peak deviatoric stress of mixtures.

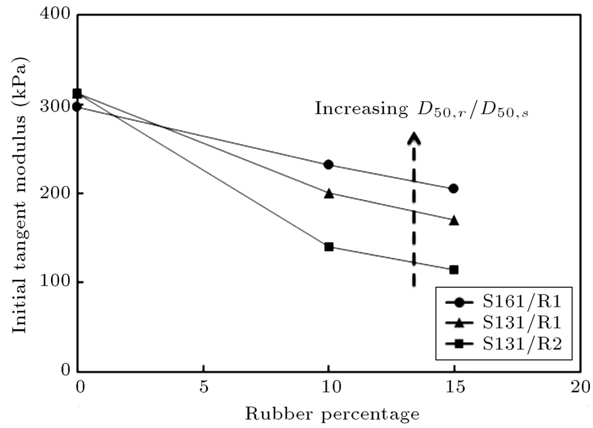

Figure 4. Effect of rubber content and $D_{50,r}/D_{50,s}$ on initial tangent modulus of mixtures.

than 15% by sand volume, strength behavior follows elastoplastic trend as expected; however, as rubber percentage exceeds 15% by sand volume, mixture behavior gradually transforms to almost linear elastic. As depicted, S131/R2-85/15 and S131/R2-75/25 diagrams can be represented by linear diagram beyond the axial strain of about 1% and 5%, respectively. This trend was observed up to about 30% of axial strain.

4. Conclusions

In this study, static triaxial experiments were performed to explore the strength behavior of mixtures having different percentages of rubber and various rubber-sand particle size ratios. The main conclusions of this research are the following:

1. Increase in tire content leads to more softening behavior and strength reduction in mixture. As $D_{50,r}/D_{50,s}$ decreases, strength reduction occurs more severely;
2. Peak deviatoric stress and initial modulus of sand-tire mixtures decrease as rubber content increases,

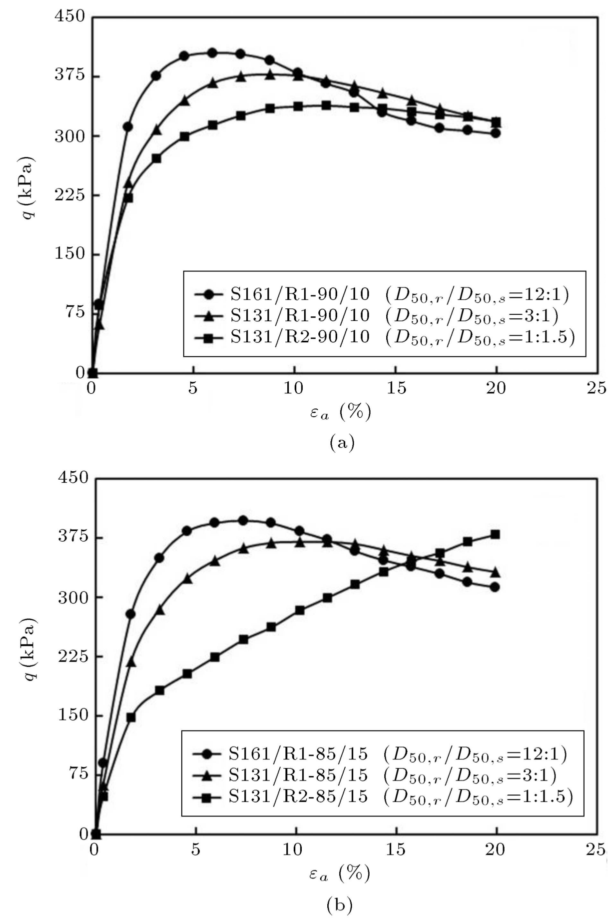

Figure 5. Effect of $D_{50,r}/D_50,s$ on strength behavior of mixtures having rubber content of (a) 10% and (b) 15% by sand volume.

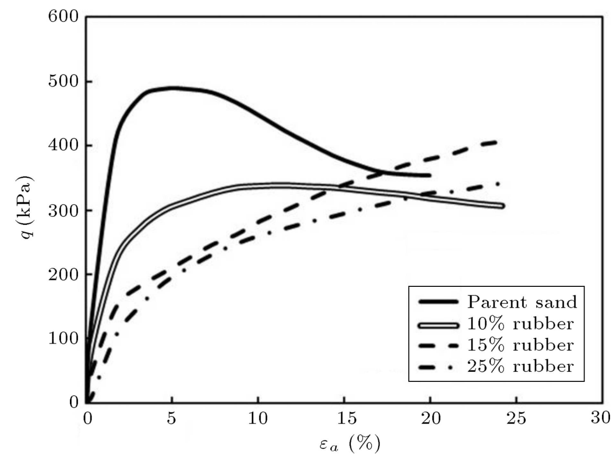

Figure 6. Rubber content influence on stress-strain behavior of mixture group S131/R2.

since rubber particles do not contribute significantly to the shear stiffness of the mixture;

3. Decrease in $D_{50,r}/D_{50,s}$ results in softer behavior and lower stiffness. As rubber-sand particle size ratio reduces, more rubber to rubber interactions occur, and rubber-like behavior then becomes more dominant;
4. All mixture groups exhibited approximately the same stress-strain trend except for mixtures of group S131/R2 containing rubber content of at least 15% by sand volume, S131/R2-85/15 and S131/R2-75/25. The two mentioned mixtures having $D_{50,r}/D_{50,s} = 0.67$ and rubber percentage of 15% and 25% by sand volume, behave differently, almost elastically, as results indicate. Mixtures of this group containing rubber content less than 15% demonstrate the general elastoplastic trend of other mixture groups; therefore, it can be inferred that at least 15% of rubber content by sand volume is needed to transform the behavior of mixture group S131/R2 from elastoplastic to approximately linear elastic;
5. Based on static test results, when rubber percentage of mixture group S131/R2 having $D_{50,r}/D_{50,s} = 0.67$ exceeds 15% by sand volume, mixture flexibility is significantly improved. Hence, the mentioned combination of sand and tire can be used as machine foundation layer and flexible pavements;
6. Results of this study could be enriched by extra experiments to investigate behavior of mixtures having wider ranges of $D_{50,r}/D_{50,s}$ and rubber content percentages. Moreover, more laboratory experiments can be performed to study the effect of coefficient of uniformity, confining pressure, and moisture content on stress-strain characteristics of sand-tire mixtures.

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