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Laboratory observation of engineering properties and deformation mechanisms of cemented rubber-sand mixtures

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HIGHLIGHTS

- Compression and microstructural characteristics of rubber-sand mixtures are studied.
- Vertical strain of rubber-sand mixtures presents three behavior regions.
- Evolution of V_s and G_0 during compression process is investigated.
- Two different deformation mechanisms of rubber-sand mixtures are proposed.

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ABSTRACT

This paper presents details of a study that deals with investigation of compression behaviors, stiffness properties, and microstructural characteristics of lightly cemented and uncemented rubber-sand mixtures. The rubber-sand mixtures specimens were prepared with various sand volume fractions to evaluate its effects on the engineering properties. The specimens were subjected to different levels of vertical stress under K_0 condition and the shear wave velocity (V_s) was measured simultaneously by bender elements during the compression process. Investigations were carried out with respect to the effect of sand fraction and the level of vertical stress on the overall rubber-sand mixtures properties including stress-strain characteristics, V_s, and small strain shear modulus (G_0). In addition, scanning electron microscopy analysis was conducted to understand the variations in microstructure and the deformation mechanisms controlling the changes in engineering properties of the cemented rubber-sand mixtures. The study reveals that sand fraction has a considerable influence on the mass density (ρ), stress-strain characteristics, and stiffness properties of cemented and uncemented mixtures. These changes are attributed to the remarkable difference of engineering properties between shredded rubber and sand particles. The vertical strain presents three behavior regions as a function of stress in semi-log scale for lightly cemented rubber-sand mixtures: bonding control, bonding degradation, and stress control. Residual strain of the specimen decreases with an increase in sand fraction, and its value of cemented specimen is much lower than that of uncemented specimen. The V_s and G_0 dramatically increase with an increase in sand fraction and vertical stress. A good linear relationship is proposed between V_s and vertical stress for uncemented rubber-sand mixtures. Additional loading of the vertical stress decreases the increment of V_s as a result of bonding degradation. The response of stress-strain and V_s can be employed as indicators of cementation degradation. Two different deformation mechanisms: rubber particles deformation and the force chains generated by sand particles were proposed for rubber-sand mixtures with different sand fractions. Rubber particles sustain loads and suffer a dramatical shape change when mixtures with a small amount of sand, whereas they play an important role in preventing the buckling of sand particle chains with high sand fraction.

1. Introduction

The number of disposed tires worldwide is increasing every year due to the increase in vehicles. It is reported that approximately 280 million tires were discarded each year in the United States, and about 40% of which are disposed in landfills or

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Notation

D_{50}	mean particle size
D_{rubber}	particle size of shredded rubber
D_{sand}	particle size of sand
e_{max}	maximum void ratio
e_{min}	minimum void ratio
G_0	small strain shear modulus
G_s	specific gravity
L	distance between two bender elements
RS	residual strain
SF	sand volume fraction
t	travel time of shear wave
V_s	shear wave velocity
V_{sand}	volume of sand
V_{total}	total volume of the rubber-sand mixtures
α, β	constants from experimental data
ε_c, ε_u	vertical strain of cemented and uncemented mixtures, respectively
$\varepsilon_c/\varepsilon_u$	normalized strain
ρ	mass density
σ	vertical effective stress
σ'_0	effective plane stress on the mixtures
Δh_1, Δh_2	large deformation and small deformation

stockpiles without effective utilization [1,2]. These stockpiles are inevitably posing a potential threat to human health and the surrounding environment [3,4]. The increasing volume of disposed rubber tires has prompted interest in developing new means to reuse them. The addition of rubber particles to soil could significantly change the physico-mechanical properties of the soil, because the soft rubber particles generate a decrease in specific gravity, density, friction angle, shear strength, stiffness, and permeability, and they also create an increase in compressibility, damping, and the maximum void ratio [5–10]. Using shredded rubber tires as a fill material consumes large quantities of stockpiles and reduces the construction cost. It is also having been considered an important way to achieve a sustainable development. Over recent decades, shredded rubber tires have been successfully used as a lightweight fill material in various civil engineering applications. The whole disposed rubber tires can also be employed as reinforcement in the construction of retaining walls, embankments, and wharfs, which produce less horizontal pressure than soil backfill [11–17]. Due to the potential to develop exothermic reactions, the use of pure shredded tires in civil engineering applications needs to be experienced significant scrutiny [18]. Hence, research about utilization of rubber tires have been turned toward to the use of rubber-sand mixtures (soft-rigid mixtures), for which no exothermic reactions has been detected by earlier researchers [19–23].

A considerable number of studies on shredded rubber tires and rubber-sand mixtures have been conducted by earlier researchers. These studies have focused on the strength, compressibility, and dynamic properties of the lightly cemented rubber-sand mixtures as well as uncemented mixtures [24–26]. Different engineering properties of rubber-sand mixtures can be obtained by adjusting the proportions of the ingredients, adding cementitious materials (such as Portland cement, fly ash, and so on), and changing the particle size ratio of rubber to sand [27–31]. Shear strength and unconfined compression strength of the rubber-sand mixtures or shredded tires have been extensively studied by earlier researchers [32–35]. Tsoi and Lee investigated the stress-strain-strength properties of lightly cemented rubber-sand admixed with fly ash [36]. These studies indicate that the content of sand and binder, particle size, and the types of shredded tires have significant effects on the aforementioned engineering properties [37]. Moreover, the environmental impacts of the mixtures, such as fire behaviors, physico-chemical characteristics, and ecotoxicological performances have also been investigated by various researchers [38–40]. The results demonstrate that the complex internal properties of ingredients and external environment could result in a considerable change in the strength-compression properties of the rubber-sand mixtures.

The particle size has an important effect on the engineering properties of the rubber-sand mixtures. Youwai and Bergado reported that when the size ratio not exceeds $D_{rubber}/D_{sand} \leqslant 6$, the particle size effects should be considered [41]. The particle size ratio between rubber (soft) particle and sand (rigid) particle determines the contact behavior of particles, internal structure, and macroscale response of the rubber-sand mixtures. Most of the previous studies investigated a much larger sized rubber than that of soil particle ($D_{rubber}/D_{soil} \geqslant 4$) [42]. However, very few researches have comprehensively addressed the influence of sand fraction on the compression and stiffness properties of lightly cemented rubber-sand mixtures with a size ratio in the range of 2 ($D_{rubber}/D_{sand} \leqslant 2$), including mass density (ρ), residual strain, elastic shear wave velocity (V_s) and small strain shear modulus (G_0). Besides, studies on the deformation mechanisms and cementation degradation of the lightly cemented rubber-sand mixtures and their connection with engineering properties have been noticed to be quite limited.

This paper presents a systematic investigation on mass density, compression behaviors, shear wave velocity, and small strain shear modulus of lightly cemented and uncemented rubber-sand mixtures ($D_{rubber}/D_{sand} \approx 2$). The specimens were subjected to different vertical stress under no lateral displacement and the shear wave velocities (V_s) were monitored during the stress-strain test by resorting to bender element technology. The evolution of small strain shear modulus (G_0) during the compression process was also studied. In addition, changes in the arrangement of sand particles and microstructural characteristics of the cemented mixtures, as sand fraction increases, were investigated by scanning electron microscopy (SEM). Based on these results, an effort has been made to explore the deformation mechanisms of lightly cemented rubber-sand mixtures and illustrate the cementation degradation under the increasing loading. It is believed that such investigations would be quite useful to facilitate the design of reusing shredded tires as fill materials in the civil engineering applications.

2. Experimental study

The compression test without lateral displacement (K_0 condition), was performed on lightly cemented and uncemented rubber-sand mixtures. The shear wave velocity (V_s) of the mixture was measured during the compression process under different vertical loads by resorting to the bender element technology. To investigate the deformation mechanism of rubber-sand mixtures, the scanning electron microscope analysis (SEM) was also carried out. Test materials, specimen preparation and testing methods are described below.

2.1. Materials

The shredded rubber tires were used as soft particles in this investigation. The sand predominantly consisted of quartz was used as rigid particles. The properties