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Compression properties and micro-mechanisms of rubber-sand particle mixtures considering grain breakage

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HIGHLIGHTS

- A region where the actual density is lower than the control density is presented.
- Rubber-sand mixtures are categorized into low, medium and high compressible materials.
- A good linear relationship is proposed between *Br* and *RV*.
- Three force transmission ways are proposed to interpret the force micro-mechanics.

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ABSTRACT

The waste materials of scrap tires are becoming more prevalent in geotechnical engineering. While adding scrap tires particles into sand particles as a filling material can reduce the stockpiles of scrap tires and minimize the environmental pollution. Therefore, investigating the effect of scrap tires-sand particle mixtures on compression properties is in urgent demand. In this study, the effect of the rubber particle content and vertical stress on the actual density, void ratio, coefficient of compressibility, modulus of compression, rebound and grain breakage is investigated systematically by a serious of laboratory tests. The test results reveal that when rubber content *RV* exceeds 50% (or less than 50%), the three-stage change trend of void ratio is proposed: accelerating reduction, deceleration stage and slow reduction (or accelerating reduction, slow reduction and stable stage). A region where the actual density is lower than the control density is given under different vertical stress and *RV*. In accordance with the coefficient of compressibility, the rubber-sand mixtures used in this paper is categorized into three groups: (1) Low compressive materials (*RV* = 0–10%); (2) Medium compressive materials (*RV* = 20–30%); (3) High compressible materials (*RV* > 50%). The addition of rubber particles to sand particles generates a significant reduction in modulus of compression, and the modulus of compression at the same rage of vertical stress decays exponentially with increasing *RV*. In addition, the plastic strain of specimens is greater than the elastic strain, and the gap between elastic strain and plastic strain is increasing with the increase of *RV*. A good linear relationship is derived between grain breakage B_r and *RV*. Obviously, the particle breakage decreases with the increase of *RV* at different vertical stress levels. Based on the analysis of SEM, three force transmission ways with different *RV* are proposed to describe the compression micro-mechanic of rubber-sand particle mixtures.

1. Introduction

According to the statistics, 13.5 million tons of scrap tires, i.e., 3.4 million tons (European Union), 4.4 million tons (United States) and 5.7 million tons (the rest of the world), are removed annually due to the rapid growth in vehicles [1]. In addition, according to Yadav's research, by 2030, the generation rate of discarded tire increases to 5000 million over the world [2]. Massive scrap tires are placed in stockpiles, landfills or burn off (see Fig. 1(a) [4]) at random without effective utilization [3,5], threatening the human health and polluting the surrounding environment unavoidably [6–9], as shown in Fig. 1(b) [10]. The growing scrap tires has attracted an attention to recycle them. Although the measures of recycling and reusing are adopted, such as fuel, insulation layer, tire recapping, crash barriers of roads, breakwaters and rubber-asphalt pavement [11,12], 70% of the scrap tires are discarded annually, which has not reduced the amount of scrap tires in

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Nomenclature

RV	rubber content in volume	ρ	natural density
V_{rubber}	volume of rubber	ρ_{dmax}	maximum dry density
V_{total}	total volume of sample	ρ_{dmin}	minimum dry density
D_{60}	constrained grain size	ρ_c	calculated density
D_{50}	median grain size	m	total mass of sample
D_{10}	effective grain size	m_r	mass of rubber
C_u	coefficient of uniformity	m_s	mass of sand
C_c	coefficient of curvature	ω_0	initial moisture content,
S_1, S_2	area enclosed by the grain gradation curve and the vertical line of 0.0074 mm	ρ_0	initial density
σ_v	vertical stress	h_0	actual initial height
e_{σ_v}	void ratio at the vertical stress of σ_v	ρ_w	water density;
$e_{12.5}$	void ratio at the vertical stress of 12.5 kPa	c_m	rubber content in mass
e_0	initial void radio	Δh_i	change height
E_s	modulus of compression	a_v	coefficient of compressibility
B_t	total grain breakage potential	a, b, c	fitted coefficient
B_{p0}	initial grain breakage potential	$IRVB$	increment ratio of void ratio
B_r	grain breakage	γ_p	plastic strain
$\Delta\gamma$	change of strain	γ_e	elastic strain
γ_t	total strain		
G_s	specific gravity		

(a) Stacking of waste tires [2] (b) Burning of waste tires[10]

Fig. 1. Environmental pollution of waste tires.

stockpiles or landfills [13,14]. According to Yadav, the landfilling, stockpiling, and burning of discarded waste rubber tire can generate massive environmental and health issues [15]. A need still exists for the development of solving the problem of scrap tires.

In recent decades, due to the good engineering characteristics (high elasticity, low specific gravity and high durability), shredded scrap tires have been successfully applied in many geotechnical engineering, such as backfill of subgrade, landfills and drainage buildings, reinforcement of retaining walls and wharfs [17,18], stabilization of asphalt pavement and earthen slopes, utilization of water proofing system, etc. [16].

From the perspective of sustainable development of energy, mixtures of shredded tires and soil as a filling material can consume massive scrap tires from stockpiles or landfills, which can not only reduce the cost of constructions, but also significantly minimize the environmental pollution induced by stacked scrap tires. Compared with the soil without rubber partials, the mixtures of rubber particles and soil can significantly change the physical-mechanical properties of soil, including the shear and tensile strength, California bearing ratio, durability and consolidation characteristics etc. [19–22]. Due to the exothermic reaction in mixtures of rubber particles and soil, investigation of rubber-sand mixtures has attracted an attention in recent years [22].

A great deal investigation on mixtures of rubber-soil and rubber-sand have been performed by relevant scholars, centering on the shear-strength behavior [21,23–25], axial strain capacity [21,24] and dynamic properties [25–29]. As the backfill or lightweight fill, the compressibility property of tire-sand mixtures is of important concerns, especially the stability and serviceability [30,31]. Mohamed found that the compressive curves was similar for the mixtures of tire shreds of sand, silt, and cohesive soil [32], but the compressibility of cohesive soil-rubber mixtures was highest [32]. Wartman concluded that the instantaneous compression characteristic was significantly affected by the tire particle size, particle fraction and load, while the influence of tire particle size and particle fraction on long-term compression was not obvious [33]. Lee pointed out that the higher the amount of rubber particles, the greater the compressibility, especially when the rubber content exceeded 30% the compressibility increased significantly [19]. Ahmed and Bosscher derived that the tire chips fraction had a significant influence on the compressibility and the response of larger shreds and smaller particles was similar [34,35]. Edil and Humphrey indicated that the tire-soil mixtures exhibited an unrecoverable strain with a level of load, behaving like an elastic material. Moreover, compared to the first cycle, cyclic loading had similar displacement curves with a decreasing rebound [35,36]. For uncemented rubber-sand mixtures, Zhang observed that the stress was related linearly to stress as the vertical stress exceeded 100 kPa during the progress of compression [20]. Despite numerous studies on the compression of rubber-sand