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# Geotechnical behaviour of the carbonate sand-granulated tire mixture

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Carbonate sand-tire mixture is used in this research as a soil improvement method to address the environmental problems regarding the accumulation of scrap tires in coastal areas. The stress-strain behaviour, internal friction angle, and the particle breakage of the carbonate sand-tire mixture are studied, and the results are compared to that of pure carbonate sand. The results revealed that the addition of the granulated tires to the carbonate sand changed its behaviour. The addition of granulated tires resulted in a decrease of both the friction angle and the quantity of particle breakage.

[**Keywords**: Breakage index; Carbonate sand; Direct shear test; Sand-tire mixture; Scrap tire]

## Introduction

The increase of scrap tires results in the increase of their accumulation in the environment, which leads to environmental disasters[1]. It is estimated that about 90 % of annually generated scrap tires recovered, in the USA and Europe[2]. However, 2.1 million tons of scrap tires in the USA and 5.5 million tons in Europe remained in stockpiles at the end of 2007 and 2010, respectively[2].

The scrap tires can be recycled and reused in various fields, one of which is civil engineering applications. These applications include sand-tire mixtures[3,4] as a soil embankment for road construction[1,5], retaining wall backfills[6], drainage material in the cover system of landfills[7], and utilization of tire shreds in construction materials such as concrete[8]. In addition, one of the most recent applications of tire shreds is its usage as a sand tire mixture for seismic isolation of structures[9,10]. Seismic isolation is of high importance in many regions, primarily onshore and offshore areas. In these regions, the structures are exposed to dynamic loadings such as wave, current, and earthquake loadings in their life cycle[11], which shows the importance of seismic isolation for them. A large portion of the soil in onshore and offshore areas, especially in the Persian Gulf and coasts of Australia, is carbonate sand[12,13]. This type of soil has a considerable amount of calcium carbonate and an inherent breakable characteristic; also, it is composed of various-shaped grains with many voids on its surface, all of which lead to different behaviour in comparison with other types of soil such as the most common silica sand[13–15]. Carbonate deposits present a different geotechnical behaviour under cyclic and monotonic loading in comparison with siliceous deposits, such as tending to contractive behaviour and having higher friction angles[16–18]. Furthermore, owing to the problematic nature of this soil[19], it seems critical to investigate different types of soil improvement methods in carbonate sands, like the aforementioned sand-tire mixture.

Qeshm Island on the north coast of the Persian Gulf is one of the regions encountered with some problems relating to carbonate sand. One of the most recent environmental challenges of this island, because of its transportation characteristics, is the accumulation of scrap tires. Besides that, the increasing number of civil engineering projects in this developing region arises the idea of using the mixture of the tire-carbonate sand mixture as a soil improvement method. This paper aims to investigate the mechanical properties of the tire-carbonate sand mixture, such as stress-strain behaviour, friction angle, and particle breakage, and compare them with the mechanical properties of pure carbonate sand.

## Materials and Methods

The carbonate sand utilized in this research was obtained from Qeshm Island at the Persian Gulf (Fig. 1). The $CaCO_3$ content of the soil was about 62 %, which is higher than the $CaCO_3$ content of many of the carbonate sands at other regions of the Persian Gulf, such as Bushehr Port and Hormoz Island[20]. The scanning electron microscopy images (SEM) of Qeshm carbonate sand shows that it has plate-shaped grains with sharp corners as well as some spiral-shaped grains (Fig. 2 A & B).

The tires used in this research were industrial granulated tire (rubber) with the size ranging from 2 to 3.35 millimeters (Fig. 2 C). Fig. 3 illustrates the particle size distribution of the Qeshm carbonate sand (QCS) and granulated tire (GT). Physical properties of QCS and GT, also, are showed in Table 1.

The mixtures of granulated tire-carbonate sand (GtCs) were prepared at various GT contents and then their minimum and maximum dry unit weight calculated according to the ASTM D4254 (2016b), and ASTM D4253 (2016a) respectively[21,22]. The proportions of GT by volume in GtCs mixture were 0 %, 10 %, 20 % and 30 %. Given the maximum and minimum dry densities and the proportion of the GT in the GtCs mixture, the samples were prepared by dry pluviation method at two different relative densities of 30 % (loose) and 70 % (relatively dense). The strain control direct shear tests were conducted according to the ASTM D3080 (1994) at overburden pressures of 100, 200, and 400 kPa[23].


Fig. 1 — Location of Qeshm Island in the Persian Gulf

Table 1 — material properties of carbonate sand and granulated tire

| Material | $G_s$ | $D_{50}$ (mm) | $C_c$ | $C_u$ | $e_{max}$ | $e_{min}$ |
|---|---|---|---|---|---|---|
| Carbonate sand | 2.60 | 0.8 | 2.89 | 7.65 | 0.948 | 0.604 |
| Granulated tire | 1.11 | 2.6 | - | - | 5.79 | 4.29 |

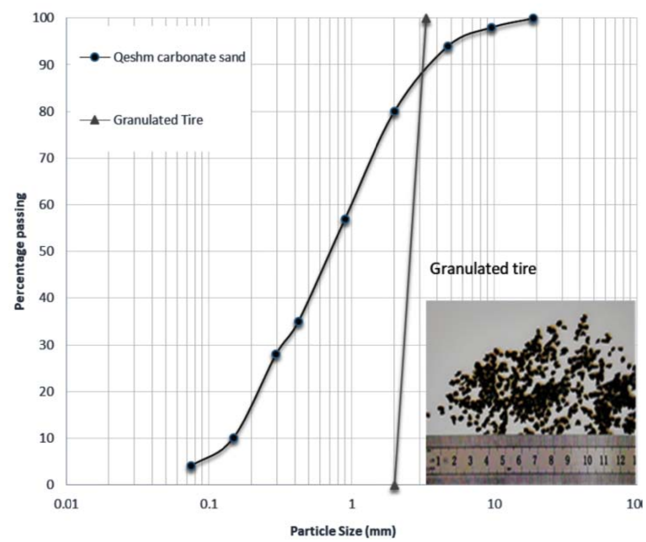
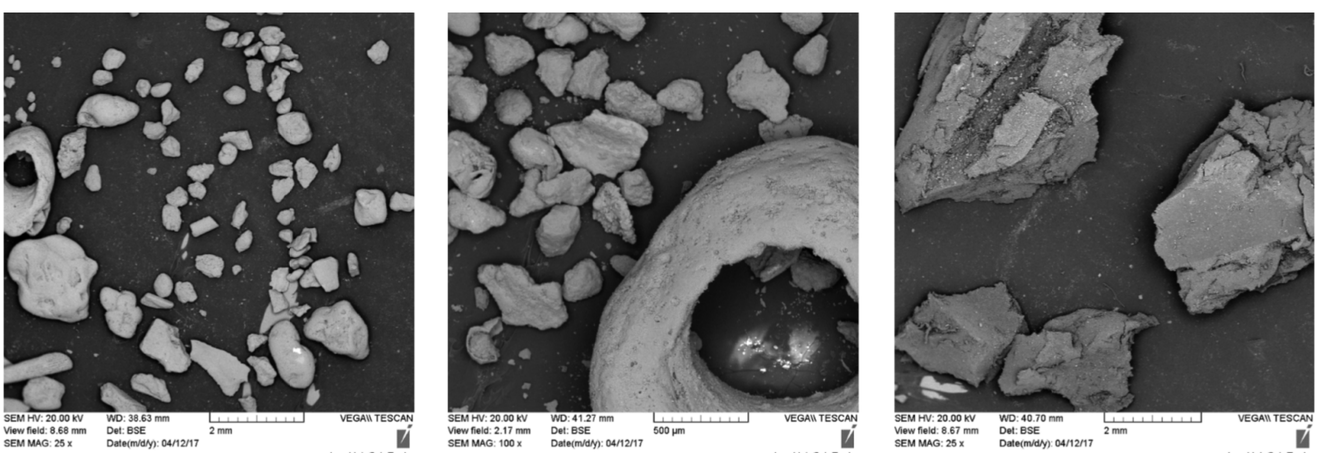



Fig. 3 — Particle size distribution of Qeshm carbonate sand and granulated tires




A) B) C)

Fig. 2 — SEM images of Qeshm carbonate sand (A & B) and granulated tire (C)

## Results and discussion

### Stress-strain behaviour

The stress-strain behaviour of the GtCs mixture with various proportions of GT at the normal stress of 100 kPa in loose and relatively dense states is presented in Fig. 4. As can be seen, the increase in the GT proportion resulted in the decrease of peak shear strength. In addition, the strain at which the maximum shear strength is reached, increases with increasing the GT content in both loose and relatively dense states. As the dilation of the GtCs mixture decreases by the addition of GT, it needs to reach higher strain to reach its peak shear strength. The stress-strain behaviour of the samples at the normal stress of 400 kPa in both loose and dense states is presented in Fig. 5. As shown, the GtCs samples with various contents of GT had a ductile behaviour with no peak shear strength in both loose and relatively dense states.

It can be inferred from Figures 4 and 5 that the effect of GT addition is higher in relatively dense samples. In other words, by adding the GT, the shear strength decreased by 5-10 % in the loose state; however, it decreased by 10-20 % in the relatively dense state. It is evident that the void ratio in the relatively dense specimens is lower, and therefore the grains' interaction is higher in them as well as when the GTs are added to the sample. So, the higher interactions resulted in the higher effect of GT addition and the decrease of shear strength.

### Internal friction angle

One of the most important parameters in the design of geotechnical structures, especially in cohesionless soils, is the internal friction angle. In this regard, the internal friction angle calculated using the following equation:

$$\varphi = \arctan\left(\tau_{max}/\sigma_n\right) \qquad \text{Eq. (1)}$$

where φ is the internal friction angle, $\sigma_n$ is the normal stress, and $\tau_{max}$ is the maximum shear stress.

The friction angles of the GtCs mixtures at various proportions of GT in both loose and relatively dense states are presented in Figures 6 and 7. Generally, the addition of the GT resulted in a decrease of the friction angle. This decrease is lower than 10 %, and it is also lower for the loose samples than dense

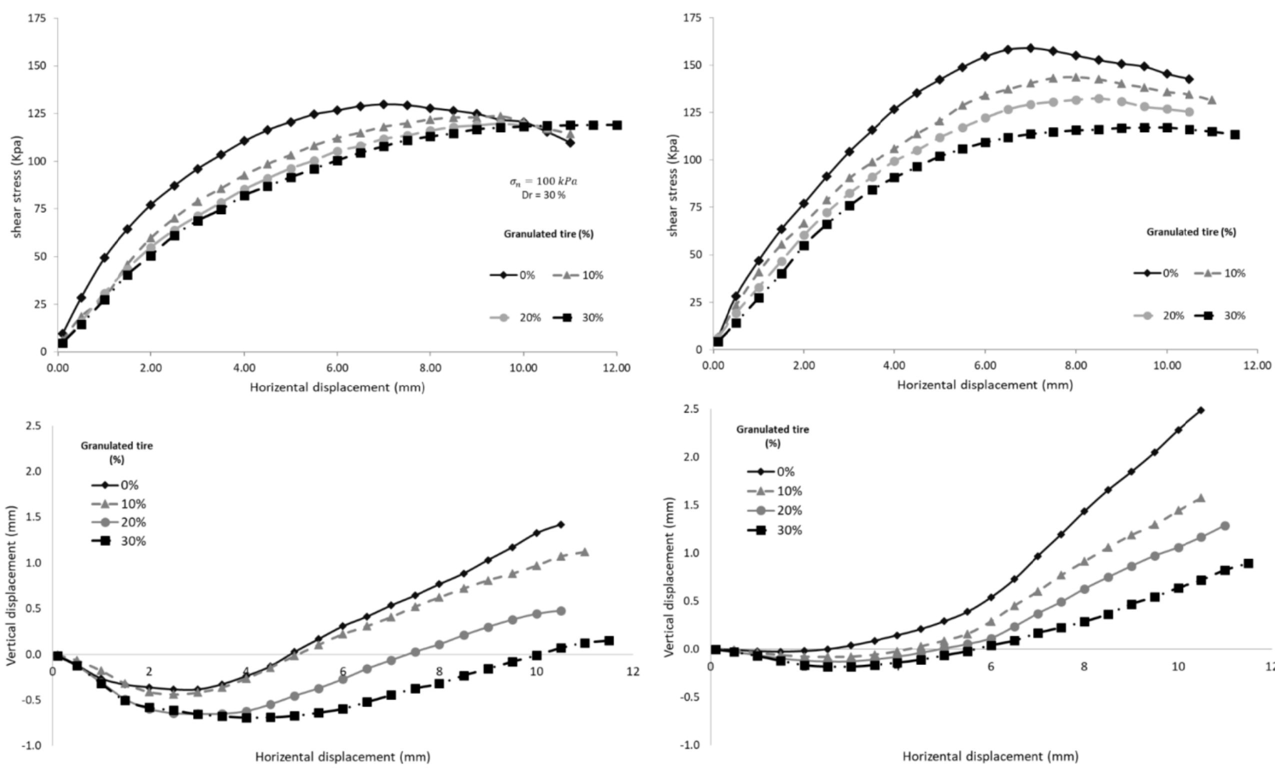



Fig. 4 — Stress-strain and volumetric behaviour of the carbonate sand-tire mixture at relatively dense and loose states and normal stress of 100 kPa

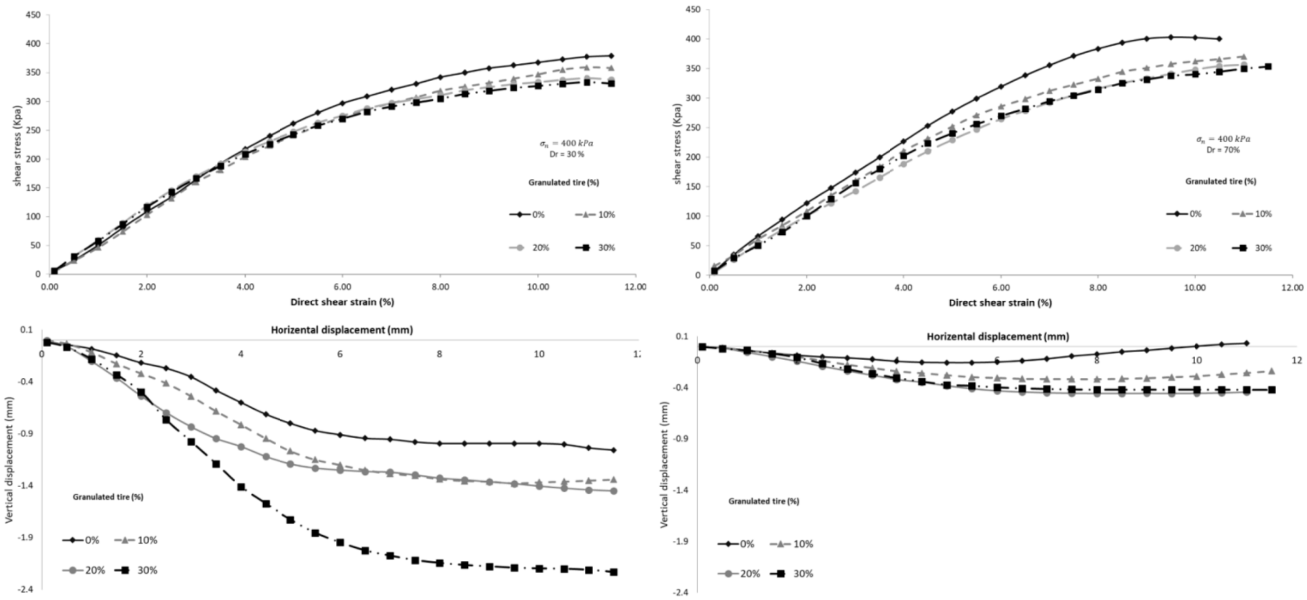



Fig. 5 — Stress-strain and volumetric behaviour of the carbonate sand-tire mixture at relatively dense and loose states and normal stress of 400 kPa

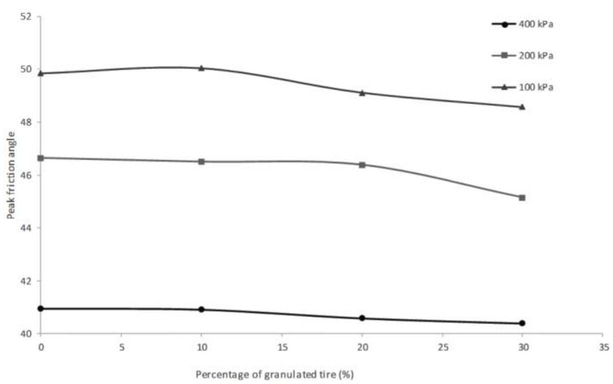



Fig. 6 — Effect of addition of granulated tire to the carbonate sand on friction angle in a loose state

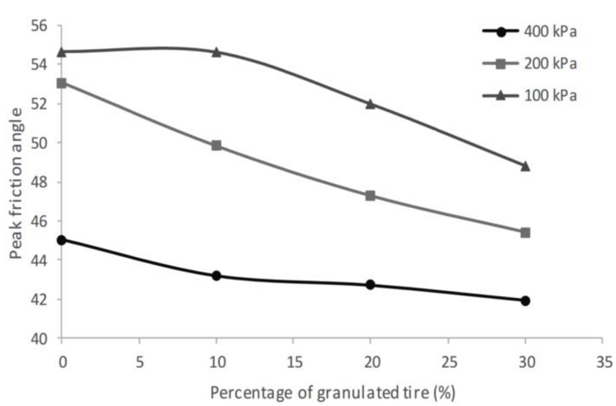



Fig. 7 — Effect of addition of granulated tire to the carbonate sand on friction angle in a relatively dense state

samples. Furthermore, the increase of the overburden pressure resulted in the reduction of the effect of GT addition. This phenomenon can be attributed to the elastic behaviour of the granulated tires and their position among the soil particles. In other words, the increase of the overburden stress resulted in the higher interaction of the soil particles, and therefore its lower variation in the friction angle in comparison with pure carbonate sand.

**Particle Breakage index**

The unique nature and shape of the carbonate sands lead to specific features, one of which is particle breakage under working loads[14,19,24]. This feature has tremendous effects on the mechanical behaviour of carbonate sands, such as the decrease of dilation[25] and the increase of the Mohr-Coulomb shear envelope curvature[20]. The Hardin method[26], which is based on the overall grain size distribution, was utilized to investigate the particle breakage. The following equation was used toward that end:

$$B_r = \frac{B_T}{B_p} \qquad \text{Eq. (2)}$$

where $B_r$ is the breakage index, $B_T$ is the area restricted between the initial and the final grain size distribution curves, and $B_P$ is the area between the initial grain size distribution curve and the line perpendicular to the horizontal axis passing the 0.075 mm (Fig. 8). The variation of the breakage

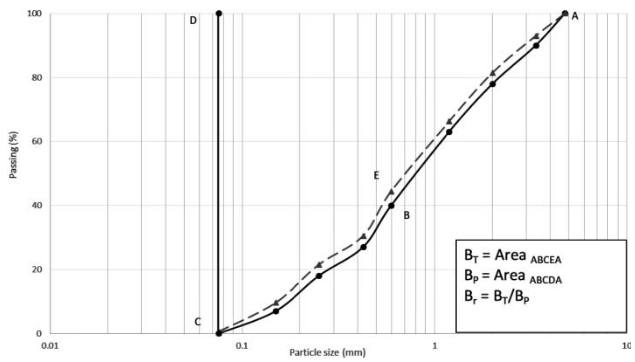



Fig. 8 — Definition of the particle breakage on the Hardin method [26]

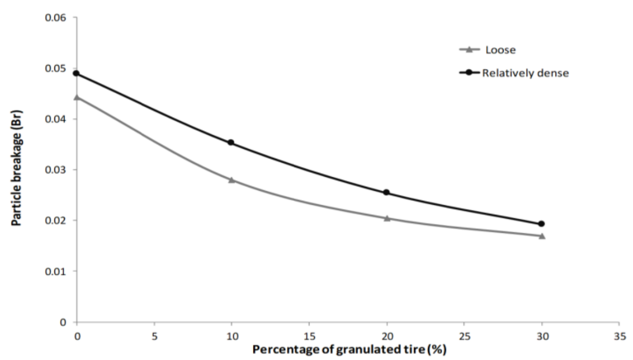



Fig. 9 — Tire addition effect on the particle breakage of the carbonate sand at the normal stress of 400 kPa

index at different GT contents is presented in Fig. 9. It can be inferred that increasing of the GT content in the mixture leads to the decrease of the breakage index in both loose and relatively dense states. It seems that the positioning of the tires among the soil particles leads to the reduction of the stress concentration at the grain edges, and therefore decrease of the particle breakage. In addition, as can be seen, the breakage index is higher for the relatively dense specimens. This result is in accordance with the results of the Shahnazari and Rezvani (2013)[20].

The particle breakage at the various overburden pressures is presented in Figures 10 and 11 for both loose and relatively dense states. As shown, the addition of the GT to the mixture reduced the particle breakage and maintained it at the relatively same quantity at different overburden pressures. This mechanism can be explained by two points. First, the major amount of particle breakage in the direct shear test occurs at the shear surface. Second, the addition of the GT to the carbonate sand can reduce the stress concentration at the grain edges. In other words, the addition of the GT compensates for the increase of the overburden stress, especially in the shear surface.

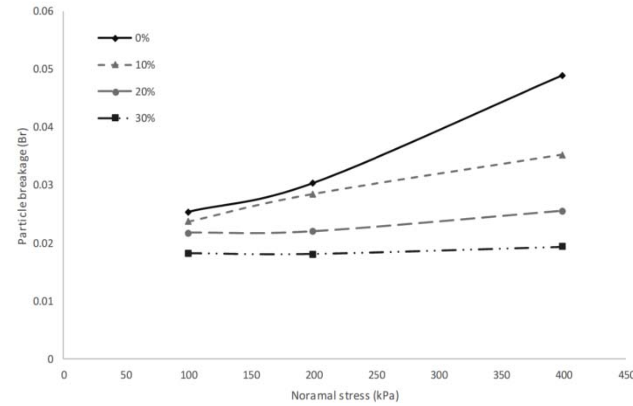



Fig. 10 — Tire addition effect on breakage of the carbonate sand at different normal stresses in a relatively dense state

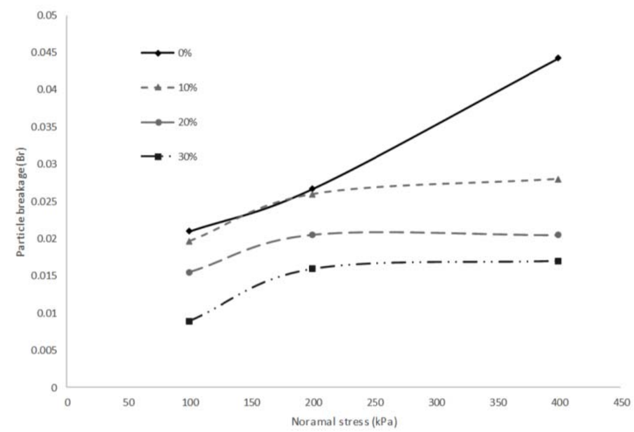



Fig. 11 — Tire addition effect on breakage of the carbonate sand at different normal stresses in a loose state

**Comparison of the results with the mixture of tire crumbs and silica sand**

Studies conducted on the mixture of silica sand and tire crumbs concluded that the addition of tire crumbs resulted in the entirely different geotechnical behaviour in comparison with the geotechnical behaviour of silica sand solely, and this behaviour is dependent on the size of the tire crumbs and soil particles[27–30]. One of the studies with the relatively similar properties of the tire crumbs is the one conducted by Neaz Sheikh et al[28]. The result of that research revealed that the addition of the tire crumbs to the silica sand resulted in the reduction of the shear strength and internal friction angle, which is similar to the results obtained in this research. Furthermore, Neaz Sheikh et al[2]. concluded that the addition of tire crumbs increased the ductility of the silica sand which is, also observed in the GtCs mixture. One of the apparent differences between silica and carbonate sands is the particle breakage at working loads which occurs to carbonate sands[20]. The particle breakage is investigated herein, and its reduction in the GtCs mixture was observed.

## Conclusion

The accumulation of tire crumbs in nature causes many environmental problems. To resolve these problems, various applications are proposed for tire crumbs, one of which is a geotechnical application as a tire-sand mixture. In this research, the mechanical properties of the granulated tire-carbonate sand mixture are investigated. The results revealed that using the granulated tires with a similar size as the carbonate sand particles in the mixture of tire-sand leads to a decrease of the shear strength. Furthermore, the addition of the granulated tires resulted in the disappearance of the peak shear strength, and hardening behaviour of the mixture. In other words, the mixture revealed more ductile behaviour. The importance of this behaviour is evident as the carbonate sand is indigenous to many onshore and offshore areas, and the structures in these areas are under the dynamic load in their life cycle. The mixture of granulated tire-carbonate sand can be used as seismic isolation owing to its ductility. Moreover, the investigation of the mechanical properties of the mixture revealed that the addition of the granulated tire to the carbonate sand reduced both the internal friction angle and the particle breakage of carbonate sands.

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