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Dynamic Behavior of Sand/Rubber Mixtures, Part II: Effect of Rubber Content on G/G_O-γ-DT Curves and Volumetric Threshold Strain

ABSTRACT: This paper examines the strain-dependent dynamic properties (G/G_O-logγ-DT curves) of dry and saturated sand–recycled rubber mixtures in a range of shearing strain amplitudes from (5×10^{-4}) % to (6×10^{-1}) % using a fixed-free torsional resonant column device. The effect of the rubber content on the pore water pressure buildup and volumetric threshold strain γ_t^v of saturated mixtures, as well as the effect of specimens' geometry on the experimental data, are also presented and discussed. Based on a comprehensive set of experimental results, a modified hyperbolic model, frequently used in practice, has been proposed. An increase in the rubber content leads to a more linear shape of the G/G_O-logγ and DT-logγ curves and a reduction in the pore water pressure buildup. Damping is expressed in terms of DT-DT_O, which eliminates the effect of the rubber content and the mean confining pressure. The final aim is to propose appropriate design G/G_O-logγ-DT curves for sand–rubber mixtures currently used in practice.

KEYWORDS: shear modulus, damping ratio, resonant column testing, sand/rubber mixtures

Introduction

Recycled rubber composed of mechanically shredded waste tires experienced important reception recently as a potential construction or fill lightweight material in civil engineering projects. Over the past two decades, an intensive effort has been made by the geotechnical research community to determine the physical and mechanical properties and develop methods for the application of the recycled rubber in geo-structures [1–7]. It is concluded that, following the recommendations of ASTM D6270-98 [8], the use of recycled rubber can lead to beneficial results from a safety point of view, with a simultaneous reduction of the overall construction cost. This is in particular true for structures founded on unstable soils.

Soil–rubber mixtures might be an attractive alternative isolation solution for reducing seismic ground motion, as reported recently by Tsang [9] and Senetakis et al. [10], who performed numerical 2D analyses on a superstructure-soil system in which the foundation soil was replaced with a sand–rubber mixture. In addition, Hyodo et al. [11], based on undrained cyclic triaxial tests, and Uchimura et al. [12] and Hazarika et al. [13], based on shaking table tests, reported a more gradual increment of pore water pressure buildup and an overall increase of the liquefaction resistance of soil–rubber mixtures with increasing rubber content.

The rather limited data in the literature concerning the dynamic response of pure recycled rubber and soil–rubber mixtures are presented and discussed, for the case of low-amplitude strains, in a companion paper by Anastasiadis et al. [14]. The present paper synthesizes past and recent experimental data of high-amplitude resonant column tests on sand–recycled rubber mixtures performed at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki [10,15–19].

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The main objectives of this paper are therefore as follows:

(1) To study the effect of rubber inclusion and percentage on the non-linear dynamic response of sand-rubber mixtures.
(2) To investigate, at a preliminary stage, the effect of rubber inclusion and percentage on the pore water pressure buildup and volumetric threshold strain of sand–rubber mixtures.
(3) To examine the potential use of simple-analytical expressions, commonly used in typical soils, to describe the non-linear dynamic response of soil–rubber mixtures.
(4) To propose normalized shear modulus degradation and damping ratio curves with shear strain increase that could be used for practical purposes on the seismic design of structures.
(5) To study the effect of a specimen's geometry on the experimental data.

The effect of the number of cycles, prestraining, and the strain-rate, as well as the effect of the relative size of rubber solids versus soil solids, is not included in the present work.

Materials Tested, Sample Preparation, and Testing Program

Results from 20 high-amplitude resonant column tests on river sand–recycled rubber mixtures are presented and discussed: 12 dry specimens 71.1 mm in diameter, and 8 fully saturated specimens 35.7 mm in diameter. Two uniform, fine to medium grained sands, namely, C2D03 and C3D06, as well as three uniform recycled rubber materials of variable mean grain size, namely, R06, R2, and R3, were used as parent materials. The physical properties of the parent materials, the testing program, the preparation of the samples, and the procedures of low-amplitude and high-amplitude measurements are presented in the companion paper by Anastasiadis et al. [14]. Four mixture groups are examined: C2D03-R2 and C3D06-R06, having rubber contents between 0 % and 15 %, are tested in fully saturated conditions, and groups C2D03-R3 and C3D06-R3, with rubber contents between 0 % and 35 % by mixture weight, are studied in dry conditions.

The range of mean confining pressure and the bounds of shearing strain amplitude are given in Table 1. Both small (35.7 mm in diameter and 82.2 mm in height) and large (71.1 mm in diameter and 142.2 mm

TABLE 1—*High-amplitude torsional resonant column testing program on dry and saturated specimens.*

	Specimen Code	Rubber Content (%)[a]	γ_d (kN/m^3)[b]	σ'_m (kPa)[c]	γ_{LA} to γ_{HA} (%)[d]
Dry, 71.1 × 142.2	C2D03-D01[e]	0	15.8	50, 100, 200	4.8×10^{-4} to 2.1×10^{-2}
	C2D03-R3-95/5-D01[f]	5	15.4	50, 100, 200, 400	4.3×10^{-4} to 1.8×10^{-2}
	C2D03-R3-90/10-D01	10	14.8	50, 100, 200	8.1×10^{-4} to 4.2×10^{-2}
	C2D03-R3-85/15-D01	15	14.2	50, 100, 200, 400	6.9×10^{-4} to 5.5×10^{-2}
	C2D03-R3-75/25-D01	25	13.3	50, 100, 200	1.5×10^{-3} to 7.4×10^{-2}
	C2D03-R3-65/35-D01	35	12.3	25, 50, 100	1.8×10^{-3} to 1.3×10^{-1}
	C3D06-D01[e]	0	16.5	25, 50, 100, 200	4.8×10^{-4} to 3.3×10^{-2}
	C3D06-R3-95/5-D01	5	16.4	50, 100, 200	6.2×10^{-4} to 1.9×10^{-2}
	C3D06-R3-90/10-D01	10	15.3	50, 100, 200, 400	4.3×10^{-4} to 2.1×10^{-2}
	C3D06-R3-85/15-D01	15	14.9	50, 100, 200, 400	3.2×10^{-4} to 4.0×10^{-2}
	C3D06-R3-75/25-D01	25	13.9	50, 100, 200, 400	6.9×10^{-4} to 2.8×10^{-2}
	C3D06-R3-65/35-D01	35	12.5	50, 100, 200	1.1×10^{-3} to 8.3×10^{-2}
Saturated, 35.7 × 82.2	C2D03-S11[e]	0	15.7	100	1.8×10^{-3} to 7.6×10^{-2}
	C2D03-R2-95/5-S11	5	15.3	100	3.2×10^{-3} to 1.6×10^{-1}
	C2D03-R2-90/10-S11	10	14.3	100	2.3×10^{-3} to 4.6×10^{-1}
	C2D03-R2-85/15-S11	15	13.8	100	2.9×10^{-3} to 5.9×10^{-1}
	C3D06-S11[e]	0	16.1	100	2.8×10^{-3} to 1.4×10^{-1}
	C3D06-R06-95/5-S11	5	15.6	100	4.5×10^{-3} to 1.6×10^{-1}
	C3D06-R06-90/10-S11	10	14.2	100	4.8×10^{-3} to 1.7×10^{-1}
	C3D06-R06-85/15-S11	15	13.8	100	5.4×10^{-3} to 3.8×10^{-1}

[a]By mixture weight.
[b]Initial dry unit weight at $\sigma'_m \approx 5$ kPa.
[c]Mean effective confining pressure where high-amplitude tests were performed.
[d]Range of shearing strain from low to high amplitude tests.
[e]Intact sands.
[f]Mixture composed of the sand C2D03 and the recycled rubber material R3 with 5 % rubber by weight.

in height) specimens were tested in order to cover a wide range of strain amplitudes, approximately from (5×10^{-4}) % to (6×10^{-1}) %. Large specimens are stiffer and thus respond more to lower shearing strains as compared to small specimens. The latest can easily reach a higher amplitude of shearing strains, in particular when accounting for the increase of flexibility with increasing rubber content. However, the G_O and DT_O values of the small specimens correspond in general to higher shearing strain amplitudes in comparison to the large specimens; as discussed in the companion paper [14], this is due to restrictions of the equipment used, and thus a more rigorous definition of G_O and DT_O of the small specimens is "apparent small-strain shear modulus" and "apparent small-strain damping ratio."

Experimental Results and Discussion

G/G_O-logγ and DT-logγ Curves of Dry and Saturated Mixtures

Figure 1 depicts the G/G_O-logγ and DT-logγ curves at $\sigma'_m = 100$ kPa of the small-saturated specimens (mixture groups C2D03-R2 and C3D06-R06) having rubber contents between 0 % and 15 %. In the same figure we plot the proposed curves by Seed et al. [20] for sandy soils. It is noticed [Figs. 1(*a*) and 1(*c*)] that an increase of the rubber content leads to more linear G/G_O-logγ curves; at a specific shearing strain amplitude, G/G_O increases with increasing rubber content. In typical soils, the more linear shape of the G/G_O-logγ curve indicates higher linearity in the region of medium to high strains and, thus, more linear DT-logγ curves. This is also true in the case of sand–rubber mixtures. As shown in Figs. 1(*b*) and 1(*d*), an increase in the rubber content leads to more linear DT-logγ curves, indicating a reversing trend at high strains as compared to small strains, as presented in Ref [14]. Consequently, the experimental results of Fig. 1, obtained at relatively high shearing strain amplitudes, verify the previous experimental investigation reported by Anastasiadis et al. [15,16] and Senetakis et al. [10,18] on dry specimens. In addition, the

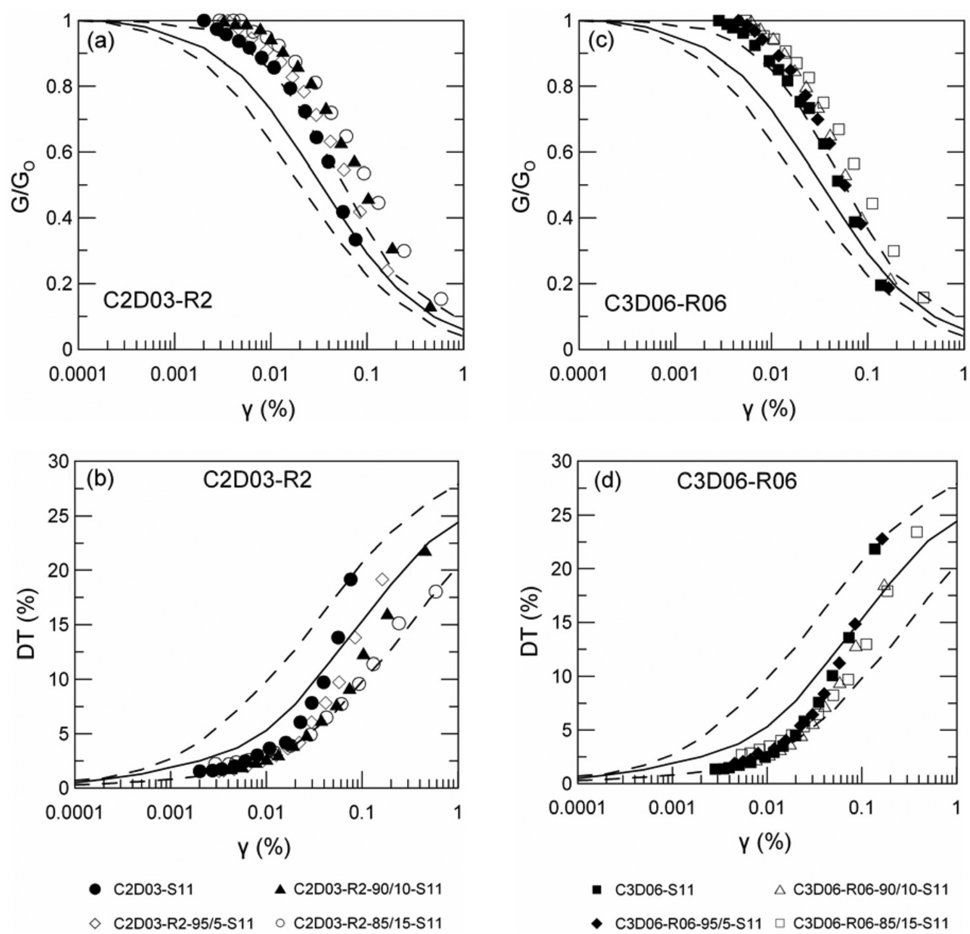

FIG. 1—*Effect of rubber content on G/G_O-logγ-DT curves of saturated specimens. The curves proposed by Seed et al. for sandy soils [20] are also plotted.*

more linear shape of the G/G$_O$-logγ curves with increasing rubber content indicates an increase of the elastic threshold γ_t^e of the mixtures.

The analysis of the experimental G/G$_O$-logγ curves of the mixtures is performed according to the modified hyperbolic model [21–23]. This model, expressed analytically in Eq 1, uses two fitting parameters: (i) the reference strain, γ_{ref}, that corresponds to G/G$_O$ = 0.5 and expresses the "linearity" of the G/G$_O$-logγ curves; and (ii) the curvature coefficient a, expressing the "overall slope" of the non-linear curves [22,24]. Moreover the damping ratio values, expressed as DT-DT$_O$, are correlated to the corresponding normalized shear modulus values G/G$_O$

$$\frac{G}{G_O} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_{ref}}\right)^a} \quad (1)$$

where:

γ = shearing strain amplitude,
γ_{ref} = reference strain (corresponds to G/G$_O$ = 0.50), and
a = curvature coefficient.

The reference shear strain of the mixtures at σ'_m = 100 kPa is presented as $\gamma_{ref,mix,100}$, and the reference strain of the natural-intact soils at the same confining pressure as $\gamma_{ref,soil,100}$. In Fig. 2(*a*) we plot the $\gamma_{ref,mix,100}$ values of the saturated specimens versus the rubber content. It is shown that the reference strain of both mixture groups increases from about (5×10^{-2}) % to about 10^{-1} % as the rubber content increases from 0 % to 15 %. As shown in Fig. 2(*b*), the increase of the reference strain with increasing rubber content (pr) can be expressed in terms of the ratio $\gamma_{ref,mix,100}/\gamma_{ref,soil,100}$ versus pr. In this figure, a simple two-order fitting curve of the experimental results is plotted. Thus, knowing the reference strain of the clean sand at σ'_m = 100 kPa and the rubber content by mixture weight (pr), the reference strain of the mixture at the same σ'_m is estimated from Eq 2

$$\gamma_{ref,mix,100} = \gamma_{ref,soil,100} \times \left[0.0014 \times (pr)^2 + 0.0437 \times (pr) + 1\right] \quad (2)$$

where:

$\gamma_{ref,mix,100}$ = reference strain of sand–rubber mixture at σ'_m = 100 kPa in percentile scale (%),
$\gamma_{ref,soil,100}$ = reference strain of the intact sand at σ'_m = 100 kPa in percentile scale (%), and
pr = rubber content by mixture weight in percentile scale (%).

Figure 3 depicts the G/G$_O$-logγ and DT-logγ curves of two large, dry specimens of variable rubber content concerning the mixture group C3D06-R3. The effect of σ'_m on the non-linear curves of the mixtures is also illustrated. G/G$_O$ values increase, whereas DT values decrease, as σ'_m increases at a specific shearing strain amplitude, following the general trend of clean sandy soils.

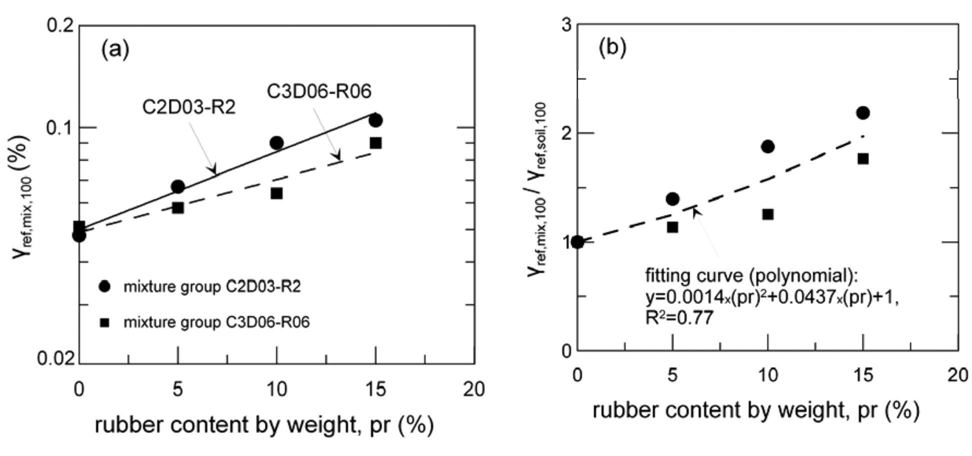

FIG. 2—*Effect of rubber content on the reference strain at* σ'_m *= 100 kPa of saturated specimens: (a) absolute values and (b) normalized values with respect to the corresponding reference strain of the intact sandy specimens.*

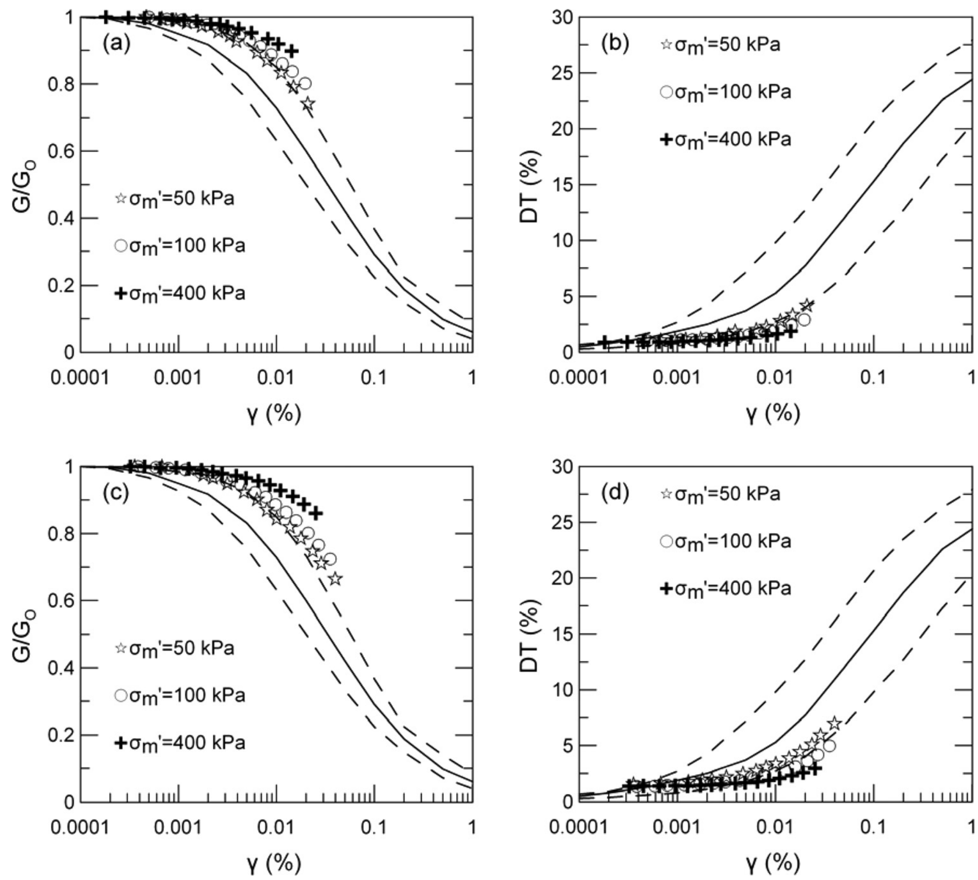

FIG. 3—*Representative G/G$_O$-logγ and DT-logγ curves of dry specimens: (a),(b) specimen C3D06-R3-90/10 and (c),(d) specimen C3D06-R3-85/15. The curves proposed by Seed et al. for sandy soils [20] are also plotted.*

In Fig. 4 we plot the G/G$_O$-logγ and DT-logγ curves of all dry specimens of this study, with the rubber content ranging from 0 % to 35 % (mixture groups C2D03-R3 and C3D06-R3) and testing conducted in a range of confining pressures σ'_m varying from 25 to 400 kPa. The scatter of the experimental data is mainly due to the influence of the rubber content and confining pressure σ'_m on the non-linear curves. Figures 5(*a*) and 5(*b*) show the $\gamma_{ref,mix,100}$ values of the dry specimens, as well as the ratio $\gamma_{ref,mix,100}/\gamma_{ref,soil,100}$ versus the rubber content. As in the case of the saturated specimens (Fig. 2 and Eq 2), the increase of the dry mixtures' reference strain can be estimated from Eq 3

$$\gamma_{ref,mix,100} = \gamma_{ref,soil,100} \times \left[0.0009 \times (pr)^2 + 0.0266 \times (pr) + 1\right] \quad (3)$$

where:

$\gamma_{ref,mix,100}$ = reference strain of sand–rubber mixture at $\sigma'_m = 100$ kPa in percentile scale (%),
$\gamma_{ref,soil,100}$ = reference strain of the intact soil at $\sigma'_m = 100$ kPa in percentile scale (%), and
pr = rubber content by mixture weight in percentile scale (%).

The effect of confining pressure on the reference strain can be expressed with the simple form of Eq 4

$$\gamma_{ref,mix} = \gamma_{ref,mix,100} \times A_\gamma \times \left(\sigma'_m\right)^{n_\gamma} \quad (4)$$

where:

$\gamma_{ref,mix}$ = reference strain of sand–rubber mixture,
$\gamma_{ref,mix,100}$ = reference strain of mixture at $\sigma'_m = 100$ kPa given from Eqs 2 and 3 for saturated specimens 35.7 mm in diameter and dry specimens 71.1 mm in diameter, respectively,
A_γ = constant value,
σ'_m = mean effective confining pressure, and
n_γ = exponent that expresses the effect of σ'_m on $\gamma_{ref,mix}$.

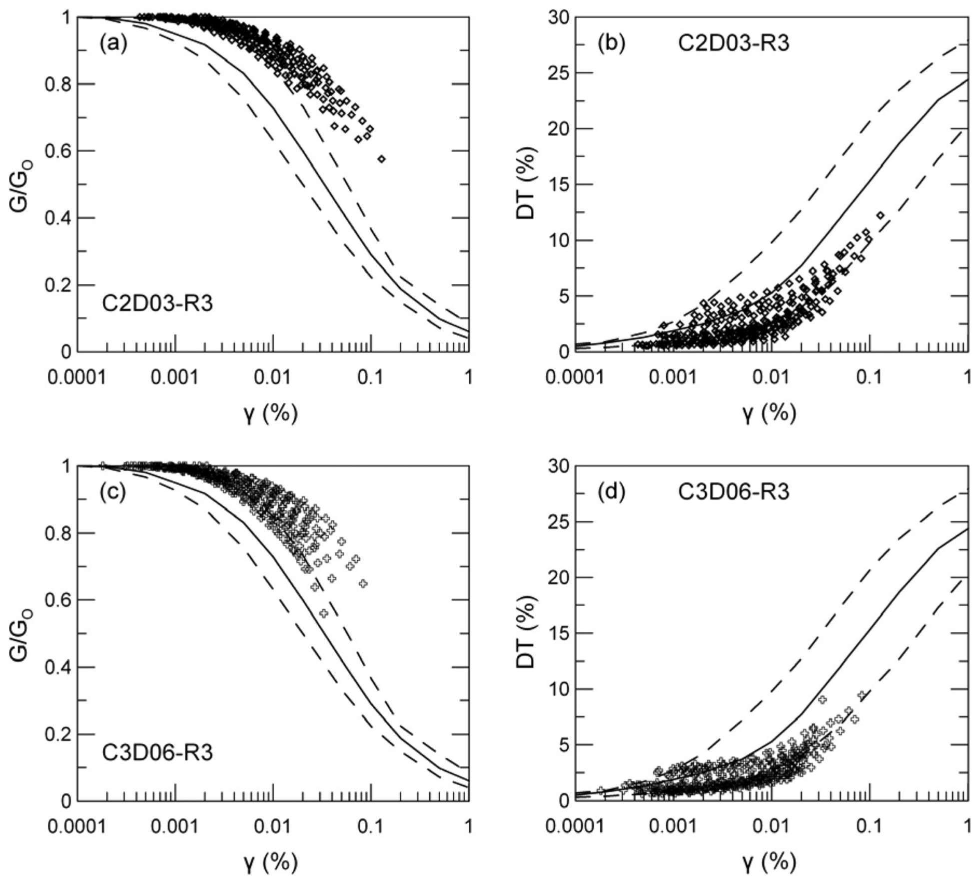

FIG. 4—*G/G_O-logγ and DT-logγ curves of dry 71.1 × 142.2 mm specimens: total experimental results. The curves proposed by Seed et al. for sandy soils [20] are also plotted.*

In Fig. 6 we plot the parameters A_γ and n_γ of the dry specimens versus the rubber content. The general trend is that A_γ increases, whereas the exponent n_γ decreases, with increasing rubber content. The increase of A_γ implies that the mixture's reference strain increases, and the decrease of n_γ implies that the effect of the confining pressure σ'_m on the mixture's G/G_O-logγ curve is reduced with increasing rubber content. These observations are also supported by Senetakis [19]. Furthermore, the positive n_γ values indicate that mixtures exhibit higher linearity with increasing σ'_m. The analysis of the experimental results concerning the dry specimens led to the following exponential expressions of A_γ and n_γ as a function of the rubber content pr

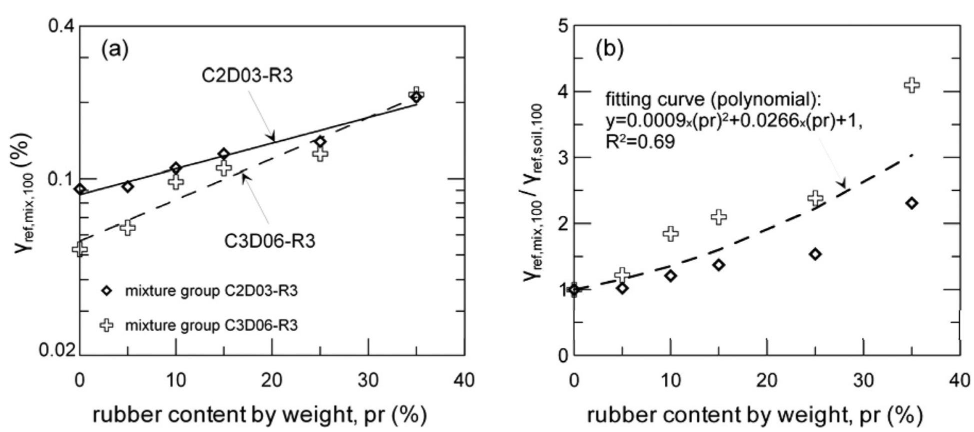

FIG. 5—*Effect of rubber content on the reference strain at $\sigma'_m = 100$ kPa of dry specimens: (a) absolute values and (b) normalized values with respect to the corresponding reference strain of the intact sandy specimens.*

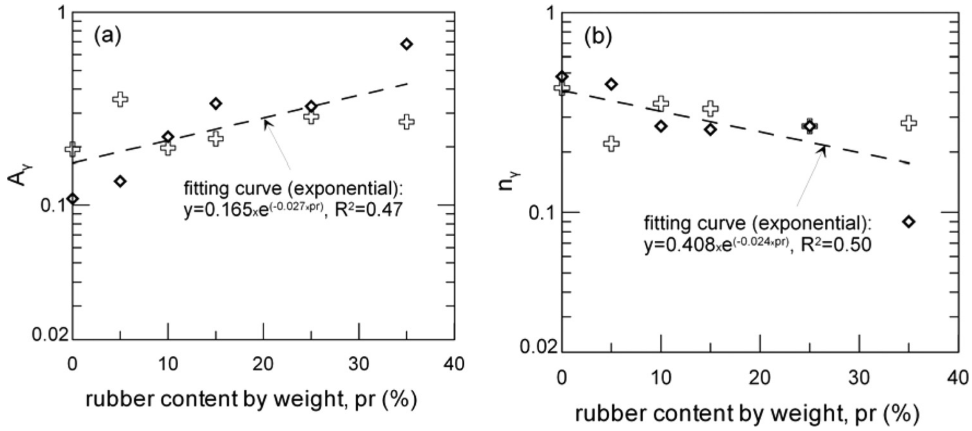

FIG. 6—*Effect of rubber content (a) on the parameter A_γ and (b) on the exponent n_γ of dry specimens (symbols are given in Fig. 5).*

$$A_\gamma = 0.165 \times e^\wedge(0.027 \times pr) \tag{5}$$

$$n_\gamma = 0.408 \times e^\wedge(-0.024 \times pr) \tag{6}$$

where:

pr = rubber content by mixture weight in percentile scale (%).

It is noted at this point that Eqs 5 and 6 are mainly applicable for mixtures that are composed of sandy soils of similar grain size distribution, as with the one under study, and in which the mean grain size of rubber solids is equal to or higher than the mean grain size of the sand solids.

The application of the modified hyperbolic model on the experimental G/G_O-logγ curves led to the estimation of the curvature coefficient (a) values of Figs. 7(*a*) and 7(*b*) for small-saturated specimens (35.7 × 82.2 mm) and large-dry specimens (71.1 × 142.2 mm), respectively. The curvature coefficient values are plotted against the rubber content. It is noticed that the parameter a is not significantly affected by the rubber content in the case of the saturated samples, whereas a slight decrease is observed in the case of the dry samples. The mean value, as well as the mean value ±1 standard deviation, of the parameter a, separately for saturated and dry specimens, is also shown in Figs. 7(*a*) and 7(*b*). It is observed that small-saturated specimens exhibit systematically higher values of the parameter a as compared to the large-dry specimens in this study, with a mean value equal to 1.26, whereas dry specimens exhibit an average value equal to 0.91. A possible explanation for these differences is that with small specimens the G_O values

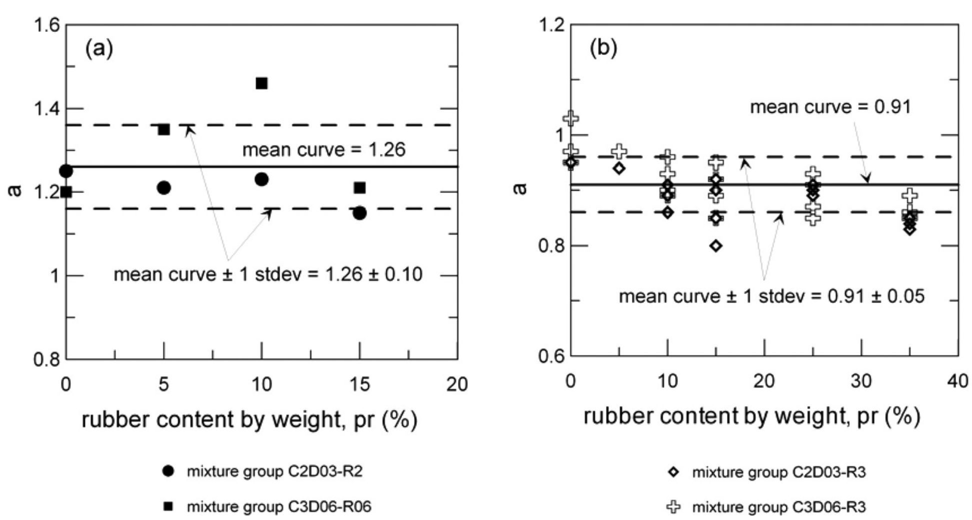

FIG. 7—*Curvature coefficient versus rubber content of (a) saturated specimens and (b) dry specimens (symbols are given in Figs. 2 and 5).*

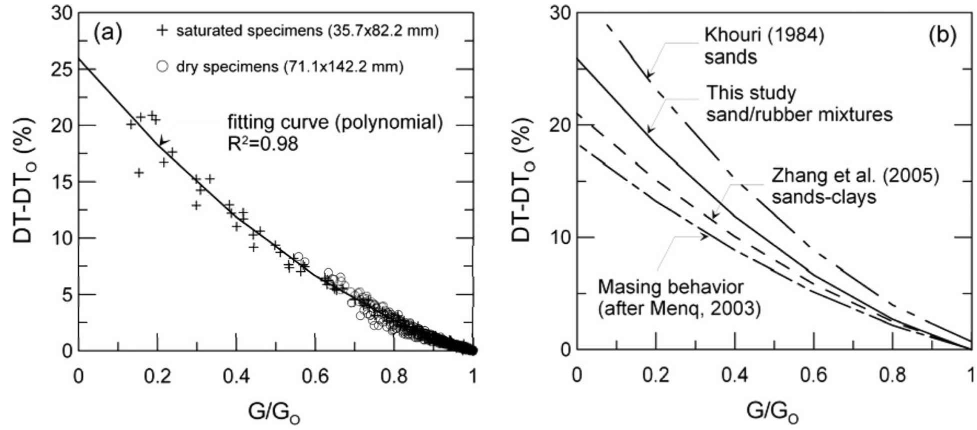

FIG. 8—*Damping ratio expressed as DT-DT$_O$ versus G/G$_O$ of saturated and dry specimens. (a) Experimental results. (b) Comparison of the fitting curve of this study with curves from the literature concerning typical soils.*

were determined at a higher shearing strain amplitude in comparison to the large specimens. As Menq [24] has reported, the higher shearing strain at which G_O is measured results in a higher overall slope of the G/G_O-logγ curve, and consequently higher values of the curvature coefficient are estimated.

To conclude, the reference strain of a sand–rubber mixture can be estimated using Eqs 2 to 6 and expressed as a function of the rubber content (expressed by mixture weight), σ'_m, and the reference strain of the intact soil. Then, the G/G_O-logγ curve can be estimated from Eq 1, with the parameter a determined herein as 1.26 and 0.91 in the case of the small-saturated and large-dry specimens, respectively. It is noted that in the above equations, the parameters $\gamma_{ref,mix}$, $\gamma_{ref,mix,100}$, $\gamma_{ref,soil,100}$, and pr are expressed as percentages, and σ'_m is in kPa.

In Fig. 8(*a*) we plot the damping ratio values, expressed as DT-DT$_O$, versus G/G_O of the saturated and dry specimens. It is noted that the expression of the damping ratio in terms of DT-DT$_O$ eliminates remarkably the effects of both the rubber content and σ'_m on the experimental results. Thus, the increase of the damping ratio values of the mixtures as G/G_O decreases can be estimated using a simple two-order relation of Eq 7. It is noted that we use herein a unique equation for both saturated and dry specimens. In Fig. 8(*b*), we compare the fitting curve of this study with proposed curves in the literature concerning typical sandy and clayey soils [24,25,28]. It must be noted that in the curve proposed by Khouri [25], a value of DT$_O$ equal to 0.60 % has been assumed. The comparison between the experimental and estimated G/G_O and DT-DT$_O$ values of this study, using Eqs 1 to 7, is given in Figs. 9(*a*) and 9(*b*), respectively.

Finally, in Fig. 10 we present the proposed G/G_O-logγ-DT curves issued from the experimental results of this study. These curves concern dry specimens of sand–rubber mixtures at $\sigma'_m = 100$ kPa for variable rubber contents expressed by mixture weight. It is noticed that an increase in the rubber content leads to more linear DT-logγ curves, due to the more linear shape that the G/G_O-logγ curves exhibit

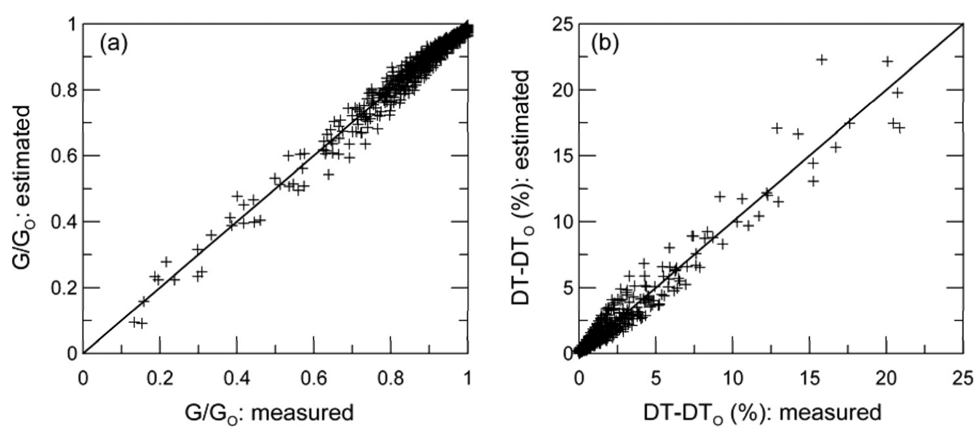

FIG. 9—*Measured versus estimated (a) G/G$_O$ values and (b) DT-DT$_O$ values of dry and saturated sand–-rubber mixtures.*

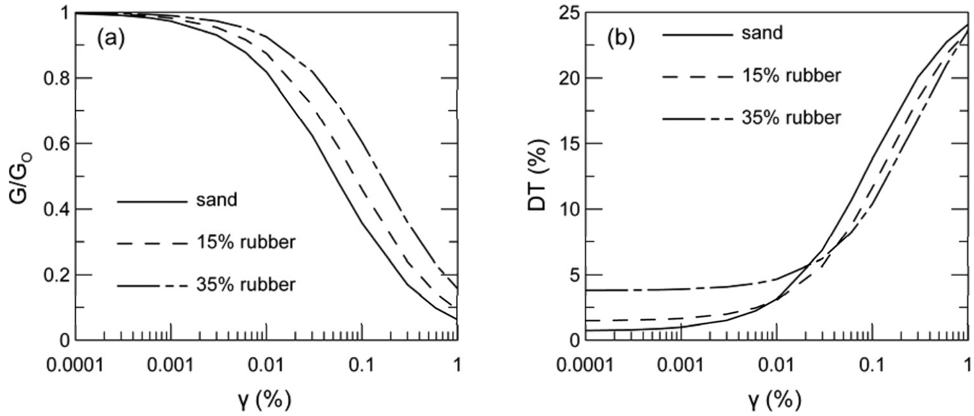

FIG. 10—*Proposed normalized shear modulus and damping ratio versus shearing strain curves of this study for sand–rubber mixtures (rubber contents correspond to mixture weight).*

$$DT - DT_O(\%) = 15.32 \times \left(\frac{G}{G_O}\right)^2 - 41.27 \times \left(\frac{G}{G_O}\right) + 25.91 \tag{7}$$

Pore Water Pressure Buildup and Volumetric Threshold Strain of Saturated Specimens

In Fig. 11 we plot the pore water pressure buildup values, expressed as $\Delta u/\sigma'_m$, versus the shearing strain amplitude γ of the saturated specimens. In Fig. 11(*a*) (mixture group C2D03-R2) it is illustrated that an increase of the rubber content leads to a reduction of pore water pressure buildup at the same shearing strain amplitude [specifically, for $\gamma > (2 \times 10^{-2})$ %]. In the case of mixture group C3D06-R06 [Fig. 11(*b*)], this trend is clearly shown for rubber content equal to 15 % by mixture weight. These observations are possibly explained by the high deformability of rubber particles, which leads to an expansion of pore water pressure buildup during the cycling loading. This general trend of more gradual pore water pressure buildup with increasing rubber content was also reported by Hyodo et al. [11], Hazarika et al. [13], and Uchimura et al. [12], who studied similar mixtures.

Let us define at this point the volumetric threshold strain γ_t^v as the shearing strain amplitude at which pore water pressure buildup occurs ($\Delta u/\sigma'_m > 0$) [26]. In Figs. 12(*a*) and 12(*b*) we plot the γ_t^v values versus the rubber content of the saturated mixture groups C2D03-R2 and C3D06-R06, respectively. In the case of mixture group C2D03-R2, we do not observe a clear trend for the effect of the rubber content on γ_t^v, whereas the γ_t^v of mixture group C3D06-R06 slightly increases with increasing rubber content. In addition, for the clean sands of this study, the threshold strain γ_t^v corresponds to a value equal to (6×10^{-3}) %,

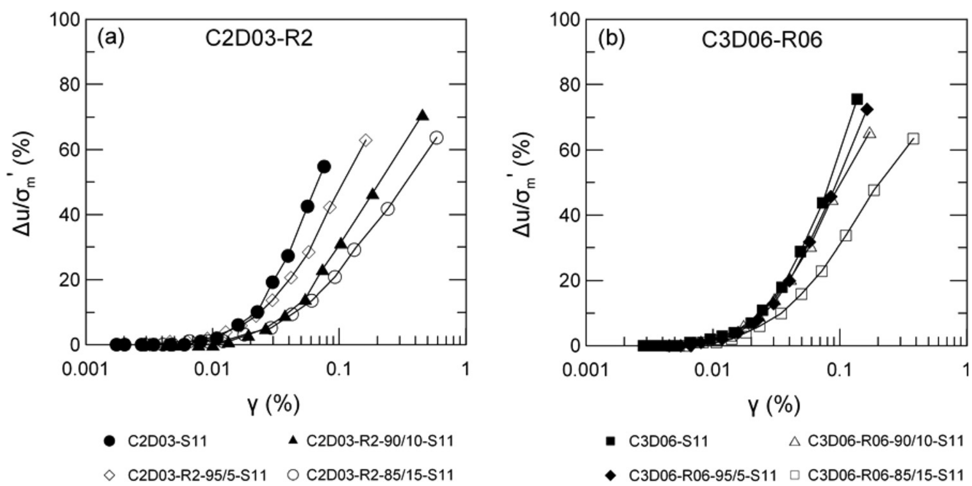

FIG. 11—*Effect of rubber content on pore water pressure buildup of saturated specimens: (a) mixture group C2D03-R2 and (b) mixture group C3D06-R06.*

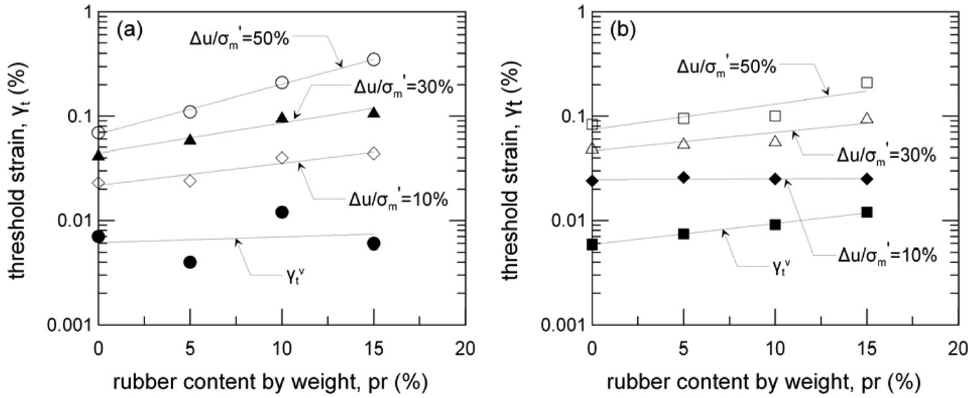

FIG. 12—*Effect of rubber content on the volumetric threshold strain* γ_t^v*, as well as on threshold strains* γ_t*, defined at different values of the ratio* $\Delta u/\sigma'_m$ *of saturated specimens: (a) mixture group C2D03-R2 and (b) mixture group C3D06-R06.*

approximately. This is consistent with the lower bound values proposed by Hsu and Vucetic for non-plastic soils [27].

Furthermore, in Figs. 12(*a*) and 12(*b*) we plot the threshold strain values that correspond to various values of the ratio $\Delta u/\sigma'_m$ (= 10 %, 30 %, and 50 %). As illustrated in Fig. 11, beyond the ratio $\Delta u/\sigma'_m = 10$ %, the rate of pore water pressure buildup increases, whereas beyond the ratio $\Delta u/\sigma'_m = 50$ %, most specimens liquefy. Considering the results presented in Figs. 12(*a*) and 12(*b*) and the above remarks, it is concluded that the effect of the rubber content on the pore water pressure buildup becomes more pronounced at higher levels of the ratio $\Delta u/\sigma'_m$ (or at higher shearing strain amplitudes).

Conclusions and Recommendations

We conducted a comprehensive set of high-amplitude resonant column tests on saturated specimens 35.7 mm in diameter and 82.2 mm in height and on dry specimens 71.1 mm in diameter and 142.2 mm in height of sand–granulated rubber mixtures composed of uniform, fine to medium grained natural sands as the physical portion and uniform rubber materials of variable contents as the synthetic portion. The main conclusions of this work, as well as the recommendations for further research, are summarized as follows:

- At a specific confining pressure, sand–rubber mixtures exhibit more linear G/G_O-logγ and DT-logγ curves as the rubber content increases.
- Based on low-amplitude and high-amplitude resonant column test results, it is possible to express the non-linear response of the mixtures with analytical expressions commonly used for typical soils.
- G/G_O-logγ curves are expressed in terms of the modified hyperbolic model; it was observed that the reference strain increases systematically with increasing rubber content and confining pressure (σ'_m), whereas the effect of σ'_m on the non-linear curves is less pronounced as the rubber content increases. The reference strain is expressed herein as a function of the rubber content, confining pressure, and reference strain of the intact soil, and thus further research is needed on soil–rubber mixtures that are composed of granular soils of variable coefficient of uniformity values. In addition, the curvature coefficient a of the modified hyperbolic model is affected by specimens' geometry; small specimens 35.7 mm in diameter exhibit systematically higher values of the parameter a and, consequently, a higher overall slope of the G/G_O-logγ curves as compared to large specimens 71.1 mm in diameter. This is possibly explained by the higher values of shearing strain amplitude at which G_O is defined in small specimens, which is related to the limitations of the equipment used in the accurate determination of the low-amplitude shear modulus of the specimens 35.7 mm in diameter. However, the overall effect of the rubber content on the parameter a of both the small and large specimens was not that important.
- DT-logγ curves were analyzed in terms of correlating the damping ratio values, expressed as DT-DT_O versus G/G_O, using a simple two-order relation. The expression of the damping ratio as DT-DT_O eliminated the effect of the rubber content and σ'_m on the experimental results.

- For a given shearing strain amplitude, the pore water pressure buildup is reduced with increasing rubber content, whereas specimens with higher rubber contents are liquefied at higher strain levels. However, the effect of the rubber content on the volumetric threshold strain was not clear. Further research is needed on this topic, in which the effect of the rubber content on specimens' volumetric threshold strain and liquefaction resistance would be studied in terms of the application of specific loading cycles as, for example, in cyclic triaxial tests.
- For design purposes, we propose specific G/G_O-logγ and DT-logγ curves of mixtures composed of uniform, fine to medium grained sands as the physical portion and uniform rubber materials of variable contents as the synthetic portion.

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