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Dynamic Behavior of Sand/Rubber Mixtures. Part I: Effect of Rubber Content and Duration of Confinement on Small-Strain Shear Modulus and Damping Ratio

ABSTRACT: The paper examines the small-strain dynamic properties of mixtures composed of sandy soils with recycled tire rubber. For this purpose, the experimental results stemming from a torsional resonant column testing program on twenty four [24] saturated and dry specimens are analyzed. The percentages of rubber used range between 0 and 35 % by mixture weight. G_O values increase whereas DT_O values decrease systematically as the content of rubber decreases and the mean confining pressure increases. Based on the experimental results we propose an analytical relationship for the estimation of G_O, which is expressed in terms of an equivalent void ratio that considers the volume of rubber solids as part of the total volume of voids, along with an analytical relationship for the estimation of DT_O. Finally, the effect of the specimen's size and the duration of confinement on the initial shear modulus and damping ratio of the mixtures are also discussed.

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

Introduction

The recycling and re-use of scrap tires has been of growing interest in civil engineering applications during the last two decades. Granulated rubber or tire chips composed of recycled scrap tires exhibit low unit weight of solids, along with low bulk density, high drainage capacity, and high elastic deformability [1–7]. In addition, physical soils, when mixed with recycled rubber, exhibit, in general, lower unit weight and satisfactory strength characteristics [5,8–12]. The physical and technical parameters of recycled rubber, tire chips, tire bales, and soil/rubber mixtures are reviewed in Edil [13], Zornberg et al. [14], Strenk et al. [15], Edeskar [7], and in ASTM D6270-98 [16].

Due to the aforementioned interesting properties of the recycled rubber materials, they are commonly used as lightweight construction material in high embankments overlying soft soils and lightweight backfill material in retaining walls and slopes (see Bosscher et al. [17], Lee et al. [11] Edil [13], Humphrey [18], Zornberg et al. [12,14]). In addition, due to their high hydraulic conductibility, recycled rubber materials are used as drainage layer at landfills [6,7,19,20]. Recently, recycled rubber-soil mixtures were proposed to be applied as an alternative low-cost isolation system beneath superstructures [21,22]. Theoretical studies (Lee et al. [11], Kaneda et al. [23], Tsang [21], Senetakis et al. [22], Mavronicola et al. [24], Pitilakis et al. [25,26]) as well as experimental investigation on large-scale models and shaking table tests (Edil and Bosscher [4], Bosscher et al. [17], Hoppe [27], Abichou et al. [28], Humphrey [18], Zornberg et al. [14], Hazarika et al. [29], Uchimura et al. [30]), have shown promising results regarding the static and dynamic response of structures and geo-structures where recycled rubber-soil mixtures or clean rubber are used instead of clean soil.

The seismic design of structures overlying a sand/rubber isolation layer, or geo-structures constructed by recycled rubber or a sand/rubber mixture, requires the knowledge of the dynamic characteristics of the

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material used; that is, the knowledge of the dynamic shear modulus and damping ratio in small and large strain ranges. So far, only a few studies have been published concerning the dynamic properties of clean rubber and sand/rubber mixtures (Feng and Sutter [31], Pamukcu and Akbulut [32], Hyodo et al. [33], Kawata et al. [34] Uchimura et al. [30], and Kim and Santamarina [35]).

For this purpose, a comprehensive experimental and theoretical research program is under way in the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle Univ. in Thessaloniki, Greece, with experimental investigation and theoretical-numerical modeling; the aim is to investigate if the use of recycled rubber-soil mixture as a foundation material could improve the seismic response of buildings and geo-structures. In this paper, as well as in the companion paper by Senetakis et al. [36], recent studies of this experimental investigation are reviewed (Anastasiadis et al. [37,38] and Senetakis et al. [22,39]) and improved with additional experimental data (Senetakis et al. [40], and Senetakis [41]).

Therefore, the main objectives of this paper are:

(a) To propose simple relationships for the estimation of small-strain shear modulus and damping ratio of sand/rubber mixtures including the effect of the rubber content, the mean confining pressure, and the initial dynamic properties of the intact soils.

(b) To present and discuss results regarding the effect of duration of the confinement and specimen's size on the small-strain behavior of mixtures composed of variable rubber contents.

It is important to note that in this paper and the companion paper (Senetakis et al. [36]), we study mixtures that are composed of uniform, fine to medium grained sands and uniform recycled rubber materials (classified as granulated rubber), that exhibit, in general, a ratio of $D_{50,r}/D_{50,s} \geq 1$, where $D_{50,r}$ and $D_{50,s}$ are the mean grain size of rubber and sand particles, respectively. The effect of the ratio of $D_{50,r}/D_{50,s}$ on the dynamic response of granular soil/rubber mixtures is thoroughly presented and discussed in Anastasiadis et al. [42], Senetakis [41], and Senetakis et al. [40,43].

Materials Tested, Sample Preparation And Testing Program

Table 1 summarizes the physical properties and the classification and compaction characteristics of the natural and synthetic materials used in this study. Materials C2D03 and C3D06 were constructed using a natural sand of sub-rounded to rounded particles, whereas materials R06, R2, and R3 were constructed using a synthetic–granulated rubber material composed of recycled tire shreds as parent material.

Table 2 summarizes the sand/rubber mixtures tested along with some important data of the experimental testing program. As shown in this table, the mixtures are categorized in four groups with respect to the intact soil and rubber used (C2D03-R2, C2D03-R3, C3D06-R06, and C3D06-R3). Sixteen specimens (mixture groups C2D03-R3 and C3D06-R3) were tested in dry conditions having a diameter equal to 71.1 mm and a height equal to 142.2 mm, whereas eight specimens (mixture groups C2D03-R2 and C3D06-R06) were tested in fully-saturated conditions having a diameter equal to 35.7 mm and a height equal to 82.2 mm. All dynamic experiments were carried out in a Drnevich longitudinal-torsional resonant

TABLE 1—*Properties and classification of physical and synthetic materials used.*

Properties/Data	Physical Materials (Natural Sand)		Synthetic Materials (Rubber)		
Material code	C2D03	C3D06	R06	R2	R3
G_s, gr/cm^{3} [a]	2.67	2.67	1.10	1.10	1.10
D_{max}, mm	0.25–0.43	0.85–2.00	2.00–4.75	2.00–4.75	4.75–6.35
D_{50}, mm	0.27	0.56	0.40	1.50	2.80
C_u	1.58	2.76	2.65	1.81	2.29
C_c	0.93	1.23	0.85	0.96	1.18
Classification	SP[b]	SP[b]	Granulated Rubber[c]	Granulated Rubber[c]	Granulated Rubber[c]
$\gamma_{d,max}$, kN/m^3	…	17.8[d]	…	6.6[e]	6.5[e]
$\gamma_{d,min}$, kN/m^3 [f]	…	14.2	…	4.5	4.6

[a] Reference [52].
[b] Reference [53].
[c] Reference [16].
[d] Reference [54].
[e] Reference [55].
[f] Reference [56].

TABLE 2—*Data of sand/rubber mixtures tested and torsional resonant column testing program.*

Mixture Group	C2D03-R3[a]	C3D06-R3[a]	C2D03-R2[b]	C3D06-R06[b]	C3D06-R3[c]
Parent sand	C2D03	C3D06	C2D03	C3D06	
Parent rubber	R3	R3	R2	R06	
Range of rubber content by mixture weight, %	0–35	0–35	0–15	0–15	0–35
D50,r/D50,s	10:1	5:1	6:1	1:1	5:1
Number of specimens tested	6	6	4	4	4
Conditions of saturation	dry	dry	saturated	saturated	dry
Specimens Geometry, mm	71.1 × 142.2	71.1 × 142.2	35.7 × 82.2	35.7 × 82.2	71.1 × 142.2
Range of σ_m’ for low amplitude Measurements, kPa	25–400	25–400	25–100	25–100	50–10
Range of σ_m’ for high amplitude measurements, kPa	25–400	25–400	100	100	…
Reference	[38][39,40]	[37][22]	[38]	…	…

[a] Scope of tests: small-strain and non-linear shear modulus and damping ratio.

[b] Scope of tests: small-strain and non-linear shear modulus and damping ratio, volumetric threshold strain.

[c] Scope of tests: effect of duration of confinement on small-strain response.

column device [44] according to ASTM D4015-92 [45] specifications. It is also noted at this point that the large specimens (71.1 mm × 142.2 mm) exhibit a ratio L/D equal to 2.0, whereas the small specimens (35.7 mm × 82.2 mm) exhibit a ratio L/D approximately equal to 2.3, where L is the height and D is the diameter of the specimens. Consequently, the difference in slenderness between large and small specimens is on the order of 15 %, which is insignificant in common engineering practice.

As a first step, sand and rubber minerals were dry mixed in order to prepare uniform samples of specific rubber content by mixture weight. Then the specimens were constructed into a metal mold in many layers of equal dry mass, in order to achieve a high relative density. Large specimens 71.1 mm in diameter were constructed in fourteen layers, whereas small specimens 35.7 mm in diameter, were constructed in five layers. All specimens were compacted at about the same compaction energy.

In the case of twelve (out of sixteen) dry specimens, low-amplitude as well as high-amplitude torsional resonant column tests were performed, with increasing steps of mean confining pressure (σ'_m) from 25 to 400 kPa. In every step, specimens were allowed to equilibrate for about 60-80 min before the low-amplitude measurements were performed. In addition, after the high-amplitude measurements at a specific confining pressure, the specimens were allowed to recover for about 30-60 min to at least 95 % of their initial stiffness.

In the case of the eight saturated specimens, low-amplitude tests were performed with increasing steps of σ'_m, equal to 25, 50, and 100 kPa, whereas high-amplitude tests were performed only at $\sigma'_m = 100$ kPa. In each step, specimens were allowed to equilibrate about 30 min before the low-amplitude measurements were performed. Prior to the resonant column testing, the usual stages of saturation and consolidation of the samples were performed.

Finally, in the case of four (out of sixteen) dry specimens, the effect of the duration of confinement on the small-strain dynamic response of the sand/rubber mixtures was studied. For this purpose, specimens of mixture group C3D06-R3, having rubber contents equal to 0, 10, 15, and 35 % by mixture weight were tested at σ'_m equal to 50 and 100 kPa.

Table 3 summarizes the information of the twenty specimens (twelve dry and eight fully-saturated) subjected to low-amplitude and high-amplitude tests with increasing mean confining pressure. Table 4 summarizes the properties of the four dry specimens for which the effect of the duration of confinement on the small-strain response of sand/rubber mixtures was investigated. In the same tables, the initial dry unit weight, void ratio, and water content of the specimens, and the range of the shearing strain amplitude, γ_{LA}, for which the initial (or small-strain) shear modulus G_O and damping ratio DT_O were defined herein are also illustrated. In the majority of the dry-large specimens, the G_O and DT_O values are defined at $\gamma_{LA} < 10^{-3}$ %. For the large specimens with rubber content equal to or higher than 25 % by mixture weight as well as for the saturated-small specimens of this study, it was difficult to define low-amplitude values of G_O and DT_O, at shearing strain levels below 10^{-3} %; this is mainly due to the flexibility of the samples and restrictions of the equipment used and thus, a more rigorous definition of G_O and DT_O of the aforementioned specimens is "apparent small-strain shear modulus" and "apparent small-strain damping ratio."

In the authors' experience, the testing program on large specimens provides a more accurate definition of the initial shear modulus and damping ratio, whereas the testing program on small-flexible specimens

TABLE 3—*Low-amplitude and high-amplitude torsional resonant column testing program on dry and saturated specimens.*

	Specimen Code	Rubber Content,[a]%	γ_d,[b] kN/m^3	e[b]	w,%	γ_{LA},[c]%
Dry, 71.1 × 142.2	C2D03-D01	0	15.8	0.661	0	$4.8–5.2 \times 10^{-4}$
	C2D03-R3-95/5-D01	5	15.4	0.596	0	$4.3–6.7 \times 10^{-4}$
	C2D03-R3-90/10-D01	10	14.8	0.547	0	$8.1–9.2 \times 10^{-4}$
	C2D03-R3-85/15-D01	15	14.2	0.517	0	$6.9–8.1 \times 10^{-4}$
	C2D03-R3-75/25-D01	25	13.3	0.447	0	$1.5–1.6 \times 10^{-3}$
	C2D03-R3-65/35-D01	35	12.3	0.443	0	$1.8–2.2 \times 10^{-3}$
	C3D06-D01	0	16.5	0.588	0	$4.8–8.2 \times 10^{-4}$
	C3D06-R3-95/5-D01	5	16.4	0.494	0	$6.2–7.5 \times 10^{-4}$
	C3D06-R3-90/10-D01	10	15.3	0.511	0	$4.3–5.8 \times 10^{-4}$
	C3D06-R3-85/15-D01	15	14.9	0.471	0	$3.2–4.6 \times 10^{-4}$
	C3D06-R3-75/25-D01	25	13.9	0.417	0	$6.9–9.1 \times 10^{-4}$
	C3D06-R3-65/35-D01	35	12.5	0.450	0	$1.1–1.8 \times 10^{-3}$
Saturated, 35.7 × 82.2	C2D03-S11	0	15.7	0.670	25.1	$1.8–3.8 \times 10^{-3}$
	C2D03-R2-95/5-S11	5	15.3	0.594	22.9	$3.2–3.8 \times 10^{-3}$
	C2D03-R2-90/10-S11	10	14.3	0.605	24.1	$2.3–4.2 \times 10^{-3}$
	C2D03-R2-85/15-S11	15	13.8	0.574	23.6	$2.9–6.2 \times 10^{-3}$
	C3D06-S11	0	16.1	0.623	23.3	$2.8–4.0 \times 10^{-3}$
	C3D06-R06-95/5-S11	5	15.6	0.573	22.1	$4.5–6.5 \times 10^{-3}$
	C3D06-R06-90/10-S11	10	14.2	0.609	24.2	$4.8–9.2 \times 10^{-3}$
	C3D06-R06-85/15-S11	15	13.8	0.562	23.1	$5.4–10.1 \times 10^{-3}$

[a] By mixture weight.
[b] Initial values at $\sigma'_m \approx 5$ kPa.
[c] Shearing strain amplitude where G_O and DT_O are defined.

provides the capability of testing materials at relatively high strain levels as discussed in the companion paper [36]. Given that the increase of the rubber content leads to an increase of the mixture's elastic threshold and to materials of higher linearity [36,40,41,43], it is believed that the testing program on large specimens provides accurate small-strain measurements not only for clean sands and mixtures with low rubber content, but also for specimens with a rubber content above 15 % by mixture weight.

This paper presents the low-amplitude experimental results and the derived analytical relationships, whereas the high-amplitude tests are presented in the companion paper [36].

Experimental Results and Discussion

Effect of Rubber Content and Specimen's Size on Small-Strain Shear Modulus and Damping Ratio

Figures 1 and 2 show the effect of the mean effective confining pressure σ'_m and rubber content pr on the initial shear modulus G_O and the initial damping ratio DT_O of the sand/rubber mixtures. Figure 1 refers to the saturated 35.7 mm × 82.2 mm specimens, and Fig. 2 refers to the dry 71.1 mm × 142.2 mm specimens. As illustrated in these figures, G_O values systematically decrease as the rubber content increases, whereas

TABLE 4—*Low-amplitude torsional resonant column testing program on dry specimens: Investigation of duration of confinement effect on initial shear modulus and damping ratio.*

Specimen Code	Rubber Content,[a] %	$\gamma_{d,}$[b] kN/m^3	e[b]	w, %	Time, days[c]	γ_{LA},[d] %
C3D06-D11	0	16.4	0.600	0	7	$4.1–8.4 \times 10^{-4}$
C3D06-R3-90/10-D11	10	15.0	0.533	0	7	$8.3 \times 10^{-4}–1.1 \times 10^{-3}$
C3D06-R3-85/15-D11	15	14.6	0.474	0	28	$5.9–6.7 \times 10^{-4}$
C3D06-R3-65/35-D11	35	11.9	0.465	0	7	$3.3–5.3 \times 10^{-3}$

[a] By mixture weight.
[b] Initial values at $\sigma'_m \approx 5$ kPa.
[c] Duration of confinement at each σ'_m step.
[d] Shearing strain amplitude where G_O and DT_O are defined.

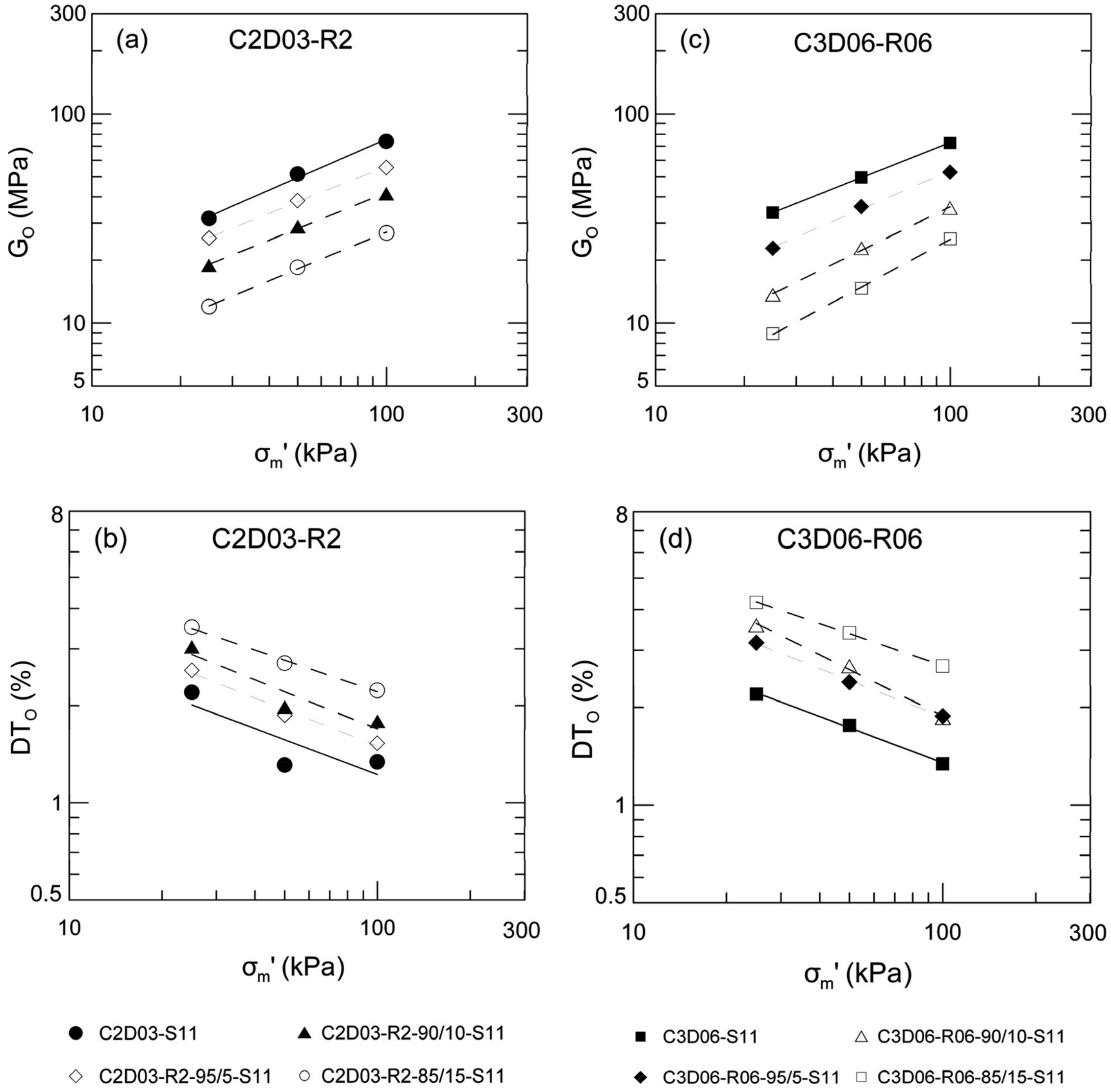

FIG. 1—*Effect of rubber content and mean confining pressure on initial shear modulus and damping ratio of saturated specimens.*

the opposite trend is observed for DT_O values. In addition, such as in clean sands, the G_O values increase and the DT_O values decrease as σ'_m increases.

To further analyze our results it is necessary to summarize few important remarks derived from recent similar tests:

- Kim and Santamarina [35] have noticed that for ratios of $D_{50,r}/D_{50,s} > 1$ (where $D_{50,r}$ is the mean grain size of rubber solids and $D_{50,s}$ is the mean grain size of soil solids), and for the rubber contents used in this study, the main mechanisms that affect the response of soil/rubber mixtures are controlled by the development of soil-to-soil and soil-to-rubber interfaces. The development of rubber-to-rubber interfaces is of low importance. Consequently, the overall response of the samples is controlled in the case of low percentages of rubber by the soil skeleton, while for low to medium percentages of rubber by the soil-to-rubber solid matrix.
- In addition, Kim and Santamarina [35] reported that the increment of rubber content and, in particular, for the rubber contents used herein, the void ratio decreases; that is, mixtures exhibit a more dense fabric of the sand/rubber solid matrix as the rubber content increases. As shown in Tables 3 and 4, the specimens of this study exhibit the general trend of decreasing void ratio with increasing rubber content as reported by Kim and Santamarina [35], a trend which was also supported by standard Proctor tests on similar mixtures [41].
- Anastasiadis et al. [37], Senetakis et al. [40], and Senetakis [41] have noticed that the effect of σ'_m on the small-strain shear modulus of clean rubber specimens is significantly lower compared to clean

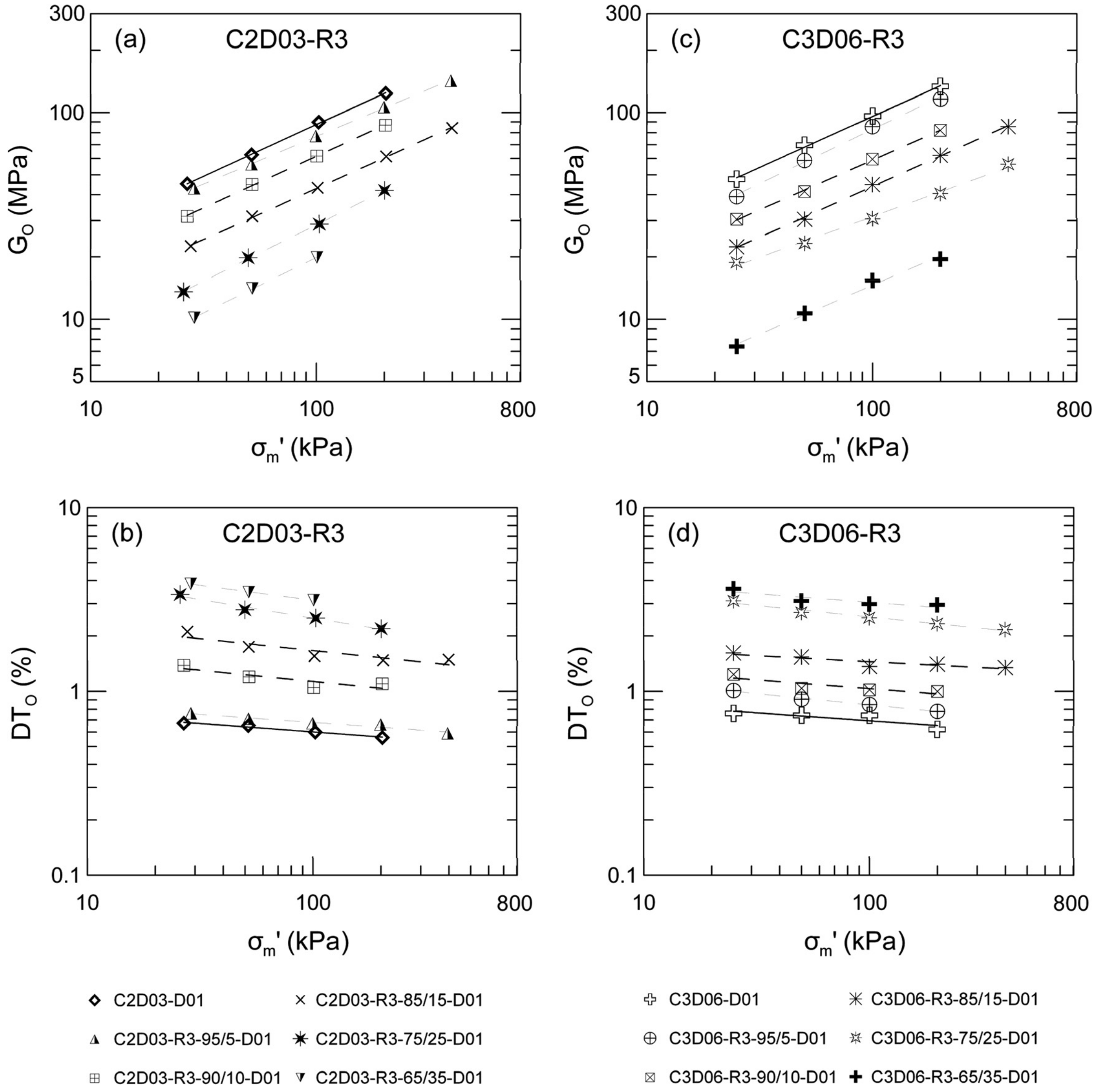

FIG. 2—*Effect of rubber content and mean confining pressure on initial shear modulus and damping ratio of dry specimens.*

soils, whereas the effect of σ'_m on the small-strain damping ratio of clean rubber specimens is relatively negligible. Furthermore, Anastasiadis et al. [37] and Senetakis [41] reported that dry and saturated sand/rubber specimens of the same geometry (71.1 mm × 142.2 mm) exhibit similar values of G_O, whereas saturated specimens exhibit slightly higher DT_O values compared to dry specimens of the same size due to strain-rate effects.

- Feng and Sutter [31], Anastasiadis et al. [37], and Senetakis et al. [40] have noticed that specimens of clean rubber materials exhibit significantly lower shear stiffness compared to clean soils (on the order of 1:100). In addition, the increase of the rubber content monotonically leads to a decrease of the shear stiffness and an increase of the damping ratio at small-strain levels.

Considering the previous remarks and the results reported in Figs. 1 and 2, it is concluded that the increase of the initial shear stiffness of the mixtures with increasing σ'_m is mainly due to the increase of normal stresses at soil-to-soil and soil-to-rubber interfaces. In addition, the decrease of the initial damping ratio with increasing $\sigma'_m$is possibly due to the effect of σ'_m on the sandy part of the solid skeleton. Furthermore, the decrease of the mixture's initial shear stiffness with increasing rubber content cannot be sufficiently represented by the void ratio.

In order to derive an analytical expression from the experimental results for the initial shear modulus (G_O) of the sand/rubber mixtures, it was decided to use the "equivalent void ratio," e_{eq} introduced first by Feng and Sutter [31]. In e_{eq}, the volume of rubber solids is considered as part of the total volume of voids, whereas the volume of solid particles that contribute to the stiffness of the sand/rubber matrix is assumed

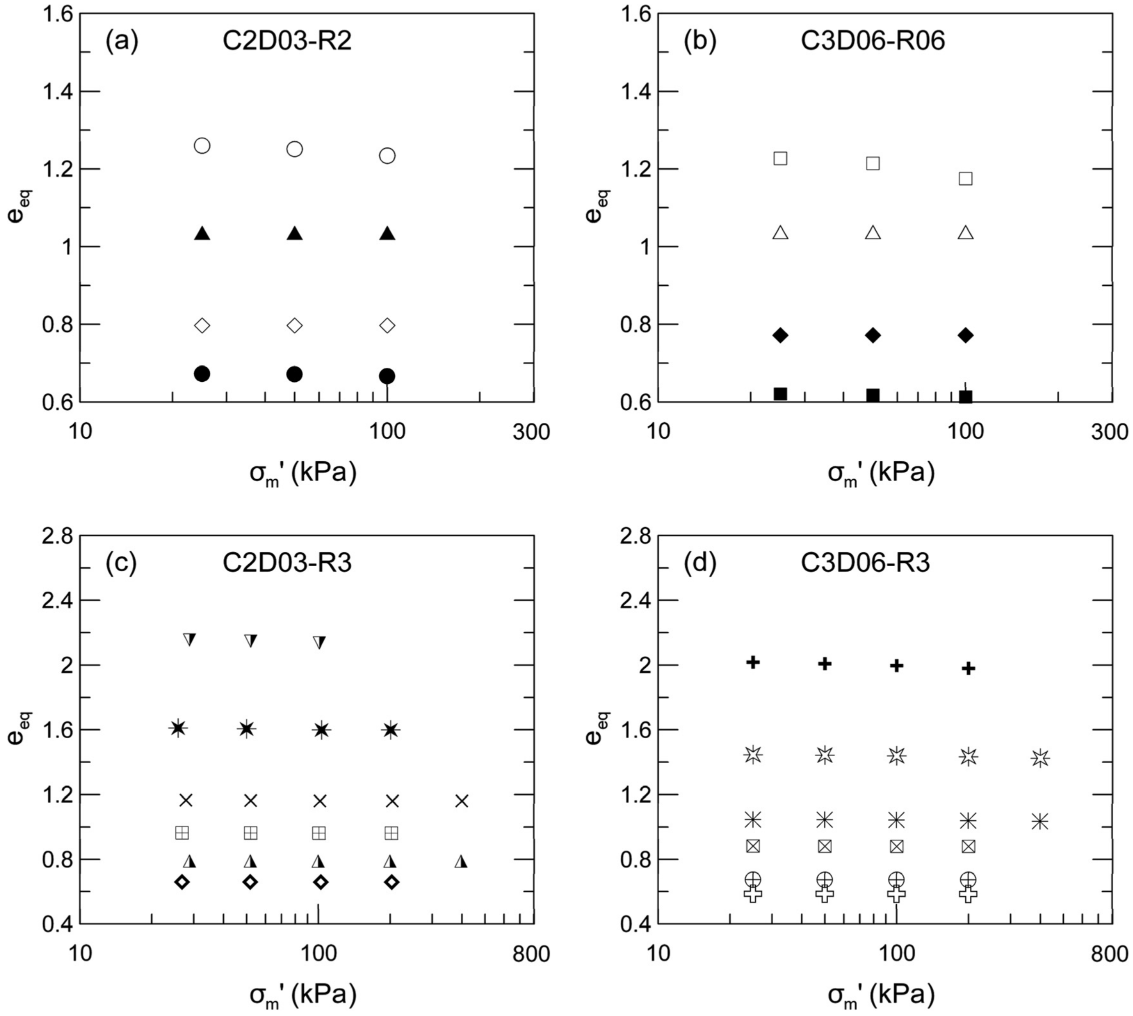

FIG. 3—*Effect of rubber content and mean confining pressure on equivalent void ratio of (a)–(b) saturated specimens, and (c)–(d) dry specimens (symbols are given in Figs. 1 and 2).*

to be the volume of the sandy particles. The analytical expression of e_{eq} is given in Eq 1, whereas the void ratio values of the mixtures are determined from Eq 2

$$e_{eq} = \frac{V_{voids} + V_{rubber}}{V_{soil}} \tag{1}$$

$$e = \frac{V_{voids}}{V_{soil} + V_{rubber}} \tag{2}$$

where

V_{soil} = volume of sandy particles,
V_{rubber} = volume of rubber particles,
V_{voids} = volume of voids.

The effect of the rubber content and σ'_m on e_{eq} of the tested specimens is shown in Fig. 3. It is observed that e_{eq} increases systematically with increasing rubber content and that, overall, the effect of σ'_m on e_{eq} is not that important. It is important to point out that the estimation of e_{eq}, for low to medium σ'_m amplitudes, assumes that the rubber particles are incompressible [46], an assumption that was also adopted by Feng and Sutter [31]. Thus, the decrease of the mixture's initial shear stiffness, as the rubber content increases, may be correlated to the increase of e_{eq}.

In Fig. 4, we plot the G_O values of the tested specimens expressed as $G_O/F(e)$, versus σ'_m. Here, F(e) is a function initially proposed by Jamiolkowski et al. [47] for sandy soils; it is given analytically with Eq 3.

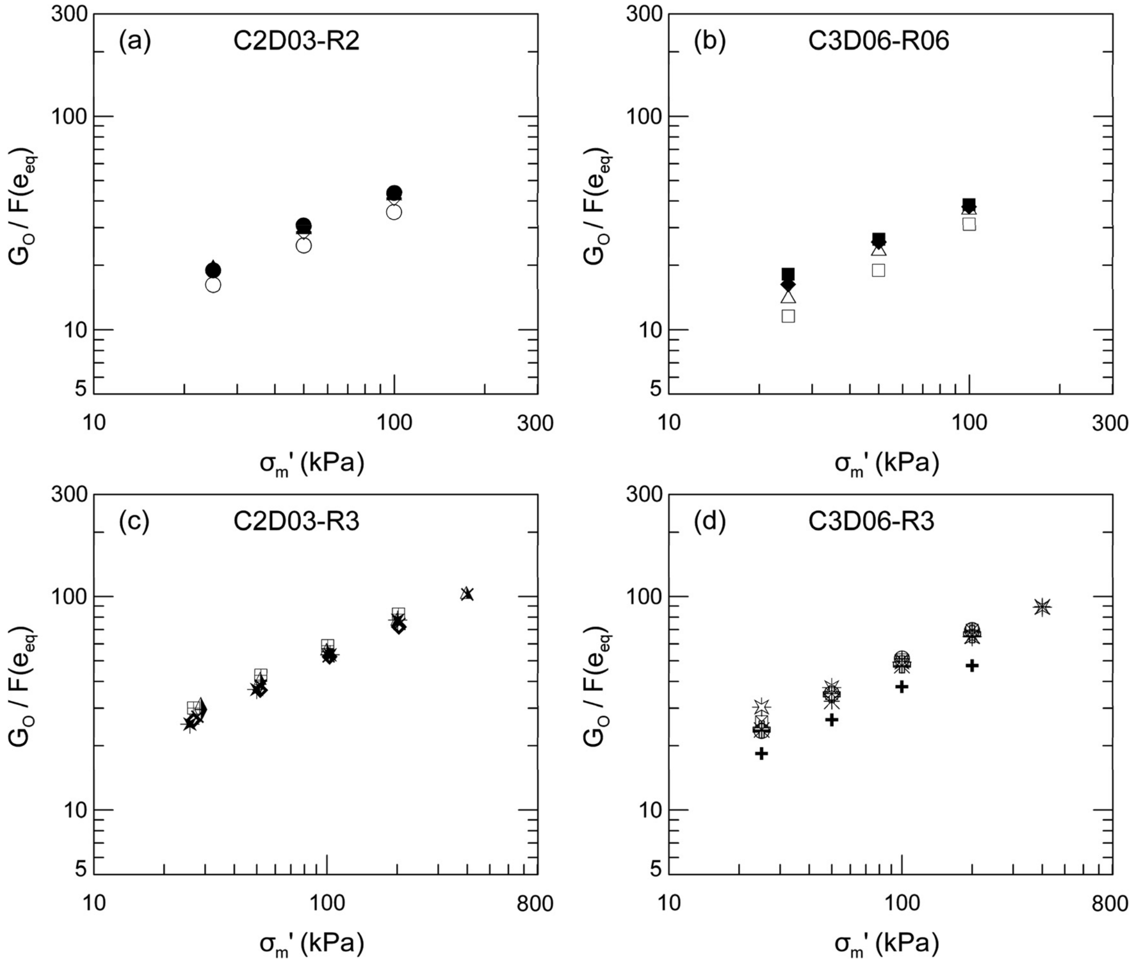

FIG. 4—*Normalized initial shear modulus values with respect to an equivalent void ratio function versus mean confining pressure of (a)–(b) saturated specimens, and (c)–(d) dry specimens (symbols are given in Figs. 1 and 2).*

In this function we introduced the e_{eq} instead of the e values. Thus, F(e) corresponds to an equivalent void ratio function, and Eq 3 may be modified to Eq 4

$$F(e) = \frac{1}{e^{1.3}} \tag{3}$$

$$F(e_{eq}) = \frac{1}{e_{eq}^{1.3}} \tag{4}$$

where

e_{eq} = equivalent void ratio given in Eq 1.

In Fig. 4 it is observed that the normalized $G_O/F(e_{eq})$ values for all specimens in each mixture group satisfactorily converge. Thus, the use of the equivalent void ratio of Eq 1 is reasonable and justified.

Furthermore, in Fig. 5 we depict the effect of the rubber content on e_{eq} of the saturated and dry mixtures, at $\sigma'_m = 100\,\text{kPa}$. In this figure, the increase of the equivalent void ratio is expressed in terms of the ratio $e_{eq}/e_{(soil)}$, where $e_{(soil)}$ is the void ratio of the intact soils. It is noticed that the increase of the ratio $e_{eq}/e_{(soil)}$ may be expressed with a simple two-order polynomial curve given in Eq 5, with a satisfactory correlation coefficient R^2. A similar relationship was also proposed by Anastasiadis et al. [42] and Senetakis [41]

$$e_{eq} = e_{(soil)} \times \left[0.0006 \times (pr)^2 + 0.0455 \times (pr) + 1\right] \tag{5}$$

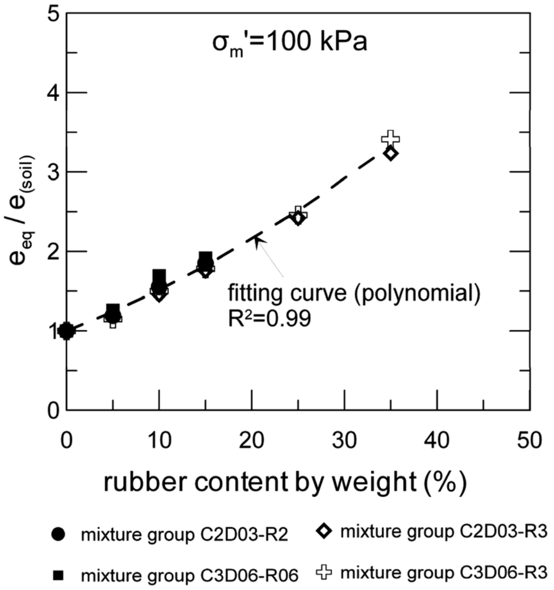

FIG. 5—*Effect of rubber content on equivalent void ratio of saturated and dry specimens at* $\sigma_m{}' = 100\,\text{kPa}$ *(*e_{eq}*: equivalent void ratio of mixture,* $e_{(soil)}$*: void ratio of clean sand).*

where

e_{eq} = equivalent void ratio of the mixtures,
$e_{(soil)}$ = void ratio of the intact soils,
pr = rubber content by mixture weight in percentile scale (%).

Knowing the void ratio of clean sand (for example, the void ratio that corresponds to a high relative density ≈ e_{min}), the equivalent void ratio of the mixture may be estimated from Eq 5 as a function of the content of rubber. Then the initial (small-strain) shear modulus of the soil/rubber mixture may be determined from Eq 6

$$G_O = A_G \times F(e_{eq}) \times (\sigma'_m)^{n_G} \tag{6}$$

where

A_G = constant value,
$F(e_{eq})$ = equivalent void ratio function given from Eqs 4 and 5,
σ'_m = mean effective confining pressure,
n_G = exponent that expresses the effect of σ'_m on G_O.

Figure 6 shows the effect of the rubber content pr on the initial damping ratio of the saturated and dry mixtures $DT_{O,mix,100}$ at $\sigma'_m = 100\,\text{kPa}$. The $DT_{O,mix,100}$ values are normalized herein with respect to the corresponding initial damping ratio of the intact soils $DT_{O,soil,100}$ at the same σ'_m. In the same figure, we illustrate the fitting curves separately for large-dry and small-saturated specimens. The increase of the small-strain damping ratio of the mixtures at $\sigma'_m = 100\,\text{kPa}$, may be expressed analytically with Eqs 7*a* and 7*b*

$$\text{Saturated } 35.7 \times 82.2 \text{ mm specimens:} \quad DT_{O,mix,100} = DT_{O,soil,100} \times e^{0.038 \times pr} \tag{7a}$$

$$\text{Dry } 71.1 \times 142.2\text{mm specimens:} \quad DT_{O,mix,100} = DT_{O,soil,100} \times e^{0.047 \times pr} \tag{7b}$$

where

$DT_{O,mix,100}$ = initial damping ratio of mixtures at $\sigma'_m = 100\,\text{kPa}$ in percentile scale (%),
$DT_{O,soil,100}$ = initial damping ratio of intact soils at $\sigma'_m = 100\,\text{kPa}$ in percentile scale (%),
pr = rubber content by mixture weight in percentile scale (%).

Finally, Fig. 7 depicts the initial damping ratio of the saturated specimens $DT_{O,mix}$ versus σ'_m. The $DT_{O,mix}$ values are normalized herein with respect to the corresponding values at $\sigma'_m = 100\,\text{kPa}$. It is

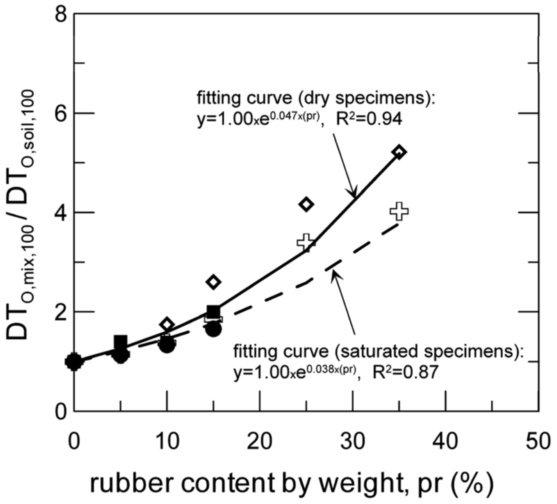

FIG. 6—*Effect of rubber content on initial damping ratio of mixtures at* $\sigma_m{}' = 100\,\text{kPa}$*,* $DT_{O,mix,100}$*, normalized with respect to the corresponding value of the clean sands, and* $DT_{O,soil,100}$ *(symbols are given in Fig. 5).*

clearly shown that the normalization in terms of the ratio $DT_{O,mix}/DT_{O,mix,100}$ eliminates the effect of the rubber content on the mixture's initial damping ratio and the initial (small-strain) damping ratio of the mixtures may be estimated from Eq 8

$$DT_{O,mix} = A_D \times DT_{O,mix,100} \times (\sigma'_m)^{n_D} \tag{8}$$

where

A_D = constant value,

$DT_{O,mix,100}$ = initial damping ratio of the mixtures at $\sigma'_m = 100\,\text{kPa}$ given from Eq 7,

σ'_m = mean effective confining pressure,

n_D = exponent that expresses the effect of σ'_m on $DT_{O,mix}$.

The analysis of the experimental results in the small-strain region led to the parameters A_G, n_G, A_D, and n_D shown in Tables 5 and 6, for dry, 71.1 mm × 142.2 mm and saturated, 35.7 mm × 82.2 mm specimens, respectively. In the same tables we show the estimated average values of these parameters and the $DT_{O,mix,100}$ values of the specimens.

It is observed that the small-saturated specimens exhibit higher values of the exponent n_G and significantly higher absolute n_D values when compared to the large-dry specimens. In addition, small specimens have lower values of G_O and higher damping ratio values. The main factor that seems to

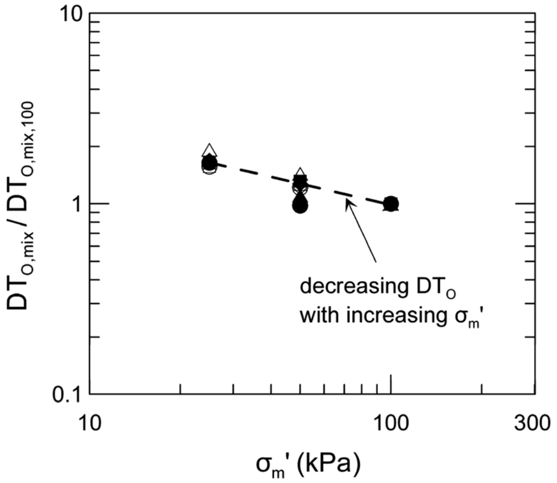

FIG. 7—*Effect of confining pressure on initial damping ratio of saturated mixtures* $DT_{O,mix}$ *normalized with respect to the corresponding value at* $\sigma'_m = 100\,\text{kPa}$*,* $DT_{O,mix,100}$ *(symbols are given in Fig. 1).*

TABLE 5—*Initial shear modulus and damping ratio parameters of dry, 71.1 mm ×142.2 mm sand/rubber specimens.*

Specimen Code	A_G	n_G	A_D	n_D	$DT_{O,mix,100}$,%
C2D03-D01	5.102	0.50	1.527	−0.09	0.60
C2D03-R3-95/5-D01	6.801	0.46	1.515	−0.09	0.67
C2D03-R3-90/10-D01	5.901	0.50	1.904	−0.12	1.05
C2D03-R3-85/15-D01	5.426	0.49	1.930	−0.13	1.56
C2D03-R3-75/25-D01	4.370	0.54	2.534	−0.20	2.50
C2D03-R3-65/35-D01	4.786	0.52	2.114	−0.17	3.13
C3D06-D01	4.995	0.49	1.402	−0.09	0.74
C3D06-R3-95/5-D01	4.451	0.52	1.747	−0.12	0.85
C3D06-R3-90/10-D01	5.511	0.48	1.580	−0.10	1.02
C3D06-R3-85/15-D01	4.975	0.48	1.434	−0.07	1.37
C3D06-R3-75/25-D01	8.396	0.39	1.865	−0.13	2.51
C3D06-R3-65/35-D01	4.300	0.46	1.856	−0.14	2.98
Average value	5.418	0.49	1.784	−0.12	…

contribute to the lower G_O values of the small specimens is the geometry of the samples since small specimens are, in general, more flexible. The effect of moisture seems to be less important on G_O, as also reported in Anastasiadis et al. [37] and Senetakis [41]. In addition, the higher DT_O values of the small specimens are mainly due to the higher shearing strain amplitude at which low-amplitude measurements were performed, as well as to strain-rate and moisture effects.

In conclusion, knowing the values of G_O, DT_O, and the void ratio (under a specific compaction energy) of a clean sand, the rubber content, and the confining pressure, the initial (small-strain) shear modulus and damping ratio of a sand/rubber mixture may be determined from Eqs 1 to 8. For the specimens tested herein, the experimental versus the estimated G_O and DT_O values are shown in Fig. 8. It should be also noted that in the above equations σ'_m is expressed in kPa, G_O in MPa, whereas pr and small-strain damping ratio are in percentile scale (%).

Effect of Duration of Confinement on Small-Strain Shear Modulus and Damping Ratio

In Figs. 9–12 we plot the variation of the void ratio, the initial shear modulus, and the initial damping ratio with the logarithm of time, in four dry specimens (71.1 mm × 142.2 mm). Considering specimens C3D06-D11 (intact sand), C3D06-R3-90/10-D11 (10 % rubber content) and C3D06-R3-65/35-D11 (35 % rubber content), the duration of the confinement is examined at σ'_m equal to 50 and 100 kPa and for a time period equal to seven [6] days at each pressure. In addition, for the specimen C3D06-R3-85/15-D11 (15 % rubber content), the duration of the confinement was studied at $\sigma'_m = 100$ kPa for 28 days. The experimental results were analyzed following well-known procedures proposed in the literature [48,49], in terms of the normalized coefficients N_G and N_D. The analytical expressions of these coefficients are illustrated in Fig. 9.

It is important to clarify at this point that time step t_1 is usually assumed to be equal to 1000 min for clayey soils, which corresponds to an efficient time period for the primary consolidation to be completed in low-drainage soils. However, as mentioned previously in this study, the sand/rubber specimens exhibit

TABLE 6—*Initial shear modulus and damping ratio parameters of saturated, 35.7 mm ×82.2 mm sand/rubber specimens.*

Specimen Code	A_G	n_G	A_D	n_D	$DT_{O,mix,100}$,%
C2D03-S11	2.790	0.60	4.744	−0.36	1.34
C2D03-R2-95/5-S11	3.145	0.56	5.492	−0.37	1.53
C2D03-R2-90/10-S11	3.220	0.57	5.500	−0.38	1.79
C2D03-R2-85/15-S11	2l654	0.57	4.425	-0.33	2.23
C3D06-S11	3.169	0.54	5.234	−0.36	1.34
C3D06-R06-95/5-S11	2.369	0.60	5.576	−0.38	1.88
C3D06-R06-90/10-S11	1.594	0.69	8.915	−0.47	1.86
C3D06-R06-85/15-S11	1.167	0.71	4.497	−0.33	2.68
Average value	2.514	0.61	5.548	−0.37	…

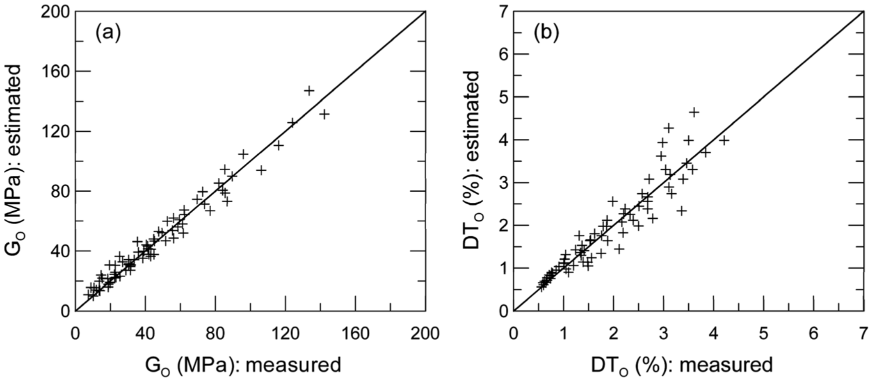

FIG. 8——*Experimental versus estimated (a) initial shear modulus, and (b) initial damping ratio values of sand/rubber mixtures.*

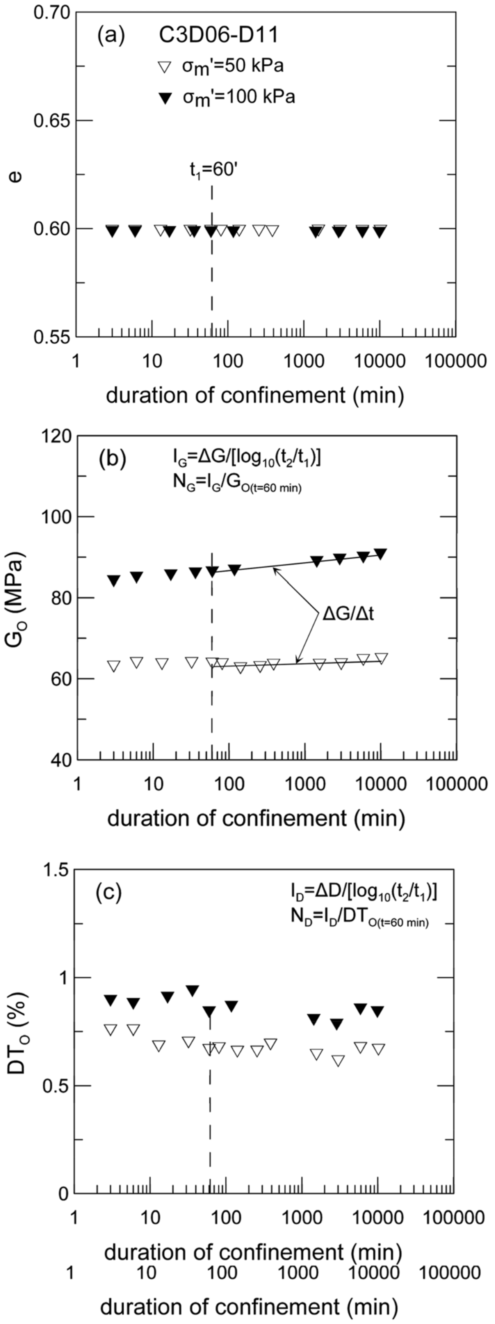

FIG. 9—*Effect of the duration of confinement on small-strain shear modulus and the damping ratio of specimen C3D06-D11.*

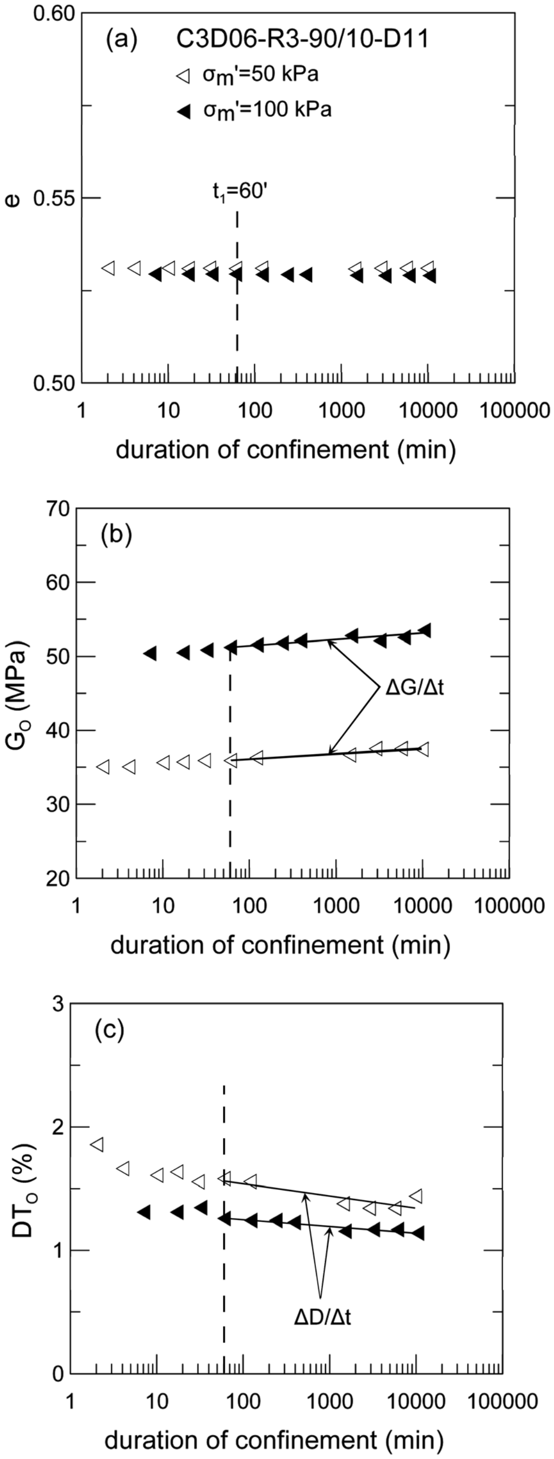

FIG. 10—*Effect of the duration of confinement on the initial shear modulus and the damping ratio of specimen C3D06-R3-90/10-D11.*

high-drainage capacity, mostly like clean granular soils, and consequently, the application of an external load increment leads to immediate settlements. For the small-saturated specimens of this study, a time period on the order of 2 to 5 min was efficient for the pore water pressure to equilibrate, whereas for the large-dry specimens, a time period of 60 min was, in general, an efficient time period for the low-amplitude resonant frequency to equilibrate. Thereafter, it was decided to use in the calculations a time step t_1 equal to 60 min, whereas time step t_2 corresponds to approximately 10^4 minutes (≈7 days) or 4×10^4 minutes (≈28 days) for the tested specimens.

In Table 7 the coefficients N_G and N_D of the tested samples are summarized. It is indicated in this table, and in Fig. 9, that the clean sand exhibits a linear increase of G_O with the logarithm of time. However,

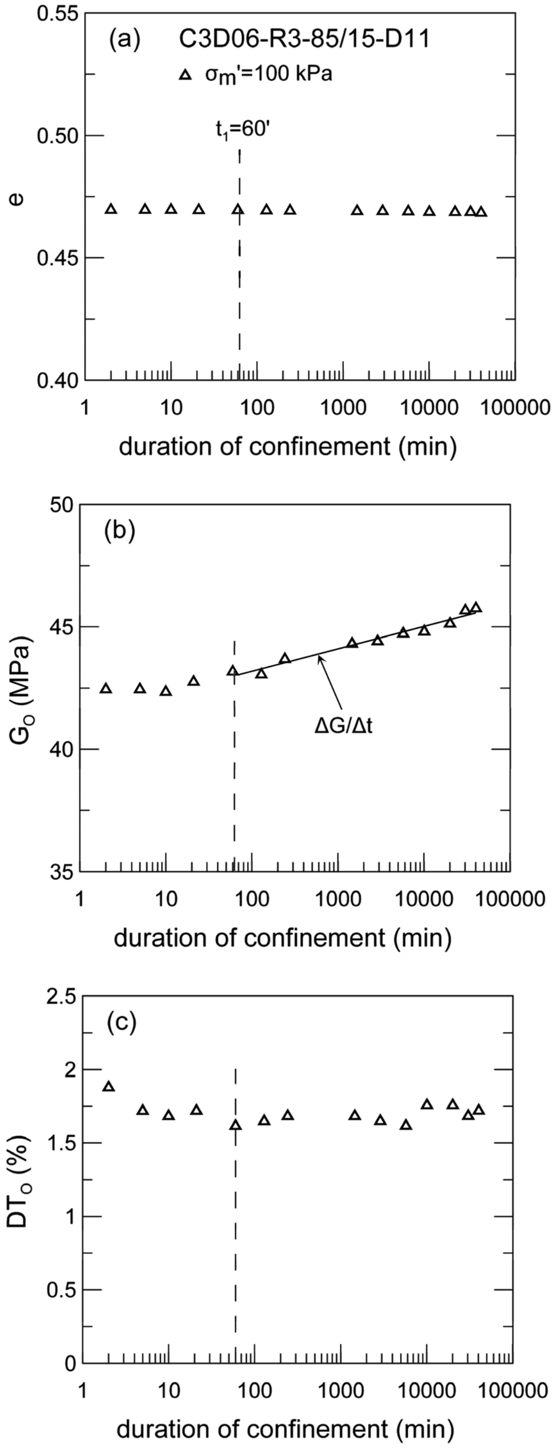

FIG. 11—*Effect of the duration of confinement on the initial shear modulus and damping ratio of specimen C3D06-R3-85/15-D11.*

the coefficient N_G is low: not larger than 1 to 3 %. These values are in good agreement with the experimental results of other researchers on similar materials (Afifi and Richart [48] Anderson and Stokoe [49], Baxter [50] and Wichtmann and Triantafyllidis [51]). In addition, the initial damping ratio of the clean sand is not clearly affected by the duration of confinement (the coefficient N_D is not determined in this case). Thus, the overall time effect on the small-strain response of the clean sand is nearly negligible.

Regarding the sand/rubber mixtures, it is observed in Figs. 10–12 and Table 7 that G_O and DT_O exhibit, in general, a linear variation with the logarithm of time. The specimen C3D06-R3-90/10-D11 presents N_G and N_D values on the order of 2 to 4 % and the specimen C3D06-R3-65/35-D11 presents N_G and N_D values on the order of 3 to 7%. It may thus be concluded that the effect of the duration of

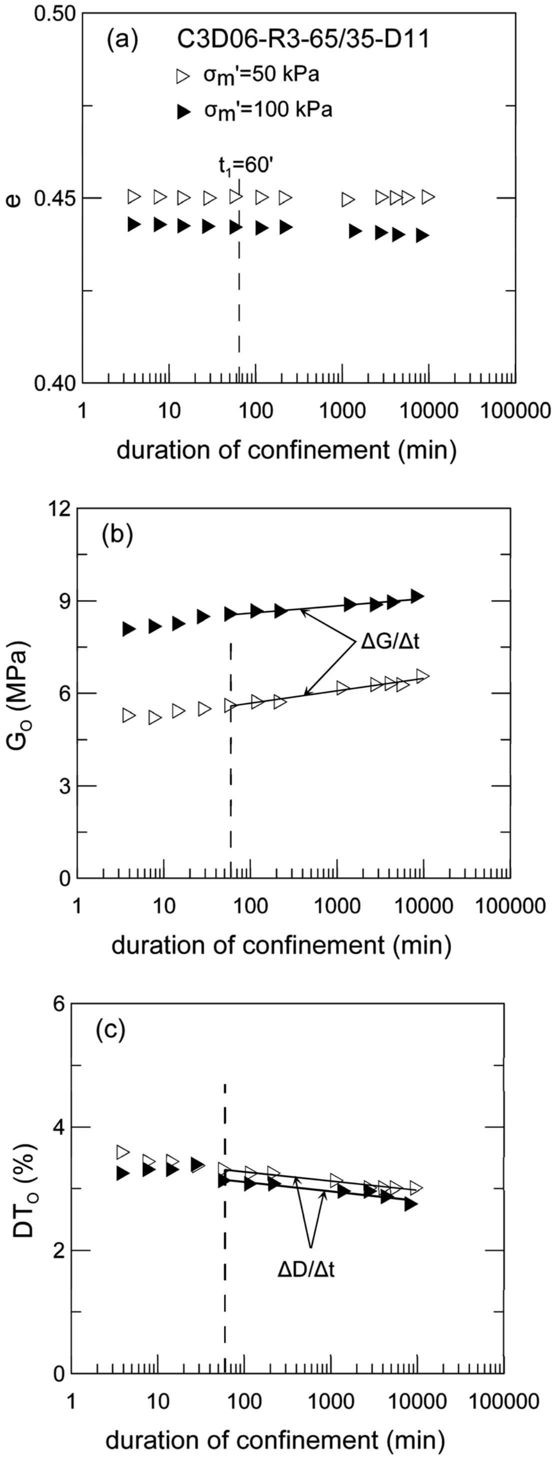

FIG. 12—*Effect of the duration of confinement on the initial shear modulus and the damping ratio of specimen C3D06-R3-65/35-D11.*

confinement is not that important in the case of the sand/rubber mixtures studied herein; however, it is observed that the time-effects are more pronounced as the rubber content increases.

Further research on this subject is certainly needed in order to systematically examine the effect of the rubber content on the parameters N_G and N_D of sand/rubber mixtures, along with the behavior of clean recycled rubber under the application of a constant confining pressure. In addition, it is questioned as to whether or not the relative size of rubber solids versus soil solids (in terms of the ratio $D_{50,r}/D_{50,s}$) affects the long-term behavior of the mixtures. At this stage, and concerning low to relatively medium rubber contents and low to medium confining pressures, the analytical relationships proposed herein adequately estimate the G_O and DT_O values of sand/rubber mixtures for practical engineering applications.

TABLE 7—*Normalized coefficients N_G and N_D of dry, 71.1 mm ×142.2 mm sand/rubber specimens.*

Specimencode	σ'_m, kPa	N_G, %	N_D, %
C3D06-D11	50	0.9	…
	100	2.3	…
C3D06-R3-90/10-D11	50	1.9	2.0
	100	3.8	4.0
C3D06-R3-85/15-D11	50	…	…
	100	2.1	…
C3D06-R3-65/35-D11	50	7.3	4.2
	100	3.3	5.8

Conclusions and Recommendations

We presented a comprehensive set of low-amplitude resonant column tests on saturated specimens 35.7 mm in diameter and 82.2 mm in height and 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 physical portion and uniform rubber materials of variable contents as synthetic portion. The main conclusions of this work and the recommendations for further research are summarized as follows:

The small-strain shear modulus G_O of the sand/rubber mixtures decreases and the damping ratio DT_O systematically increases with increasing rubber content and decreasing mean confining pressure. Based on the experimental results, we found that it is possible to express the small-strain shear modulus G_O of a sand/rubber mixture, using an equivalent void ratio, in which the volume of the rubber solids is considered as part of the total volume of voids. This is possible because of the small contribution of rubber solids on the shear stiffness of the sand/rubber matrix.

It was also observed that the specimen's geometry affects the small-strain behaviour of the samples. Small-saturated specimens 35.7 mm in diameter exhibit, in general, lower values of G_O and higher damping DT_O values compared to large-dry specimens 71.1 mm in diameter. Moreover, the confining pressure affects the small-strain response of the 35.7 mm diameter specimens in a more pronounced way. Regarding G_O, this behaviour may be explained as a scale effect and lower flexibility of small specimens, while for the damping ratio DT_O, it is believed that besides the lower stiffness of smaller specimens, the strain-rate and moisture effects may also have an important role. Furthermore, the duration of the confinement on the small-strain behaviour of the soil/rubber mixtures is found, in general, to be of low importance; however, an increase of the rubber content leads to more pronounced time-effect phenomena.

Simple relationships were proposed for the estimation of G_O with the rubber content, mean confining pressure, and equivalent void ratio e_{eq}. Equally simple expressions are proposed for the estimation of DT_O with the rubber content and mean confining pressure. The rubber percentages of the studied mixtures satisfactorily cover the range of rubber/sand mixtures used in practice. However, it is believed that further research is needed on mixtures that are composed of granular soils and recycled rubber or tire chips that cover a wider range of mean grain size and coefficient of uniformity values and variable values of the ratio $D_{50,r}/D_{50,s}$. In addition, comprehensive studies on similar materials using different laboratory methods as, for example, cyclic triaxial tests or bender elements and low-amplitude tests on specimens of larger sizes are also needed in order to enrich the findings of this work.

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