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Small-Strain Shear Modulus and Damping Ratio of Sand-Rubber and Gravel-Rubber Mixtures

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Abstract This study examines the small-strain dynamic properties of mixtures composed of sandy and gravelly soils with granulated tire rubber in terms of shear modulus (G_O), and damping ratio in shear (D_{min}). Torsional resonant column tests are performed on dry, dense specimens of soil-rubber mixtures in a range of soil to rubber particles size 5:1–1:10 and rubber content from 0 to 35% by mixture weight. The experimental results indicate that the response of the mixtures is significantly affected by the content of rubber and the relative size of rubber to soil particles. Concering the small-strain shear modulus, an equivalent void ratio is introduced that considers the volume of rubber particles as part of the total volume of voids. Based on a comprehensive set of test results a series of equations were developed that can be used to evaluate the shear modulus and damping ratio at small shear strain levels if the confining pressure, the content of rubber by mixture weight, the grain size of soil and rubber particles, and the dynamic and physical properties of the intact soil are known.

Keywords Shear modulus · Damping ratio · Soil-rubber mixtures · Resonant column testing

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1 Introduction

The reinforcement of soils using tire shreds and granulated rubber is a modern application in civil engineering following the pressing need of exploring innovative and beneficial ways of using recycled materials in common engineering projects. Granulated tire rubber materials composed of recycled tire shreds exhibit interesting physical, mechanical and dynamic properties.

Several researchers have summarized practical or experimental civil engineering projects that performed satisfactory, where pure tire rubber, tire balls, or soil-rubber mixtures were used as construction or fill material (Humphrey and Manion 1992; Bosscher et al. 1993 and Bosscher et al. 1997; Edil and Bosscher 1992, 1994; Hoppe 1994; Foose et al. 1996; Zornberg

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et al. 2004a, b; Abichou et al. 2004; Humphrey 2004; Edeskar 2006). Granulated tire rubber has been used as backfill material in retaining walls, to reduce the lateral earth pressures (Humphrey and Sandford 1993; Humphrey et al. 1997; Lee et al. 1999; Kaneda et al. 2007), as construction material in embankments overlying soft or unstable soils to reduce the vertical stresses and settlements (Bosscher et al. 1997; Zornberg et al. 2004a; Edil 2004; Edincliler 2007; Humphrey 2007), or as drainage layer (Reddy and Saichek 1998; Edeskar 2006; Karmokar 2007). In addition, pure rubber and soil-rubber mixtures have been proposed as isolation system to modify the seismic response of foundations/superstructures (Tsang 2008; Senetakis et al. 2009; Pitilakis et al. 2010, 2011), retaining walls (Hazarika 2007; Hazarika et al. 2007, 2008) and buried pipes (Uchimura et al. 2007).

Considering relatively low to medium rubber content, the main factors that affect strongly the dynamic behavior of soil-rubber mixtures are the content of rubber, the contrast in particle size, shape and mass density of rubber solids compared to the soil solids as well as the dynamic properties of the soil part of the mixtures (Kim and Santamarina 2008; Senetakis et al. 2011a). The predominant behavior that the mixtures exhibit, that is soil-like or rubber-like behavior, depends on the predominant interfaces of the soil-rubber solid skeleton. Ahmed (1993) and Zornberg et al. (2004a) have indicated that for content of rubber by mixture weight below 35–40%, the mixtures exhibit high shear strength, satisfactory compaction characteristics, dilatant behavior and the response of the mixtures is characterized as sand-like.

Kim and Santamarina (2008) examining the response at small-strain amplitudes of sand-rubber mixtures using a modified oedometer cell instrument with bender-elements and a ratio D_{soil}/D_{rubber} equal to 1:10, indicated that up to a specific content of rubber by mixture volume on the order of 20%, the shear wave velocity of the mixtures increases, and above that content the trend is reversed. This increase of small-strain shear stiffness with a simultaneous increase of damping ratio as the content of rubber increases in the mixture and up to a specific rubber content was also observed by Pamukcu and Akbulut (2006), on sand-rubber mixtures having a ratio D_{soil}/D_{rubber} equal to 1:1. On the other hand, Feng and Sutter (2000) as well as Anastasiadis et al. (2009) performing resonant column tests on sand-rubber mixtures having a ratio D_{soil}/D_{rubber} equal to 1:4 and 1:5 respectively, indicated that an increase of rubber content leads to a monotonically decrease of shear stiffness at low strain levels and to an increase of mixtures damping ratio. In addition, Anastasiadis et al. (2009), Senetakis (2011) and Senetakis et al. (2011a) reported a more linear behavior of soil-rubber mixtures as the content of rubber increases in the region of medium to high shearing strain amplitudes ($\gamma = 10^{-2}$–10^{-1}%).

In previous studies both the static and dynamic properties of pure rubber and soil-rubber mixtures have been studied. The compaction, compressibility and strength characteristics of rubber materials and granular soil-rubber mixtures are presented in Humphrey and Manion (1992), Edil and Bosscher (1992, 1994), Bosscher et al. (1993), Foose et al. (1996), Masad et al. (1996), Wu et al. (1997), Lee et al. (1999), Zornberg et al. (2004a), Edeskar (2006), Kawata et al. (2007), Edincliler (2007) and others, whereas the effect of rubber content on the dynamic response and liquefaction potential of the aforementioned mixtures as well as the effect of rubber on the dynamic response of geo-structures when used as fill or construction material were presented in Feng and Sutter (2000), Pamukcu and Akbulut (2006), Kim and Santamarina (2008), Hyodo et al. (2007), Kawata et al. (2007), Uchimura et al. (2007), Hazarika et al. (2008), Anastasiadis et al. (2009) and Senetakis et al. (2011a). Recently, Anastasiadis et al. (2012) and Senetakis et al. (2012) proposed analytical relationships for the estimation of shear modulus and damping ratio of granular soil/rubber mixtures in a wide range of shearing strain amplitudes. In addition, Anastasiadis et al. (2012) and Senetakis et al. (2012) examined the effect of duration of confinement on the response of the mixtures of variable rubber content as well as the effect of specimens' size on the experimental data. However, the aforementioned studies were limited only on mixtures that were composed of fine to medium grained uniform sands as physical portion and the ratio D_{soil}/D_{rubber} was equal to or lower than unity.

The present paper examines the small-strain dynamic properties in terms of shear modulus and damping ratio of mixtures composed of clean granular soils involving uniform sands, gravely sands and gravels as well as well-graded gravelly soils as physical portion and granulated tire rubber of different particle sizes as synthetic portion. The experimental program involved torsional resonant column tests, and is part of an extensive research program aiming to investigate the dynamic behaviour and characteristics of soil-rubber mixtures (Senetakis 2011; Anastasiadis et al. 2012; Senetakis et al. 2012). Considering the high permeability that granular soil-rubber mixtures exhibit as well as the main applications of the aforementioned materials, the specimens of this study were examined in dry conditions and high relative density. Particular emphasis is placed on the evaluation of the influence of the relative size of rubber solids in comparison to the soil solids as well as the content of rubber in the mixture and the effect of the coefficient of uniformity of the soil part of the mixtures on the shear modulus (G_O) and damping ratio (D_{min}) at low strain levels. In addition, based on the test results a series of simple equations was developed that may be used for practical purposes to estimate the G_O and D_{min} of the aforementioned complex materials for given the mean confining pressure, the content of rubber by mixture weight, the ratio of mean grain size of soil particles via rubber particles, the initial dynamic properties as well as the grain size characteristics of the pure soil in a range of rubber solids size versus soil solids size from 10:1 to 1:5. The effect of rubber content on the dynamic response of the aforementioned mixtures in the range of medium to high strain levels is comprehensively presented and discussed by Senetakis (2011) and Senetakis et al. (2011b).

2 Materials Tested, Sample Preparation and Testing Program

2.1 Materials Used

Seven granular soils of different grain size distribution ($D_{50} = 0.27$–7.80 mm and $C_u = 1.2$–12.5) and four approximately uniform rubber materials of different mean grain size ($D_{50} = 0.35$–3.00 mm) are used. All natural (sands, gravels) and synthetic (rubber) materials have a coefficient of curvature near to unity. Three of the granular soils are composed of natural sand of sub-rounded to rounded particles, whereas the other four soils are composed of quarry sandy gravel of sub-angular to angular particles. The granulated rubber materials of this study are composed of recycled tire shreds. Table 1 summarizes the physical properties of the materials used, whereas Figs. 1 and 2 show the grain-size distribution curves of the soils and the rubber materials, respectively.

2.2 Experimental Equipment and Sample Preparation

All dynamic experiments were performed in a fixed-free type longitudinal—torsional resonant column apparatus (Drnevich 1967). The specimen is rigidly fixed at bottom and the excitation is applied at the top-active end while the excitation is achieved using sinusoidal electromagnetic force of controlled magnitude. In order to obtain measurements in resonance, the excitation frequency at each step of force magnitude is adjusted, until the velocity at the active end of the specimen is 180 degrees out of phase with the applied force. The tested specimens of approximately 71.1 mm diameter and 142.2 mm height were constructed in dry conditions using a metal mold. The ASTM D4015-92 specifications were followed for procedures and data reduction.

Soil and rubber materials were first dry mixed in the appropriate percentages; then dry specimens were constructed in layers into the device using the uniform mixture. Specifically, specimens were constructed very carefully in many layers of equal dry mass material using a funnel and following the under-compaction method. For this purpose, a metal rod tamper was used and the tips were applied at increasing number from the bottom to the top layers. All specimens of the clean granular soils and the soil-rubber mixtures were constructed using the same number of layers and tips in order to retain approximately constant the compaction energy. During the specimens preparation it was observed that for low content of rubber and relatively high ratio of soil particles versus rubber particles size, segregation during the construction was not avoided; for this reason minimizing of any vibration during sample preparation was mandatory.

2.3 Testing Program

Forty-two torsional resonant column tests were performed on dense to very dense, dry soil-rubber specimens using different percentages of granulated tire rubber in a range of mean confining pressures of 25–400 kPa. Performing low amplitude measurements during the application of the isotropic confining

Table 1 Physical properties of materials used for the construction of soil-rubber mixtures

	Material code	Initial material	D_{50} (mm)[a]	C_u [b]	γ_S (gr/cm^3)[c]
Sandy and gravely materials	C2D03	Rounded fluvial sand	0.27	1.58	2.67
	C3D06	Rounded fluvial sand	0.56	2.76	2.67
	C2D1	Rounded fluvial sand	1.33	2.13	2.67
	C2D3	Angular sandy gravel	3.00	2.45	2.67
	C6D3	Angular sandy gravel	2.90	5.95	2.67
	C13D3	Angular sandy gravel	3.00	12.50	2.67
	C1D8	Angular sandy gravel	7.80	1.22	2.67
Granulated rubber materials	R03	Recycled tire rubber	0.34	1.95	1.10
	R06	Recycled tire rubber	0.40	2.65	1.10
	R2	Recycled tire rubber	1.50	1.81	1.10
	R3	Recycled tire rubber	2.80	2.29	1.10

[a] Mean grain size of particles

[b] Coefficient of uniformity = D_{60}/D_{10}

[c] Specific gravity of particles

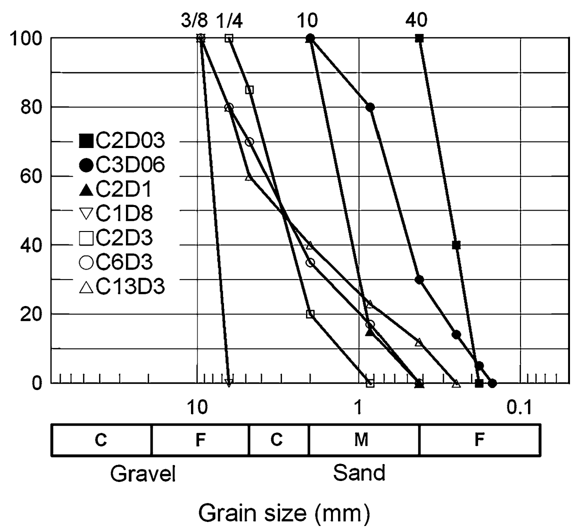

Fig. 1 Grain-size distribution curves of clean granular soils

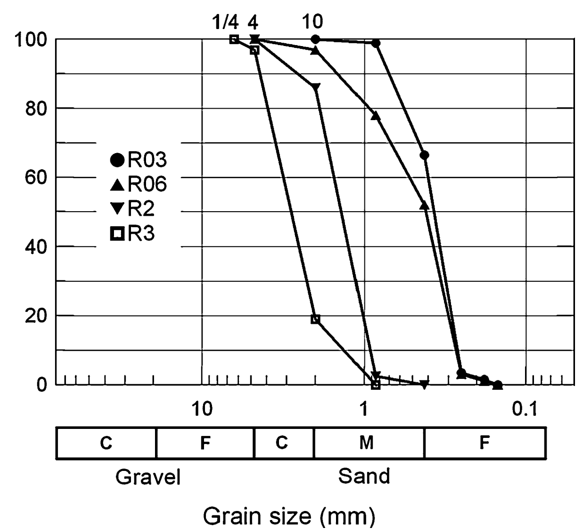

Fig. 2 Grain-size distribution curves of clean granulated rubber materials

pressure at various specimens and for close time steps, it was observed that 60–80 min was an appropriate time period for all specimens to equilibrate and to stabilize the measured values of shear modulus and damping ratio at low shear strain levels. Thus, for all specimens, each confining pressure was applied for 60–80 min before the torsional excitation. This time period was also reported by Anastasiadis et al. (2009) and Senetakis (2011), as a sufficient time to consolidate of high-drainage capacity saturated clean sands and specimens of sand-rubber mixtures. Similar time period is also reported by Menq (2003) on his extensive experimental study on the dynamic properties of granular soils.

The main characteristics of the test series conducted in this study are summarized in Table 2. Each test series involves low-amplitude as well as high-amplitude resonant column measurements focusing on the effect on low strain shear modulus (G_O) and damping ratio (DT_{min}) of various parameters. The first test series comprises five uniform to poor graded soils

Table 2 Torsional resonant column testing program on dry, dense soil-rubber mixtures: main characteristics of tested specimens (71.1 mm diameter and 142.2 mm height)

Mixture group code	$D_{50,r}/D_{50,s}$	Percentage of rubber by mixture weight (%)					
		0	5	10	15	25	35
C2D03/R3[a]	10:1	●	●	●	●	●	●
C2D03/R03	1:1		●		●	●	
C3D06/R3	5:1	●	●	●	●	●	●
C2D1/R3	2:1	●			●	●	●
C2D3/R3	1:1	●	●	●	●	●	●
C2D3/R06	1:5		●		●	●	●
C6D3/R3	1:1	●	●		●		●
C13D3/R3	1:1	●	●		●	●	●
C1D8/R2	1:5	●	●		●	●	

● Tested specimens

[a] Specimens of soil-rubber mixtures using C2D03 and R3 as soil and rubber respectively

(C2D03, C3D06, C2D1, C2D3 and C1D8), with increasing mean grain size ($D_{50} = 0.27$, 0.60, 1.33, 3.00 and 7.80 mm respectively), tested in mixtures with rubber materials R3 and R2 (mixture groups C2D03/R3, C3D06/R3, C2D1/R3, C2D3/R3 and C1D8/R2). The aim is to examine, the influence of rubber content and relative size of rubber solids versus soil solids in a range of rubber content varying from 0 to 35% by mixture weight, and for mean grain size of rubber solids versus soil solids, $D_{50,r}/D_{50,s}$, equal to 10:1, 5:1, 2:1, 1:1 and 1:5, respectively.

In addition, the effect of rubber content on mixtures' dynamic properties including soils of the same mean grain size as well as the same ratio $D_{50,r}/D_{50,s}$ but with different coefficient of uniformity is studied. For this purpose, two well graded soils having mean grain size equal to 3.00 mm and a ratio $D_{50,r}/D_{50,s}$ equal to 1:1, as the material C2D3 exhibit, but coefficient of uniformity equal to 5.95 and 12.5 (C6D3 and C13D3 materials, respectively) are tested in mixtures with rubber material R3 (mixture groups C6D3/R3 and C13D3/R3, respectively).

Finally, the effect of rubber content on mixtures' dynamic properties including uniform soils of the same ratio $D_{50,r}/D_{50,s}$ but different mean grain size of soil solids is studied. For this purpose, the soils having code names C2D03 and C2D3 are tested in mixtures with finer rubber grains (R03 and R06). The aforementioned mixtures (C2D03/R03 and C2D3/R06) exhibit a ratio $D_{50,r}/D_{50,s}$ equal to 1:1 and 5:1, respectively, as the mixtures C2D3/R3 and C1D8/R2. This test series allowed the evaluation of the effect of the mean grain size of soil solids and the ratio $D_{50,r}/D_{50,s}$ on the dynamic properties of the mixtures in a more detailed manner.

2.4 Effect of Rubber Percentage on Soil-Rubber Unit Weight and Void Ratio

Table 3 summarizes the void ratio values of specimens of mixture group C3D06/R3 that were constructed in the resonant column device as well as the parameters e_{max} and e_{min} of a compaction testing program on similar mixtures (C3D06/R2 samples) presented in Senetakis (2011). In general e_{min} and e values decrease with increasing rubber content. Most specimens exhibit slightly lower void ratio values in comparison to the e_{min} values of similar mixtures. Thus, it was assumed that C3D06/R3 specimens having rubber contents equal to 0, 5, 15 and 25% were constructed at a relative density equal to 100%, whereas the specimen having 10% content of rubber was constructed at a relative density on the order of 91%. The sample preparation method followed in this study led intensively to the construction of dense to very dense specimens.

Figure 3 shows the effect of percentage of rubber on the void ratio and dry unit weight of three out of nine soil-rubber mixture groups that were tested in this study, at a mean confining pressure of 25 kPa. The general trend is that void ratio and dry unit weight of soil-rubber mixtures decrease with increasing rubber content. Consequently, an increase in rubber content

Table 3 Relative density estimation of dry specimens of mixture group C3D06/R3 tested in this study on the basis of standard compaction results on similar materials

Percentage of rubber by mixture weight (%)	e^{a}_{max}	e^{a}_{min}	e^{b}	D_r (%)[c]
0	0.840	0.591	0.588	100
5	0.809	0.539	0.494	100
10	0.854	0.475	0.511	91
15	0.863	0.480	0.471	100
25	0.790	0.425	0.417	100

[a] Experimental values of a standard compaction testing program on mixture group C3D06/R2 (Senetakis 2011)

[b] Values of dry 71.1 × 142.2 mm specimens of mixture group C3D06/R3 tested in Resonant Column

[c]Assumed values of dry specimens of mixture group C3D06/R3

in the mixture leads to a denser soil-rubber structure due to the lower void ratio, (also marked in Table 3), as well as to a more lightweight material due to the lower unit weight.

In Table 4 the tested specimens are categorized in six (6) groups based on the content of rubber by mixture weight. The values of dynamic shearing strain at which low-amplitude shear modulus and damping ratio are defined, increase with the content of rubber in the mixture. This is more pronounced for relatively high percentages of rubber, due to the flexibility of the rubber solids. Thus, low-amplitude resonant column measurements that are performed at specific torsional forces are obtained at higher cyclic shearing strains as the percentage of rubber increases. In addition, an extension of the elastic-linear region is observed as the content of rubber increases, in specific for percentages above 15% by mixture weight. In the same table, the corresponding percentages of rubber in terms of mixture volume are shown. It should be noted that percentages of rubber equal to 25% and 35% by weight of mixture correspond to percentages of 45 and 55% by mixture volume, respectively. These percentages of rubber content in the mixture correspond roughly to the threshold between sand-like and rubber-like behaviour.

3 Results and Discussion

3.1 Effect of Rubber Inclusion and Content

The general trend of the effect of rubber inclusion and content on mixtures small-strain dynamic properties is illustrated in Fig. 4a and b, where we present the experimental results with respect to the fine uniform sand (code: C2D03) and the rubber material R3, that is C2D03/R3 mixture group. Shear modulus at low strain levels, G_O, decreases while damping ratio in shear, D_{min}, increases with the content of rubber in the mixture. This trend was observed at all specimens tested in this study and is more pronounced for percentages of rubber by mixture weight above 10% regarding the G_O and above 5% regarding the D_{min} values. The pure granulated rubber material (code: R3) tested by Anastasiadis et al. (2009) exhibit approximately 100 times lower values of shear modulus and 10 times higher damping ratio in comparison to the pure sandy soil specimen. The small-strain shear

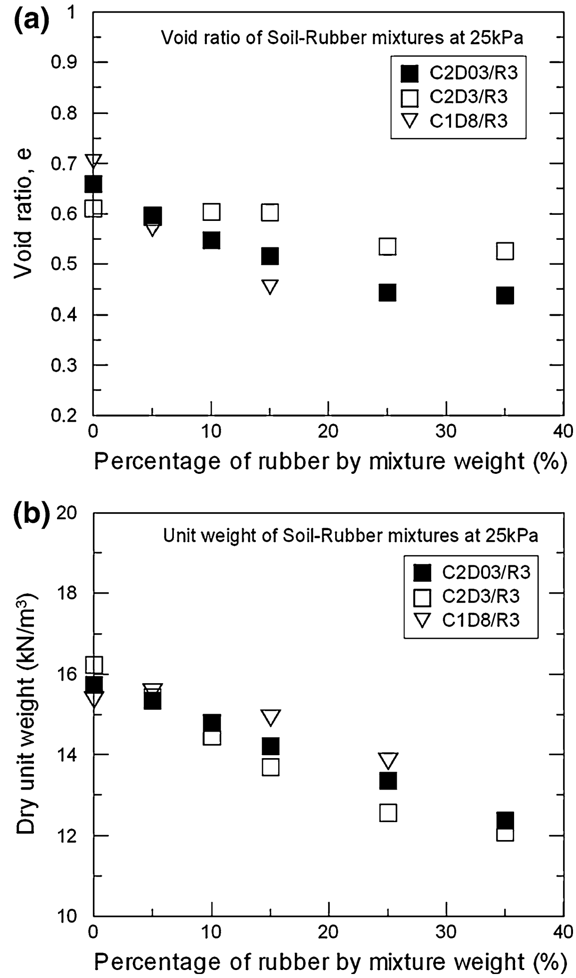

Fig. 3 Effect of rubber percentage on **a** void ratio and **b** dry unit weight of soil-rubber mixtures (values at a mean confining pressure of 25 kPa)

Table 4 Torsional resonant column testing program on dry, dense soil-rubber mixtures: Range of shear strain values at which G_O and D_{min} values are referred in this study

Soil-rubber group	Percentage of rubber by mixture weight (%)	Percentage of rubber by mixture volume (%)	Low amplitude shearing strain, γ (%)[c]
100/0[a]	0	0	1.15×10^{-4}–8.16×10^{-4}
95/5[b]	5	10	1.47×10^{-4}–6.40×10^{-4}
90/10	10	20	3.59×10^{-4}–9.40×10^{-4}
85/15	15	30	2.70×10^{-4}–9.83×10^{-4}
75/25	25	45	6.80×10^{-4}–2.60×10^{-3}
65/35	35	55	8.90×10^{-4}–4.60×10^{-3}

[a] Group of pure soil specimens

[b] Group of specimens with 5% rubber by mixture weight

[c] Dynamic shearing strain at which G_o and D_{min} are defined in this study

modulus and damping ratio values obtained for the pure granulated rubber ($G_O \approx 1$ MPa and $D_{min} \approx$ 6–7%) are in good agreement with results reported by Feng and Sutter (2000) on similar material. The experimental results of mixture groups C2D03/R3 and C3D06/R3 concerning the region of small strain levels are analytically presented by Anastasiadis et al. (2012).

3.2 Stiffness

The significant low shear stiffness of the rubber specimen (code: R3) compared to the pure sandy specimen (code: C2D03) indicates that the contribution of granulated tire rubber solids on the small-strain dynamic shear stiffness of the sand-rubber matrix is negligible. This is shown in Fig. 5 where we plot the G_O values versus the mean confining pressure (σ'_m) in log scale with respect to two specimens of mixture group C2D03/R3 (C2D03/R3-95/5: 5% rubber content, C2D03/R3-75/25: 25% rubber content by mixture weight). In the same figure we plot the analytically derived G_O values of the aforementioned specimens using empirical relations proposed in the literature for clean granular soils (Saxena and Reddy 1989; Menq 2003). In these empirical relations an equivalent void

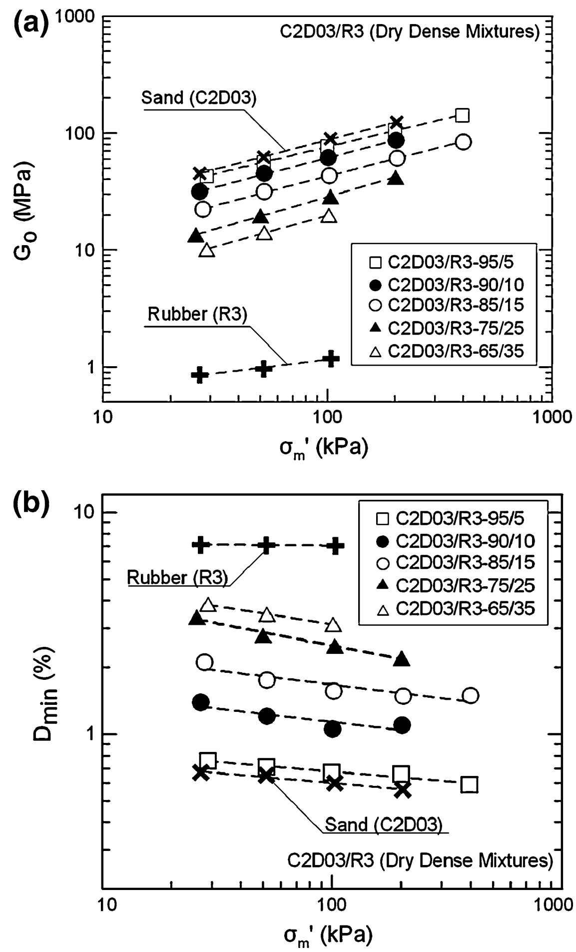

Fig. 4 Effect of rubber percentage on **a** small-strain shear modulus and **b** small-strain damping ratio of mixture group C2D03/R3 (C2D03/R3-95/5: specimen with 5% rubber content by mixture weight)

ratio e_{eq} is used, instead of the typical void ratio, defined as (Fenq and Sutter 2000):

$$e_{eq} = \frac{V_{Voids} + V_{Rubber}}{V_{Soil}} \tag{1}$$

where, e_{eq} is the equivalent void ratio of the soil-rubber mixture, V_{Voids} is the volume of the voids, V_{Rubber} is the volume of the rubber solids and V_{Soil} is the volume of the soil solids. Therefore, due to the small contribution of the soft rubber solids on the shear stiffness of the soil-rubber matrix, the volume of rubber solids is assumed to be part of the total volume of voids. The empirical relations developed on the basis of e_{eq} and inspired of similar expression of granular soils, are proved evaluate in a satisfactory

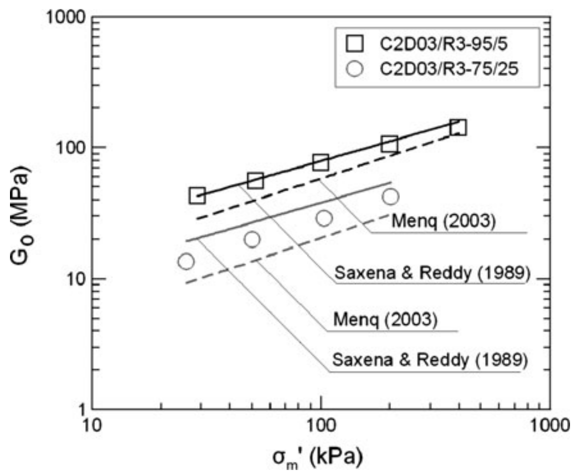

Fig. 5 Experimentally and analytically derived small-strain shear modulus values versus mean confining pressure of specimens of mixture group C2D03/R3 (C2D03/R3-95/5: specimen with 5% rubber by mixture weight)

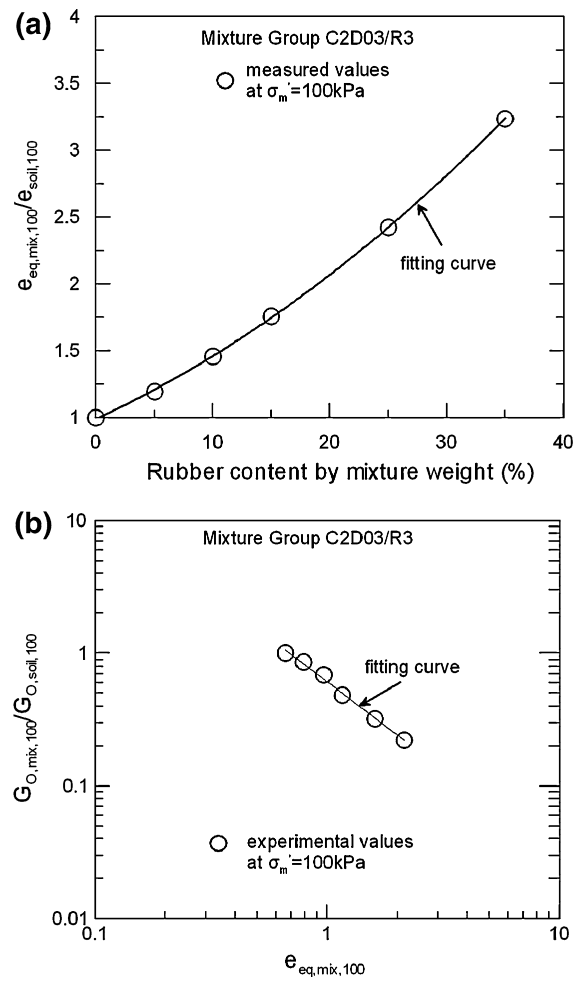

Fig. 6 **a** Effect of rubber percentage on the equivalent void ratio and **b** effect of equivalent void ratio on the small-strain shear stiffness of specimens of mixture group C2D03/R3 at a mean confining pressure of 100 kPa

manner the small-strain shear modulus of mixtures of granular soils with granulated tire rubber.

Even though the general trend of soil-rubber mixtures is that void ratio decreases as the percentage of rubber increases in the mixture (see Fig. 3 and Table 3), which leads to a denser soil-rubber matrix, the shear stiffness of all mixtures of this study decreases systematically as the percentage of rubber increases. This is due to the increase of mixtures' equivalent void ratio, e_{eq}, as the content of rubber increases as illustrated in Fig. 6a. In specific, we plot in this figure the equivalent void ratio values, symbolized as $e_{eq,mix,100}$ of specimens of mixture group C2D03/R3 for variable rubber contents, at a mean confining pressure equal to 100 kPa. The $e_{eq,mix,100}$ is normalized herein with respect to the void ratio of the intact sand, symbolized as $e_{soil,100}$, at the same confining pressure. It is clearly shown that the ratio $e_{eq,mix,100}/e_{soil,100}$ increases as the content of rubber increases, and thus, the addition of rubber leads to a decrease of the solid-sandy part per mixture volume that contributes to the overall stiffness of the sand-rubber matrix. In Fig. 6b we plot the small-strain shear modulus values of specimens of mixture group C2D03/R3 at $\sigma_m' = 100$ kPa, symbolized as $G_{O,mix,100}$, normalized with respect to the corresponding shear modulus value of the intact sand, symbolized as $G_{O,soil,100}$, versus the equivalent void ratio. It should be noted that $e_{eq,mix,100}$ at 0% percentage of rubber corresponds to the void ratio of the pure sandy specimen ($e_{soil,100}$), and that the incremental values of $e_{eq,mix,100}$ correspond to the incremental values of rubber percentage in the mixture. It is shown that the ratio $G_{O,mix,100}/G_{O,soil,100}$ decreases linearly with increasing $e_{eq,mix}$ in log scale. All specimens of this study followed a similar trend as mixture group C2D03/R3 shown in Fig. 6a and b.

3.3 Damping

In Fig. 7a, the small-strain damping ratio values, symbolized as $D_{min,mix}$, of mixture group C2D03/R3 for variable rubber contents, are plotted against the

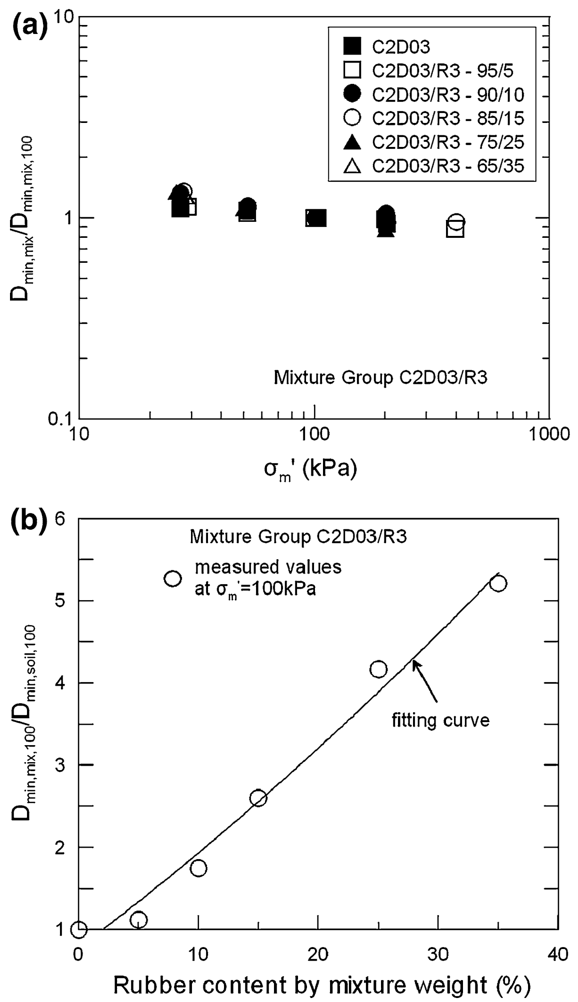

Fig. 7 **a** Effect of mean confining pressure on the small-strain damping ratio of soil-rubber mixtures and **b** effect of rubber content on the small-strain damping ratio of soil-rubber mixtures at $\sigma_m' = 100$ kPa

mean confining pressure. $D_{min,mix}$ values are normalized with respect to the corresponding values of the specimens at $\sigma_m' = 100$ kPa, symbolized as $D_{min,mix,100}$. It is noticed that the normalization of damping ratio values in terms of $D_{min,mix}/D_{min,mix,100}$ eliminates the effect of rubber percentage on the experimental results. It is also observed that the effect of mean confining pressure on D_{min} values of all specimens, expressed as the slope of the $\log D_{min} - \log \sigma_m'$ curves, has a similar trend, independently from the percentage of rubber in the mixture.

Figure 7b shows the effect of rubber content on the $D_{min,mix,100}$ values of the specimens of mixture group C2D03/R3; $D_{min,mix,100}$ are normalized herein with respect to the corresponding value of the intact soil at the same confining pressure, symbolized as $D_{min,soil,100}$. It is observed that the increase of rubber content leads systematically to higher small-strain damping ratio values. This is due to the significant contribution of rubber solids on the damping capacity of the soil-rubber matrix and the interaction between soil-rubber particles which exhibit significantly different elastic and thermal properties (Pamukcu and Akbulut 2006).

3.4 Mean Confining Pressure

The effect of mean confining pressure on the equivalent void ratio values of five on a total number of six dense to very dense specimens of mixture group C2D03/R3 is illustrated in Fig. 8. The increase of mean confining pressure is followed by a decrease of the equivalent void ratio which is not significant for the range of rubber contents used herein. Consequently, for dense to very dense granular soil-rubber mixtures with rubber content up to approximately 50% by mixture volume, and for relatively low to medium confining pressures (25–400 kPa), the void ratio of the mixtures is not significantly affected by the confining pressure.

3.5 Non-Linear Behaviour

In Fig. 9 we plot the G/G_O–$\log\gamma$–D experimental curves of a representative test series of mixture group

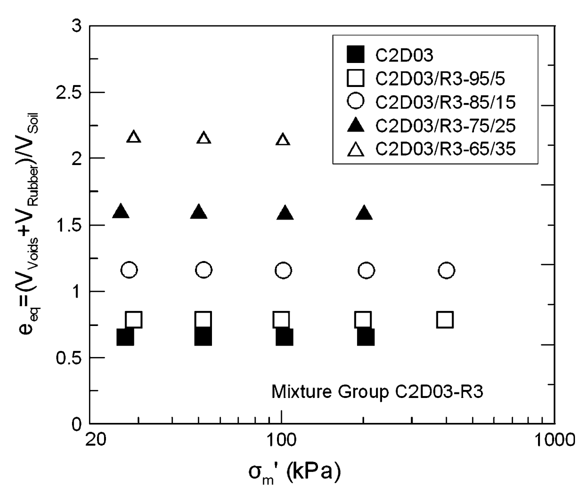

Fig. 8 Effect of mean confining pressure on the equivalent void ratio of soil-rubber mixture group C2D03-R3 (C2D03:intact sand, C2D03-R3-95/5: specimen with 5% rubber by mixture weight)

C2D03/R3 at a mean confining pressure equal to 50 kPa. The increase of rubber content leads systematically to more linear G/G_O–logγ curves and smoother D–logγ curves due to the increased rubber to rubber interaction. At relatively high strain levels all damping ratio values tend to converge due to the smoother shape of the curves with increasing the content of rubber.

The effect of rubber percentage on the non-linear dynamic properties of the mixtures is more clearly shown in Fig. 10. In specific, Fig. 10a shows the evolution of the reference strain, γ_{ref} (shearing strain amplitude at $G/G_O = 0.5$) of the specimens of mixture group C2D03/R3 at mean confining pressure equal to 50 kPa. In this case, in order to extend the non-linear curves of Fig. 9a at higher strains, the modified hyperbolic model (Darendeli 2001) was used, adopting a curvature coefficient, $a = 0.85$ that is a fit value for all curves of the experimental investigation with respect to mixture group C2D03/R3. The observed increase of γ_{ref} values with the rubber content suggests a trend of more linear G/G_O–logγ curves with increasing the content of rubber, also shown in Fig. 9a. On the other hand, the overall slope of the G/G_O–logγ curves, expressed with the curvature coefficient (a) is not significantly affected by the rubber inclusion.

Figure 10b indicates a well-fit between damping ratio and normalized shear modulus values of all specimens of mixture group C2D03/R3 at $\sigma_m' = 50$ kPa, independently of the content of rubber. In order to eliminate the effect of small-strain damping ratio on the experimental results, we express herein the damping ratio values in terms of $D - D_{min}$. The normalization of damping ratio in the form of $D - D_{min}$ and not in the form of D/D_{min} is in general better related with the G/G_O values, due to the greater effect of D_{min} on the ratio D/D_{min} (Menq 2003).

3.6 Small-Strain Shear Modulus of Sand-Rubber and Gravel-Rubber Mixtures

Based on the total results of seven clean granular soils tested in mixtures with granulated tire rubber at different contents of rubber by mixture weight, analytical expressions were developed in order to quantify the effect of the independent quantities and parameters involved in soil-rubber dynamic behaviour at small strain levels.

All pure soil specimens tested herein were dense to very dense. Even though different values of the coefficient of uniformity may lead to a different void ratio of the pure soil specimens, the main factor that affects the shear stiffness is the mean grain size, D_{50}. For example, as shown in Fig. 11, three specimens having mean grain size equal to 3.00 mm and variable coefficients of uniformity (materials C2D3, C6D3 and C13D3), exhibit approximately the same G_O values at a mean confining pressure equal to 100 kPa, even though these specimens have different void ratio values (0.609, 0.447 and 0.478, respectively).

The small-strain shear modulus of all dense to very dense clean soils of this study at 100 kPa is well correlated to the mean grain size, expressed herein as $D_{50,s}$ (Fig. 11). This correlation may be expressed with the following equation:

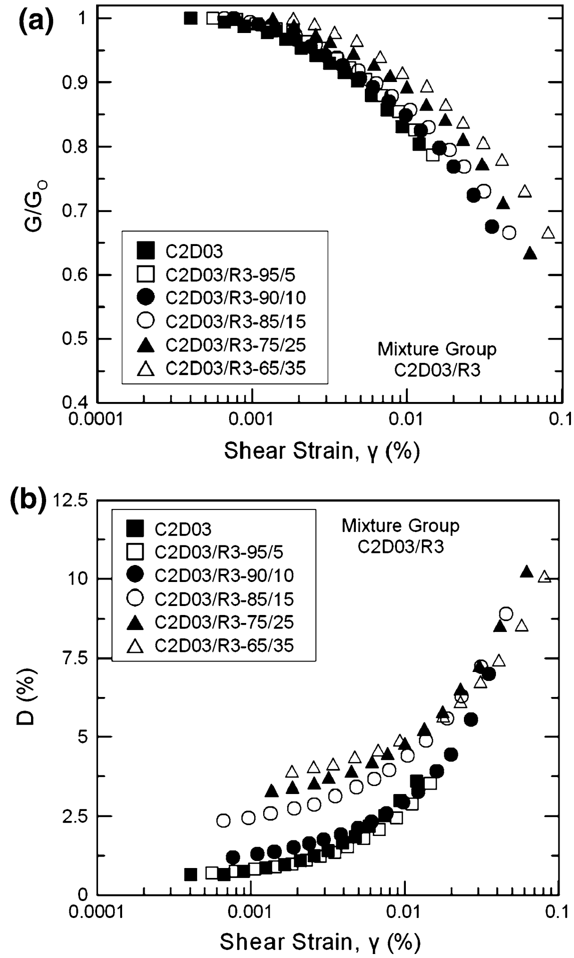

Fig. 9 Effect of rubber percentage on the non-linear dynamic properties of soil-rubber mixtures: Specimens of mixture group C2D03/R3 at a mean confining pressure equal to 50 kPa

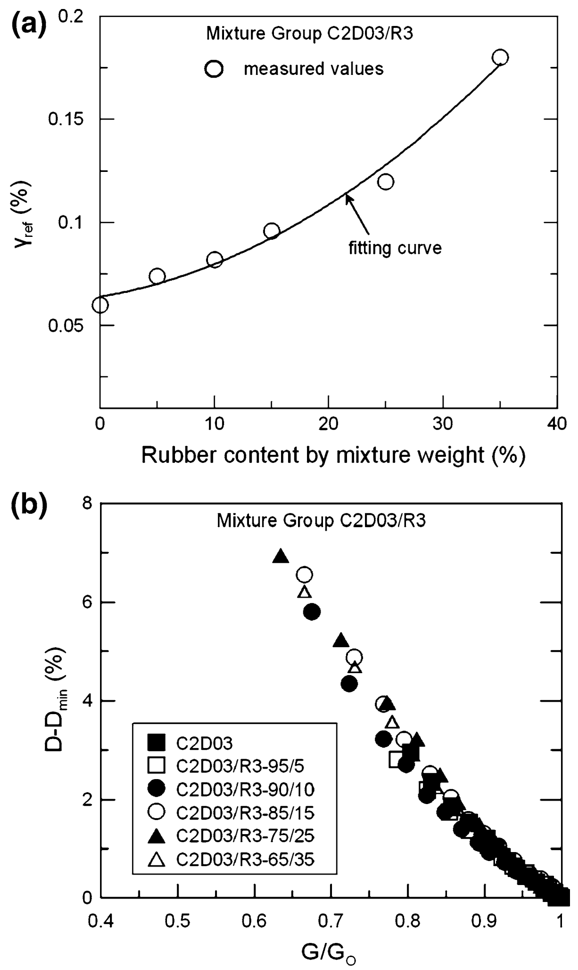

Fig. 10 **a** Reference strain values versus rubber percentage and **b** normalized damping ratio with respect to damping ratio at small-strains versus normalized shear modulus of specimens of mixture group C2D03/R3 at a mean confining pressure equal to 50 kPa

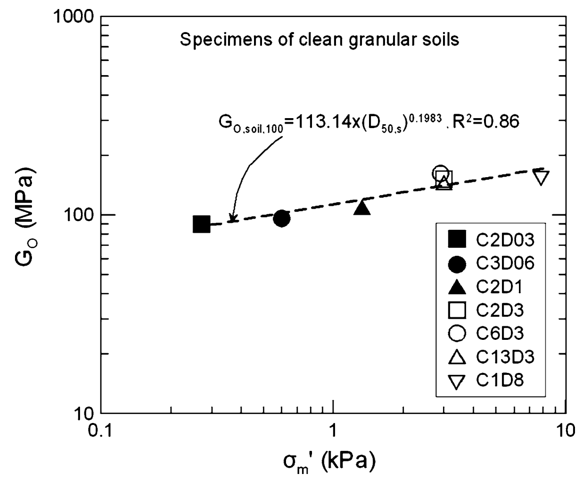

Fig. 11 **a** Small-strain shear modulus at a mean confining pressure of 100 kPa versus mean grain size of dense to very dense clean sandy and gravelly specimens

$$G_{O,soil,100} = 113.14 \cdot \left(D_{50,s}\right)^{0.1983} \quad (2)$$

where $G_{O,soil,100}$ is the small-strain shear modulus in MPa of the dense to very dense clean granular soils at a mean confining pressure of 100 kPa and $D_{50,s}$ is the mean grain size of the soil particles, given in mm.

In all soil-rubber mixtures tested in this study an increase in rubber content leads to a reduction of small-strain shear modulus. Considering the fact that the actual shear stiffness of the soil-rubber solid matrix is essentially due to the shear stiffness of the soil part, an equivalent void ratio (see Eq. 1) may be introduced in order to consider the volume of rubber solids as part of the total volume of voids. In Fig. 12 we present the general trend of the effect of rubber percentage on the equivalent void ratio for all mixtures, at a mean confining pressure of 100 kPa. This effect is expressed in terms of the equivalent void ratio of each mixture versus the void ratio of the pure soil specimen (ratio $e_{eq,mix,100}/e_{soil,100}$). It should be noted, that all specimens were prepared under approximately similar compaction energy with the same number of layers and same number of tips. We observe that an increase in rubber percentage leads to an increase in specimen's equivalent void ratio, expressed as an increase of the ratio ($e_{eq,mix,100}/e_{soil,100}$). The aforementioned increase is more pronounced for percentages of rubber above 15% by mixture weight, which is a percentage of rubber by mixture volume equal to 30%, approximately.

In addition, the results plotted in Fig. 8 indicated that the increase of rubber percentage leads to specimens of higher volume of voids and consequently to lower overall shear stiffness. This reduction of shear stiffness is more pronounced as the percentage of rubber increases due to the development of rubber-to-rubber interfaces, which means that the behaviour of the soil-rubber solid matrix is gradually modified from sand-like to rubber-like.

Based on the data of Fig. 12, the equivalent void ratio of granular soils-rubber mixtures may be expressed as a function of rubber percentage and the initial void ratio of the clean soil prepared at the same compaction energy and under the same confining pressure with the following polynomial equation:

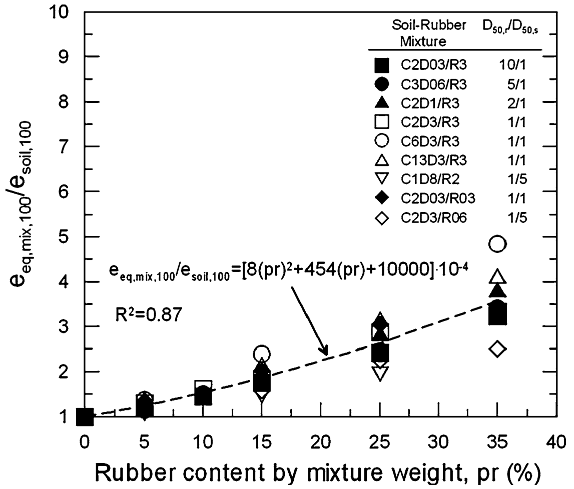

Fig. 12 Equivalent void ratio of soil-rubber mixtures via void ratio of clean granular soils at a mean confining pressure of 100 kPa against the percentage of rubber by mixture weight

$$e_{eq,mix,100} = e_{soil,100} \cdot (0.0008 \cdot pr^2 + 0.0454 \cdot pr + 1) \quad (3)$$

where $e_{eq,mix,100}$ is the equivalent void ratio of the mixture at a mean confining pressure of 100 kPa, $e_{soil,100}$ is the void ratio of the clean granular soil at the same mean confining pressure and pr is the content of rubber by mixture weight in percentile scale (%).

An increase in rubber percentage leads to an increase of the equivalent void ratio, resulting to a decrease of small-strain shear modulus of the mixtures compared to the corresponding shear modulus of the pure soil. The aforementioned increase of mixtures' equivalent void ratio with increasing the content of rubber was also supported by standard compaction tests on sand-rubber mixtures (Senetakis 2011). In Fig. 13a we plot the ratio $G_{O,mix,100}/G_{O,soil,100}$, where $G_{O,mix,100}$ and $G_{O,soil,100}$ is the small-strain shear modulus of the mixture and the clean soil, respectively, at $\sigma_m' = 100$ kPa, versus the equivalent void ratio of three mixture groups. There is a clear trend of linear reduction of the ratio $G_{O,mix,100}/G_{O,soil,100}$ with the increase of $e_{eq,mix,100}$ in log scale. Consequently, the effect of equivalent void ratio on mixtures shear stiffness may be expressed with the following equation:

$$\frac{G_{O,mix,100}}{G_{O,soil,100}} = A_{G,100} \cdot F(e_{eq,mix,100}) \quad (4)$$

where $A_{G,100}$ is a parameter of the regression analysis and $F(e_{eq,mix,100})$ is a function of the equivalent void

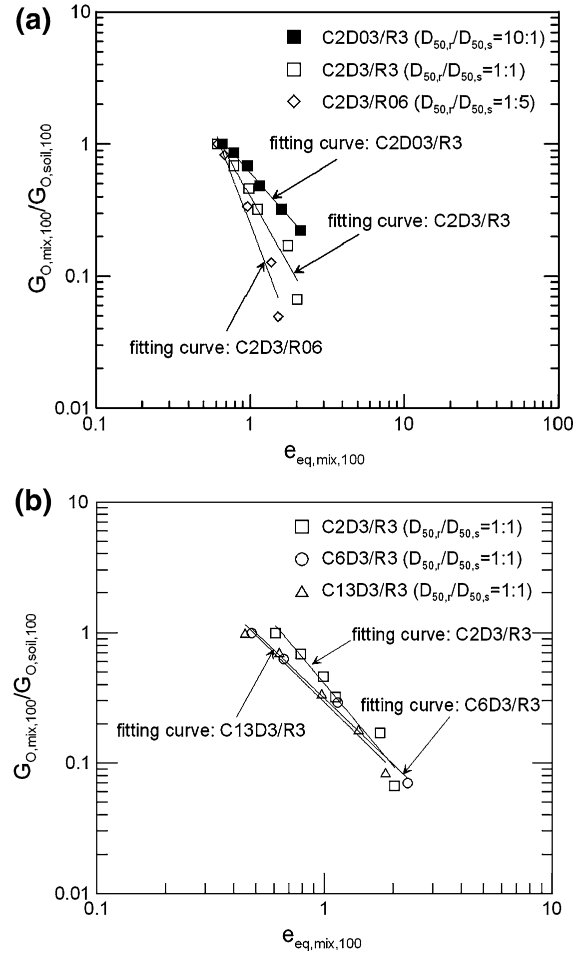

Fig. 13 Effect of equivalent void ratio on small-strain shear modulus of mixtures composed of **a** uniform soils and variable values of the ratio $D_{50,r}/D_{50,s}$ and **b** soils of variable coefficient of uniformity and constant ratio $D_{50,r}/D_{50,s}$

ratio of the mixture at a mean confining pressure equal to 100 kPa. $F(e_{eq,mix,100})$ is expressed as :

$$F(e_{eq,mix,100}) = \frac{1}{(e_{eq,mix,100})^{x_e}} \quad (5)$$

where x_e represents the effect of the equivalent void ratio (or rubber percentage) on the slope of the $G_{O,mix,100}/G_{O,soil,100}$, versus $e_{eq,mix,100}$ curve in log scale.

Figure 13a shows that for the case of uniform granular soils, the slope of the $\log G_{O,mix,100}/G_{O,soil,100}$ versus $\log e_{eq,mix,100}$ curve increases, as the ratio of soil solids size versus rubber solids size increases and the absolute value of the exponent x_e increases as well. On the other hand, Fig. 13b shows that for mixtures with the same ratio of soil versus rubber solids size, expressed as $D_{50,r}/D_{50,s}$, but variable coefficient of uniformity of the soil part, the absolute value of the exponent x_e is slightly lower for the mixtures composed of well graded soils (mixture groups C6D3-R3 and C13D3-R3), compared to the mixture composed of uniform to poor graded soil (mixture group C2D3-R3). Thus, the effect of the ratio $D_{50,r}/D_{50,s}$ on the exponent x_e should be examined for uniform and well graded soils separately.

The effect of the ratio $D_{50,s}/D_{50,r}$ on the exponent x_e, is shown graphically in Fig. 14a, where $D_{50,s}$ is the mean grain size of soil solids (uniform soils) and $D_{50,r}$ is the mean grain size of the rubber solids. The exponent x_e increases with the ratio $D_{50,s}/D_{50,r}$ and thus, as the relative mean grain size of soil solids increases compared to the rubber solids, the slope of the $G_{O,mix,100}/G_{O,soil,100}$ versus $e_{eq,mix,100}$ curve also increases. It is concluded then that the decrease of mixtures' small-strain shear modulus with increasing the content of rubber is more pronounced as the relative size of soil versus rubber particles increases. This is mainly due to more pronounced increase of the rubber-to-rubber contacts as the ratio $D_{50,s}/D_{50,r}$ increases. The increase of rubber-to-rubber contacts practically leads to a soil-rubber matrix that is gradually transformed from soil-like to rubber-like behavior. The findings of this work concerning the important effect of the ratio $D_{50,s}/D_{50,r}$ on soil-rubber mixtures' stiffness was also reported by Kim and Santamarina (2008).

In Fig. 15a it is indicated that for mixtures having soils of the same ratio of $D_{50,s}/D_{50,r}$ but higher coefficient of uniformity, the exponent x_e is slightly reduced, possibly due to the variety of soil solids size, that leads to slightly less pronounced development of rubber-to-rubber interfaces in comparison to the case of mixtures of uniform soils. Based on the data of Fig. 15a it is concluded that the mixtures of well graded soils exhibit an exponent x_e approximately 0.8 times the corresponding value of mixtures composed of uniform soil. The effect of the ratio $D_{50,r}/D_{50,s}$ on the exponent x_e is described then with Eq. 6a and 6b for mixtures of uniform and well graded soils respectively:

$$x_e = 2.1365 \cdot \left(\frac{D_{50,s}}{D_{50,r}}\right)^{0.22} \quad \text{Mixtures of uniform soils} \tag{6a}$$

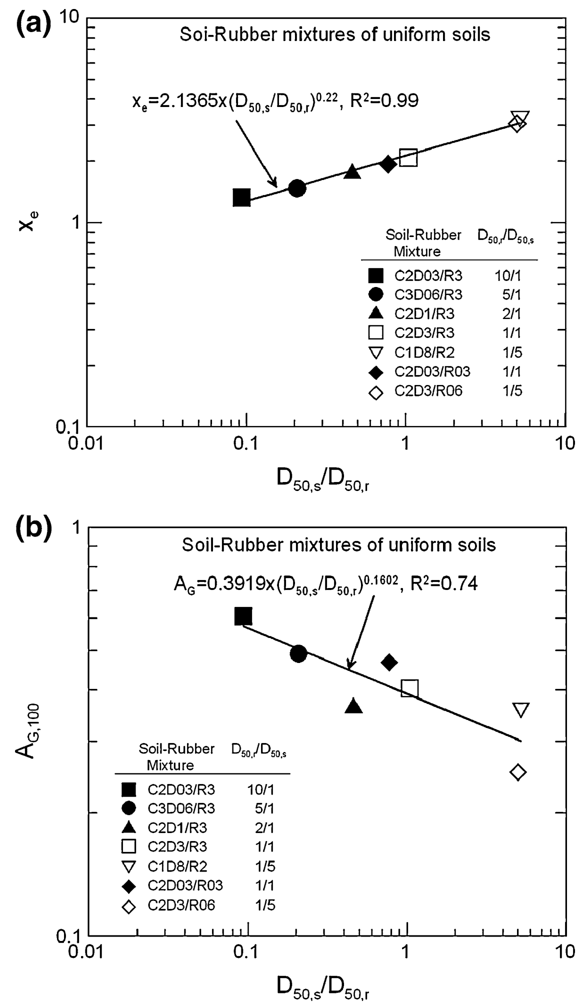

Fig. 14 Effect of ratio of mean grain size of soil solids versus rubber solids ($D_{50,r}/D_{50,s}$) on **a** the exponent x_e and **b** the parameter A_G (experimental results concerning soil-rubber mixtures composed of uniform soils)

$$x_e = 1.7306 \cdot \left(\frac{D_{50,s}}{D_{50,r}}\right)^{0.22} \quad \text{Mixtures of well - graded soils} \tag{6b}$$

Figures 14b and 15b show the effect of the ratio $D_{50,s}/D_{50,r}$ on the parameter $A_{G,100}$ for mixtures of uniform and well-graded soils, respectively. For mixtures of well-graded soils, $A_{G,100}$ is about 0.75 times the corresponding value of mixtures composed of uniform soils. Equation 7a and 7b describes the variation of $A_{G,100}$ with the ratio $D_{50,s}/D_{50,s}$ for mixtures of uniform and well graded soils, respectively:

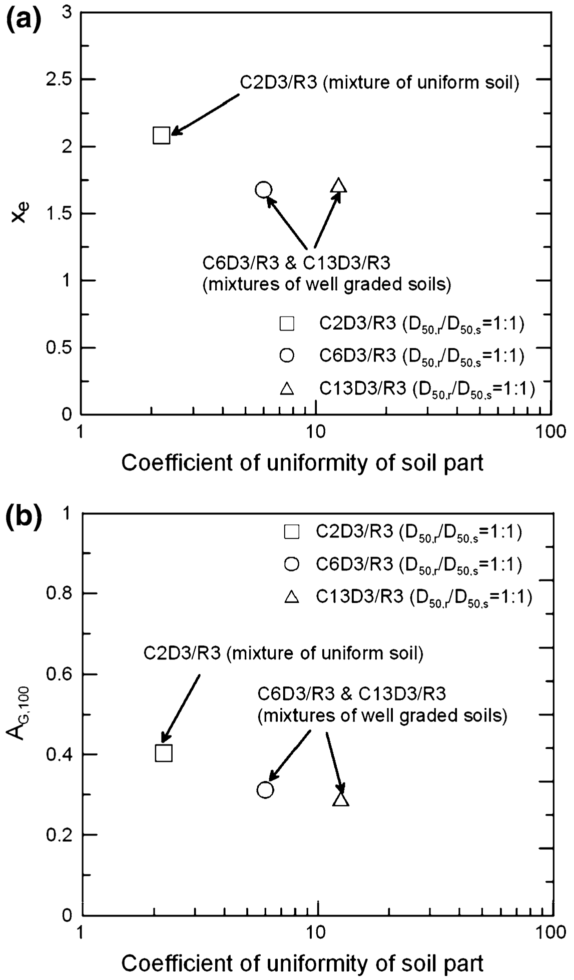

Fig. 15 Effect of coefficient of uniformity of soil part on **a** the exponent x_e and **b** the parameter A_G of soil-rubber mixtures composed of soils of the same $D_{50,s}$ and ratio $D_{50,s}/D_{50,r}$ but different coefficients of uniformity

$$A_{G,100} = 0.3919 \cdot \left(\frac{D_{50,s}}{D_{50,r}}\right)^{-0.1602} \quad \text{Mixtures of uniform soils} \tag{7a}$$

$$A_{G,100} = 0.3292 \cdot \left(\frac{D_{50,s}}{D_{50,r}}\right)^{-0.1602} \quad \text{Mixtures of well-graded soils} \tag{7b}$$

The small-strain shear modulus of dense to very dense soil-rubber mixtures, at a mean confining pressure of 100 kPa, may be evaluated through Eq. 8 from the initial small-strain shear modulus of the clean soil at the same confining pressure, using two correction terms; the first one is the void ratio of the clean soil at 100 kPa that corresponds to a solid matrix of high relative density, and the second one which describes the percentage of rubber in the mixture that affects the equivalent void ratio and the ratio of mean grain size of soil solids via rubber solids:

$$G_{O,mix,100} = G_{O,soil,100} \cdot A_{G,100} \cdot \frac{1}{(e_{eq,mix,100})^{x_e}} \tag{8}$$

where $G_{O,mix,100}$ and $G_{O,soil,100}$ is the small-strain shear modulus (in MPa) of the soil-rubber mixture and the pure dense to very dense soil, respectively. For the clean soils of this study, $G_{O,soil,100}$ may be estimated from Eq. 2 as a function of the mean grain size of the soil particles (Eq. 2). In addition, $e_{eq,mix,100}$ is the equivalent void ratio of the soil-rubber mixture that considers the volume of rubber solids as part of the total volume of voids and is given from Eq. 3 as a function of rubber percentage by mixture weight and the void ratio of the pure soil at a high relative density, x_e is an exponent given from Eq. 6a and 6b for mixtures of uniform and well graded soils, respectively. Finally $A_{G,100}$ is a parameter given from Eq. 7a and 7b for mixtures of uniform and well graded soils, respectively. The parameters x_e and $A_{G,100}$ are directly related to the ratio $D_{50,s}/D_{50,r}$, where $D_{50,s}$ is the mean grain size of the soil solids and $D_{50,r}$ is the mean grain size of the rubber solids.

For confining pressures different than 100 kPa the shear modulus of the mixtures, symbolized as $G_{O,mix}$ may be estimated through Eq. 9, as a function of $G_{O,mix,100}$ and σ'_m. In Eq. 9, A_G and n_G are parameters of the regression analysis, whereas n_G expresses the slope of the diagram $G_{O,mix,100}$-σ'_m in log scale.

$$G_{O,mix} = G_{O,mix,100} \cdot A_G \cdot \left(\sigma'_m\right)^{n_G} \tag{9}$$

From the experimental results of this study, there was not a clear trend of the effect of rubber percentage or the ratio $D_{50,s}/D_{50,r}$ on the parameters A_G and n_G of Eq. 9. The main factor that is shown to affect the aforementioned parameters is the coefficient of uniformity of the soil part of the mixtures. Thus, the parameters A_G and n_G may be estimated from the relation between the $G_{O,mix}/G_{O,mix,100}$ and the σ'_m values separately for mixtures of uniform and well graded soils, assuming an exponential fitting curve of the experimental results.

Figure 16a and b shows that the exponent n_G is higher for soil-rubber mixtures having well graded

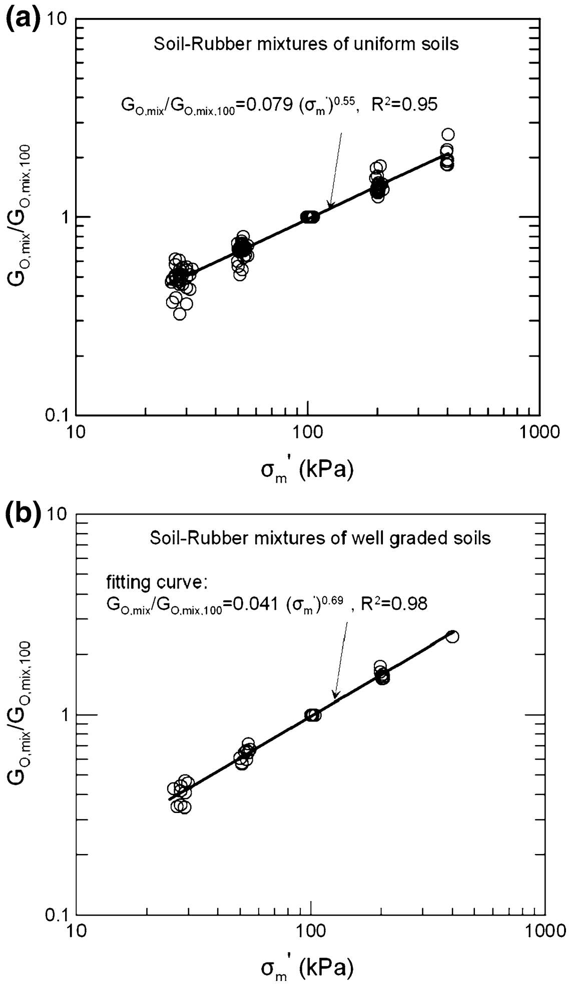

Fig. 16 Effect of mean confining pressure on the small-strain shear modulus of soil-rubber mixtures composed of **a** uniform soils and **b** well-graded soils

soils. This is valid also in the case of pure granular soils (Menq 2003; Wichtmann and Triantafyllidis 2009; Senetakis 2011). The opposite trend is shown for the case of the constant A_G, which is getting higher values for mixtures composed of uniform soils. It is concluded that the effect of mean confining pressure on the small-strain shear modulus of soil-rubber mixtures may be expressed from Eq. 10a and 10b separately for mixtures of uniform and well graded soils:

$$G_{O,mix} = G_{O,mix,100} \cdot 0.079 \cdot \left(\sigma'_m\right)^{0.55} \quad \text{Mixtures of uniform soils} \tag{10a}$$

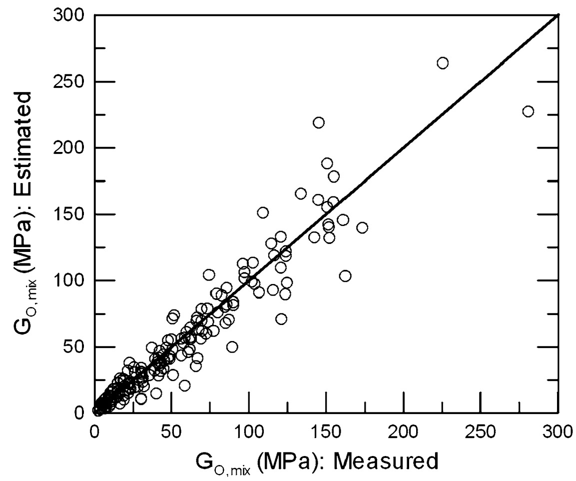

Fig. 17 Measured versus estimated values of small-strain shear modulus of soil-rubber mixtures

$$G_{O,mix} = G_{O,mix,100} \cdot 0.041 \cdot \left(\sigma'_m\right)^{0.69} \quad \text{Mixtures of well-graded soils} \tag{10b}$$

In Fig. 17 the experimental results are compared with the values stemming from the analytical expressions presented in this paragraph (Eqs. 2–10).

3.7 Small-Strain Damping Ratio of Sand-Rubber and Gravel-Rubber Mixtures

Granulated tire rubber is a material that exhibits significantly higher small-strain damping ratio compared to pure granular soils that exhibit typical values of D_{min} in a range of 0.5–1.0%. The inclusion of rubber solids in the soil-rubber solid skeleton as well as the interaction of soil and rubber solids, which are materials having significantly different elastic and thermal properties, leads to an increase of the mixtures' damping ratio. This increase of damping ratio is more pronounced as the percentage of rubber increases.

The effect of mean confining pressure on the small-strain damping ratio of soil-rubber mixtures may be expressed with the general form of Eq. 11:

$$D_{min,mix} = D_{min,mix,100} \cdot A_D \cdot \left(\sigma'_m\right)^{n_D} \tag{11}$$

where, $D_{min,mix}$ and $D_{min,mix,100}$ are the small-strain damping ratio of the soil-rubber mixture and the corresponding damping ratio at a mean confining pressure of 100 kPa, A_D is a constant term (parameter of the regression analysis) and n_D is an exponent that

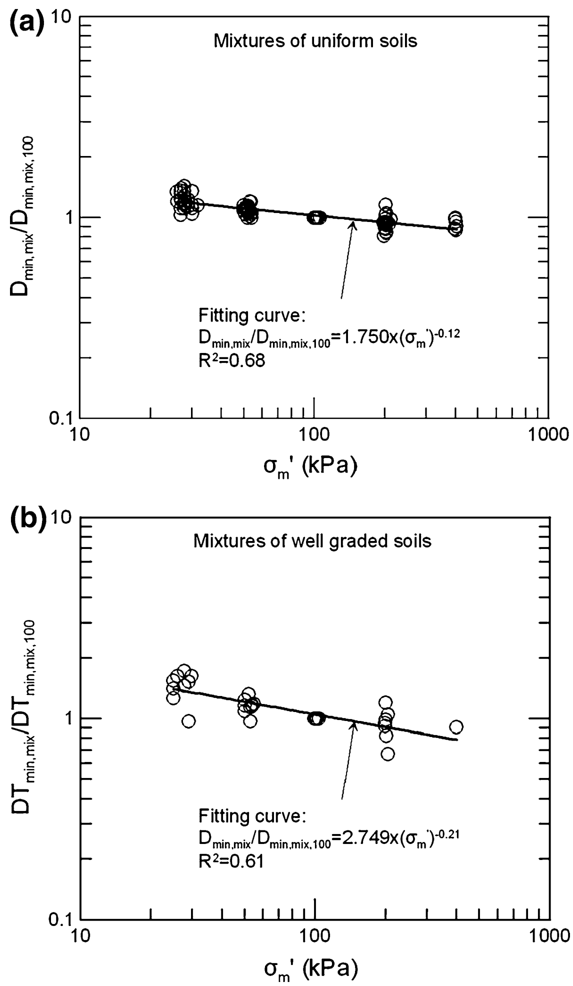

Fig. 18 Effect of mean confining pressure on the small-strain damping ratio of soil-rubber mixtures composed of **a** uniform soils and **b** well-graded soils

represents the effect of mean confining pressure on the small-strain damping ratio.

In Fig. 18 the experimental values of $D_{min,mix}$ via $D_{min,mix,100}$ are plotted versus the mean confining pressure. As for the shear modulus we did not observe a clear trend on the effect of the percentage of rubber or the ratio $D_{50,s}/D_{50,r}$ on the parameters A_D and n_D. However, mixtures of well-graded soils exhibit in general higher absolute values of the exponent n_D in comparison to mixtures of uniform soils and thus, the mean effective confining pressure has a relatively more pronounced effect on the damping ratio of mixtures of well-graded soils in comparison to mixtures of uniform to well graded soils. Equation 12a and 12b are deduced from the experimental data for

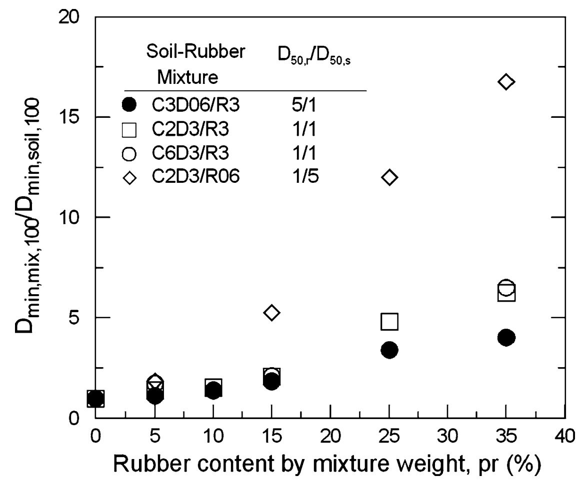

Fig. 19 Effect of rubber percentage on the small-strain damping ratio at a mean confining pressure equal to 100 kPa of soil-rubber mixtures of variable values of the ratio $D_{50,r}/D_{50,s}$

mixtures of uniform and well-graded soils, respectively. It is noted that in Eq. 12a and 12b, σ_m' is given in kPa, whereas $D_{min,mix}$ and $D_{min,mix,100}$ are given in percentile scale (%).

$$D_{min,mix} = D_{min,mix,100} \cdot 1.750 \cdot \left(\sigma_m'\right)^{-0.12} \quad \text{Mixtures of uniform soils} \qquad (12a)$$

$$D_{min,mix} = D_{min,mix,100} \cdot 2.749 \cdot \left(\sigma_m'\right)^{-0.21} \quad \text{Mixtures of well graded soils.} \qquad (12b)$$

In Fig. 19, the effect of rubber percentage on the ratio $D_{min,mix,100}/D_{min,soil,100}$ in soil-rubber mixtures of variable $D_{50,s}/D_{50,r}$ ratios is shown; $D_{min,mix,100}$ is the small-strain damping ratio of the mixture at 100 kPa and $D_{min,soil,100}$ is the corresponding damping ratio of the clean soil at the same confining pressure. As it was expected, small-strain damping ratio of soil-rubber mixtures is higher compared to the corresponding damping ratio of the pure soil and the increase is more pronounced as the percentage of rubber increases. The modification from sand-like to rubber-like behavior, as the percentage of rubber increases, is more pronounced for higher ratios of $D_{50,s}/D_{50,r}$. As for the small-strain shear modulus, the modification from sand-like to rubber-like behavior is observed at lower percentages of rubber with increasing $D_{50,s}/D_{50,r}$; thus a more important increase of mixtures' small-strain damping ratio is observed as the ratio $D_{50,s}/D_{50,r}$ increases.

In Fig. 20a–c, the effect of rubber percentage on the ratio $D_{min,mix,100}/D_{min,soil,100}$ is plotted for the following cases; $D_{50,s} \ll D_{50,r}$, $D_{50,s} \gg D_{50,r}$, and $D_{50,s} \approx D_{50,r}$.

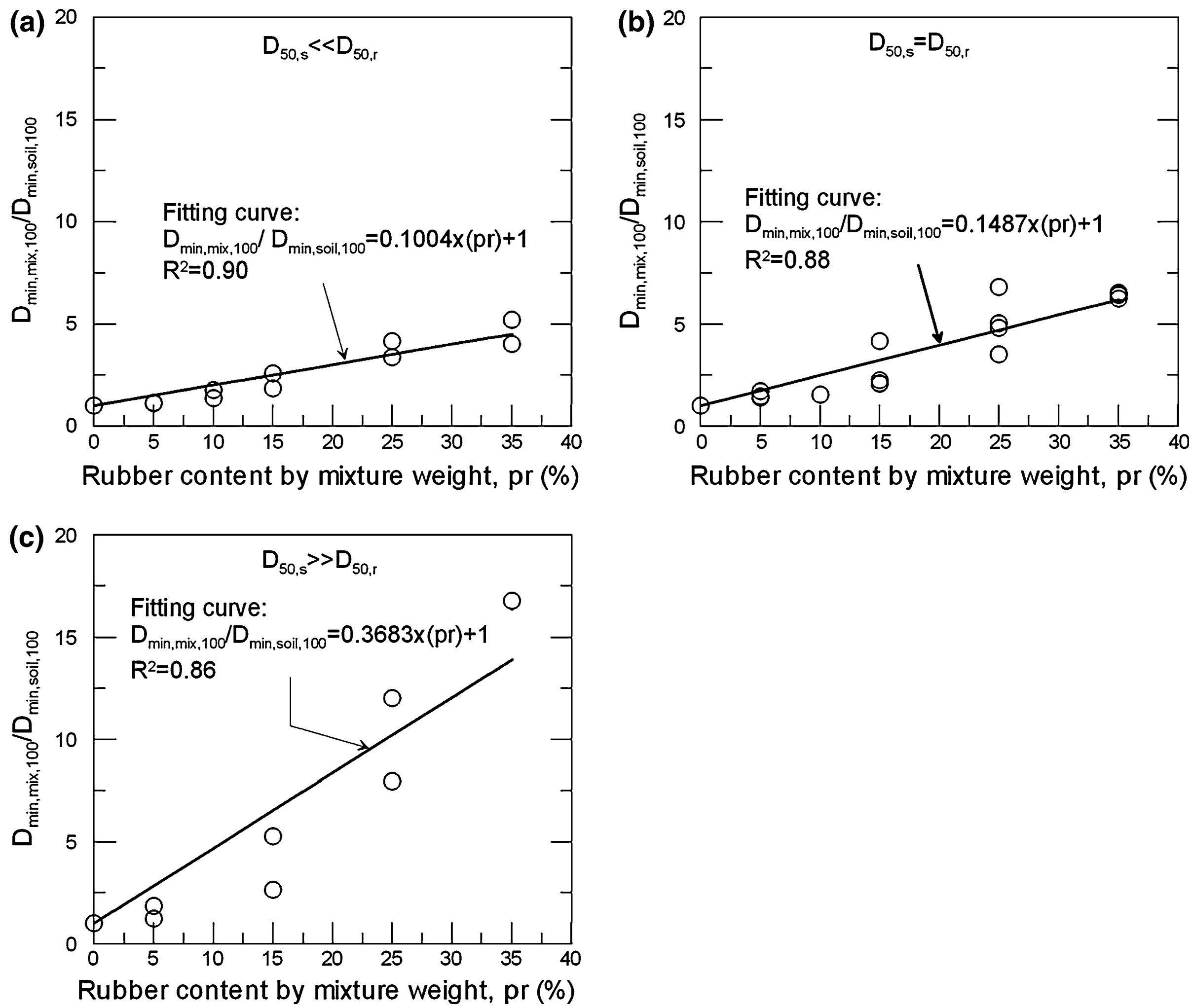

Fig. 20 Effect of rubber percentage on the small-strain damping ratio at a mean confining pressure equal to 100 kPa of soil-rubber mixtures of **a** $D_{50,s} \ll D_{50,r}$ **b** $D_{50,s} \gg D_{50,r}$ **c** $D_{50,s} \approx D_{50,r}$

Equation 13a–13c give the analytical expressions, respectively:

$D_{50,s} \ll D_{50,r}$

$$D_{min,mix,100} = D_{min,soil,100} \cdot [0.1004 \cdot (pr) + 1] \quad (13a)$$

$D_{50,s} \approx D_{50,r}$

$$D_{min,mix,100} = D_{min,soil,100} \cdot [0.1487 \cdot (pr) + 1] \quad (13b)$$

$D_{50,s} \gg D_{50,r}$

$$D_{min,mix,100} = D_{min,soil,100} \cdot [0.3683 \cdot (pr) + 1] \quad (13c)$$

$D_{min,mix,100}$ is the small-strain damping ratio of the soil-rubber mixtures at a mean confining pressure of 100 kPa, $D_{min,soil,100}$ is the corresponding damping ratio of the pure soil and pr is the percentage of rubber by mixture weight. $D_{min,mix,100}$, $D_{min,soil,100}$ and pr are given in percentile scale (%).

Finally, the small-strain damping ratio of a granular soil-rubber mixture at any given confining pressure and content of rubber, may be estimated from Eq. 14, as a function of mean confining pressure, percentage of rubber by mixture weight, the ratio $D_{50,s}/D_{50,r}$ and the initial small-strain damping ratio of the clean soil at 100 kPa:

$$D_{min,mix} = D_{min,soil,100} \cdot A_D \cdot (a \cdot pr + b) \cdot \left(\sigma'_m\right)^{n_D} \quad (14)$$

where, $D_{min,soil,100}$ is approximately 0.58% of the average value for the clean granular soils of this study,

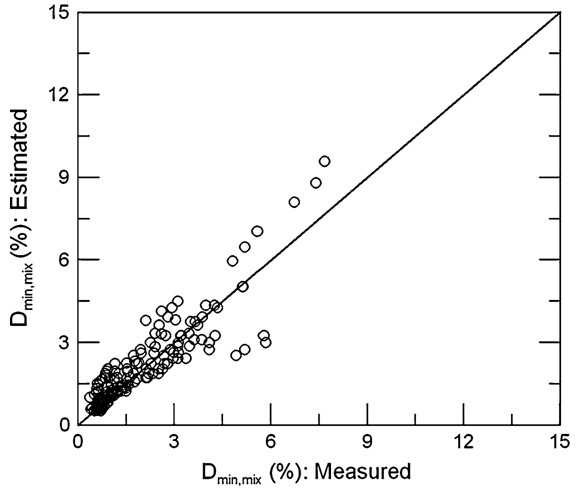

Fig. 21 Measured versus estimated values of small-strain damping ratio of soil-rubber mixtures

A_D is getting a value of 1.750 and 2.749 and $n_D = -0.12$ and -0.21 for soil-rubber mixtures of uniform and well-graded soils, respectively; $a = 0.1004$, 0.1487 and 0.3683 for $D_{50,s} \ll D_{50,r}$, $D_{50,s} \approx D_{50,r}$ or $D_{50,s} \gg D_{50,r}$, respectively and $b = 1$; pr is the percentage of rubber by mixture weight in percentile scale (%), σ_m' is the mean effective confining pressure in kPa, whereas $D_{min,mix}$ and $D_{min,soil,100}$ are given in percentile scale (%). The experimental results are plotted versus the values calculated from the above analytical expressions (Eq. 12–14) in Fig. 21.

4 Conclusions

An experimental testing program involving dry, dense specimens of pure sands, gravely sands and gravels as well as sand-granulated rubber and gravel-granulated rubber mixtures was undertaken to evaluate the effect of rubber inclusion and content on the dynamic characteristics of rubber-soil mixtures and in particular to evaluate the small strain shear modulus and damping of various mixtures. Evaluation of the results in this study led to the main following conclusions:

- Granulated tire rubber materials composed of recycled tire shreds are lightweight materials presenting soft particles and significant overall lower shear stiffness, (approximately 100 times lower) compared to clean granular soils. At the same time the aforementioned materials have significant high damping ratio in shear, (approximately 10 times higher), and in general an elastic behavior.
- For the percentages of rubber used in this study (0–35% by mixture weight), the soil-rubber mixtures' void ratio and dry unit weight are reduced as the percentage of rubber increases.
- Soil-rubber mixtures exhibit lower small-strain shear stiffness as the percentage of rubber increases in the mixture. This is mainly due the negligible contribution of the soft rubber solids on the shear stiffness of the soil-rubber solid skeleton. Thus, an equivalent void ratio may be introduced, in which the volume of rubber voids is assumed to be part of the total volume of voids, and the part of the skeleton that exhibits shear stiffness is due to the soil particles only.
- Soil-rubber mixtures exhibit higher small-strain damping ratio as the percentage of rubber increases. This is due to the deformability of rubber particles as well as to the interaction of soil-rubber particles, which are materials having significantly different elastic and thermal properties.
- An increasing number of rubber-to-rubber contacts leads to an increase of soil-rubber mixture's damping ratio.
- Three main factors are affecting the response of soil-rubber mixtures: (a) the percentage of rubber, (b) the relative size of soil particles in comparison to the rubber particles, and (c) the grain size characteristics (expressed herein in terms of mean grain size and coefficient of uniformity) of the soil part of the mixtures.
- Simple analytical expressions have been proposed to estimate the small-strain shear modulus and damping ratio of dense to very dense soil-rubber mixtures, for percentages of rubber not exceeding the 50% of the mixture volume. The analytical formulas are expressed in terms of simple geotechnical parameters like mean confining pressure, the percentage of rubber, the relative size of soil solids versus rubber solids, $D_{50,s}/D_{50,r}$, the grain size characteristics and the initial dynamic properties of the soil used in the mixtures and finally the void ratio of the clean soils.
- The increase of rubber inclusion in the mixtures, leads to the development of more pronounced rubber-to-rubber contacts, and the mixture behaviour is changing from soil-like to rubber-like. This

transformation depends on the ratio $D_{50,soil}/D_{50,rubber}$; for higher values of this ratio the rubber-like behaviour is presented at lower percentages of rubber.

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