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EXPERIMENTAL INVESTIGATION OF THE DYNAMIC PROPERTIES OF GRANULAR SOIL/RUBBER MIXTURES USING A RESONANT COLUMN DEVICE

Kostas SENETAKIS[1], Anastasios ANASTASIADIS[2] and Kyriazis PITILAKIS[3]

ABSTRACT

This paper discusses some important factors that affect the dynamic response of mixtures of sandy and gravelly soils with granulated tire rubber. Fifteen torsional resonant column tests were performed on dry-dense specimens, using three granular soils as physical part, and two uniform rubber materials of different grain size, as synthetic part of the samples. The content of rubber ranges between 0% and 35% by mixture weight. In addition, one specimen of clean rubber was also studied. It is concluded that rubber mixtures with soils leads in general to "composite" materials of lower shear stiffness and higher small-strain damping. Moreover specimens with high rubber content exhibit more linear G/G_O-logγ and DT-logγ curves. For relatively low rubber content, the dynamic response of the mixtures is significantly controlled by the physical soil part. In general, mixtures of high non-linear soil part, for example a well-graded gravelly sand, will also exhibit high non-linearity, whereas mixtures of low non-linear soil part, for example a uniform fine-grained sand, will also exhibit low non-linearity. For high percentages of rubber, the relative size of rubber particles ($D_{50,r}$) in comparison to soil particles ($D_{50,s}$), expressed in terms of the ratio $D_{50,r}/D_{50,s}$, seems to be an important factor that controls the behavior of the mixtures. The experimental results indicate that the behavior of mixtures with higher values of the ratio $D_{50,s}/D_{50,r}$, is transformed from sand-like to rubber-like at lower rubber content.

Keywords: resonant column, shear modulus, damping ratio, mixtures, granulated tire rubber

INTRODUCTION

Reinforcement of soils with synthetic materials seems to be a modern issue in civil engineering performances with promising results. The addition of granulated tire rubber or rubber chips composed of recycled tire shreds in physical soils has been examined from many researchers the last two decades in the laboratory (Humphrey & Manion, 1992, Edil & Bosscher, 1994, Foose et al., 1996 Bosscher et al., 1997, Lee et al., 1999, Feng & Sutter, 2000, Zornberg et al., 2004, Pamukcu & Akbulut, 2006, Kim & Santamarina, 2008, Anastasiadis et al., 2009, Senetakis et al., 2009). In general, soil/rubber mixtures exhibit lower unit weight and void ratio as rubber content increases, as well as higher elastic deformability and small-strain damping ratio in comparison to clean soils. It is marked also that sand/rubber mixtures exhibit high hydraulic conductibility. That is the application of an external force on these mixtures leads mainly to primary settlements, whereas secondary settlements are negligible. It has been also marked in the literature that for relatively low to medium percentages of rubber, these materials exhibit satisfactory strength and compressibility parameters.

The above characteristics of soil/rubber mixtures indicate that the addition of rubber in physical soils may lead to the improvement of the static and dynamic behavior of geomaterials used in geotechnical projects.

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[1] PhD Candidate, Department of Civil Engineering, Aristotle University of Thessaloniki, e-mail: ksenetak@civil.auth.gr
[2] Lecturer, Department of Civil Engineering, Aristotle University of Thessaloniki, e-mail: anas@civil.auth.gr
[3] Professor, Department of Civil Engineering, Aristotle University of Thessaloniki, e-mail: kpitilak@civil.auth.gr

In some cases as mentioned by Edil (2004), for example in high embankments overlying soft soils, as well as in cases where the reduction of lateral earth pressures on retaining walls is compulsory, the use of soil/rubber mixtures instead of clean soil may lead to optimum technical and economical results.

In this study, some important factors that affect the dynamic response of mixtures of sandy and gravelly soils with granulated tire rubber are investigated. The results herein are part of an extensive experimental testing program on physical and synthetic materials that is in progress the last three years at the laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki.

MATERIALS TESTED, SPECIMENS PREPARATION AND TESTING PROGRAM

Table 1 summarizes the physical soils used in this study. Material C2D03 is a fine-grained uniform sand of rounded particles, material C13D3 is a well-graded gravelly sand of angular particles and material C1D8 is a fine gravel of angular particles. Unit weight of soil solids is approximately equal to 2.67 gr/cm^3. In addition, Table 2 summarizes the uniform rubber materials, R2 and R3, used in this study. These materials are composed of recycled tire shreds and exhibit a unit weight of solids approximately equal to 1.10 gr/cm^3. In Figure 1, the grain-size distribution of the materials used is graphically shown.

Table 1. Physical soils used

No.	Material code	Classification$^{(1)}$	$G_s^{(2)}$ (gr/m^3)	Gravel content (%)	D_{max} (mm)	D_{50} (mm)	$C_u^{(3)}$	$C_c^{(4)}$
1	C2D03	SP	2.67	0	0.25-0.43	0.27	1.58	0.93
2	C1D8	GP	2.67	100	6.35-9.53	7.80	1.22	0.94
3	C13D3	SP-SW	2.67	40	6.35-9.53	3.00	12.50	0.94

$^{(1)}$ ASTM D2487-00 $^{(2)}$ ASTM D854-02 $^{(3)}$ $C_u=D_{60}/D_{10}$ $^{(4)}$ $C_c=D_{30}^2/(D_{10}\times D_{60})$

Table 2. Rubber materials used

No.	Material code	Classification$^{(1)}$	$G_s^{(2)}$ (gr/m^3)	D_{max} (mm)	D_{50} (mm)	$C_u^{(3)}$	$C_c^{(4)}$
1	R2	Tire chips	1.10	2.00-4.75	1.50	1.81	0.96
2	R3	Tire chips	1.10	4.75-6.35	2.80	2.29	1.18

$^{(1)}$ ASTM D6270-98 $^{(2)}$ ASTM D854-02 $^{(3)}$ $C_u=D_{60}/D_{10}$ $^{(4)}$ $C_c=D_{30}^2/(D_{10}\times D_{60})$

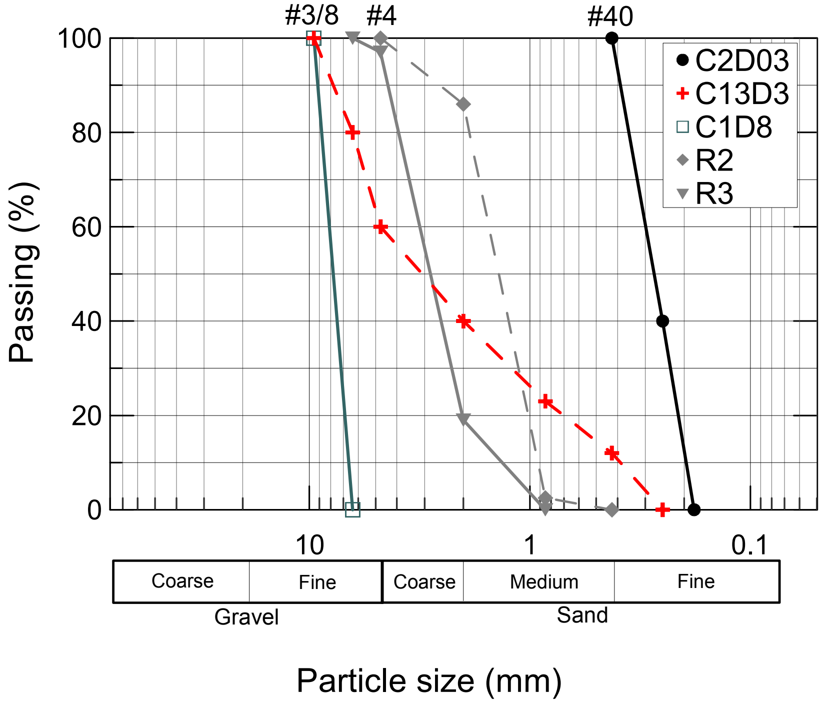


Figure 1. Grain-size distribution of materials used

Table 3 summarizes the sixteen specimens tested in this study. The experimental device used herein is a resonant column apparatus that follows the fixed-free configuration (Drnevich, 1967). All specimens were tested in dry conditions, having a diameter approximately equal to 71.1 mm and a height about two times the diameter. The sixteen specimens shown in Table 3 were tested at a high relative density. For this purpose, specimens were constructed into a metal mold in many layers of equal mass. Every layer was compacted with a metal rod. To construct relatively uniform samples, the compaction tips increased at the top layers. Before the specimens' construction, the soil and rubber materials were dry mixed in the appropriate percentages. In order to construct samples at about the same compaction energy, all specimens were compacted at the same number of layers as well as the same number of tips. All tests and analysis of the results were performed according to ASTM D4015-92 specification.

Low-amplitude as well as high-amplitude torsional resonant column tests were performed at increasing steps of mean confining pressure, equal to 25, 50, 100 and 200 kPa. In every confining pressure step, specimens were allowed to equilibrate about 60-80 minutes before the low-amplitude measurements were performed. In addition, after the high-amplitude measurements at a defined confining pressure, specimens were allowed to recover about 30-60 minutes at least 95% of their initial stiffness. The shearing strain amplitude, γ_{LA}, at which initial shear modulus, G_O, and initial damping ratio, DT_O, are defined in this study are also shown in Table 3. In most specimens, γ_{LA} is equal or less than 10^{-3}%, except for the case of high rubber contents or in the case of the clean rubber specimen. In these cases, due to the flexibility of the specimens it was not possible for accurate low-amplitude measurements at very low strains to be conducted. In addition, Table 3 shows the initial dry unit weight as well as the initial void ratio of the tested specimens. It is noticed that in general dry unit weight and void ratio decreases as rubber content increases.

Table 3. Resonant column testing program

No.	Specimen code	Rubber content(4) (%)	Rubber content(5) (%)	γ_d(6) (kN/m^3)	void ratio(6)	γ_{LA}(7) (%)
1	C2D03(1)	0	0	15.8	0.660	4.8-5.2×10^{-4}
2	C2D03-R3-95/5(3)	5	10	15.4	0.597	4.3-6.7×10^{-4}
3	C2D03-R3-90/10	10	20	14.8	0.547	8.1-9.2×10^{-4}
4	C2D03-R3-85/15	15	30	14.2	0.516	6.9-8.1×10^{-4}
5	C2D03-R3-75/25	25	45	13.4	0.444	1.5-1.6×10^{-3}
6	C2D03-R3-65/35	35	55	12.4	0.438	1.8-2.2×10^{-3}
7	C1D8(1)	0	0	15.4	0.715	3.5-7.2×10^{-4}
8	C1D8-R2-95/5	5	10	15.6	0.569	7.4-9.3×10^{-4}
9	C1D8-R2-85/15	15	30	14.9	0.454	6.2-7.3×10^{-4}
10	C1D8-R2-75/25	25	45	13.8	0.442	1.5-1.6×10^{-3}
11	C13D3(1)	0	55	18.1	0.448	1.4-4.4×10^{-4}
12	C13D3-R3-95/5	5	10	16.9	0.450	4.4-5.3×10^{-4}
13	C13D3-R3-85/15	15	30	15.3	0.447	1.1-1.2×10^{-3}
14	C13D3-R3-75/25	25	45	13.7	0.472	8.5×10^{-4}-2.0×10^{-3}
15	C13D3-R3-65/35	35	55	12.7	0.461	3.8-4.0×10^{-3}
16	R3(2)	100	100	7.4	0.455	1.3-2.8×10^{-2}

(1) clean soils (2) clean rubber (3) mixture composed of the soil C2D03 and the rubber material R3
(4) by mixture weight (5) by mixture volume (6) initial values at σ_m'=25 kPa
(7) shearing strain amplitude at which G_O and DT_O are defined

DYNAMIC RESPONSE OF CLEAN RUBBER MATERIALS

Figure 2 shows the initial (small-strain) shear modulus, G_O, and damping ratio, DT_O, versus mean effective confining pressure, σ_m', of the clean rubber specimen, R3, in comparison to the specimens of the fine-grained sand, C2D03, and the fine gravel, C1D8. In the same figure the exponents n_G and n_D that express the effect of σ_m' on the parameters G_O and DT_O are also given. It is clearly shown that specimen R3 exhibits significantly lower shear stiffness (about 100 times) as well as higher damping ratio (about 10 times) in comparison to the specimens of typical soils. In addition, it is marked that σ_m' is significantly less important on the small-strain properties of the clean rubber material (remarkably low values of n_G and n_D exponents) in comparison to typical granular soils.

Figure 3 shows the G/G_O-logγ and DT-logγ curves of specimen R3 at two different σ_m' amplitudes. In the same figure the theoretical curves proposed by Seed et al. (1986) for sandy soils are also presented. It is noticed that specimen R3 exhibits remarkably high linearity. However, a low reduction of G/G_O as well as a minor increment of DT values is observed at strains above 3×10^{-1}%. It is concluded that at relatively small to medium strains, rubber materials exhibit high damping ratio in comparison to clean soils, due to the high elastic deformability that rubber particles exhibit, but at high strains this trend reverses due to the remarkably linear response of rubber materials. The experimental results concerning the rubber specimen R3 were also presented in Anastasiadis et al. (2009).

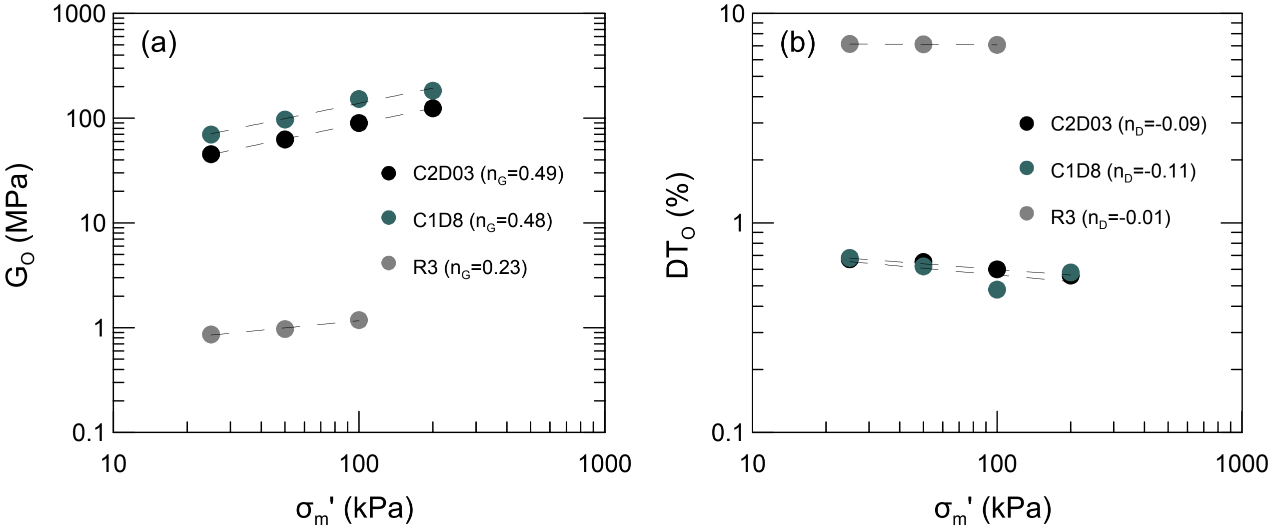


Figure 2. Initial shear modulus and damping ratio versus confining pressure of clean rubber specimen R3 in comparison to clean sandy and gravelly specimens (C2D03 and C1D8 respectively)

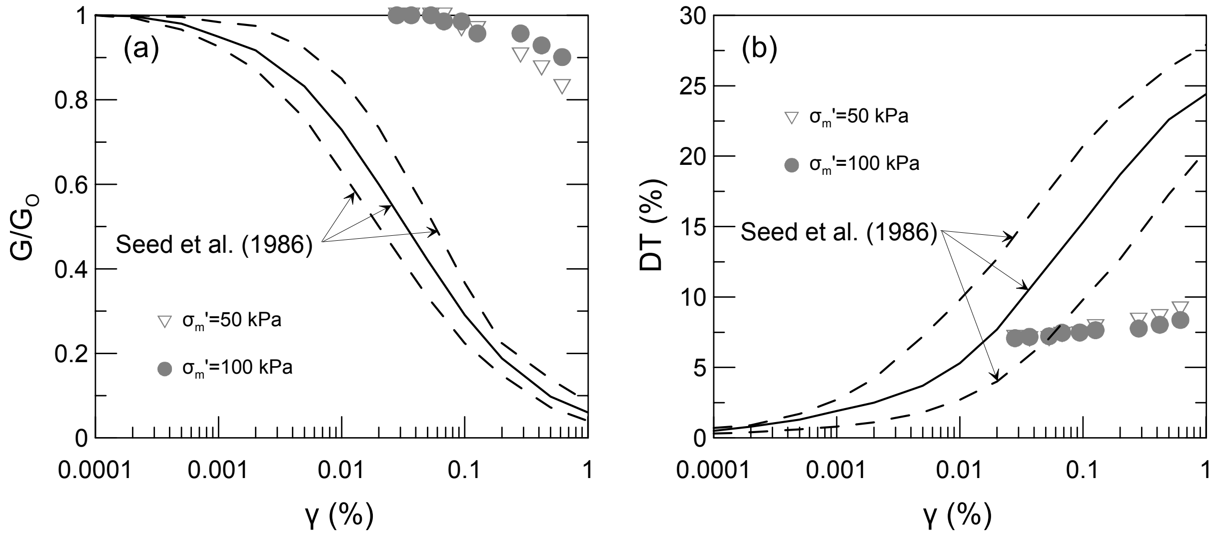


Figure 3. Normalized shear modulus and damping ratio versus shearing strain curves of clean rubber specimen R3 in comparison to theoretical curves proposed by Seed et al. (1986) for sandy soils

EFFECT OF RUBBER CONTENT ON THE SMALL-STRAIN RESPONSE OF SOIL/RUBBER MIXTURES

Figures 4 to 6 show the effect of rubber content on the small-strain parameters, V_s, G_O and DT_O of mixture groups C2D03-R3 and C13D3-R3. It is noticed that specimens exhibit lower shear stiffness (expressed in terms of V_s or G_O) as well as higher damping ratio as rubber content increases. This behavior has been also reported by Feng & Sutter (2000), Anastasiadis et al. (2009) and Senetakis et al. (2009) on similar materials. On the other hand, Kim & Santamarina (2008) have noticed a small increment at first of V_s or G_O at small rubber contents on the order of 5-10% by mixture weight, whereas this trend reverses at higher percentages of rubber. In this study, there was no evidence of an increment of shear stiffness of the specimens as rubber content increases. However, it is noticed in Figures 4a and 5a that a very small addition of rubber (on the order of 5% by mixture weight) in soil C2D03, practically does not decrease the parameters V_s and G_O.

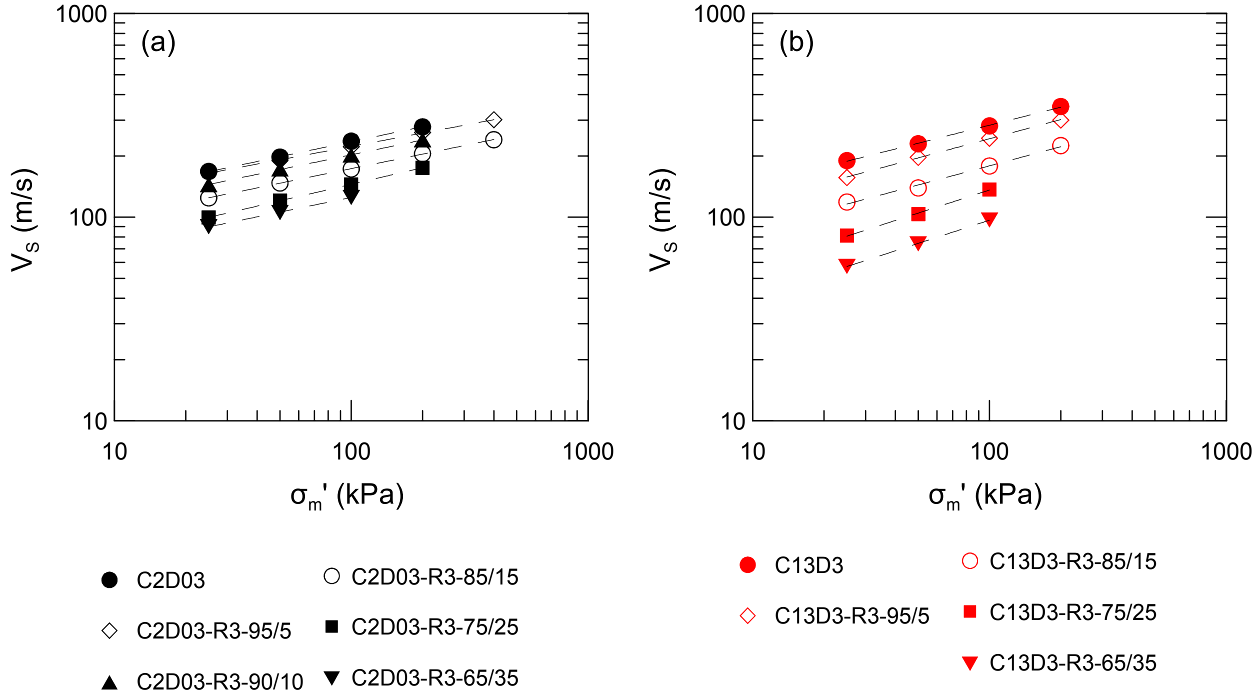


Figure 4. Effect of rubber content on V_s of (a) mixture group C2D03-R3 and (b) mixture group C13D3-R3

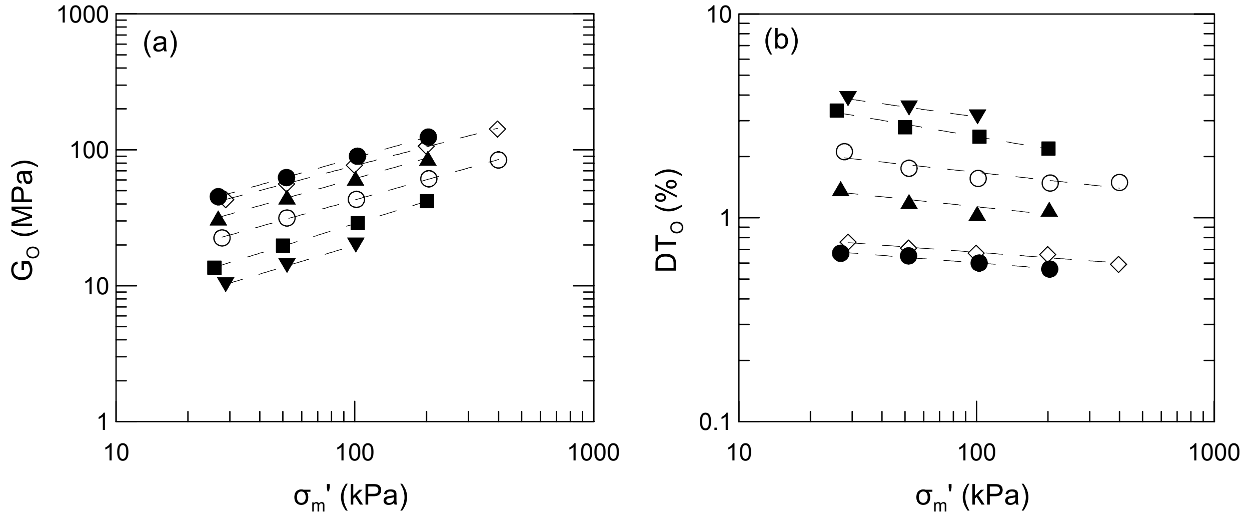


Figure 5. Effect of rubber content on (a) G_O and (b) DT_O of mixture group C2D03-R3 (symbols are given in Figure 4)

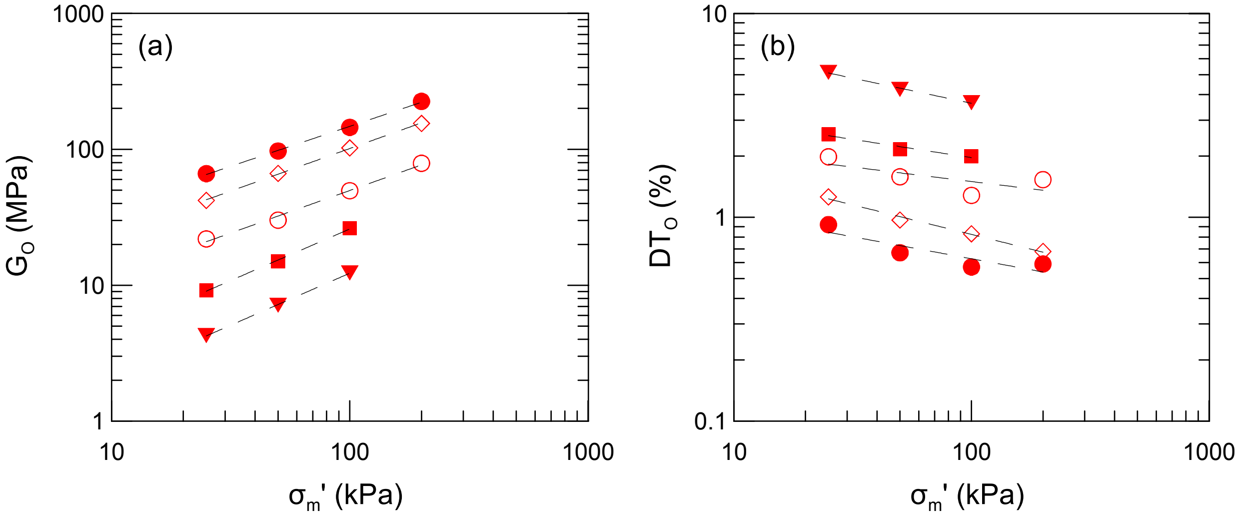


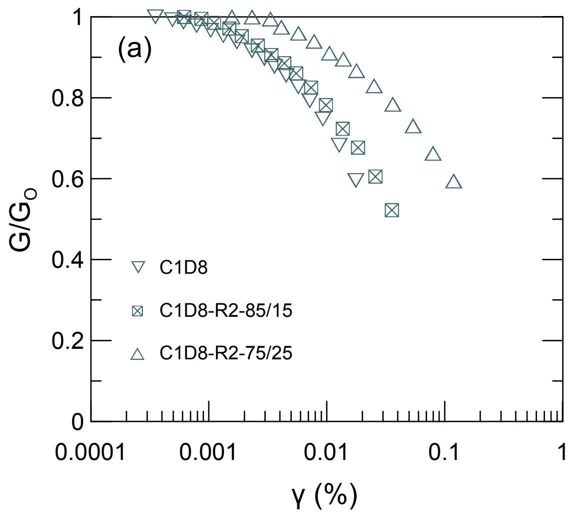
Figure 6. Effect of rubber content on (a) G_O and (b) DT_O of mixture group C13D3-R3 (symbols are given in Figure 4)

EFFECT OF RUBBER CONTENT ON THE RESPONSE OF SOIL/RUBBER MIXTURES AT MEDIUM TO HIGH STRAINS

Figure 7 presents the non-linear G/G_O-logγ and DT-logγ curves of mixture group C1D8-R2 for rubber contents equal to 0, 15 and 25% by mixture weight, at σ_m'=50 kPa. Concerning Figure 7a, it is noticed that specimens exhibit more linear behavior (that is lower reduction of G/G_O values at the same shearing strain amplitude) as rubber content increases. This effect is more pronounced in the case of C1D8-R2-75/25 specimen. Concerning Figure 7b, it is noticed that at relatively small to medium strains (up to a level of 10^{-2}%) specimens of higher rubber content exhibit higher damping ratio values. This is mainly due to the significant effect of the high deformable rubber particles on the small-strain damping capacity of the mixtures, as previously mentioned. However, it is marked in the same figure that this trend reverses at high strains, that is specimens of higher rubber content exhibit lower damping ratio values.

It is mentioned at this point that geomaterials owe their damping ratio at high strains mainly on their non-linearity, or in other words on their trend of decreasing shear modulus as shearing strain amplitude increases. Due to the relatively low to medium rubber contents used herein (up to about 50% by mixture volume), the tested specimens exhibit a significant non-linear response at high strains, as shown in Figure 7a. In addition, like on clean soils, the increment of damping ratio of these complex materials at high strains is mainly due the non-linearity of their behavior. This was also the case of the clean rubber specimen shown in Figure 3. The high linear response of R3 material led to a very small decrement of its shear modulus as well as to an insignificant increment of its damping ratio at high strains. Thus, the more linear behavior that specimens exhibit as rubber content increases, the less increment in damping ratio is expected to occur at high strains.

The above remarks are more clearly shown by plotting the G/G_O values against the corresponding DT values of specimens of mixture group C1D8-R2. This is done in Figure 8. In order to eliminate the effect of rubber content on the small-strain damping ratio of the specimens, DT values are plotted in terms of $DT-DT_O$. It is noticed that the increment of damping ratio values of all specimens may be expressed as a function of G/G_O reduction. In addition, Figure 8 indicates that if the G/G_O-logγ curve of a soil/rubber mixture as well as its small-strain damping ratio are known, the DT-logγ curve may be estimated using an analytical relationship of the literature that correlates the DT-DT_O to the G/G_O values of clean granular soils.



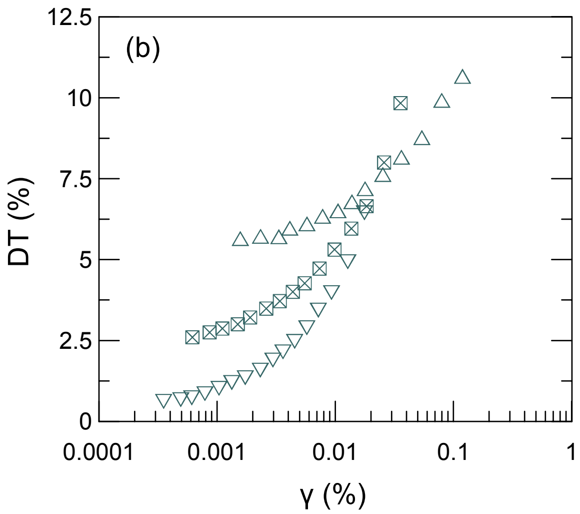


Figure 7. Effect of rubber content on the G/G_O-logγ and DT-logγ curves of mixture group C1D8-R2 at σ_m'=50 kPa

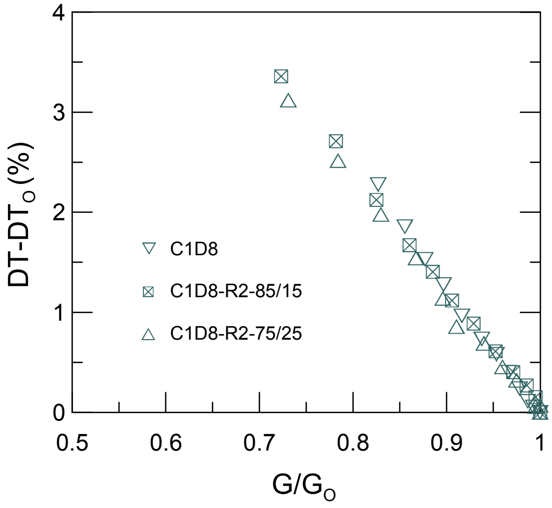


Figure 8. Correlation between G/G_O and DT-DT_O values of mixture group C1D8-R2 at σ_m'=50 kPa

SOME IMPORTANT FACTORS ON THE REFERENCE STRAIN OF SOIL/RUBBER MIXTURES

The G/G_O-logγ curves of the tested specimens were analyzed herein in terms of the modified hyperbolic model proposed by Darendeli (1997, 2001). This model uses two fitting parameters: the reference strain, γ_{ref}, and the curvature coefficient, a. Parameter γ_{ref} expresses the linearity, whereas parameter a expresses the overall slop of the G/G_O-logγ curves. In this study there was not a clear trend noticed on the effect of rubber content or σ_m' on the parameter a. Some representative results are given in Figure 9.

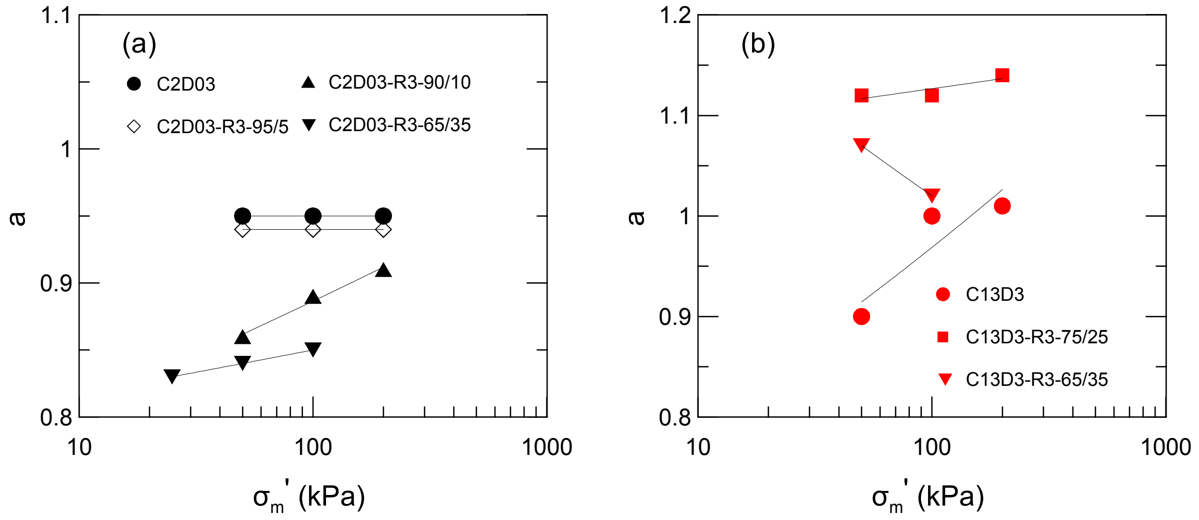


Figure 9. Effect of rubber content and σ_m' on the fitting parameter a of (a) mixture group C2D03-R3 and (b) mixture group C13D3-R3

Let us symbolize the reference strain of the mixtures as $\gamma_{ref,mix}$ at this point, as well as the reference strain of the mixtures at σ_m'=100 kPa as $\gamma_{ref,mix,100}$. In Figure 10 we present the $\gamma_{ref,mix,100}$ values of mixture groups C2D03-R3 and C13D3-R3 as a function of rubber content. It is clearly shown that specimens exhibit higher $\gamma_{ref,mix,100}$ values as rubber content increases. This trend expresses analytically the more linear shape of the G/G_O-logγ curves of the mixtures as rubber content increases. However, it is also noticed in this figure that specimens of the more non-linear soil, C13D3 (that is the well-graded gravelly sand of this study) exhibit clearly lower values of reference strain in comparison to specimens of mixture group C2D03-R3 (composed of the more linear physical soil C2D03). Thus, if one wants to predict the non-linear behavior of a soil/rubber mixture, not only the rubber content but also the behavior of the parent-natural soil should be taken into consideration.

Another important aspect of the non-linear behavior of soil/rubber mixtures is the effect of mean confining pressure. Figure 11 shows the effect of σ_m' on the reference strain of some specimens tested herein. It is noticed that despite the rubber content, specimens exhibit higher reference strain values (or in different words more linear G/G_O-logγ curves) as σ_m' increases.

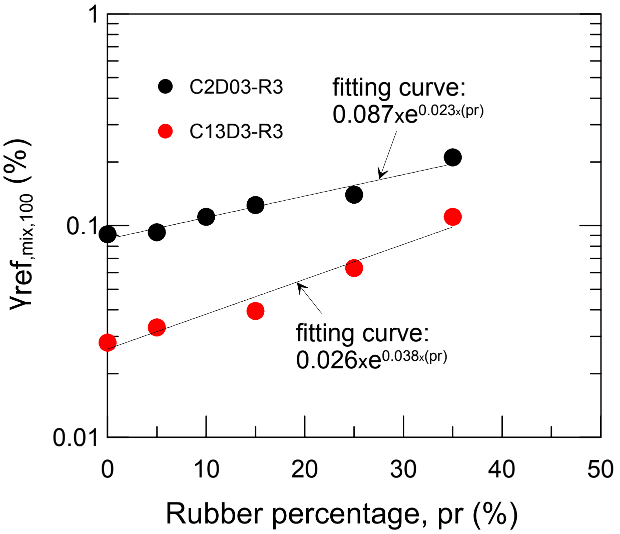


Figure 10. Effect of rubber content and grain size characteristics of the physical part (parent soils) of the mixtures on the reference strain at σ_m'=100 kPa: mixtures of the more non-linear parent soil C13D3 exhibit higher non-linearity in comparison to mixtures of the more linear soil C2D03

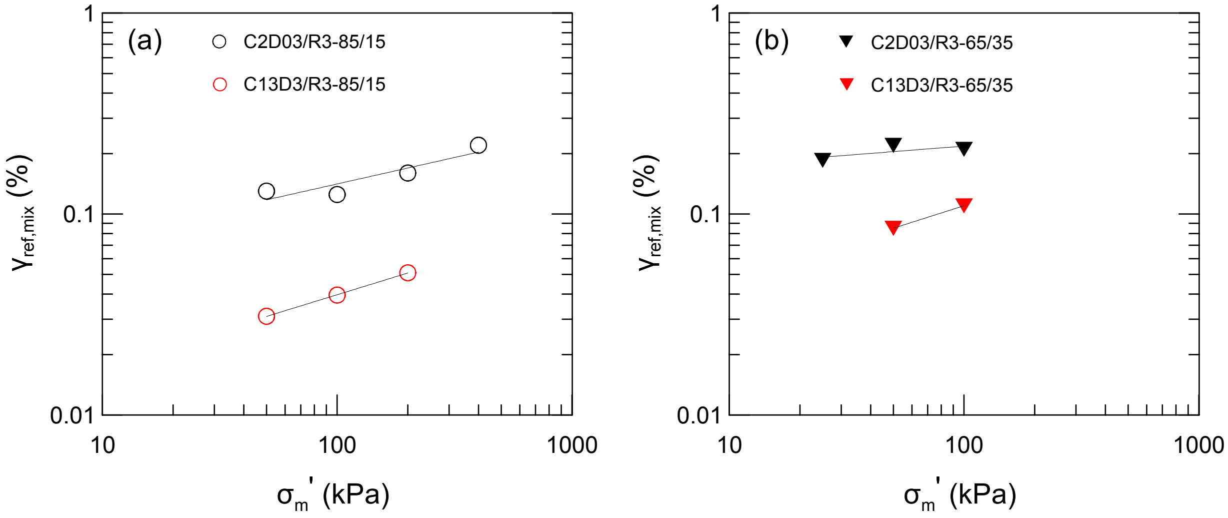


Figure 11. Effect of σ_m' on the reference strain of soil/rubber mixtures

Finally, an important factor that seems to be affecting the non-linear response of soil/rubber mixtures is the relative size of soil solids in comparison to the rubber solids. Let us symbolize the mean grain size of the parent natural soils tested in this study as $D_{50,s}$, whereas the mean grain size of the rubber materials as $D_{50,r}$. In Figure 12 we present the increment in reference strain of the mixtures as a function of rubber content of the three mixture groups tested herein at σ_m'=100 kPa. This increment in reference strain is expressed in terms of the ratio $\gamma_{ref,mix,100}/\gamma_{ref,soil,100}$, where $\gamma_{ref,soil,100}$ is the reference strain of the parent soils at the same confining pressure. It is noticed that reference strain of mixtures increases in a more pronounced manner as the ratio $D_{50,r}/D_{50,s}$ decreases. That is the effect of rubber content in mixtures' response becomes more pronounced for lower percentages of rubber as the size of soil particles increases in comparison to the rubber particles. This notice was first remarked by Kim & Santamarina (2008), but their study focused on the small-strain behavior of soil/rubber mixtures. Thus, Figure 12 clearly shows that except for the rubber content, the ratio $D_{50,r}/D_{50,s}$ controls significantly the dynamic response of the mixtures.

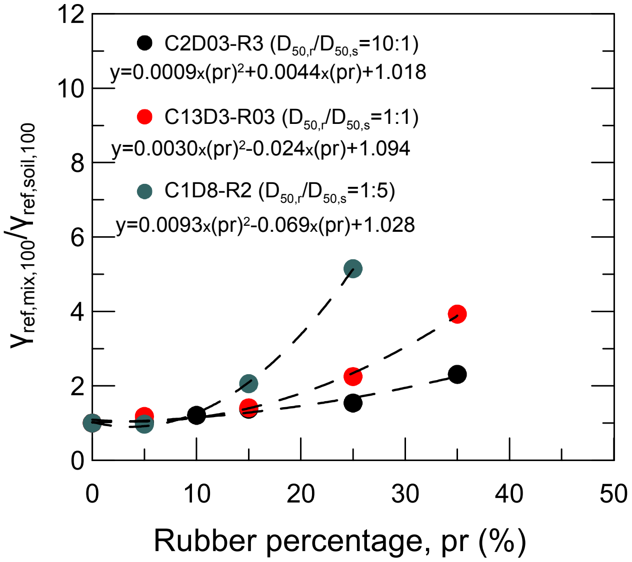


Figure 12. Effect of rubber content and relative size of rubber particles versus soil particles on the reference strain of soil/rubber mixtures

CONCLUSIONS

The study summarizes some important factors that affect the linear and non-linear response of mixtures of sandy and gravelly soils with granulated tire rubber. Rubber content is certainly the most important factor. Mixtures of higher percentages of rubber exhibit lower shear stiffness in general, higher small-strain damping ratio and a more linear response at high strains. Like on clean soils, the increment in DT values of the mixtures (normalized with respect to the corresponding small-strain values in terms of $DT-DT_O$) may be correlated to the corresponding G/G_O values. For relatively low to medium rubber content percentage, the non-linear behavior of the mixtures is significantly affected by the dynamic characteristics of the natural soils. For example, a mixture composed of a high non-linear soil will exhibit more pronounced non-linear behavior, compared to a mixture of the same rubber content but a low non-linear soil. In addition, the dynamic response of soil/rubber mixtures is significantly affected by confining pressure, (in a similar trend that σ_m' affects the behavior of clean soils), and the relative size of rubber particles in comparison to soil particles. All these parameters should be taken into consideration for an accurate estimation of the response of soil/rubber mixtures.

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