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The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Liquefaction susceptibility of volcanic soil/rubber mixtures

A. Tsinaris, A. Anastasiadis, D. Pitilakis & K. Pitilakis
Aristotle University, Thessaloniki, Greece

ABSTRACT: The aim of this paper is the evaluation of earthquake induced liquefaction susceptibility of saturated lightweight mixes of volcanic soil (pumice) with granulated rubber derived from recycled used tires at a percentage equal to 0%, 10%, and 30% per dry mixture weight. The main examined parameters are the grain size distribution of the examined solid materials, the cyclic shear stress ratio, and the percentage of rubber in the mixtures. Based on the above test program some useful conclusions can be drawn about the cyclic strength of the examined primary materials, the onset of liquefaction as well as the number of loading cycles which are required in order to determine the "initial liquefaction", in relation to all the aforementioned parameters.

1 INTRODUCTION

The study of liquefaction susceptibility is a very important subject in Geotechnical Engineering, as it has been associated with many destructive earthquakes (Niigata 1964, Kobe 1995 etc.). The liquefaction response of volcanic soils (pumice sands) has been studied by several researchers (Marks et al. 1998, Orense et al. 2006, 2012, Orense & Pender 2013, 2015, Licata et al. 2015) through extensive laboratory tests i.e. through cyclic triaxial and cyclic shear tests.

However, through an extensive review of the available literature, one finds a relatively small amount of research into the evaluation of earthquake induced liquefaction susceptibility of lightweight volcanic soil/granulated rubber mixtures (Hazarika et al. 2008, Hyodo et al. 2008, Shariatmadari et al. 2017). For that purpose, a comprehensive testing program was implemented, consisting of several series of liquefaction tests by means of applied stress control conditions on saturated mixes of pumice with granulated rubber, derived from recycled used tires, at a percentage equal to 0%, 10%, and 30% per dry weight mixtures.

2 TESTED MATERIALS AND TESTING PROGRAM

The present work is part of a dynamic test program carried out at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki, where there have been performed a great number of tests (>300) on soil/granulated rubber mixtures, including Resonant Column Tests, Cyclic Triaxial Tests, Monotonic Triaxial Tests and Direct Shear Strain Tests (Anastasiadis et al. 2012, Senetakis et al. 2012, Pistolas 2015, Tsinaris et al. 2018).

2.1 *Materials*

The granular material of volcanic origin (pumice) concerns vitreous rhyolites from the area of Nissyros Island (Greece), while the synthetic material (rubber) is derived from recycled used tires. Two uniform coarse pumice fractions of mean grain size, D_{50}, equal to 2.16mm and 7.08mm were studied as primary physical material, denoted as LWC3D2 and LWC1D7, whereas one granular fraction of rubber of mean grain size, D_{50}, equal to 3.38mm was studied as primary synthetic material, denoted as R3. The specific gravity of soil solids, G_s, was found equal to 1.97gr/cm^3 and 1.72gr/cm^3, for the two pumice fractions, and 1.15 for the rubber fraction. The mean grain size ratio of the examined mixtures, $\lambda = D_{50,s}/D_{50,r}$, is equal to 0.64 and 2.10. Table 1 summarizes the physical characteristics of the natural volcanic soils (LWC3D2 and LWC1D7) and the elastic material (R3) used in the present study.

2.2 *Testing program*

In total, eighteen (18) cylindrical saturated specimens with dimensions of about 100mm in height and 50mm in diameter were tested in the cyclic triaxial apparatus by adopting the standard specification ASTM D5311-92, of which six (6) concern pure pumice and twelve (12) mixtures of pumice with rubber. All specimens (pure pumice fractions and pumice/rubber mixtures) were prepared in dry conditions and they were compacted at the same number of layers of equal mass, as well as the same number of tips reaching values of relative density $D_r \approx 80$-90%. However, due to the high porosity of the solid soil granules of pumice it was not easy to completely saturate the corresponding specimens for the tests, so the pumice sands were first boiled in water in order to remove the entrapped air from the grains.

The cyclic triaxial tests are performed by means of applied stress control and aim to determine the samples resistance against cyclic loading through a series of liquefaction tests, under cyclic loading and undrained conditions (CU). The amplitude of the applied confining pressure was 100kPa, the imposed loading frequency for every load cycle was 0.5Hz, the amplitude of the targeted cyclic shear stress ratio ($CSR = \sigma_d/2\sigma'_c$) ranged between 0.30 and 0.48, while the maximum number of cycles, N_{cyc}, was 200. The applied axial strain amplitude, ε, ranges from 0.001% to 1.28%, corresponding to an applied shear strain amplitude, γ, that ranges from $0.128 \cdot 10^{-2}$% to 2.0%, through the estimation of the following relationships (Equation 1,2):

$$G = \Delta\tau/\Delta\gamma \tag{1}$$

where G = shear modulus; Δτ = shear stress; and Δγ = shear strain.

$$\Delta\gamma = \Delta\varepsilon_\alpha \cdot (1 + v) \tag{2}$$

where $\Delta\varepsilon_\alpha$ = axial strain; and v = Poisson ratio.

Finally, in the present research the criteria used to determine the state of the "initial liquefaction" are the excess of a pore water pressure ratio of $r_u \geq 95\%$ and/or a double amplitude of axial strain of $\varepsilon^{DA} = 5\%$.

3 EXPERIMENTAL RESULTS

3.1 *Pure soil fractions*

Figures 1 and 2 show some representative experimental results of the examined pure pumice (LWC3D2 and LWC1D7) fractions, in relation to the cyclic shear stress ratio, CSR, as those

Table 1. Natural properties of the examined materials.

Material	Code	G_s (gr/cm^3)	D_{50} (mm)	C_u*	e_{max}	e_{min}	$\gamma_{d,min}$ (kN/m^3)	$\gamma_{d,max}$ (kN/m^3)
Pumice	LWC3D2	1.97	2.16	2.52	2.235	1.691	6.09	7.32
Pumice	LWC1D7	1.72	7.08	1.47	2.009	1.866	5.72	6.00
Rubber	R3	1.15	3.38	1.68	1.636	0.726	4.20	6.40

* $C_u = D_{60}/D_{10}$

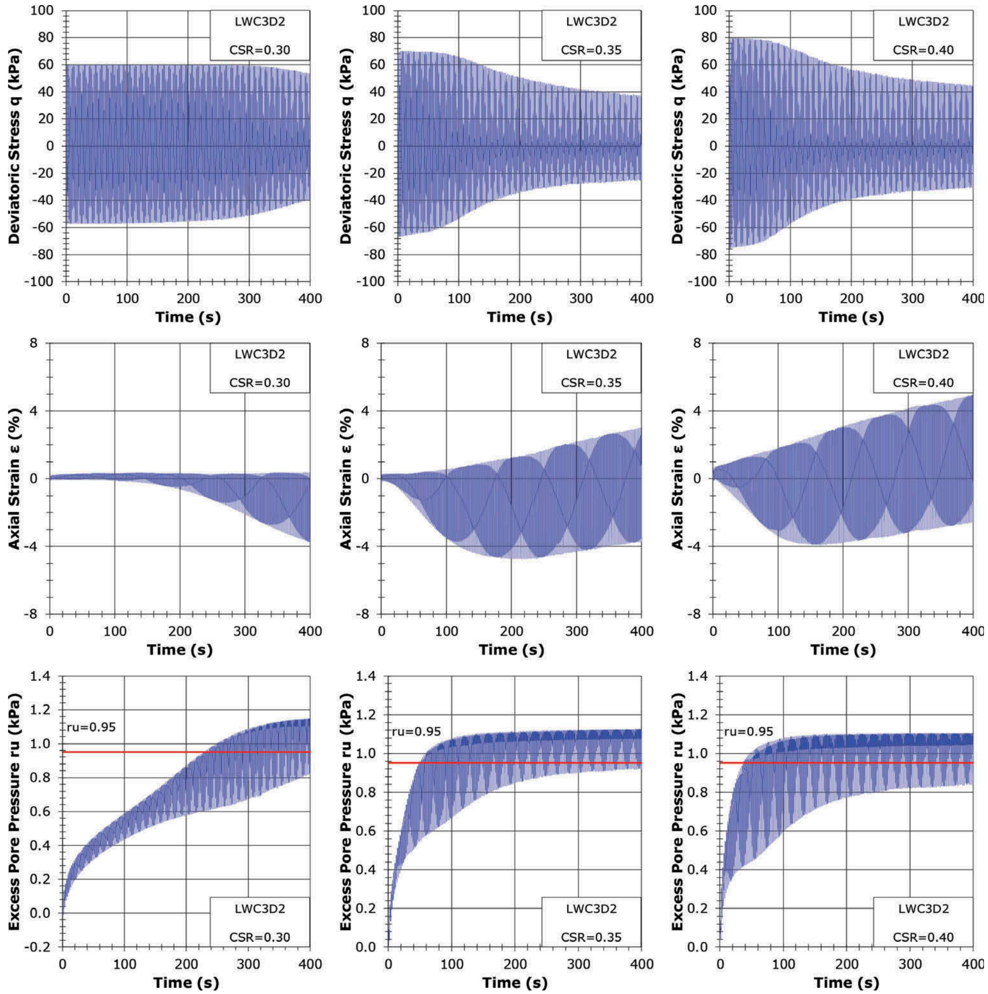

Figure 1. Variation of deviatoric stress, q, axial strain, ε(%), and excess pore water pressure ratio, r_u, with time of pumice fraction LWC3D2 under different values of cyclic shear stress ratio, CSR.

resulted from the cyclic triaxial device. Figure 1 shows the variation of deviatoric stress, q, axial strain, ε(%), and excess pore water pressure ratio, r_u, (defined as the excess pore water pressure, u, normalized by the initial confining pressure, σ'_m) with time for all LWC2D3 tested specimens, under three different values of cyclic shear stress ratio and an uniform and constant level of effective confining stress equal to 100kPa.

According to Figure 1, it is noticed that the deviatoric stress of the examined pure pumice fractions decreases with increasing number of cycles, due to the buildup of excess of pore water pressures, r_u, the high axial strain amplitude, ε_a, and the influence of the frequency of the excitation (speed loading). However, it can be observed that for small levels of CSR (≈0.3) and depending on the soil gradation of each tested material, as the deviator stress amplitude starts to decrease the sample does not fail before the 50th loading cycle. This can be also verified by the low values of the corresponded axial strain, ε(%) and excess pore-water pressure ratio, r_u. By increasing the level of the applied CSR value the behaviour of the specimen begins to get more affected, since it is noticed that: (a) the deviatoric stress deceased more rapidly, (b) the axial deformation increased faster, and (c) the ratio of excess pore pressure increased faster, with the number of cycles.

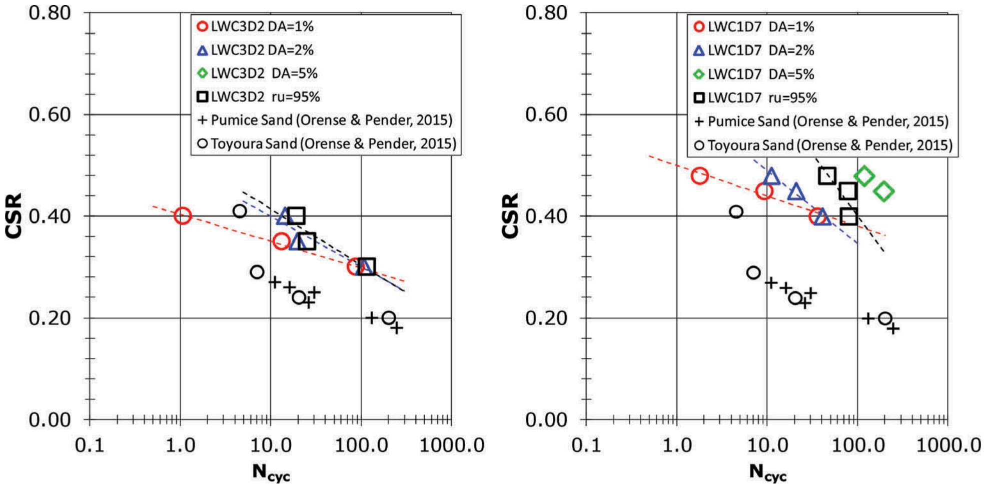

Figure 2. Cyclic strength curves of pure soil fractions at σ'$_m$=100kPa, and derived values (Orense & Pender 2015) for Pumice Sand (D_r=70%) and Toyoura Sand (D_r=90%) under σ'$_m$=100kPa and f=0.1Hz.

As regards the effect of the coefficient of uniformity, C_u, and the mean grain size, D_{50}, of the examined saturated solid materials of high density, on the cyclic strength of the pumice soil fractions (LWC3D2 and LWC1D7), the experimental results show that the decrease of the coefficient of uniformity, C_u, or/and the increase of the mean grain size, D_{50}, leads to higher required values of cyclic shear stress ratio in order to exceed one of the two liquefaction criteria.

Figure 2 shows the number of cycles required to induce 1.0%, 2.0% and 5.0% double amplitude of axial strains, as well as the number of cycles required to induce 95% of pore water pressure ratio for given levels of CSR for all examined soil specimens, under an uniform and constant value of effective confining stress equal to 100kPa. It appears that the soil gradation of the examined material can affect cyclic strength of the specimens, since the reduce of the coefficient of uniformity, $C_{u,s}$, or/and the increase of the mean grain size, $D_{50,s}$, increases the number of loading cycles which are required in order to determine the "initial liquefaction", as well as the required values of cyclic shear stress ratio in order to exceed one of the two liquefaction criteria.

3.2 *Soil/rubber mixtures*

Figures 3–6 show some representative experimental results of the examined pumice/rubber (LWC3D2/R3 and LWC1D7/R3) group mixtures in relation to the cyclic shear stress ratio, CSR, and the rubber percentage, r(%), as those resulted from the cyclic triaxial device. Figures 3 and 4 show the variation of deviatoric stress, q, axial strain, ε(%), and excess pore water pressure ratio, r_u, with time, for group mixtures LWC2D3/R3-90/10 and LWC1D7/R3-70/30 for a percentage of rubber in the mixture equal to 10% and 30% respectively, under three different values of cyclic shear stress ratio and an uniform and constant level of effective confining stress equal to 100kPa.

According to Figures 3 and 4, it can be observed that the deviatoric stress of pumice/rubber group mixtures decreases with increasing number of cycles and both r_u and ε_a are significantly influenced and it seems that the behaviour of the specimen begins to get affected by the presence of rubber. That results from the fact that the addition of the rubber leads to:

a. A smaller and smoother (flat) reduction of the deviatoric stress with the increasing number of cycles, especially for mixtures with rubber percentage ≥30%.

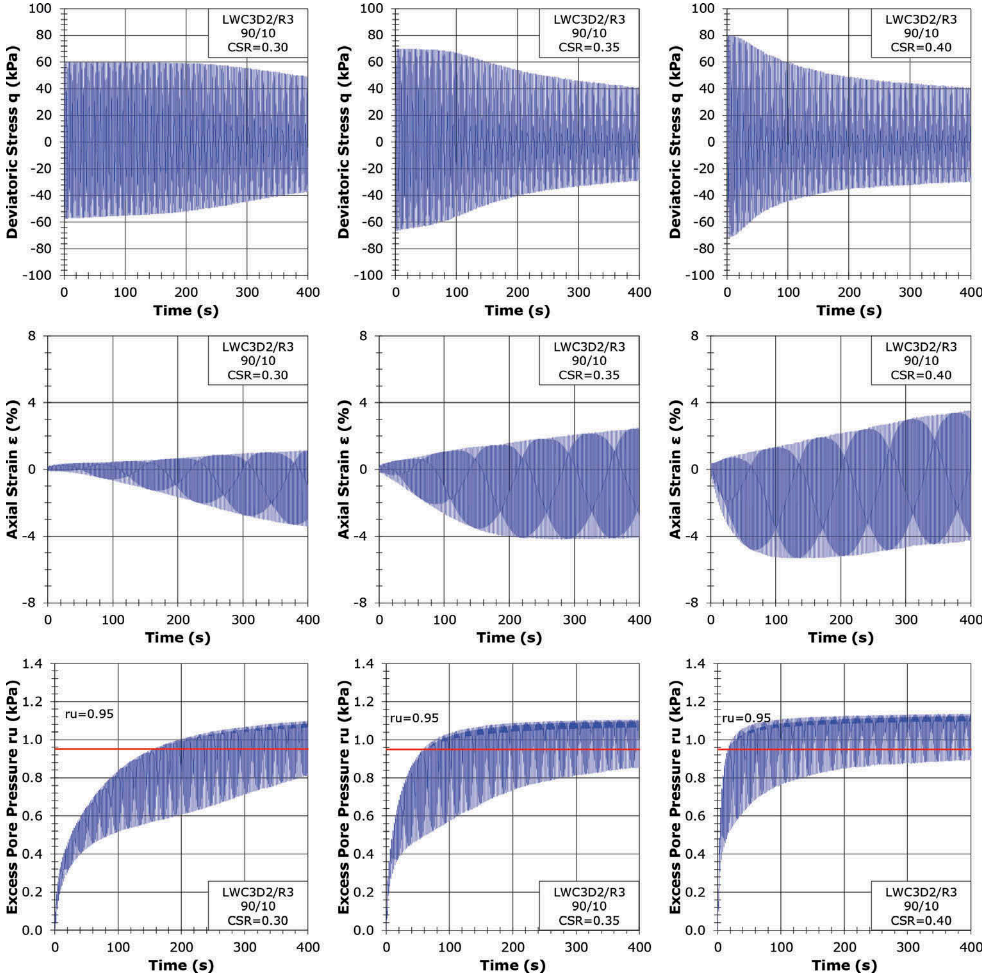

Figure 3. Variation of deviatoric stress, q, axial strain, ε(%), and excess pore water pressure ratio, r_u, with time of pumice/rubber mixture LWC3D2/R3-90/10 under different values of cyclic shear stress ratio, CSR

b. A faster increase of axial deformation, which is not combined by a corresponding reduction of specimens' strength, for mixtures with rubber percentage <30%.
c. A rapid increase of the ratio of excess pore pressure for mixtures with rubber percentage <30%. For rubber percentage ≥30% by mixture weight the addition of the rubber content has beneficial effect since it increases the required number of loading cycles.
d. Strength curves for pumice mixtures with rubber have a steeper gradient that those of typical pure sands.

As regards the effect of the mean grain size, D_{50}, and therefore the effect of the mean grain diameter ratio, $\lambda = D_{50,s}/D_{50,r}$, on the cyclic strength of the pumice/rubber group mixtures, the experimental results show that the increase of the ratio $D_{50,s}/D_{50,r}$ leads to higher required values of shear stress ratio in order to exceed one of the two liquefaction criteria, while it reduces the reduction rate of the deviatoric stress during cyclic loading.

Figures 5 and 6 show the number of cycles required to induce 1.0%, 2.0% and 5.0% double amplitude of axial strain (red, blue and green line respectively), as well as the number of cycles required to induce 95% of pore water pressure ratio (black line) for given levels of CSR for all

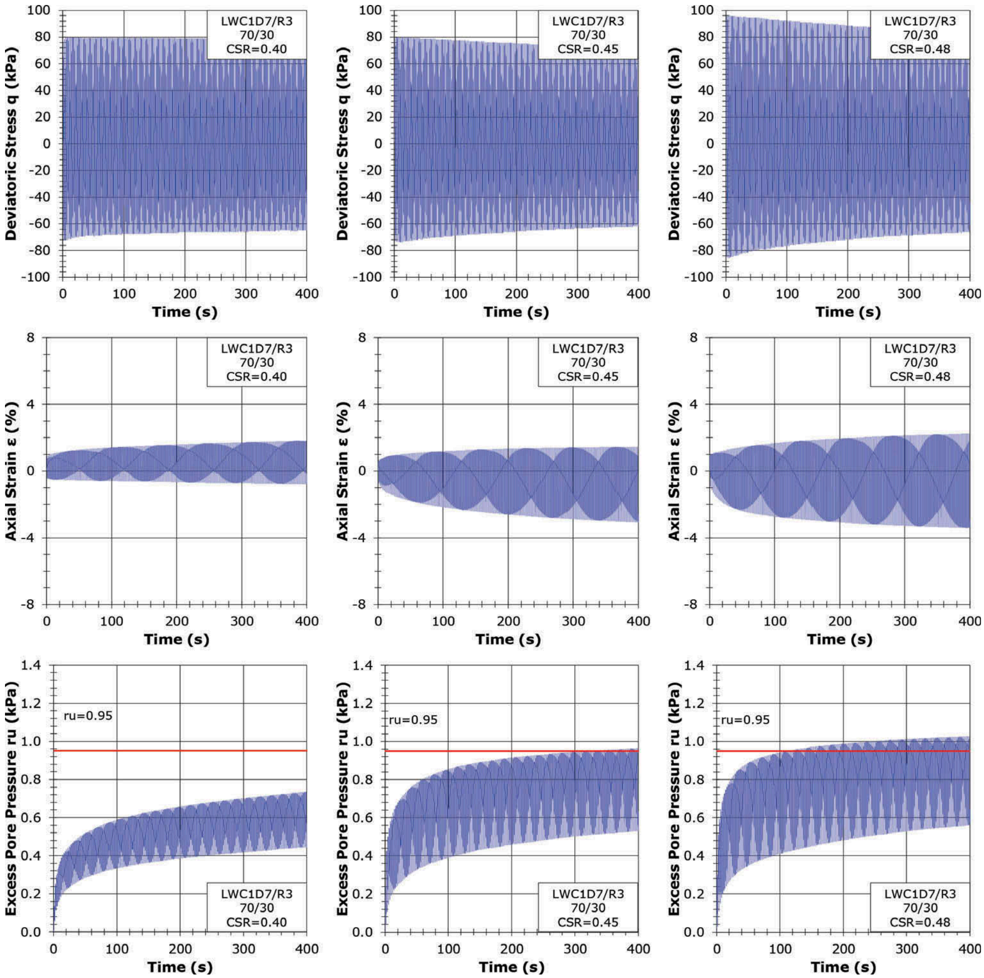

Figure 4. Variation of deviatoric stress, q, axial strain, ε(%), and excess pore water pressure ratio, r_u, with time of pumice/rubber mixture LWC1D7/R3-70/30 under different values of cyclic shear stress ratio, CSR

examined specimens, under an uniform and constant value of effective confining stress equal to 100kPa. It appears that the addition of the rubber can affect cyclic strength of the mixtures, since it reduces the number of loading cycles which are required in order to determine the "initial liquefaction", while the further increase of the percentage of rubber (≥30%) has the tendency to improve the above behaviour.

4 CONCLUSIONS

The most important parameters affecting the behaviour of the examined soil/rubber mixtures under dynamic loading are the rubber percentage in mixture's mass, r(%), and the relative ratio of the mean diameter of the mixture granules, $\lambda = D_{50,s}/D_{50,r}$. The experimental results of the present study show that: a) the addition of the rubber leads to a smaller and smoother reduction of the deviatoric stress with the increasing number of cycles, especially for mixtures with rubber percentage ≥30%, b) the rubber content affects the mixtures' resistance against cycling loading, since the specimens' axial deformation increases but without affecting, at least

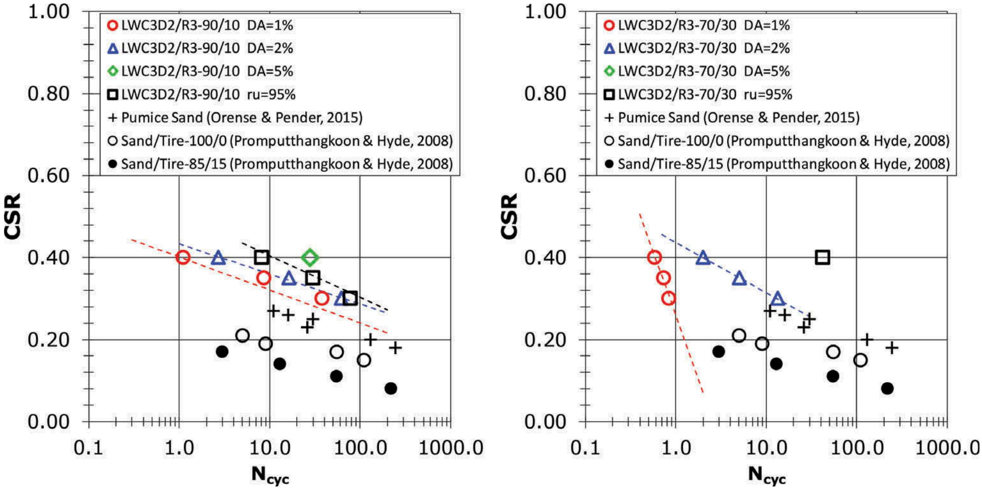

Figure 5. Cyclic strength curves of pumice/rubber group mixture LWC3D2/R3 and derived values from literature for Pumice Sand (Orense & Pender, 2015) and Sand/Tire Mixtures (Promputthangkoon & Hyde, 2008) at σ'_m=100kPa

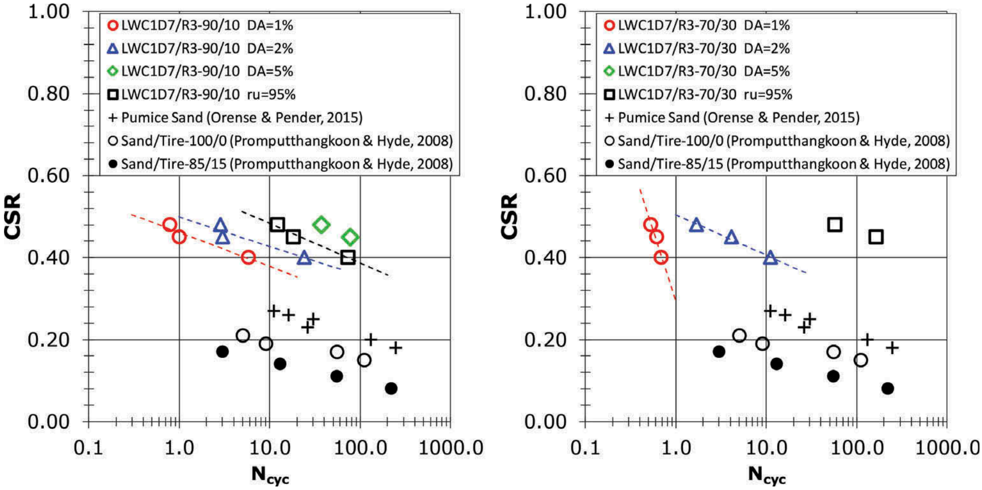

Figure 6. Cyclic strength curves of pumice/rubber group mixture LWC1D7/R3 and derived values from literature for Pumice Sand (Orense & Pender, 2015) and Sand/Tire Mixtures (Promputthangkoon & Hyde, 2008) at σ'_m=100kPa

at the same rate the specimens' strength reduction, for mixtures with rubber percentage <30%, c) the effect of the mean grain diameter ratio, $\lambda=D_{50,s}/D_{50,r}$, on the cyclic strength of dense pumice/rubber mixtures, the experimental results show that the increase of the ratio $D_{50,s}/D_{50,r}$ leads to higher required values of shear stress ratio in order to exceed the "initial liquefaction", as the elastic granules will fill the gaps among the soil grains, preventing the excess of pore-water pressure, d) saturated volcanic/rubber mixtures of high relative density exhibit satisfactory and sufficient resistance against liquefaction, compared to common soil/rubber mixtures of similar particle size and density, despite the particular porous nature and the grain-crushable behaviour of the volcanic materials under intense cyclic loading and high levels of confining pressure and axial strain.

ACKNOWLEDGMENTS

We acknowledge support by the project “HELPOS - Hellenic Plate Observing System” (MIS 5002697) which is implemented under the Action “Reinforcement of the Research and Innovation Infrastructure”, funded by the Operational Programme “Competitiveness, Entrepreneurship and Innovation” (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund).

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