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RESEARCH ARTICLE

ASSESSING THE DYNAMIC RESPONSE OF SAND INCORPARATING EXPANDED GLASS GRANULES THROUGH RESONANT COLUMN TEST

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Abstract

In contemporary geotechnical stabilization applications, there is a simultaneous drive to make applications as light and durable as possible while also preferring the utilization of waste products in soil improvement endeavors due to their dual merits of fostering environmental sustainability and conferring economic benefits. In this study, the use of expanded glass granules as a waste material was implemented to harmonize with this perspective, wherein reference sand and expanded glass granules were systematically mixed in varying proportions by mass and volume. Subsequently, the dynamic behavior of the mixture samples was rigorously assessed through a resonant column test between 0.001 - 0.1% shear strain amplitude and under various cell pressures. The variations in modulus reduction and initial shear modulus of the expanded glass granules added specimens were subjected to analysis, the shear modulus values of the samples mass-prepared (1, 2%) were obtained at least 12% and 21% higher than the reference sand, respectively. Similarly, the shear modulus values of the mixture sample prepared at 2.5% by volume were 20% higher than the reference sand at different effective pressures. The specimens prepared at 5% by volume demonstrate shear modulus values that were akin to those of the reference sand. The shear modulus values of the mixture samples prepared by volume (7.5, 10 and 15%) were found to be relatively lower than those of the reference sand. In the experimental study, it was discovered that the high angle of internal friction of the expanded glass granules exerts an influence on the variation in modulus reduction. According to the results of the experimental study, expanded glass granules show positive results in shallow geotechnical soil stabilization applications.

Keywords

Sand,
Expanded glass granules,
Modulus reduction,
Initial shear modulus,
Resonant column

Time Scale of Article

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1. INTRODUCTION

The world is grappling with an escalating volume of waste material, surpassing the capacity of our storage infrastructure. Based on projections, the global waste generation is expected to double by 2050 and triple by 2100 compared to 2016 levels. A substantial portion of this waste, approximately 30%, originates from construction activities, playing a pivotal role in contributing over 33% of the world's carbon emissions[1-3]. In addition, recycling one kilogram of glass effectively replaces for 1.2 kilograms of newly extracted raw materials, leading to a reduction in both CO_2 emissions and the requirement for pristine natural resources. This makes a significant contribution to preventing the depletion of our natural resources[4]. In an effort to handle these issues, a potential remedy lies in repurposing these waste materials across diverse engineering applications.

In the field of geotechnical engineering, while lime, bitumen, and cement etc. have been widely used as conventional soil stabilizers for a considerable period of time, recent advances in research have revealed the potential effectiveness of several chemical and chemical-free substances as alternatives or

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supplements to lime or cement, including fly ash, geotextile, waste stone powder, polymers, geofoam, polyurethane, waste tire scraps and waste glass etc. [5-13]. The results of related studies conducted to improve the dynamic parameters of soils have shown that the strength of soils can be increased with various waste additives.

From this perspective, the primary focus in this study is to investigate the shallow improvement of soils, especially sands, with expanded glass granules obtained from waste glass by using resonant column test. The manufacturing stage of expanded glass granules (GG) initiates with the comminution of waste glass fragments, reducing them to smaller pieces while simultaneously eliminating extraneous elements like aluminum and steel. Following this, the recycled glass material is subjected to a precise fine grinding process, which is a crucial factor in determining the final quality of the foam glass. To attain the desired characteristics, the resultant product undergoes a surface treatment involving the application of a composite consisting of glass flower, binder, and a foaming agent, followed by an expansion process. These expanded glass granules (GG) serve as innovative constituents in the fabrication of superior-grade building materials and essential industrial resources. Converting recycled glass materials into diverse-sized white granules is achieved through a manufacturing process that entails blending finely ground glass with expanding agents. These mixtures are subsequently subjected to exceedingly high temperatures, resulting in granules ranging from 0.045 mm to sizes surpassing 16 mm. These granules have varying bulk densities, commencing at 140 kg/m^3 and extending upwards of 500 kg/m^3. The distinctive porous composition of expanded glass granules excels in enhancing thermal and acoustic properties by adeptly ensnaring air in its voids[4, 14, 15].

Expanded glass granules possess a diverse array of uses owing to their production in various sizes. They are used in a wide range of industries, including agriculture, automotive, oil and gas, machinery, biofiltration, and construction engineering. While their widespread use in construction for thermal insulation, they also serve as a constituent in the formulation of the subsequent items: dry blends like plaster, mortar, shotcrete, aerated autoclaved concrete, construction bricks and barriers, drainage systems, stone aggregate, acoustic insulation, and fire-resistant materials[16-19]. In the geotechnical engineering applications, including railway and road embankments and artificially engineered slopes, the utilization of recycled materials, particularly glass, has experienced a surge in popularity due to its commendable durability and eco-friendly attributes[20-24]. The Fine Recycled Glass (FRG), Medium Recycled Glass (MRG) samples were found to exhibit behavior similar to the geotechnical engineering behavior of well-graded natural sand and gravel mixtures, and the evaluations proved that they comply with the requirements published by EPA Victoria for the use of aggregates as poor materials[20]. The results of numerical simulations show that lightweight materials derived from glass tend to slightly reduce rail vibration in the critical speed range[21]. Another study confirmed that permeable concrete road subgrade made of expanded glass granules has similar mechanical properties to natural fine aggregate subgrade and can act as a frost protection layer for road subgrade[23]. Recent scientific research has demonstrated that recycled glass and their byproducts, bearing similarities in origin to natural sand, can serve as viable substitutes in construction endeavors encompassing both superstructures and infrastructure[13, 25-29]. Furthermore, empirical evidence from diverse investigations has underscored the discernible influence of glass fragment characteristics, including size and form rounded or angular), on their efficacy within geotechnical implementations[30]. Despite the obvious advantages of expanded glass granules, their underutilization in soil stabilization and lack of dynamic studies persist. Recognizing this gap, the research aims to provide insight into this subject.

Consequently, in the study, the modulus reduction variation and the initial shear modulus of sand prepared by mixing with expanded glass granules at different ratios (1, 2, 2.5, 5, 7.5, 10, 15%) were investigated through a resonant column test between 0.001 – 0.1% shear strain amplitude and under different effective pressures (25, 50, 75, 100 kPa). In order to fully understand the interaction of between the glass granules and reference sand, the tests were carried out dry and independent of the dynamic effect of water. The scientific investigation furnishes persuasive substantiation affirming the advantageous impact exerted by GG on both the modulus reduction variation and initial shear modulus. The evidence clearly underscores that the high angle of internal friction, as well as the volumetric characteristics inherent to expanded glass granules, bestow substantial advantages upon the engineering properties of sand.

2. TEST METHOD, MATERIAL and PREPARATION

Seismic hazard assessment examines the impact of earthquakes on structures, particularly during sudden ground movements. The response of structures to seismic vibrations depends on the dynamic properties of the soil like shear resistance. Grasping these attributes is crucial for foreseeing potential harm and crafting resilient constructions. The initial shear modulus, known as G_{max} or G_0 (≈ at 0.001 %), is a foundational factor that imparts crucial insights into the resilience and stiffness of the ground under cyclic dynamic loading. This characteristic, often denoted as the initial, maximum or low-level shear strength, is established over laboratory or in-situ studies employing various techniques for instance dynamic triaxial, the bender element and resonant column (RC) test methods. Among these tests, RC test stands out as a dependable means of gauging shear strength across a strain spectrum of 0.001 to 0.1 %, turning it an indispensable laboratory instrument for assessing dynamic response of soil. The RC test involves subjecting a hollow type or solid type soil column to vibration in one of its inherent modes. As part of this research, solid specimens were meticulously prepared. Subsequently, the computation of the wave propagation velocity is undertaken, utilizing the resonant frequency as a foundational parameter. The RC device in operation employs an electric motor to induce harmonic torsional vibrations to the specimen. This excitation imposes a consistent amplitude torsional harmonic load across a spectrum of frequencies, with concurrent measurement of the response curve. The initial-mode resonant frequency measurement is employed to deduce the shear wave velocity. The shear wave velocity and soil density are used to calculate the initial shear modulus. Gradually escalating the amplitude of the torsional harmonic load during each test session yields the shear modulus across diverse strain ranges[31, 32].

As previously noted, following the production phase, the expanded glass granules (GG) undergo sorting based on various grain size distributions. Prior to determining the expanded glass granule size employed for the investigation, a numbers of RC tests were carried out using a range of grain diameters, spanning from 0.25 to 8 mm. Based on the findings of these tests, the GG diameter of 2 – 4 mm, which exhibited the highest initial shear modulus, was singled out from the six distinct grain diameters. The physical and chemical properties of the expanded glass granules provided by the manufacturer are given in Table 1 and Table 2 respectively. The fundamental fractional data meet the criteria of LST EN 13055–1:2004/AC:2016[33, 34]. Because of its granular composition, GG effectively preserve temperature by ensnaring air within. Owing to its distinctive hollow framework, it takes in no more than 15% of its overall weight, even when entirely immersed in water. It's crucial that water absorption doesn't escalate over time, and the material retains its original thermal isolation properties and stability. Resistance to both organic and inorganic chemicals is a characteristic of expanded glass granules, preventing any decomposition or deterioration. The sealed voids within the expanded glass granules pores guarantee this material remains unaltered for numerous years (https://stikloporas.com/expanded-glass).

The reference sand (RS), laboratory properties are given in Table 3, is a non-uniform natural sand that complies with UNE EN 196-1 standards with a silica content of 98% and a generally round grain diameter[35].

Table 1. The physical properties of GG provided by manufacturer

GG	G_s	D (mm)	Moisture absorption % by mass	φ	$\rho_{d(max)}$ (gr/cm^3)	CS MPa
	0.34	2 – 4	15	45^0	0.275	1.4

Gs: Relative density; D: Used diameter; φ: Angle of internal friction; CS: Compressive strength

Table 2. The chemical properties of GG provided by manufacturer

	pH	SiO_2	Al_2O_3	$Ka_2O + Na_2O$	CaO + MgO	Fe_2O_3	Heat Resistant / Melt ^0C
GG	9–11	71–73	1.5–2.0	13–14	8–10.5	<0.3	750 / 1000

Table 3. The laboratory properties of reference sand (RS).

	D_{50} (mm)	D_{10} (mm)	C_u	C_c	φ	G_s	e_{min}	e_{max}
Reference Sand (RS)	0.63	0.13	6	1.28	33^0	2.637	0.415	0.674

D_{50}: Mean diameter; **D_{10}:** Effective particle size; **C_u & C_c:**Uniformity and curvature coefficient; **φ:** Internal friction angel; **G_s:** Relative density; **e_{max} & e_{min}:** Max. and min. void ratio

Following the previous clarification, this study involved the preparation of test samples at varying volumetric mixing ratios (2.5, 5, 7.5, 7.5, 10%) and mass proportions (1, 2%). The RS and GG underwent mechanical mixing within a pan, adhering to designated proportions, for a designated duration to guarantee even distribution (Figure 1a). It is well known that the presence of water significantly outweighs other factors in its impact on the response of soils, particularly granular ones, under cyclic dynamic loads. Consequently, to explore the dynamic interaction between GG and RS, the composite specimens were prepared in a completely dry state. In both volume and mass combinations, the volume and mass of RS and GG were steadfastly maintained and then subjected to RC testing (Figure 1b). The reference specimens (Reference sand and expanded glass granules) and mixture specimens, as per the specifications outlined in Table 4 and Table 5, were placed within the RC testing apparatus.

Table 4. The RC test properties of reference specimens (RS&GG) and mixed specimens by mass.

		Reference Samples		Mixed Samples by Total Mass	
		GG100	RS100	RS99/GG1	RS98/GG2
M_T (gr)	*GG*	70.19	0	4.35	8.70
	RS	0	435	430.65	426.30
	Total	70.19	435	435	435
M_W	*gr*	0			
D	*mm*	50			
H	*mm*	130			
V_T	*cm^3*	255.25			
σ'_0	*kPa*	25; 50; 75; 100			
ρ_d	*gr/cm^3*	0.275	1.704	1.704	1.704

M_T & M_W: Total and water mass; **H & D:** Height and diameter; **V_T:** Volume; **σ'_0:**Effective pressure; **ρ_d:** Dry density

Table 5. The RC test properties of mixed specimens by volume.

		Mixed Samples by Total Volume				
		RS97.5/GG2.5	RS95/GG5	RS92.5/GG7.5	RS90/GG10	RS85/GG15
M_T (gr)	*GG*	1.75	3.51	5.26	7.02	10.53
	RS	424.36	413.48	402.60	391.72	369.96
	Total	426.12	416.99	407.87	398.74	380.49
M_W	*gr*	0				
D	*mm*	50				
H	*mm*	130				
V_T	*cm^3*	255.25				
σ'_0	*kPa*	25; 50; 75; 100				
ρ_d	*gr/cm^3*	1.669	1.634	1.598	1.562	1.491

M_T & M_W: Total and water mass; **H & D:** Height and diameter; **V_T:** Volume; **σ'_0:**Effective pressure; **ρ_d:** Dry density

Geotechnical engineering practices, including building slope reinforcement, providing constructing road and railway embankments or backfill support for retaining walls, primarily focus on shallow soil improvement and rehabilitation processes. Therefore, for this research, all the samples were subjected to effective cell pressures of 25, 50, 75, and 100 kPa.

(a) (b)

Figure 1. An example of mixture samples (GG10RS90) and RC test apparatus located at ESOGU Lab.

3. EXPERIMENTAL RESULTS

3.1. Results of Reference Samples (RS100&GG100)

In order to compare the experimental results, RS100 and GG100 specimens were first subjected to RC testing under the specified effective cell pressures. The shear modulus and modulus reduction graphs of both RS100 and GG100 along wide range of shear strain amplitudes are given in Figure 2. Upon analyzing the results depicted in the relevant graphs, considerably higher shear modulus values for RS100 were observed compared to GG100 between $\gamma = 0.001 – 0.03\%$ (Figure 2a, 2b). Significantly higher shear modulus values for RS100, as compared to GG100, were recorded as the effective cell pressure applied (75 – 100 kPa) to the specimens was increased (Figure 2a). The graphs show that, as the shear strain amplitude increases, the relative difference in shear modulus values for RS100 compared to G100 decreases, and even at high shear strain amplitude levels (as approaches to 0.1%), the data of GG100 remains higher (Figure 2a, 2b). Considering that the primary purpose of the study was to investigate the effects of GG on soil improvement due to their high angle of internal friction, the resilience of the shear modulus values of GG100 to decrease becomes evident as the deformation level increase. The modulus reduction graphs of both RS100 and GG100are also given in Figure 2 to support the corresponding case (Figure 2c, 2d).

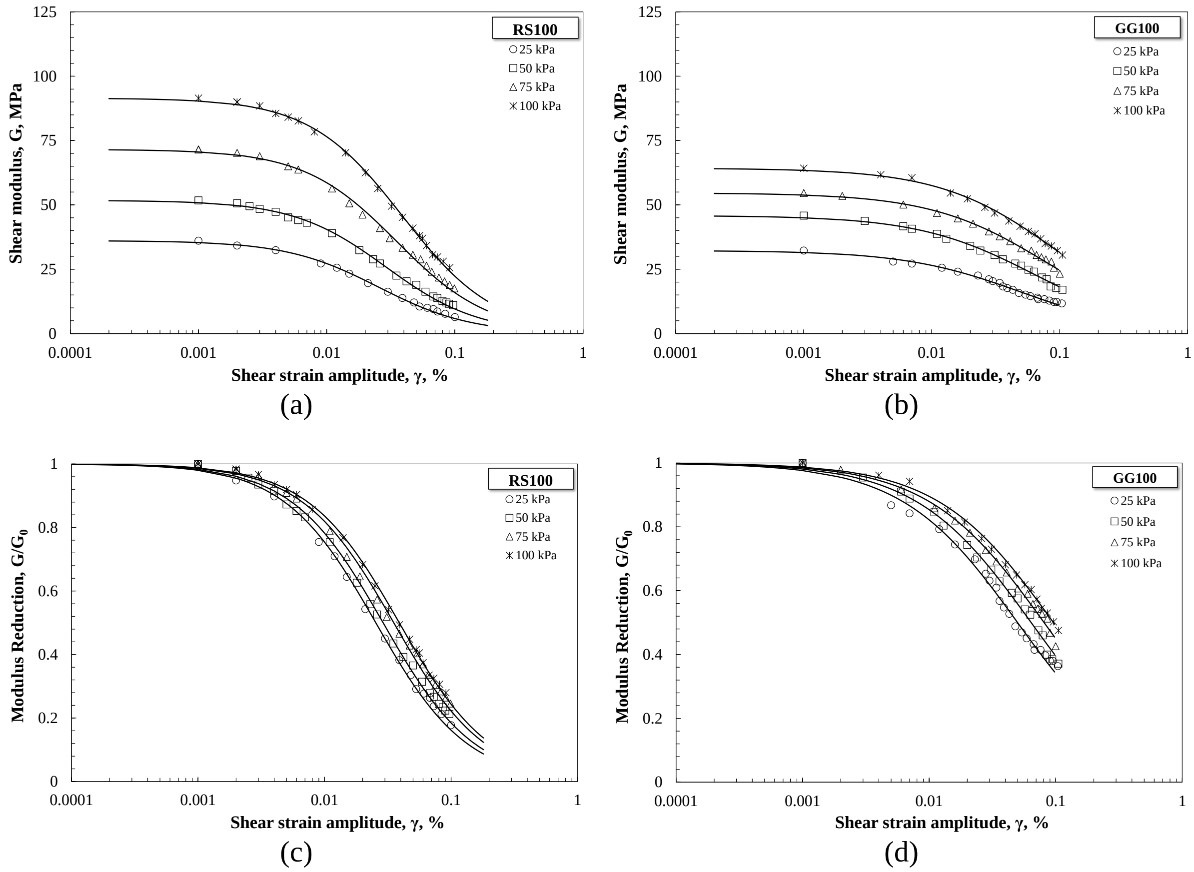

Figure 2. Shear modulus of RS100 (a) and GG100 (b); modulus reduction of RS100(c) and GG100(d).

3.2. Mathematical Model of Reference Sample (RS100&GG100)

The hyperbolic model is employed to forecast soil behavior in boundary value problems and provides the mathematical framework for describing nonlinear soil behavior. The reference shear strain amplitude (γ_r) within the hyperbolic model is defined as the strain that aligns with halve of the shear modulus. In the hyperbolic model, two tangent lines shape and limit the stress-strain curve of the analyzed samples. Small strains are characterized by G_0 in the tangent, which illustrates the elastic modulus, while the upper limit of the stress τ_f, representing the soil resistance, is denoted by the horizontal asymptote at large strains. The following differential expression of the stress-strain curve enclosed by tangents is presented where n is arbitrarily chosen [13, 36].

$$\frac{d\tau}{d\gamma} = G_0\left(1 - \frac{\tau}{\tau_f}\right)^n \tag{1}$$

This statement expresses that the tangent to the stress-strain curve gets a value of G_0 at $\tau = 0$ and undergoes a decreasing trend as stress levels increase, eventually reaching zero at $\tau = \tau_f$. Excluding the situation when n = 1, by integrating Eq. 1, the condition can be fulfilled, $\gamma = 0$ when $\tau = 0$ where (γ_r) is defined as the reference strain[36].

$$\gamma = \frac{\gamma_r}{n-1}\left[\frac{1}{\left[1 - \left(\tau/\tau_f\right)\right]^{n-1}} - 1\right] \tag{2}$$

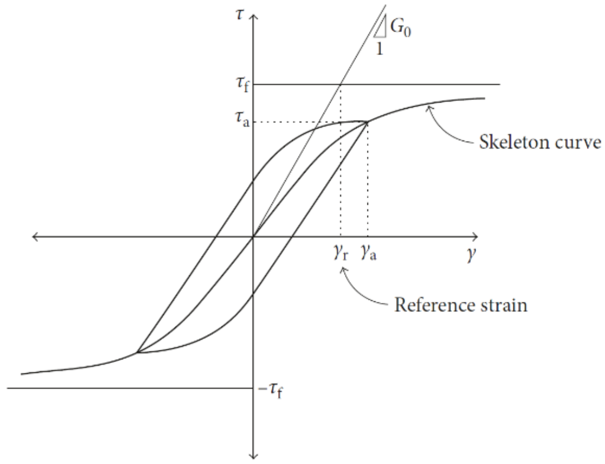

Figure 3. Reference strain definition in hyperbolic model[36]

Defined as follows, it represents the strain value in an elastic material when it reaches its failure stress;

$$\gamma_r = \frac{\tau_f}{G_0} \tag{3}$$

The reference strain represents the strain a soil would reach at the point of failure stress if it exhibited purely elastic behavior, as shown in Figure 3. The stress-strain curve can be derived as follows from Eq. 2. by assigned n = 2;

$$\tau = \frac{G_0 \gamma}{1 + \frac{\gamma}{\gamma_r}} \tag{4}$$

The modulus reduction is calculated using the following formula;

$$\frac{G}{G_0} = \frac{1}{1 + \frac{\gamma_a}{\gamma_r}} \tag{5}$$

where γ_a is the cyclic shear strain amplitude and $G = \tau_a / \gamma_a$. It has been found that when the shear strain reaches the reference strain, the secant shear modulus is reduced to half of its initial value[36]. The hyperbolic model exhibited in Eq. 5 is associated with the curvature coefficient (n), which influences the curvature of the modulus reduction trend lines, according to Darendeli[37]. The following correlation (Eq. 6) was employed to generate the trend lines concerning modulus reduction and initial shear modulus for both RS100 and GG100 in Figure 2, within the scope of the analyses. The curves obtained from the given equation were used to compare the test result graphs of the mixture samples with the test results of the RS100. The curvature coefficient (n) and reference strain values (γ_r) of the RS100 and GG100 are given in Table 6 according to the effective cell pressure variation.

$$\frac{G}{G_0} = \frac{1}{1 + \left(\frac{\gamma_a}{\gamma_r}\right)^n} \tag{6}$$

Table 6. The reference strain and coefficient of curvature values of RS100&GG100 to obtain the mathematical model

	RS100		GG100	
σ'_0 (kPa)	**n**	**γ_r %**	**n**	**γ_r %**
25	1.2	0.0254	0.95	0.050
50		0.0290		0.064
75		0.0352		0.081
100		0.0389		0.096

σ'_0: Effective cell pressure; γ_r: Reference strain; n: Coefficient of curvature

3.3. RC Results of Samples with GG

3.3.1. Results of mass-mixture samples

As mentioned before, the mixed specimens were prepared as a percentage of the total mass (1 and 2%). In Figure 4, the shear modulus and modulus reduction graphs of the mass-mixture specimens prepared at 1% and 2% (RS99/GG1 and RS98/GG2) ratios are given in comparison with RS100 values. The straight lines shown in the graphs are obtained from the RS100 test results and are derived from Eq. 6. When the shear modulus & shear deformation amplitude graph of the RS99/GG1, which has the same dry unit density as that of RS100 and is calculated to be 1.704 gr/cm^3, was examined, the shear modulus values of the RS99/GG1 specimen were significantly higher than those of RS100 at all effective cell pressures (Figure 4a).

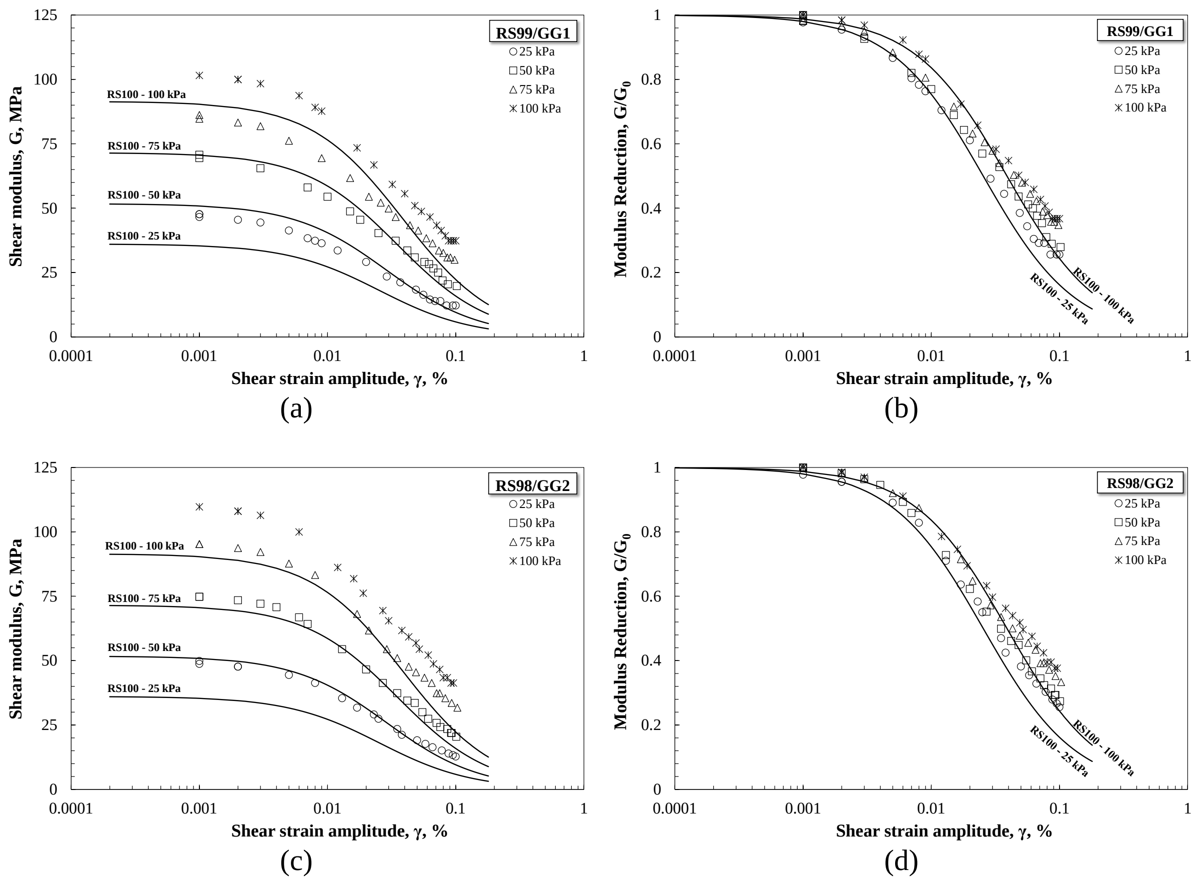

Figure 4. Shear modulus of RS99/GG1(a) and RS98/GG2 (c), modulus reduction of RS99/GG1(b) and RS98/GG2 (d)

When the modulus reduction graph of RS99/GG1 was analyzed, between γ = 0.03 – 0.1%, higher modulus reduction values than RS100 were observed (Figure 4b). Similarly, the shear modulus values of the RS98/GG2 specimen were significantly higher than the RS100 under all effective cell pressures, when the comparison between the shear modulus values of the RS98/GG2 specimen and RS100 was conducted (Figure 4c). In Figure 4d, the shear modulus of RS98/GG2 specimen also resists to decrease as the shear deformation amplitude increases between γ = 0.03 – 0.1%. RS99/GG1 and RS98/GG2 specimens, both specimens have a dry density of 1.704 gr/cm^3, when compared among themselves, the shear modulus values of RS98/GG2 specimen were significantly higher (Figure 4a, 4c). Both samples have significantly higher shear modulus than RS100. The main reason for this result is that the GG fills the voids in the solid specimen, resulting in compact specimens in comparison with the reference sample. Furthermore, when the modulus reduction graph of GG100 was examined, the effect of the high angle of internal friction of GG100 on the modulus reduction was emphasized (Figure 2d). It can be asserted that the modulus reduction values of the mass-mixed specimens are similarly influenced by the high angle of internal friction of GG between γ = 0.03 – 0.1% (Figure 4b, 4d).

3.3.2. Results of volume-mixture samples

As mentioned in the study, the mixed samples were prepared as a percentage of the total volume (2.5, 5, 7.5, 10 and 15%). Figure 5 shows the shear modulus and modulus reduction graphs of RS97.5/GG2.5 and RS95/GG5. The dry densities of both samples were 1.669 gr/cm^3 and 1.634 gr/cm^3 respectively, which are lower than RS100.

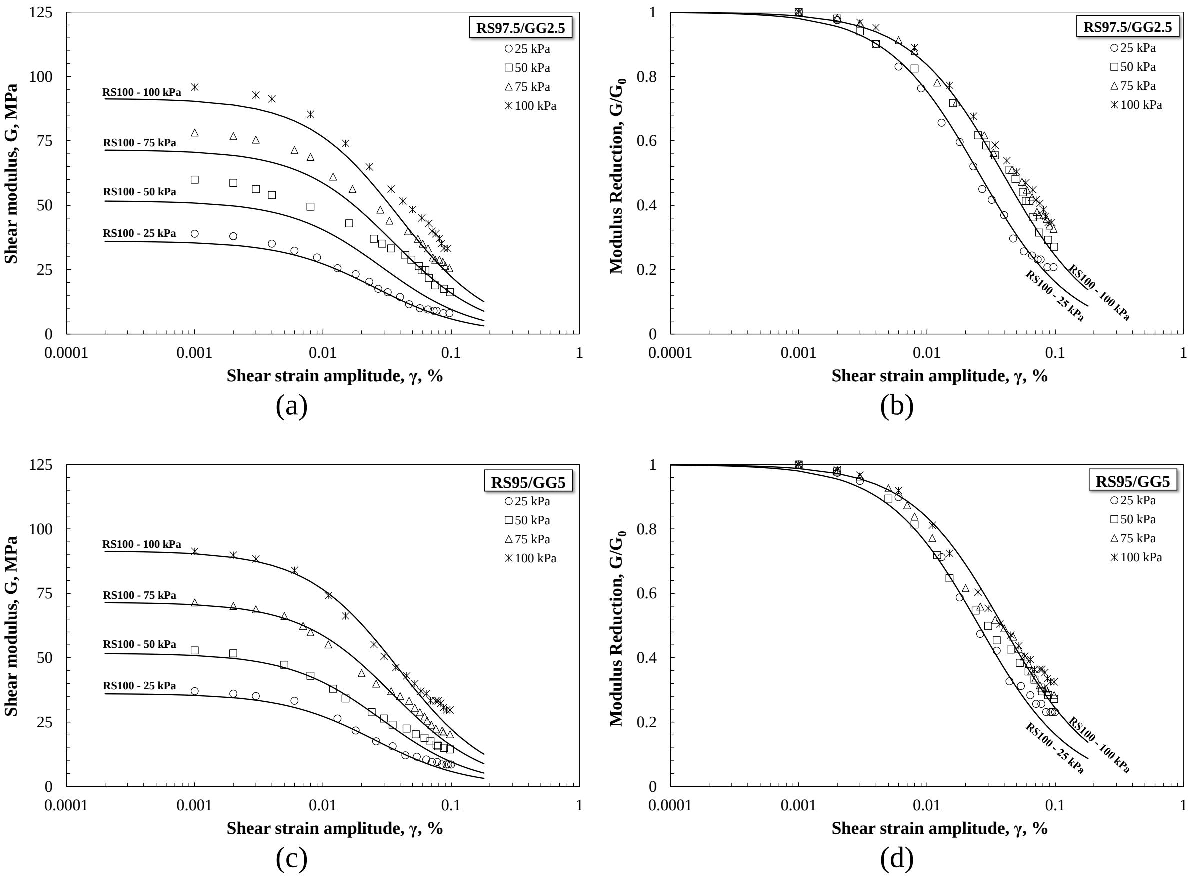

Figure 5. Shear modulus of RS97.5/GG2.5(a) and RS95/GG5 (c), modulus reduction of RS97.5/GG2.5(b) and RS95/GG5 (d)

The graph shows that the shear modulus values of RS97.5/GG2.5 are significantly higher compared to RS100 at all effective cell pressures (Figure 5a). RS97.5/GG2.5 followed a similar trend with RS100 between γ = 0.01 – 0.05% and below 25 kPa pressure (Figure 5a). It can be seen that the void filling effect of GG is also effective on RS97.5/GG2.5. Except for the 25 kPa values, the modulus reduction values of RS97.5/GG2.5 were higher than those of RS100 at all remaining cell pressure values between γ = 0.03 – 0.1% (Figure 5b).

At all effective cell pressures and between γ = 0.001 – 0.08%, RS95/GG5, whose dry density was calculated to be 4% lower than the RS100, obtained similar shear modulus values to the RS100 (Figure 5c). The shear modulus value of the RS95/GG5 specimen was slightly higher than RS100 between γ = 0.08 – 0.1% (Figure 5c). The modulus reduction values of RS95/GG5 were higher than the RS100 at all remaining cell pressure values between γ = 0.03 – 0.1% except 25 kPa.

Figure 6 shows the shear modulus and modulus reduction graphs of RS92.5/GG7.5, RS90/GG10 and RS85/GG15 specimens with mixed ratios of 7.5, 10 and 15% by volume, respectively. The unit density values of these samples were 7, 8.5 and 12% lower than RS100. When the shear modulus graphs of all three specimens are examined, it is evident that the shear modulus values of the respective samples are lower than RS100 along γ = 0.001 – 0.035% under all effective cell pressures (Figures 6a, 6c and 6e). On the other hand, it can also be seen from the graphs that the shear modulus values of all three specimens are higher than RS100 due to the increasing shear strain amplitudes after γ = 0.035% under all effective pressures (Figure 6a, 6c and 6e).

When the modulus reduction graphs of RS92.5/GG7.5, RS90/GG10 and RS85/GG15 are examined, it is clear that the modulus reduction values of all samples follow a similar trend with the variation of RS100 modulus reduction along γ = 0.001 – 0.035% under all effective cell pressures (Figures 6b, 6d and 6f). Nevertheless, it is also seen from the graphs that the modulus reduction values of RS92.5/GG7.5, RS90/GG10 and RS85/GG15 are higher than the modulus reduction values of RS100 with increasing shear strain amplitudes after γ = 0.035% under all effective pressures (Figures 6b, 6d and 6f).

To explain the behavior of RS92.5/GG7.5, RS90/GG10 and RS85/GG15 shown in Figure 6, it should first be noted that these specimens contain a high volume of expanded glass granules, which causes the specimens to contain many voids. The voids in the RS92.5/GG7.5, RS90/GG10 and RS85/GG15 cause the shear modulus values to be low compared to RS100 γ = 0.001 – 0.035% at all effective cell pressures. The most important feature of granular soils is that they can be compacted by vibration. Increasing the shear strain amplitude during the RC experiment is possible by increasing the applied torque, which also increases the vibration on the specimen. With increasing shear strain amplitude, RS92.5/GG7.5, RS90/GG10 and RS85/GG15 become relatively dense and the high angle of internal friction of GG reduces the decrease of the shear modulus, which also explains the behavior of RS92.5/GG7.5, RS90/GG10 and RS85/GG15 after shear strain amplitude γ = 0.035%.

4. CONCLUSION

The main objective of this experimental investigation involves the study of the dynamic behavior exhibited by a composite material composed of reference sand (RS) mixed with expanded glass granules (GG) by using a (RC) resonant column test device. The mixture specimens prepared both by mass (1, 2%) and volume (2.5, 5, 7.5, 10 and 15%), test details given in Table 4 and 5, were tested in the shear deformation range of γ = 0.001 - 0.1% under effective cell pressures of 25, 50, 75 and 100 kPa. As previously explained, the fact that GG is a chemically inert material, allows us to attribute the results of this research to the physical interactions between RS and GG. It is also known that water has an effect on the behavior of granular soils under dynamic loading, so all mixture samples were prepared dry to avoid the effects of water.

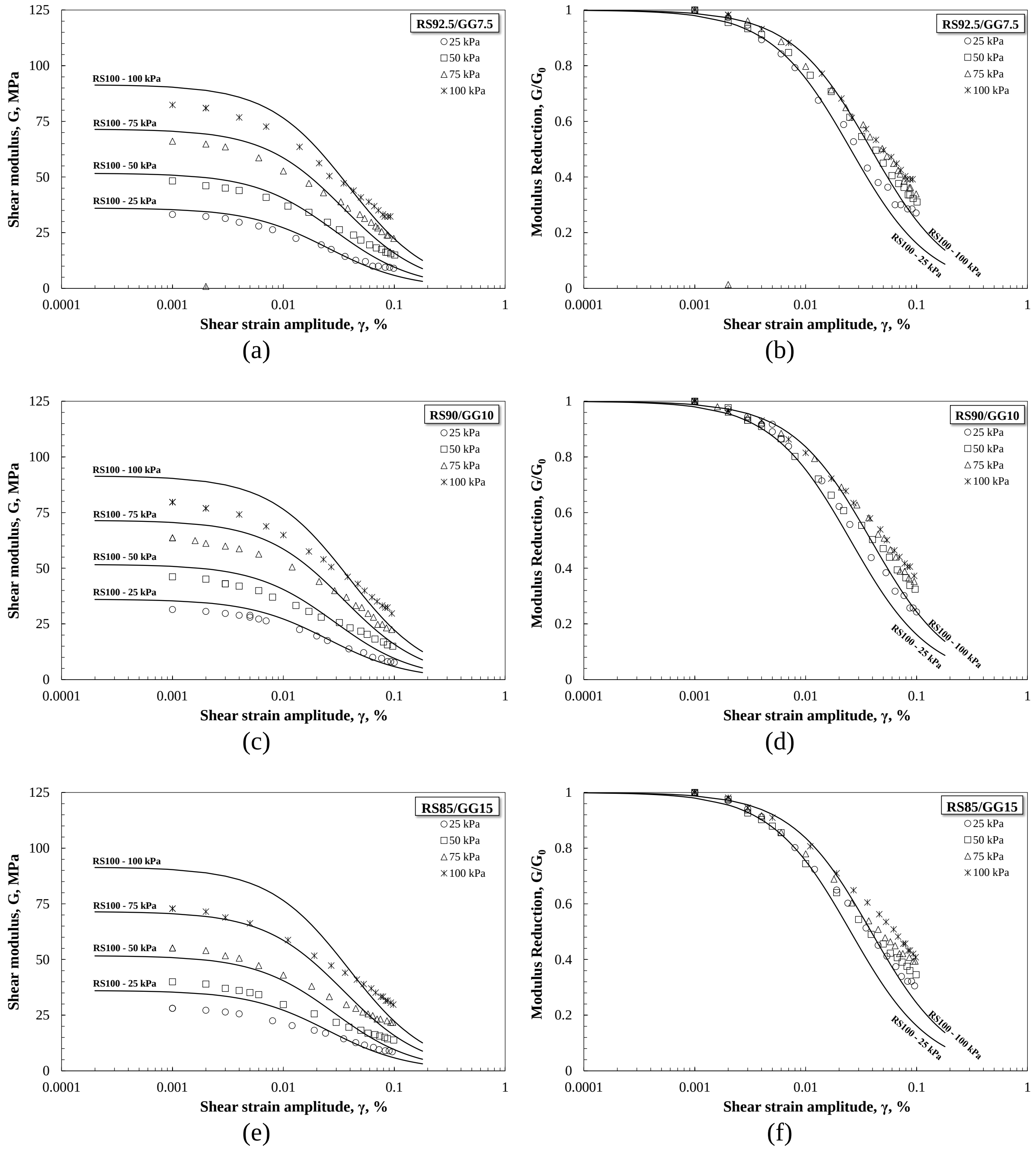

Figure 6. Shear modulus of RS92.5/GG7.5(a), RS90/GG10 (c) and RS85/GG15 (e), modulus reduction of RS92.5/GG7.5(b), RS90/GG10 (d) and RS85/GG15 (f)

When the behavior of the RS99/GG1 and RS98/GG2 prepared with the same grain density as RS100 was examined, it was found that the expanded glass granules filled the voids in these samples quite well. Both specimens have very high shear modulus values compared to RS100, although they have the same density as RS100 at all effective cell pressures through all shear strain amplitudes. Upon examination of the modulus reduction variations of both samples, it was once more observed from the experiments that the modulus reduction values exceeded RS100 after γ = 0.03%. It is clear that the effect of GG on the mass-prepared samples is twofold. First of all, the GG were well dispersed in the mass-prepared specimens and provided compression, which resulted in higher shear modulus values than RS100 along all shear strain amplitudes. The second positive aspect is the effect of the high angle of internal friction of GG on the modulus reduction values with increasing shear strain amplitudes. The expanded glass granule has been a crucial aspect in ensuring that the modulus reduction values of the mass-prepared specimens remained higher than RS100 with increasing deformation after $\gamma = 0.03\%$ at all effective pressures.

RS97.5/GG2.5 and RS95/GG5, which are prepared by volume, are 2% and 4% lighter than RS100, respectively. RS97.5/GG2.5 has relatively higher shear modulus values than RS100, on the other hand, RS95/GG5 has similar values with RS100. Similar to the results of the mass-prepared samples, RS97.5/GG2.5 and RS95/GG5 can be used as a substitute for RS100 depending on the test results. The similar results of the effects of expanded glass granules on samples prepared by mass can also be observed in the results of these two samples.

RS92.5/GG7.5, RS90/GG10 and RS85/GG15 samples, prepared by volume, have densities that are 7%, 8.5% and 12% lower than that of RS100, respectively. The test results indicate that RS92.5/GG7.5, RS90/GG10 and RS85/GG15 exhibit lower shear modulus values when compared to RS100 along $\gamma = 0.001 – 0.035\%$ at all effective cell pressures. On the contrary, the shear modulus values of all three specimens exceed RS100 as the shear strain amplitudes increase after $\gamma = 0.035\%$ under all effective pressures. A similar assessment applies to the modulus reduction variation of these specimens.

As expected under the corresponding test conditions, the favorable impact on both especially modulus reduction values and the shear modulus values of mixed samples is considered to be influenced by the high angle of internal friction exhibited by the GG (effective along $\gamma = 0.03 - 0.1\%$) and the physical volume occupied by the GG (effective along $\gamma = 0.001 - 0.03\%$). It was observed that the results obtained from this study were in agreement with the results obtained by mixing expanded glass granules with clays[13]. When the ratios recommended in the study are increased, the amount of the main soil material decreases. In this case, the behavior of expanded glass granules is dominant. The feasibility of using expanded glass granules as a soil stabilization agent in shallow geotechnical applications is elucidated by the present study. It is underscored by experimental evidence that, depending on the specified boundary conditions, expanded glass granules can be used as a viable modality. To comprehensively understand its potential contributions, subsequent investigations into the attributes of the material and its application in different soil types and boundary frameworks are considered imperative.

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CONFLICT OF INTEREST

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CRediT AUTHOR STATEMENT

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REFERENCES

[1] Ferdous W, Manalo A, Siddique R, Mendis P, Yan Z, Wong H, Lokuge W, Aravinthan T, Schubel P. Recycling of landfill wastes (tyres, plastics and glass) in construction - A review on global waste generation, performance, application and future opportunities. Resources Conservation and Recycling. 2021;173.

[2] Akinade O, Oyedele L. Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS). Journal of Cleaner Production. 2019;229:863-73.

[3] Baek C, Park S, Suzuki M, Lee S. Life cycle carbon dioxide assessment tool for buildings in the schematic design phase. Energy and Buildings. 2013;61:275-87.

[4] Sommariva L, Weinberger K, Pierucci S, Klemes J. Energy and Natural Resources Saving In The Production of Expanded Glass Granules. Icheap12: 12th International Conference on Chemical & Process Engineering. 2015;43:2437-42.

[5] Shi J, Xiao Y, Hu J, Wu H, Liu H, Haegeman W. Small-strain shear modulus of calcareous sand under anisotropic consolidation. Canadian Geotechnical Journal. 2022;59:878-88.

[6] Ashango AA, Patra NR. Behavior of Expansive Soil Treated with Steel Slag, Rice Husk Ash, and Lime. Journal of Materials in Civil Engineering. 2016;28:06016008.

[7] Sarajpoor S, Ghalandarzadeh A, Kavand A. Dynamic behavior of sand-bitumen mixtures using large-size dynamic hollow cylinder tests. Soil Dynamics and Earthquake Engineering. 2021;147:106801.

[8] Lang L, Li F, Chen B. Small-strain dynamic properties of silty clay stabilized by cement and fly ash. Construction and Building Materials. 2020;237:117646.

[9] Saride S, Dutta TT. Effect of Fly-Ash Stabilization on Stiffness Modulus Degradation of Expansive Clays. Journal of Materials in Civil Engineering. 2016;28:04016166.

[10] El-kady MS, Azam A, Yosri AM, Nabil M. Modelling of railway embankment stabilized with geotextile, geo-foam, and waste aggregates. Case Studies in Construction Materials. 2023;18:e01800.

[11] Umu SU, Okur D, Yilmaz G, Firat S. A Study on The Stiffness and Damping Characteristics of Sand/Rubber Mixtures Under Dynamic Loading Conditions. Journal of Polytechnic-Politeknik Dergisi. 2014;17:13-21.

[12] Okur DV, Umu SU. Dynamic properties of clean sand modified with granulated rubber. Advances in Civil Engineering. 2018;2018.

[13] Umu SU. Assessment of sustainable expanded glass granules for enhancing shallow soil stabilization and dynamic behaviour of clay through resonant column tests. Engineering Science and Technology, an International Journal. 2023;42:101415.

[14] da Silva RC, Puglieri FN, de Genaro Chiroli DM, Bartmeyer GA, Kubaski ET, Tebcherani SM. Recycling of glass waste into foam glass boards: A comparison of cradle-to-gate life cycles of boards with different foaming agents. Science of The Total Environment. 2021;771:145276.

[15] Rodrigues C, König J, Freire F. Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. Sustainable Production and Consumption. 2023;36:161-70.

[16] Adewoyin O, Adesina A, Das S. Performance Evaluation of Thermal-Efficient Lightweight Mortars Made with Expanded Glass as Aggregates. Journal of Materials in Civil Engineering. 2022;34.

[17] Lecheb S, Chellil A, Chahour K, Safi B. Foamed glass granulated-based self-compacting mortars: open-porosity effect on rheological and mechanical properties. Cement Wapno Beton. 2021;26:242-52.

[18] Augonis A, Ivanauskas E, Bocullo V, Kantautas A, Vaiciukyniene D. The Influence of Expanded Glass and Expanded Clay on Lightweight Aggregate Shotcrete Properties. Materials. 2022;15.

[19] Guo P, Meng W, Du J, Stevenson L, Han B, Bao Y. Lightweight ultra-high-performance concrete (UHPC) with expanded glass aggregate: Development, characterization, and life-cycle assessment. Construction and Building Materials. 2023;371:130441.

[20] Disfani M, Arulrajah A, Bo M, Hankour R. Recycled crushed glass in road work applications. Waste Management. 2011;31:2341-51.

[21] Lenart S, Kaynia A. Dynamic properties of lightweight foamed glass and their effect on railway vibration. Transportation Geotechnics. 2019;21.

[22] Kazmi D, Serati M, Williams D, Qasim S, Cheng Y. The potential use of crushed waste glass as a sustainable alternative to natural and manufactured sand in geotechnical applications. Journal of Cleaner Production. 2021;284.

[23] Kurpińska M, Grzyl B, Pszczola M, Kristowski A. The Application of Granulated Expanded Glass Aggregate with Cement Grout as an Alternative Solution for Sub-Grade and Frost-Protection Sub-Base Layer in Road Construction. Materials. 2019;12:3528.

[24] Saberian M, Li J, Boroujeni M, Law D, Li C-Q. Application of demolition wastes mixed with crushed glass and crumb rubber in pavement base/subbase. Resources, Conservation and Recycling. 2020;156:104722.

[25] Baldovino JdJA, Izzo RLdS, Silva ÉRd, Rose JL. Sustainable Use of Recycled-Glass Powder in Soil Stabilization. Journal of Materials in Civil Engineering. 2020;32:04020080.

[26] Baradaran MS, Qazanfari R, Baradaran S. Study of soil reinforcement in the east of Mashhad using glass granule. Materials Research Express. 2023;10:055202.

[27] Benny JR, Jolly J, Sebastian JM, Thomas M. Effect of glass powder on engineering properties of clayey soil. International Journal of Engineering Research & Technology. 2017;6:228-31.

[28] Otsubo M, Towhata I, Hayashida T, Liu B, Goto S. Shaking table tests on liquefaction mitigation of embedded lifelines by backfilling with recycled materials. Soils and Foundations. 2016;56:365-78.

[29] Sandiani M, Tanzadeh J. Laboratory assessing of the liquefaction potential and strength properties of Sand soil treated with mixture of nanoclay and glass fiber under dynamic and static loading. Journal of Materials Research and Technology. 2020;9:12661-84.

[30] Xiao Y, Long L, Evans TM, Zhou H, Liu H, Stuedlein AW. Effect of Particle Shape on Stress-Dilatancy Responses of Medium-Dense Sands. Journal of Geotechnical and Geoenvironmental Engineering. 2019;145:04018105.

[31] Drnevich VP. Recent Developments in Resonant Column Testing. ASCE annual meeting Proceedings, Richart Commemorative Lectures, . Detroit, MI.1985.

[32] ASTM. Standard test methods for modulus and damping of soils by the resonant-column method. American Society for Testing & Materials2000. p. 582-601.

[33] EN13055-1. 13055-1. Lightweight Aggregates—Part 1: Lightweight Aggregates for Concrete, Mortar and Grout. British Standard: London, UK2004.

[34] EN13055. EN 13055:2016, Lightweight aggregates. 2016.

[35] UNE.EN.196-1:2018. Methods of testing cement - Part 1: Determination of strength. 2018. p. 36.

[36] Ishihara K. Soil Behaviour in Earthquake Geotechnics: Clarendon Press; 1996.

[37] Darendeli MB. Development of a new family of normalized modulus reduction and material damping curves: The University of Texas at Austin; 2001.