Direct shear response of gravel-glass-rubber mixtures

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ABSTRACT: This paper reports on preliminary results of a feasibility study aimed at evaluating the potential use of recycled crushed green glass bottles and recycled granulated tire rubber mixed with gravel. Specifically, dry specimens of selected gravel-glass-rubber mixtures (GGRMs) are tested using a medium-size (100 mm × 100 mm × 53 mm - width × length × height) direct shear apparatus under three normal stress levels: 30, 60 and 100 kPa. The effect of glass and rubber content by volume on the peak shear strength, friction angle and energy absorption of the mixtures is investigated. It is shown that GGRMs having 40% rubber content by volume possess adequate strength (i.e., friction angle > 30º), reduced compressibility and excellent energy absorption properties, making such materials suitable structural fills for typical geotechnical applications.

KEYWORDS: recycled glass; recycled rubber; gravel; direct shear; strength; energy absorption.

1 INTRODUCTION

The use of fresh construction geomaterials has been historically a primary resource for industry; however, nowadays, the secondary use/recycling of waste materials (e.g., industrial by products; commercial wastes, construction and demolition wastes etc.) is becoming more prominent in the construction industry. Any form of secondary usage reduces the need for fresh primary resources, minimises waste and increases sustainability (Chiaro et al. 2015, 2020, Přikryl et al. 2016, Arulrajah et al. 2015, Qi et al. 2020, Ghorbani et al. 2021).

In New Zealand, over 6.3 million waste tyres are produced each year (Waste Management, 2021). Ministry for the Environment reported that 66,150 tonnes of glass and 77,690 tonnes of rubber head to NZ's landfills. Waste sent to landfills increased by 47% from 2009/2010 to 2018/2019 (Ministry for the Environment, 2021). Such large volume of discarded material indicates that the need to reuse/recycle waste material is key to becoming a more sustainable country.

Recycled tyre rubber and recycled glass have interesting properties from a geotechnical engineering perspective, such as high strength and good durability (Wartman et al. 2004, Tasalloti et al. 2021b, c). The supply of these waste materials is potentially high, and the cost is relatively low. The benefits of using these materials are enhanced if they can replace virgin construction materials made from non-renewable resources. The appealing characteristics of these materials as a construction geomaterial can be exploited in a beneficial manner to help make the industry more sustainable.

The recycling of rubber-derived waste tyres mixed with gravel for sustainable geotechnical applications has been studied by Chiaro et al. (2019, 2021) and Tasalloti et al. (2020, 2021a, c). It has been found that gravel-rubber mixtures (GRMs) with volumetric rubber content (R_B) ≤ 40% have adequate strength and energy dissipation properties to be used as structural fill materials in geotechnical applications (Tasalloti et al. 2021c). The use of gravel-like size rubber particles in GRMs has been also reccommended. While different rubber sizes show no effect on the strength, the larger rubber particles (similar in size to the gravel) show less compressibility (Tasalloti et al. 2021c) and minimal leaching of toxic materials (Banasiak et al. 2021).

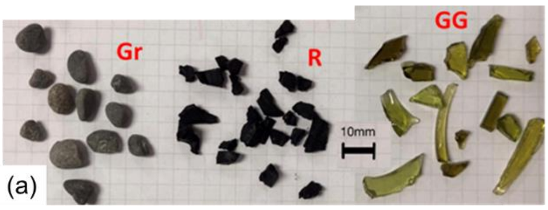
Research into the geotechnical engineering characteristics of crushed glass alone has been completed by Wartman et al. (2004). Results of direct shear tests indicate that the friction angles is 47º–62º, which is comparable to that of gravelly soils (Tasalloti et al. 2021b, c). Thus, recycled glass could potentially be used in geotechnical applications. One possibility is to use it to partially replace gravel in GRMs and produce gravel-recycled glass-recycled rubber mixtures (GGRMs).

This study investigates for the first time the geotechnical properties and energy absorption properties of GGRMs by means of detailed laboratory investigations, building on the previous study by the authors on GRMs (Chiaro et al., 2019, 2020, 2021) and Tasalloti et al. (2020, 20121a, b).

2 TEST MATERIALS AND PROCEDURE

2.1 *Materials*

The materials tested in this study were a rounded pea gravel (specific gravity, G_s = 2.66; mean diameter D_{50} ≈ 5.5 mm), granulated recycled rubber (G_s = 1.15; D_{50} ≈ 5.3 mm) and crushed green glass (G_s = 2.50; D_{50} ≈ 5.5 mm). Representative photos and particle size distribution curves of the different materials are shown in Figure 1.



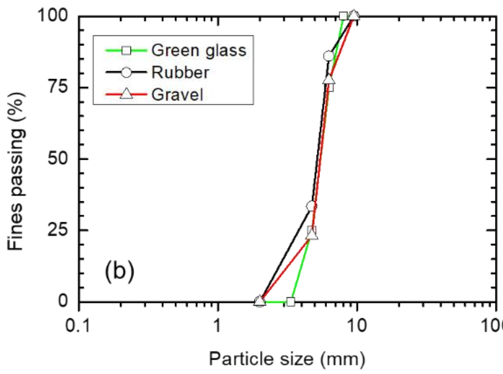


Figure 1. Materials tested in this study: (a) photographic images; and (b) particle size distribution curves.

The gravel and rubber were commercially available. The gravel was washed and dried before any testing began to remove any trace fines material. The rubber is free from steel wires. The green glass was crushed from wine bottles, and then sieved to obtain the required particle size distribution. Particles that were too large were crushed until they passed through the 8 mm sieve. It contained a large range of particle shapes, with a significant amount of long, slender pieces.

As shown in Figure 2, different GGRMs mixtures were formed by keeping the volumetric rubber content (R_B) constant at 0.4 (i.e., 40%), but changing the proportion by volume of green glass (G_L) and gravel (G_R) in the mixtures. The volumetric fraction of each material was calculated using Equations 1−3, where V_{Glass}, V_{Rubber} and V_{Gravel} are the volume of the glass, rubber and gravel in the mixture respectively.

$$G_L = \frac{V_{\text{Glass}}}{V_{\text{Glass}} + V_{\text{Gravel}} + V_{\text{Rubber}}} \tag{1}$$

$$R_\text{B} = \frac{V_{\text{Rubber}}}{V_{\text{Glass}} + V_{\text{Gravel}} + V_{\text{Rubber}}} \tag{2}$$

$$G_R = \frac{V_{\text{Gravel}}}{V_{\text{Glass}} + V_{\text{Gravel}} + V_{\text{Rubber}}} \tag{3}$$

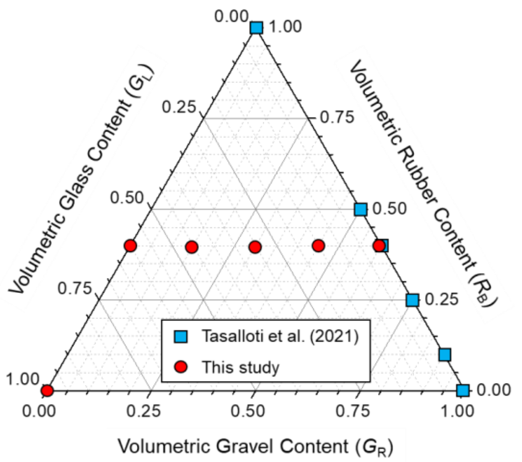


Figure 2. GGRMs tested in this study and GRMs tested by Tasalloti et al. (2021a, c).

2.2 *Test procedure*

2.2.1 *Compaction test*

Compaction characteristics of GGRMs were determined by means of Proctor tests (ASTM D698). The steel mould used in this study had a diameter of 152.7 mm and a height of 116.4 mm. In each test, 3 layers were compacted by applying 56 blows of impact load. To streamline the process and maintain consistency, an automatic compaction device was used.

To limit the segregation between the different materials, the mixtures were prepared in small batches of approximately 900 g and then poured into the compaction mould very carefully.

Preliminary tests indicated that for specimens with a water content of 5% or more, water was lost through the base of the mould. This is due to the high permeability (i.e., free draining) nature of GGRMs. Thus, being unable to control the water content, all further compaction tests were conducted on dry specimens.

2.2.2 *Direct shear test*

Direct shear box tests were conducted following ISO 17892-10:2018. The size of the soil box was 100 mm × 100 mm × 53 mm. A schematic illustration of the direct shear box apparatus used in this is shown in Figure 3.

Dry specimens were prepared in the soil box by tamping method at a dry density corresponding to 90-95% degree of compaction. The specimens were tested under three effective normal stress levels of 30, 60 and 100 kPa. After the normal stress was applied on the mixtures, sufficient time was allowed for the material to fully compress/consolidate. The 100 kPa tests required the most time to consolidate, approximately two hours. The vertical displacement was recorded during the one-dimensional compression process. Once vertical settlement increment became negligible, the specimens were sheared at a constant horizontal displacement rate of 1.0 mm/min. Tests were concluded when the horizontal displacement achieved 15.0 mm.

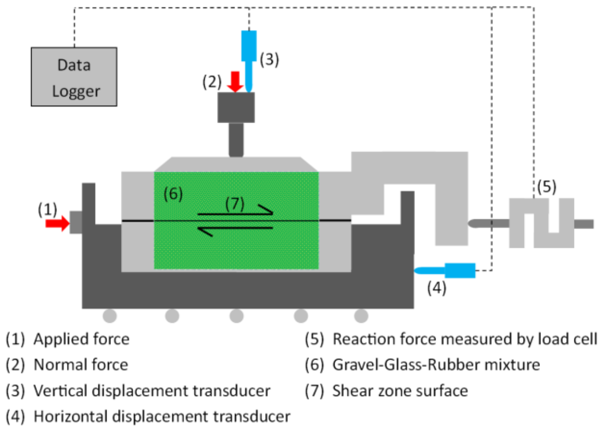


Figure 3. Schematic illustration of the direct shear box device used in this investigation.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Compaction*

The results of the compaction tests are reported in Figure 4 for GGRMs (R_B = 0.4) and green glass only (refence test). For the sake of comparison, the data points for gravel, rubber and GRM (R_B = 0.4) reported by Tasalloti et al. (2021a, c) are shown as well. It is observed that the dry density (ρ_{dry}) of GGRMs decreases almost linearly with increasing volumetric glass content (G_L) from 1265 kg/m^3 to 1086 kg/m^3. This is mainly due to the slightly different specific gravity of the gravel (G_s = 2.66) and that of the green glass (G_s = 2.50).

The lower values of the dry density obtained for GGRMs (R_B = 0.4), as compared to the glass (ρ_{dry} = 1430 kg/m^3) and gravel (ρ_{dry} = 1753 kg/m^3) alone, are the results of the presence of light-weight rubber particles (G_s = 1.15; ρ_{dry} = 649 kg/m^3) in the mixtures.

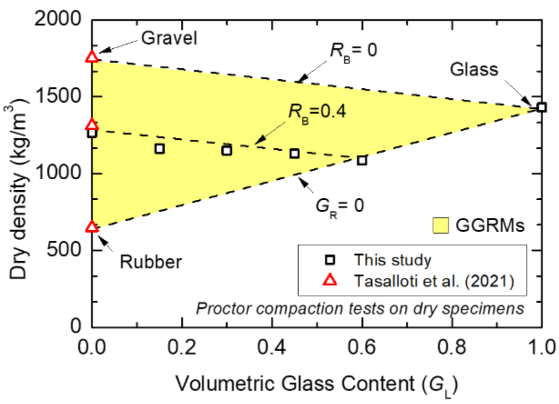


Figure 4. Results of Proctor compaction tests for GGRM (R_B = 0.4).

The dry density of GRMs decreases linearly with increasing R_B (Tasalloti et al., 2021b). Similarly, this current study indicates that the dry density of glass-rubber mixes (i.e., G_R = 0) also decreases linearly with increasing R_B; while for the GGRMs the dry density decreases linearly with G_L. Interestingly, the liner trend shown in Fig. 4 that connects the data points for GGRMs with R_B = 0.4 is parallel to that of gravel-glass mixtures (R_B = 0).

Sieve analyses were carried out before and after each test to evaluate the amount of glass particle breakage induced by compaction (Fig. 5). For instance, in the case of GGRMs (R_B = 0.4; G_L = 0.15−0.6), an increase of particle breakage with increasing G_L was observed; yet, at G_L = 0.6 the breakage was less than 2%. In contrast, for the green glass alone (G_L = 1), the amount of particles breakage was of about 7.2%. That is, the soft rubber particles in the GGRMs act as a cushion that absorbs part of the impact energy delivered to the specimen and reduces the breakage of glass particles during compaction.

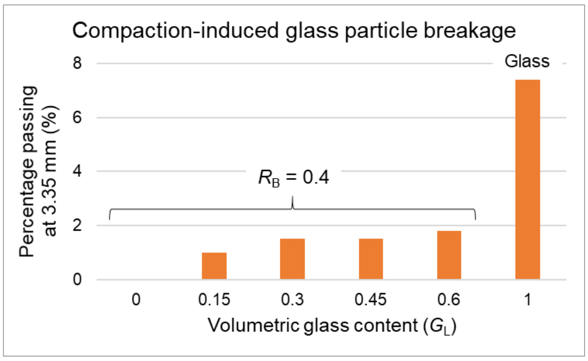


Figure 5. Glass particle breakage in Proctor compaction tests for GGRMs (R_B = 0.4) and pure glass.

3.2 *Shear strength*

Results of the direct shear tests showing the different stress paths and volumetric responses for pure rubber, pure green glass, pure gravel and GGRMs (R_B = 0.4) under 100 kPa normal stress are shown in Figures 6 and 7.

The gravel displays a stiff behavior typical of dense hard-grained soils, characterized by a high peak strength and brittle failure. Its volumetric response is primarily dilative. In contrast, the soft rubber has a ductile response with no clear peak and contractive volumetric behavior. The green glass response is somehow between that of the stiff gravel and that of the soft rubber. This is because green glass particles although stiff (not as the gravel ones), they are highly crushable under shearing especially when subjected to higher normal stress.

Due to the presence of softer rubber particles in the mixtures, the mechanical response of the GGRMs (R_B = 0.4) is more ductile than that observed for the pure gravel and pure glass. The variation of G_L (= 0−0.6) in the mixtures does not affect the overall response qualitatively nor quantitatively, but it is rather the R_B (= 0.4) responsible for the observed ductile behavior.

By analyzing the load-transfer mechanisms, Chew et al. (2022) have indicated that in the case of GRMs, three distinct material-like behavioral responses exist: gravel-like for 0.3 < R_B, dual (intermediate) behavior for 0.3 ≤ R_B < 0.6, and rubber-like behavior for R_B ≤ 0.6. In the gravel-like materials the load-transfer mechanism is primarily governed by the interaction between gravel grains, due to the limited amount of rubber particles in the mixtures; this leads to a brittle mechanical response. Vice versa, in the rubber-like materials the load-transfer mechanism is due mainly to the interaction between rubber particles, because of the limited amount of gravel grains in the mixtures; this leads to a ductile mechanical response. Alternatively, in the case of dual (intermediate) materials, the strong force network responsible for the load-transfer mechanism is jointly shared between the gravel grains and rubber particles; this results in an intermediate brittle/ductile mechanical response. The tests results reported in Fig. 6 indicate that GGRMs (R_B = 0.4) is similar to that of GRMs (R_B = 0.4); thus, they can be considered intermediate materials, which mechanical response is between that of the gravel/glass and that of the rubber.

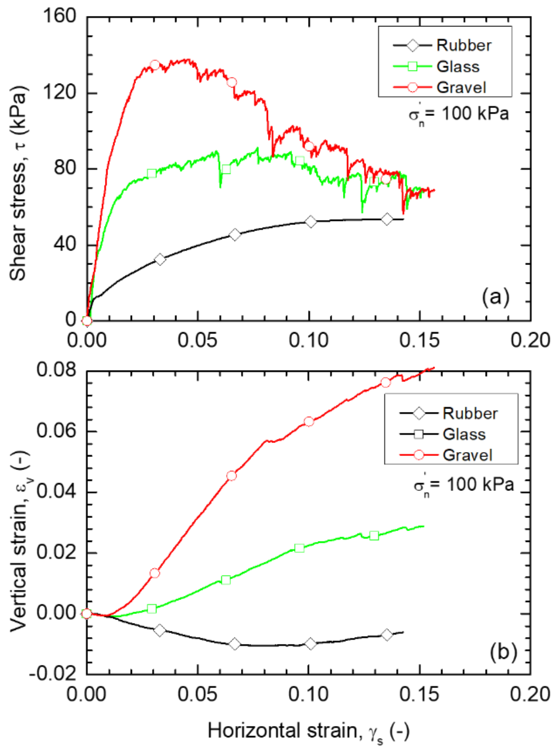


Figure 6. Direct shear test results for rubber, glass and gravel at 100 kPa normal stress: (a) stress-strain paths; and (b) volumetric responses.

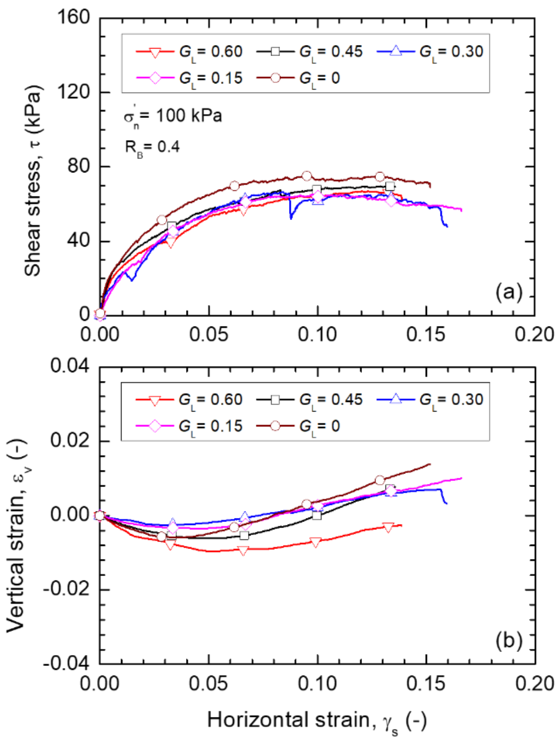


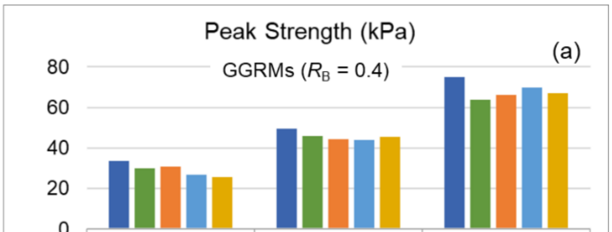
Figure 7. Direct shear test results for GGRMs (R_B = 0.4) at 100 kPa normal stress: (a) stress-strain paths; and (b) volumetric responses.

Peak strength (i.e., the maximum shear stress) and associated peak friction angles were evaluated for GGRMs (R_B = 0.4) at the different normal stress levels, and the results are summarized in Figure 8. For the sake of completeness, the friction angle of these cohesionless materials was also estimated based on the Mohr-Coulomb (MC) failure criterion as reported in Figure 8(b).

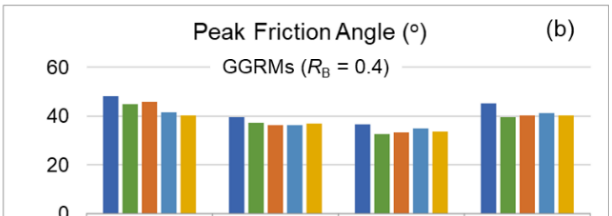
The peak strength significantly increases with increasing normal stress. Moreover, at any normal stress level, the peak strength of GGRMs with G_L = 0.15−0.6 is slightly lower that that without G_L (i.e., GRM). This is due to the crushability of the glass grains under shearing.

Considering only the GGRM with G_L, it can be observed that the effect of G_L on the strength is not unique. The data suggest that it decreases with G_L at 30 kPa normal stress from 30 kPa to 26 kPa, but increases with G_L at 100 kPa normal stress from 64 kPa to 69 kPa. At 60 kPa, it remains constant approx. 45 kPa.

The peak friction angle values decrease with increasing normal stress. Moreover, the MC friction angle values (40° − 41°) are comprised between those obtained at 30 kPa (40° − 45°) and 60 kPa (36° − 37°), and seem to be insensitive to the G_L variation. Significantly, irrespective of the G_L, GGRMs (R_B = 0.4) have a peak friction angle greater than 30°, making them suitable structural fill materials (Chiaro et al., 2015) for typical geotechnical applications (e.g., embankments, foundations, retaining structure backfill).



G_L	σn = 30 kPa	σn = 60 kPa	σn = 100 kPa
0	33.5	49.6	74.8
0.15	30.0	45.7	64.0
0.3	30.9	44.3	66.0
0.45	26.8	44.0	69.7
0.6	25.6	45.5	67.0



G_L	σn = 30 kPa	σn = 60 kPa	σn = 100 kPa	MC
0	48.2	39.6	36.8	45.3
0.15	45.0	37.3	32.6	39.7
0.3	45.8	36.4	33.4	40.2
0.45	41.8	36.3	34.9	41.1
0.6	40.5	37.2	33.8	40.3

Figure 8. Direct shear response of GGRMs (R_B = 0.4) at 30, 60 and 100 kPa normal stress: (a) peak strength; and (b) peak friction angle.

3.3 *Energy absorption*

The energy absorption characteristics of GGRMs are evaluated using the strain energy density concept (Indraratna et al., 2019). As shown in Figure 9, strain energy density *(E)* represents the area under the shear stress-strain curve up to failure, which in this study is defined as the state where the specimen reaches the peak shear stress (τ_f). For the examined GGRMs (R_B = 0.4), the peak stress is achieved at a peak shear strain (γ_f) ≈ 0.13 (Fig. 6b).

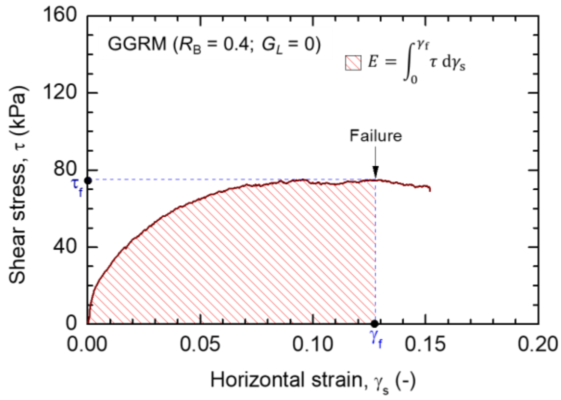


Figure 9. Example of energy strain density calculation for GGRMs.

The summary plot in Figure 10(a) show that as the normal stress increases, the *E* increases, which suggests that more work input is absorbed by the specimens under higher normal stress levels. In contrast, there is a negligible influence of the G_L on the *E* values of GGRMs (R_B = 0.4).

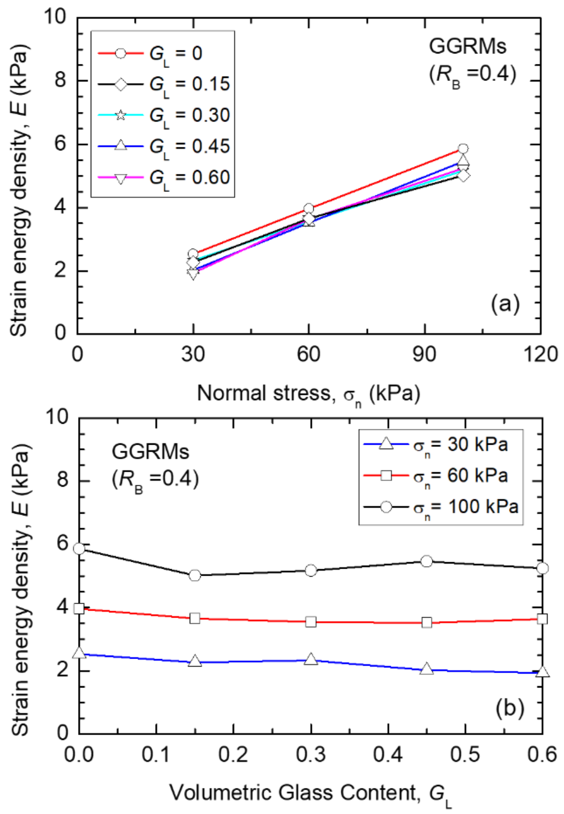


Figure 10. Strain energy density of GGRMs (R_B = 0.4) evaluated by direct shear tests: (a) effect of normal stress; and (b) effect of volumetric glass content.

To gain a better understanding of the energy absorption properties of GGRMs, the case of GRMs is examined. Figure 11 reports the *E* for GRMs with R_B = 0, 0.1 and 0.25 (gravel-like materials), 0.4 and 0.5 (dual materials), and 0.7 and 1 (rubber-like materials) as evaluated by Chiaro (2023). It is evident that when rubber is added to gravel, E increases reflecting the high energy absorbed of the rubber aggregates. Yet, for any normal stress level applied, it appears that a peak strain energy density value is achieved at R_B = 0.4 – 0.5 (dual mixtures), and no further increase in the strain energy density is observed beyond this point. This is essentially because the increase in ductility (i.e., failure occurring at larger shear strain level (refer to Figs. 6 and 7) is compromised by the decrease in the peak strength.

Therefore, comparing Figures 10 and 11, it is evident that irrespective of the G_L, GGRMs (R_B = 0.4) perform as well as GRMs (R_B = 0.4) in terms of energy absorption. That is, the addition of rubber aggregates to the mixtures improves the energy absorption and dynamic properties, while replacing gravel with glass does not reduce the energy absorption of the materials. To date, GRMs with R_B = 0.4 have been proposed for use as filters for dampening vibrations and seismic energy waves in geotechnical seismic isolation systems (Chiaro et al., 2022); the results of this study suggest that GGRMs as well could be used in GSI systems as well.

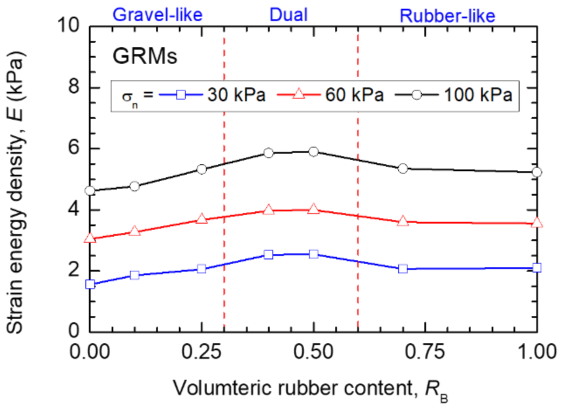


Figure 11. Strain energy density of GRMs evaluated by direct shear tests (datapoints from Chiaro 2023).

4 CONCLUSIONS

This paper reported on preliminary results of a feasibility study aimed at evaluating the potential use of recycled crushed green glass bottles and recycled granulated tire rubber mixed with gravel. Dry specimens of selected gravel-glass-rubber mixtures (GGRMs) were tested using a medium-size direct shear apparatus under 30, 60 and 100 kPa normal stress. The effect of glass and rubber content by volume on the peak shear strength, friction angle and energy absorption of the mixtures was investigated. The following main conclusions can be drawn from the study:

- The shear strength of GGRMs with 40% rubber content by volume is comparable to that of gravel-rubber mixture without glass in terms of mechanical response, peak shear strength and friction angle.
- The friction angle of GGRMs is found to be greater than 30º; thus, such synthetic materials could be used as structural fills in typical geotechnical applications;
- The energy absorption of GGRMs with 40% rubber content by volume is similar to that of gravel-rubber mixture without glass; thus, GGRMs could be also used as filters in GSI systems to absorb the seismic waves passing through it.

5 ACKNOWLEDGEMENTS

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