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# DYNAMIC BEHAVIOUR OF CRUSHED ROCK AND WASTE GLASS MIXTURES: EVALUATION OF LAYERED TECHNIQUES

Mustafa Al-saedi [1*], Amin Chegenizadeh [2], Ayad Salih Sabbar [3], and Hamid Nikraz [4]

## ABSTRACT

The results of a laboratory study on the dynamic behaviour of layered samples of waste glass (G) mixed with crushed rock (R) in road applications are presented in this paper. The study used stratified samples rather than homogeneous. The glass was added to the rock samples in various proportions, including 12%, 24%, and 45%. A series of tests were then conducted, namely the repeated loading triaxial (RLTTs) and dynamic shear tests. The testing program encompasses a wide range of variables pertaining to the location, thickness, and moisture content of the GR layers. The sieve analysis results revealed a reasonable agreement between the gradation curves of all blends and the base course restrictions. In the conceptual framework of the RLTT results, the homogeneous mixture of crushed rock with 24% glass exhibited a higher value of resilient modulus ($M_r$) and a lower value of permanent deformation ($P_d$) than the stratified samples. It's interesting to note that certain layered samples with varying amounts of glass showed higher $M_r$ than the rock sample. The moisture content of the layered specimens was found to be strongly associated with both the $M_r$ and the $P_d$ values, whilst the layer thickness was found to be negatively related to both the $M_r$ and the $P_d$. Furthermore, the $P_d$ increased when the rock layer was located in the bottom of the stratified sample. The results also confirm that the stratified samples illustrated higher dynamic shear strength than those of the homogeneous ones.

*Key words:* Crushed rock, waste glass, layered structure, resilient modulus.

## 1. INTRODUCTION

Over the past years, waste glass has been widely utilised in many civil engineering applications as an alternative to natural soil due to an increase in its amount and its availability for recycling. Sorting crushed glass by colour is required in the glass industry. So, utilising natural sand in the glass industry is less expensive than crushed glass. Therefore, previous studies have focused on using waste glass in substitution of raw materials such as coarse aggregate in concrete application and road construction rather than glass production. According to the Australian Government (2017), Australia produces approximately 1.36 million tonnes of bottles, jars, and glass containers each year, posing a serious health and environmental risk. Several economic aspects are related to the use of glass in road layers, including the low cost of glass when compared to the cost of base or subbase materials, and hence the lower cost of road construction. Furthermore, the cost of transporting and storing waste glass will be reduced if it is directly used in pavement layers, which consume large amounts of materials.

The resilient modulus ($M_r$) and permanent deformation ($P_d$) are the most crucial parameters in the assessment of granular materials when subjected to repeated loads. Regarding that assessment, the RLTT test provides critical data for estimating the $M_r$ and $P_d$ of granular materials. Christopher *et al.* (2006) referred that RLTT tests also assess the long-term deformation over a large number of cycles. The authors also stated that the $M_r$ is calculated by dividing the applied cyclic deviatoric stress by the recoverable axial strain over a set number of cycles. According to previous studies related to the ability of roads to bear repetitive loads, $M_r$ is a fundamental parameter for the load-carrying ability of the pavement (Lekarp *et al.* 2000). The simplest concept of the $P_d$ is the strain remaining after the unloading stage. More comprehensively, the $P_d$ can be used to evaluate the long-term performance of the pavement as well as the rutting phenomenon (Lekarp *et al.* 2000; Rahbar-Rastegar 2017).

A substantial number of studies have examined the effectiveness of using the GR mixtures in pavement applications by highlighting the aspects, including economics, environmental, dynamic behavior, and shear strength (Disfani *et al.* 2011a; Disfani *et al.* 2011b; Disfani *et al.* 2012). The outcomes of these studies concluded that the general features of the G are similar to those of natural soil and that the GR mixtures meet the requirements of the pavement materials (Disfani *et al.* 2009). Within this topic, Arulrajah *et al.* (2012) examined the suitability of basic and dynamic characteristics of the GR mixture in pavement applications. The summary of this study indicated that the grain size distribution, California bearing ratio (CBR), and Los Angeles abrasion values of the GR mixtures containing 30% glass content satisfied the subbase requirements. Before this study, Viswanathan (1996) investigated the effect of adding different glass cullet contents (5%, 10%, 20%, 50%, and 100%) on mechanical properties of crushed rock. The results showed insignificant effects of 20% glass on the optimum moisture content (OMC), the maximum dry density (MDD), and the shear strength of the mixture. In contrast, an apparent reduction in shear strength was associated with additional glass content. The research study by Rana (2004) referred that the OMC and

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[1*] Lecturer (corresponding author), Department of Civil Engineering, College of Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq (e-mail: mustafa.al@uowa.edu.iq or mustafi_73@yahoo.com).

[2] Senior Lecturer, Civil Engineering. Department of Civil Engineering, Curtin University, Australia.

[3] Ph.D., Iraqi Ministry of Construction, Housing, Municipalities and Public Works.

[4] Professor, Department of Civil Engineering, Curtin University, Australia.

the MDD of the caliche-glass mixtures decreased when the glass cullet increased. In contrast, both the $M_r$ and the $P_d$ of the caliche-glass mixture increased by up to 30% glass ratio. A further investigation on the GR mixture reported a positive correlation between the glass content and both the workability and the hydraulic conductivity of the GR mixtures (Disfani *et al.* 2012).

Shear strength of aggregate containing glass has also been examined in several studies. The experimental study conducted by Disfani *et al.* (2011) demonstrated that the presence of glass caused a positive impact on the shear strength of sand and aggregate samples. Based on the results of Disfani *et al.* (2009), there are similarities between many characteristics of the GR mixture and the raw aggregate. Among the many results from studies of particle size of waste glass have found that the size of waste glass played a vital role in the resilience behaviour, and the $M_r$ of the GR mixture at high-stress levels decreased with additional glass content (Senadheera *et al.* 1995). In studying the effect of glass on the internal friction value of a soil-glass mixture, Grubb *et al.* (2006) reported an increase in the internal friction angle of the dredged-glass mixture as the glass content increased, where the angle values increased from 34° to 39° when the glass increased from 0% to 80%. Regarding the deformation assessment of glass-soil mixture, Arnold *et al.* (2008) stated that the deformation resistance of the aggregate-crushed glass mixtures was significantly reduced with increasing glass content of up to 50%. Arulrajah *et al.* (2014) also concluded that the $M_r$ and the $P_d$ values of both mixtures of recycled concrete aggregate-glass and waste rock-glass dropped down as the glass content increased. The effect of glass content on CBR of the GR mixtures was investigated by Ali *et al.* (2011). The results showed that the CBR value was notably reduced from 181% to 121% when the glass content increased from zero to 50%.

Previous studies on the dynamic behaviour of unbound materials showed that numerous investigations have been conducted on homogeneous samples. However, reviews of the dynamic behaviour of heterogeneous samples are still limited, where the heterogeneity means a multi-layer sample, while the homogenous sample consists of one homogenous layer. The simulation of the layered structure in pavement layers is one of the applications of the heterogeneous sample. In recent years, there has been an increasing amount of literature on layering techniques in dynamic applications because many cases and projects deal with the layered structure rather than a single layer of soil or rock. Multi-layered structures are essential when considering land subsidence, excavation stability, and slope failure (Pujades *et al.* 2014; Zeng *et al.* 2015). A multi-layering technique was also used in Taiwan on a multi-layered aquifer system (Lin *et al.* 2015). The layered structure can be critical when tailing dams for mining waste are constructed. A series of geological studies were conducted by Zhang *et al.* (2015) on tailing materials to investigate the static and dynamic characteristics of the materials in tailing dams. Three types of samples were employed to assess the static and dynamic behaviour of layered techniques: coarse tailings samples, fine tailings samples, and a layered coarse-fine tailings specimen. The layered samples of coarse-fine tailings showed lower shear strength and internal friction angle than the layered samples of coarse and fine tailings samples. Moreover, the upper layer of the layered specimens showed higher $P_d$ than the lower layer, and the interface layer between the coarse and fine layers had higher $P_d$ than other layers.

Other studies reported that the stiffness of multi-layered soil increased with increasing the layer depth (Gibson 1974; Atkinson 1975; Gazetas 1981). Giroud (2004) indicated that adding an aggregate layer above the soft soil layer on the unpaved road may increase its stiffness. The important feature that evaluates the efficiency of a heterogeneous sample under loads is stability, which can be directly affected by the interface layer in between (Oliveira and Falorca 2020). Liakas *et al.* (2017) argued that the percentage of materials in each layer of heterogeneous specimens plays a significant role in the layered samples strength. Through the summary of the research above, it appears that the analysis of the dynamic behaviour of layered (heterogenous) samples is still limited. Therefore, this study aims to explore the dynamic responses of layered samples of crushed rock mixed with different waste glass content. For this purpose, a series of RLTTs and dynamic shear tests were conducted on the layered samples of rock containing 12%, 24%, and 45% of waste glass. The experiments include a wide range of conditions, such as location, thickness, and moisture content of the GR layers.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The rock used in this study was collected from Gosnells Quarry, Western Australia (WA). The glass that was mixed with the crushed rock was collected from the Perth Bin Hire recycling site, located in Duffy Street, Bayswater, WA. The G samples were collected from stockpiles according to the American Society for Testing and Materials (ASTM), then kept in plastic bags in the soil laboratory at Curtin University (Al-saedi 2020).

### 2.2 Sample Preparation Method

The present work was designed to provide an in-depth examination of the effect of sample structure and waste glass percentages on the dynamic behaviour of crushed rock-glass mixtures. For this purpose, five different types of samples prepared by mixing crushed rock with three glass proportions (12%, 24%, and 45%) were adopted, the dimensions of each sample were 100 × 200 mm. Regarding the structure of homogenous samples, four-layered samples were utilised in Table 1. Homogeneous samples were prepared by direct mixing of crushed rock with the desired waste glass percentage, and this type of sample was denoted by letter (h). Layered samples were prepared by using different distribution patterns of pure rock and rock-glass layers. The first structure, which is denoted by letter (a), represents the consecutive distribution of the ($GR_{xi}$) layer followed by the R layer. The samples marked by latter (b) depict the arrangement of two ($GR_{xi}$) layers, followed by two (R) layers. Structures (c) and (d) represent the distribution of four ($GR_{xi}$) layers followed by four (R) layers and four (R) layers followed by four ($GR_{xi}$) layers, respectively. Repeated loading triaxial tests (RLTT) were employed in this study to characterise the dynamic behaviour of the mixtures based on AASHTO (2003). RLTT was used widely in the literature to assess the deformation and the resilient modulus of different types of soil (Nowamooz *et al.* 2013). During the test, a repeated axial cyclic stress ($\sigma_1$) and confining pressures ($\sigma_3$) is subjected to a cylindrical sample of soil. A series of loading unloading phases was applied on a specimen of unbound material till fails or exceeds the deformation limitations. Within each stress regime, the specimen is cyclically loaded with axial deviatoric stress while static confining stress is simultaneously applied. Axial loading within each stress regime is repeated for many cycles. The quick shear test follows the following steps:

- The shear test applies confining stress to the specimen as specified by the setup parameter. Axial loading is applied at the specified strain rate.
- The shear test terminates either by activation of the stop button or when the specimen strain reaches the termination strain parameter value.
- During the shear test, an axial loading strain rate is applied to the specimen while frequent sampling of all transducers occurs. The shear test continues until it is manually stopped or when the permanent accumulated strain reaches the present termination strain value.

All samples were prepared by using the same procedure but the distribution of layers was different. Depending on the dry density, the weight of each mixture was estimated and then mixed well with its OMC. The weight of each mixture was divided into eight equal parts; each part was compacted until it reached the required height. After compressing all layers inside the mould, the specimen was carefully placed in the triaxial cell. After that, the stress paths were subjected to a sample, and the results were collected. Figure 1 (i to v) shows the preparation procedure for the RLTT samples.

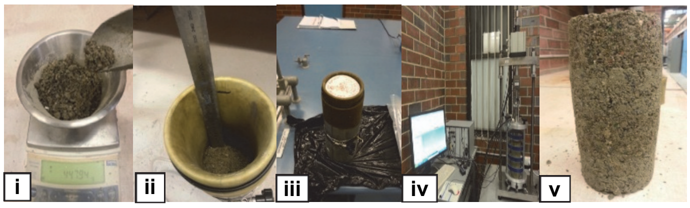


**Fig. 1 Sample preparation steps: (i) check the weight of each layer; (ii) checking the height of each layer during the compaction process; (iii) fully compacted sample; (iv) fully compacted sample in RLTT device; (v) example of a layered sample (b)**

**Table 1 Structure of the samples used in the current work**

| Symbol | h | a | b | c | d |
|---|---|---|---|---|---|
| Specimen | GR *xi* | GR *xi* | GR *xi* | GR *xi* | R |
| | | R | GR *xi* | GR *xi* | R |
| | | GR *xi* | R | GR *xi* | R |
| | | R | R | GR *xi* | R |
| | | GR *xi* | GR *xi* | R | GR *xi* |
| | | R | GR *xi* | R | GR *xi* |
| | | GR *xi* | R | R | GR *xi* |
| | | R | R | R | GR *xi* |

where: R is the crushed rock sample; GR is the crushed rock-glass mixture; *xi* is the glass content (12%, 24%, and 45%)

## 3. RESULTS AND DISCUSSION

The experiments in the present research included some of the index tests, such as particle size distribution and MDD of pure crushed rock and GR mixtures. The sieve analysis tests and modified proctor compaction tests were conducted based on Australian Standard AS 1289.5.1.1 (2003). Table 2 illustrates the results of compaction tests and the fines content of the GR mixtures. Figures 2 and 3 show the particle size distribution curves of pure rock, GR12, GR24, and GR45 before and after compaction waves. As can be seen, all GR mixtures are located between the upper and lower limits of VicRoads for base materials, which means all blends satisfy the base material requirements for road applications. Despite the fine percentages increased after the compaction, as shown in Fig. 3, there is a satisfactory agreement between the curves of the GR mixtures and the VicRoads limits (VicRoads, 2010). Table 2 presents the effects of glass content on the OMC and the MDD of the GR samples. The values of the MDD decreased from 2.35 t/m$^3$ to 2.325 and 2.25 when the glass content increased from 12% to 24% and 45%, respectively. The low density of the glass particles compared to that of rock caused to decrease in the MDD of the GR mixtures. Table 2 also reported a significant increase in the OMC of the GR mixtures as a result of the glass increase. This finding was consistent with the results of Arulrajah *et al.* (2014), who reported that the OMC values of recycled concrete aggregate decreased steadily and then increased upon the addition of glass. The glass particles have less absorption and less sensitivity to water than crushed rock, and that could explain the reduction in the OMC of the R when the glass content reached 12%. Beyond this ratio and despite the smooth surfaces of glass grains, the fine grains of rock can adhere to the fine grains of glass, thereby increasing the particle surfaces, which leads to an increase in the absorption area of the mixtures and, consequently, increasing the OMC values.

**Table 2 The results of compaction tests of the glass-rock mixtures**

| Glass content (%) | MDD (t/m$^3$) | OMC (%) | Fines (%) |
|---|---|---|---|
| 12 | 2.35 | 5.75 | 6 |
| 24 | 2.33 | 5.90 | 7.75 |
| 45 | 2.25 | 6.25 | 8 |

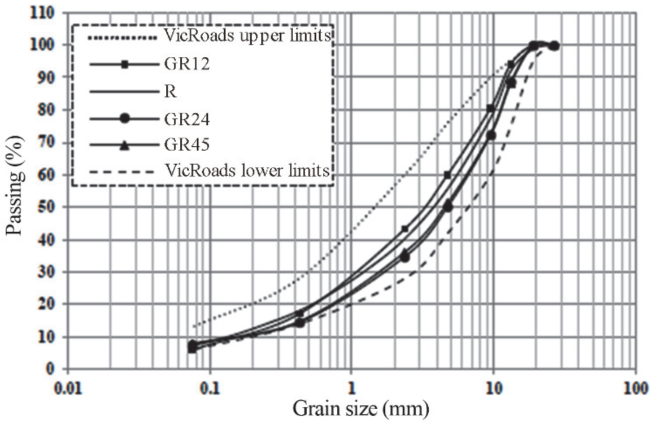


**Fig. 2 Gradation curves of the glass-rock mixtures before compaction**

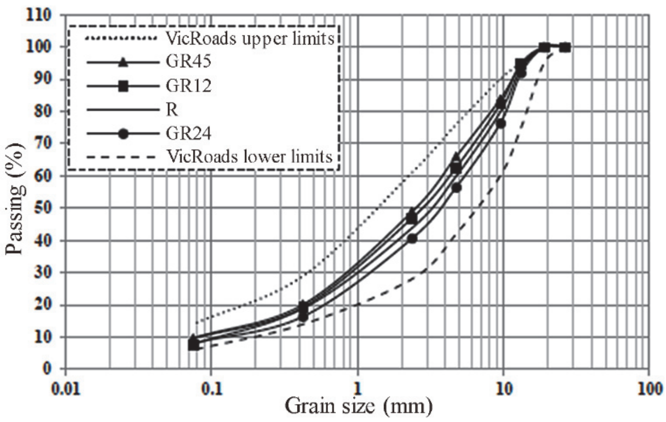


**Fig. 3 Gradation curves of the glass-rock mixtures after compaction**

## 4. PERMANENT DEFORMATION

RLTT tests were accomplished on the homogenous and the layered samples to assess the effect of the variation in the number, location, and moisture content of the GR layer on the resilience deformation of the modified samples under cyclic loadings. Assessing the impact of the G content on the deformation response of the layered samples is the secondary goal of this study. Figure 4 shows the relationships between $P_d$ and the number of sequences of cycles of homogeneous samples of the R and GR mixtures. The $P_d$ for all samples increased gradually as the sequence number increased. Also, all specimens exhibited the same trend of a slight reduction in $P_d$ when the number of sequences rose from zero to 1, after that, $P_d$ increased gradually as sequence number increased. The homogenous samples of pure rock exhibited lower values of $P_d$ compared to other samples. However, the homogenous samples of the GR mixtures showed different behaviours. The $P_d$ significantly increased when the G content was 12%, then reduced by increasing the G content to 24%, followed by a slight increase when the G content increased to 45%. The consistency between the GR24 and GR45 samples is clear during the first five sequences. Beyond that, the GR45 sample showed high $P_d$ than the GR24 sample. Despite that, the angularity of particles positively affects the $P_d$ of soils (Mehrjardi *et al.* 2012), the smoothness of surfaces and the low density of the glass particles inversely affected the deformation behaviour of the GR mixtures. These findings proved the previous conclusion of Disfani *et al.* (2012) concerning the use of other additives to improve the mechanical properties of glass-soil in pavement applications.

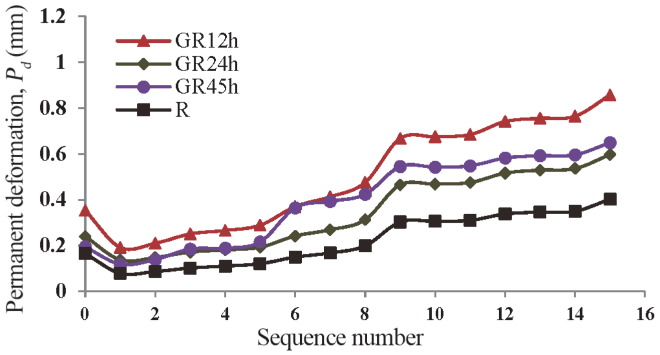
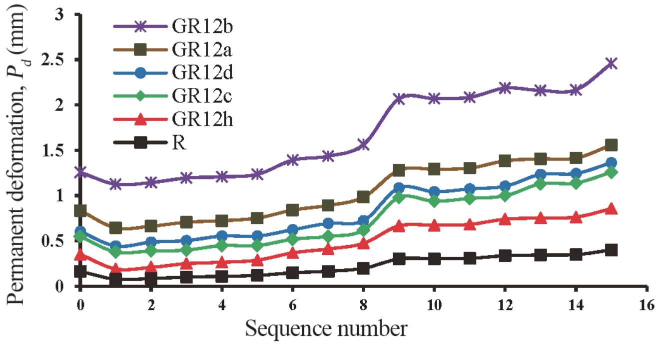
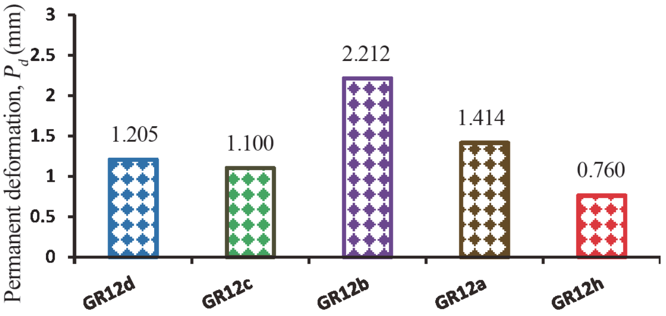


**Fig. 4 Permanent deformations of homogeneous samples**

The effect of the sample structure on the $P_d$ of the layered samples of the GR mixtures is presented in Figs. 5, 6, and 7. Figure 5 shows the deformations of the GR12 samples prepared by mixing R with 12% G. The symbols a, b, c, and d represent the layer distribution patterns, as shown in Table 1. All layered samples of the GR12 mixtures exhibited higher $P_d$ than the homogenous ones, while the values were different depending on the layer distribution pattern. The $P_d$ of the GR12 significantly increased from 0.76 mm of the homogenous samples to 1.413 mm and 2.21 mm for the layered samples types (a) and (b), respectively. However, the $P_d$ values were notably reduced to 1.1 mm and 1.2 mm with specimen types (c) and (d), respectively. Layered samples type (b) which were prepared by placing two layers of the GR12 followed by two layers of the R, exhibited higher values of $P_d$ than other types. Increased the number and the thickness of layers in the sample resulted a negative impact on deformation resistance, as shown in Fig. 5. This was clear when $P_d$ values were reduced from 2.21 mm for the samples type (b) to 1.1 mm and 1.2 mm for the samples types (c) and (d), respectively.



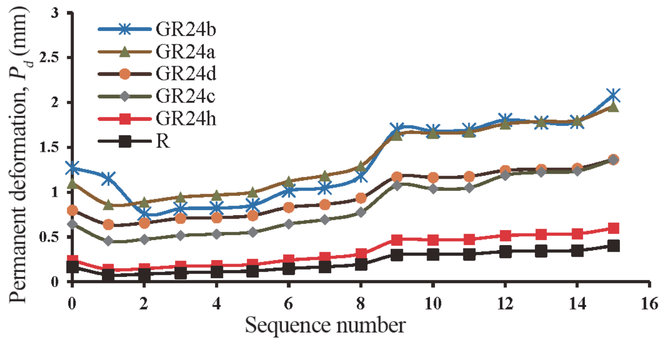
(a) Deformation behaviour



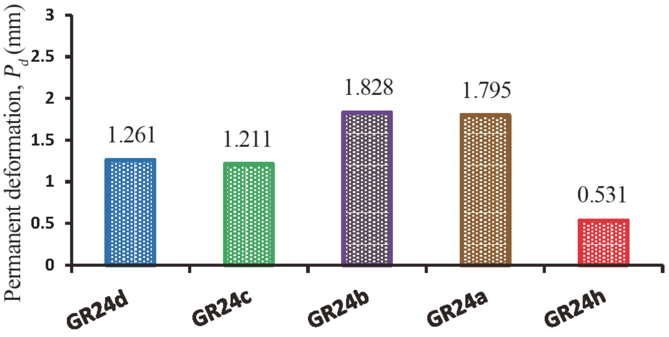
(b) Effect of the layered sample structure on $P_d$

**Fig. 5 Permanent deformations of layered samples with 12% glass**

The results of $P_d$'*s* of the layered samples prepared by mixing R with 24% G (GR24) are shown in Fig. 6. The layered samples of GR24 exhibited an increasing trend in $P_d$ compared to the homogenous ones. The values of $P_d$ increased from 0.53 mm for GR24h to 1.79 mm and 1.82 mm for samples types (a) and (b), respectively. However, sample types (c) and (d) showed a considerable reduction in $P_d$ values, which were reduced to 1.21 mm and 1.26 mm, respectively. Figure 6 shows a clear trend of gradual increment of the $P_d$ values of the GR24h, GR24a, GR24c, and GR24d samples as the sequence number increased. Whereas layered samples of GR24b showed a different trend, the amounts of $P_d$ were initially reduced until they reached sequence number 8. After that, the values increased gradually until the end of the test. Data



(a) Deformation behaviour



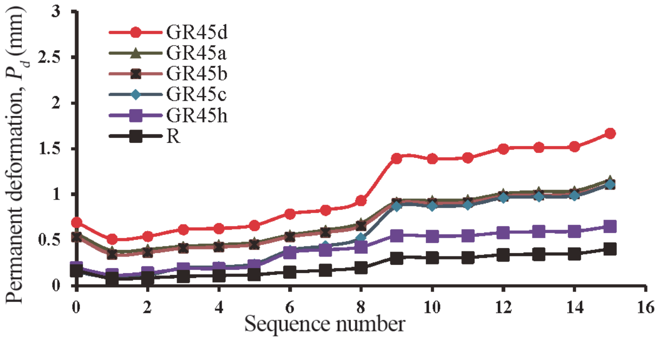
(b) Effect of the layered sample structure on $P_d$

**Fig. 6 Permanent deformations of layered samples with 24% glass**

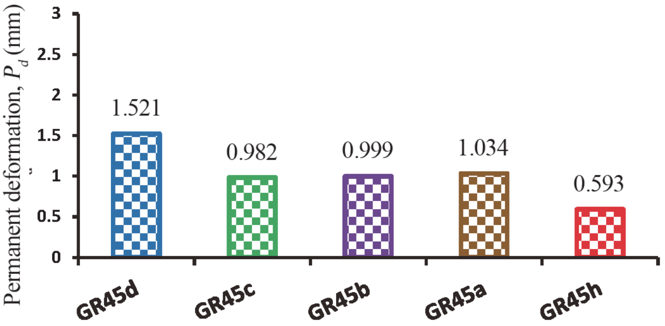
in Fig. 6(b) also highlighted the impact of the number and thickness of layers on the deformation resistance of GR layered samples. The $P_d$ values are reduced by reducing the number of layers and increasing the depth of the layer.

The findings of the present study indicate that the G content has a substantial effect on the $P_d$ values of both the homogeneous and layered samples of the GR mixtures. Both types of samples displayed different behaviour with increasing the G content, while the effect of G was more apparent in the layered samples than in the homogenous ones. The $P_d$ values of the homogenous samples increased with increasing the G content from zero to 12%; then they significantly diminished with increasing the G content up to 45%. The research study by Arnold *et al.* (2008) also observed that the $P_d$ of aggregate were significantly reduced when mixed with up to 50% of G. Arulrajah *et al.* (2014) also stated that the $P_d$ of the recycled concrete aggregate-glass and the waste rock-glass mixtures reduced when the G content increased.

From the data in Fig. 7, it is apparent that the homogenous sample of GR45 exposed a lower $P_d$ value than other layered specimens. The values of $P_d$ were significantly raised from 0.59 mm of the homogenous samples to 1.034, 0.999, 0.982 mm when the structure of the samples changed to a, b, and c, respectively. Sample type GR45(d) showed the highest value of $P_d$ with a value of 1.52 mm. A remarkable contrast appeared between the behaviour of the GR mixtures. In the GR45 samples, the highest value of $P_d$ was linked with layered samples type (d). Nevertheless, other types of blends, GR12 and GR24, noted the lowest amounts of $P_d$ in class (d). Moreover, sample types a, b, and c in GR45 exhibited almost identical $P_d$ values, while GR12 and GR24 showed inconsistent behaviour.



(a) Deformation behaviour



(b) Effect of the layered sample structure on $P_d$

**Fig. 7 Permanent deformation of layered samples with 45% glass**

The relationship between the $P_d$ values for all types of the samples and the G content is presented in Fig. 8. $P_d$'s of the layered samples profoundly depend on the G content and characteristics of layers such as number, location, and thickness. The layered samples showed inconsistent behaviour with the G content increased. The layered samples with a glass content of 12% prepared by using structure type (b) showed a higher value of $P_d$ than other layered samples. All layered samples showed almost the same amounts of $P_d$ when prepared by using structures (c) and (d). Also, layered samples types (c) and (d) exhibited lower values of $P_d$ than samples types (a) and (b), which indicates the effect of the number of layers on the behaviour of rock-glass mixtures. What is interesting about the data in Fig. 8 is that the structure of the sample might reduce the inversely effect of glass content on $P_d$'s of rock-glass mixtures. This effect was clearly shown by comparing the layered samples types (a) and (b) of GR12, which revealed that the sample type (b) showed higher $P_d$ than the sample type (a). At the same time, the difference was sharply reduced when samples GR12 were prepared by using structure types (c) and (d).

All layered samples showed insignificant development in deformation response with increasing the G content up to 45%, in which $P_d$ remains near-constant during the load sequences. The number and location of the layers also play a significant role in the dynamic behaviour of the GR mixtures. As can be seen from Fig. 8, the sample type (d) reported significantly less $P_d$ than the other samples. The advantage of placing a rock layer at the bottom of the layered sample is noticeable in the figure. This behaviour could be attributed to the interface layer in between, which affects the stability of the sample (Gabriel and Falorca 2020). Therefore, the stability was reduced as the number of interface layers increased. The most likely cause of the above results could be the presence of different materials on both sides of the interface layer, which caused an apparent reduction in the deformation resistance, as

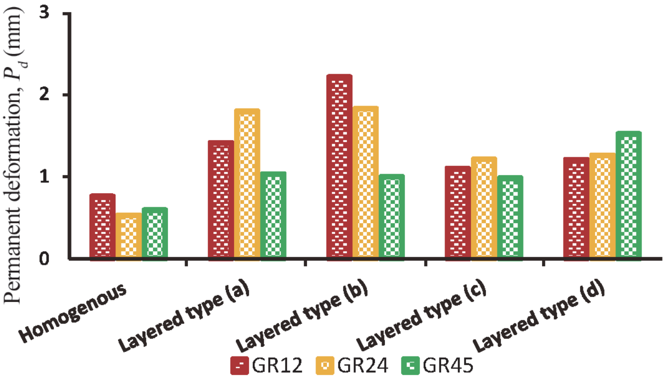


Fig. 8 Permanent deformations of all types of GR mixtures

concluded by Lin *et al.* (2015). The $P_d$ of the GR45 type (d) sample is influenced by the GR ratio, where the high ratio led to increasing the resistance of the sample against deformation. On the other hand, the high ratio at the bottom led to increasing the $P_d$ during the last seven stages of the loading sequence. A layer near the top of a specimen undergoes higher deformation than the other layers (Zhang *et al.* 2015), and therefore the presence of the GR layers near the top enhanced the stability of GR type (c), and increased their ability to resist deformations.

Considering the dry-back process in the field, both the GR24 and R layers were prepared at 100% and 70% of the OMC to assess the effect of moisture content on the $P_d$ and to obtain high accuracy of the laboratory results. Our procedure for the dry back followed the same phases as VicRoads (2010) when the water absorption of the material was greater than 1.5%. Figure 9 reveals that GR24 type (a) at 70% OMC performed better resistance against deformation than the sample at 100%. Many previous studies reported a negative correlation between the moisture content of soils and the deformation resistance (Disfani *et al.* 2012; Azam and Cameron 2012). The slight improvement in $P_d$ was attributed to the stability of the fabric, as the voids are filled with fine materials instead of the drained water, which led to improving the density and, consequently, low $P_d$ of the sample. Whereas, the high level of water content led to increasing pore water pressures and then a decrease in significant stress (Magnusdottir and Erlingsson 2002).

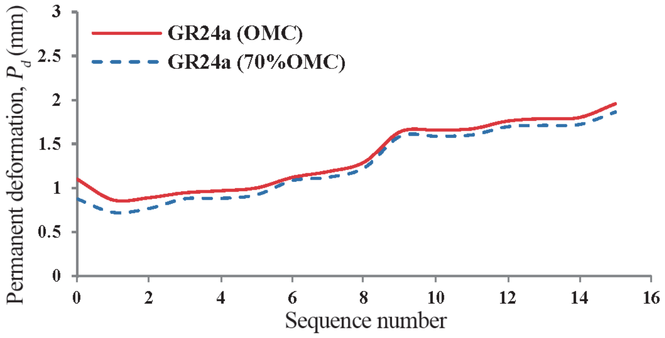


Fig. 9 Effect of moisture content on permanent deformations of the GR24 sample

## 5. RESILIENT MODULUS

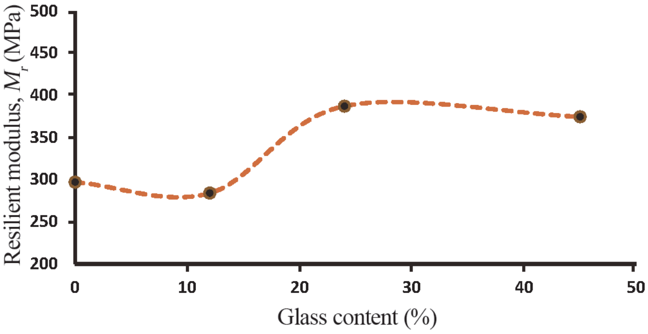
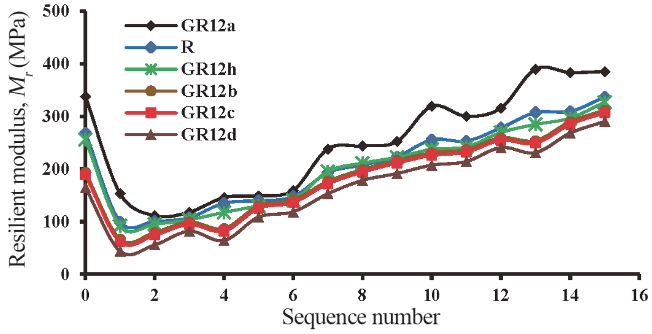


Fig. 10 Resilient modulus of homogenous samples of GR mixtures

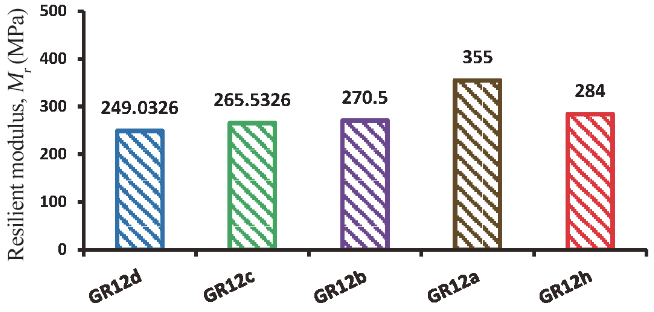
The collected resilient modulus data for different samples with the variation of the GR ratio is shown in Figs. 10 to 14. From Fig. 10, it can be seen that the $M_r$ values of the homogenous samples were slightly reduced from 297 MPa of pure rock (R) to 284 MPa when rock was mixed with 12% of glass (G). Then the $M_r$ value sharply increased to 387.2 MPa with increasing the G content up to 24%. With increasing the G content up to 45%, the homogenous samples showed a slight reduction in the $M_r$ values to 374.6 MPa. In general, the G addition causes a 30% and 26% increase in $M_r$ values when R was mixed with 24% and 45% G, respectively. The study by Senadheera *et al.* (2005) also pointed out that the $M_r$ and $P_d$ of caliche-glass cullet mixtures increase with increasing G content. The study implemented by Clean Washington Center reported that mixing R with up to 50% glass cullet produced an appropriate for pavement applications. In contrast, the study by Ali *et al.* (2011) reported that the $M_r$ of the GR mixtures is not sensitive to moisture and G content. Arulrajah *et al.* (2014) also stated that the $M_r$ of recycled concrete aggregate-glass mixtures decreased with increasing G content, as the stiffness and durability of G are lower than of recycled aggregate.

Effects of the sample structure on the dynamic behaviour of GR mixtures are presented in Figs. 11 to 14. Although all layered samples showed the same behavior trend of gradual increment in $M_r$ with the number of cycle sequences, the highest values of $M_r$ were different for each glass content. It appears from Fig. 11 that the $M_r$ value of GR12 increased from 284 MPa for the homogenous sample to 355 MPa for the layered sample type (a). The $M_r$ values of GR12 mixtures were reduced to 270.5, 265.53, and 249 MPa when the sample structure changed to types (b), (c), and (d), respectively. With increasing glass content to 24% and 45%, the layered samples exhibited different behaviour. In both mixtures, GR24 and GR45, the homogenous samples showed higher $M_r$ values than the layered samples. Layered samples type (a) in both blends GR24 and GR45 showed higher $M_r$ values than other types of the structure. In contrast, samples of structure types (b), (c), and (d) in GR24 and GR45 exhibited almost the same values as $M_r$.

The present study shows the possible benefit of the layered structure and the glass content in improving the resilience behaviour of crushed rock. An improvement in the $M_r$ values of R was noticeable with the addition of G. Despite that, the sample of GR45 type (a) showed lower modules than the sample GR12; the high level of G content reflected a considerable improvement in the $M_r$ value compared to both the GR24 and R samples. With high G proportions of 24% and 45%, it is visible that the homogeneous samples showed higher $M_r$ than the layered specimens. Based on the conclusion of Babiker *et al.* (2014), the layered samples show lower cohesion than the homogenous samples, and that could be the possible explanation for the above result.

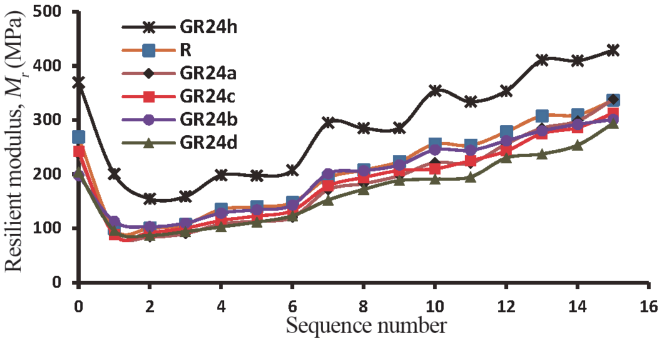


(a) Resilience behaviour

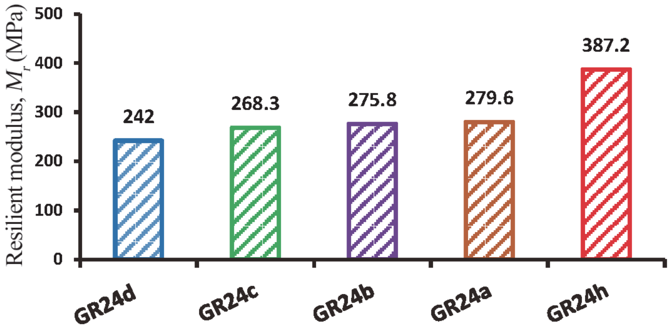


(b) Effect of the layered sample structure on $M_r$

**Fig. 11** **Resilient modulus of layered sample with 12% glass**



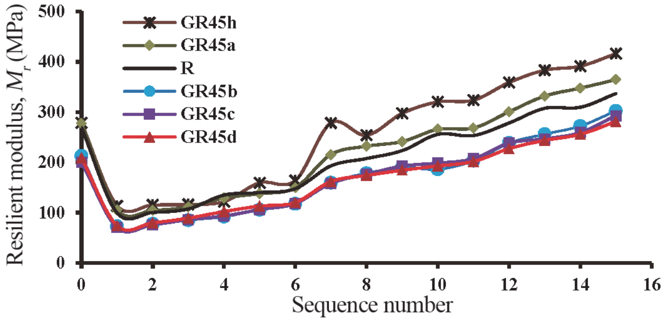
(a) Resilience behaviour



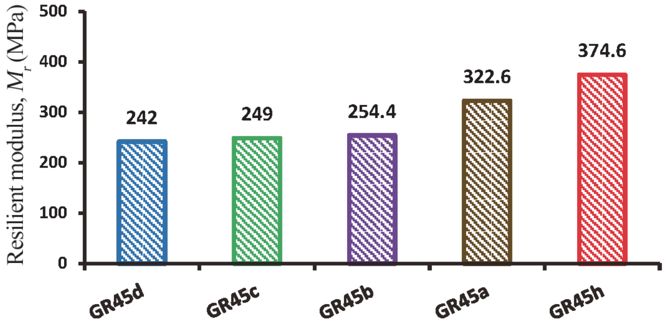
(b) Effect of the layered sample structure on $M_r$

**Fig. 12** **Resilient modulus of layered samples with 24% glass**

Interestingly, the GR24h, GR45h, GR12 type (a), and GR45 type (a) specimens showed higher $M_r$ than the R sample. The effect of the layer thickness on the $M_r$ of the layered samples can also be shown in Figs. 11 to 14. The GR12 sample type (b) exhibits the lowest $M_r$ value than the sample type (a). Thus, a positive correlation was noticed between the $M_r$ and the GR layer thickness during the first twelve sequences. In general, the $M_r$ of the layered samples is considerably dependent on the thickness of the GR layer.



(a) Resilience behaviour



(b) Effect of the layered sample structure on $M_r$

**Fig. 13** **Resilient modulus of layered samples with 45% glass**

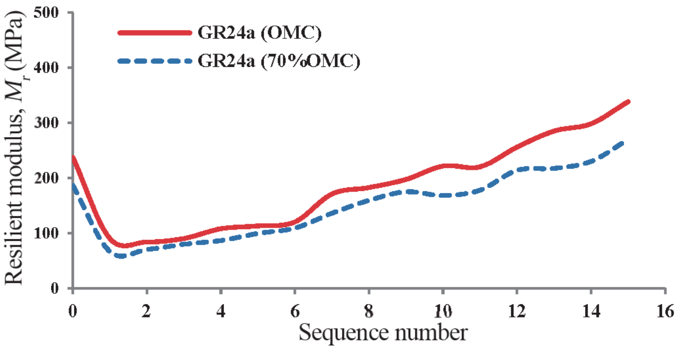


**Fig. 14** **Resilient modulus of the GR24 sample at different moisture content**

According to a basic comparison between the samples types (a) and (b) with different glass contents, 12%, 24%, and 45%, the single-layered samples (type (a)) exhibited higher $M_r$ than the double-layered samples (type (b)). The role of increasing the number of interface layers between two different layers may be responsible for raising the $M_r$ of the single-layered samples. Around the interface layer, between the R and GR layers, fine and medium particles of R and G tried to fill the voids between the GR mixtures, which caused enhanced soil fabric around the interface areas. This result was consistent with the findings of Zhang *et al.* (2015), who concluded that the motion of fine and coarse particles near the interface is more active than in other parts of the layered sample, as the fine materials move to fill the voids of the coarse tailing. The effect of the location of the GR layer on the $M_r$ values of GR mixtures was also investigated in this section. A reduction in $M_r$ samples type (d) was noticed because of the location of R layers in the upper half of the sample. Hence, the GR layer location can be considered an operational parameter affecting the $M_r$ of the layered samples. On the other hand, unreliable variation in the $M_r$ of the GR45 type (d) sample was noticeable by relocating the GR45 layer.

The effect of moisture content on the resilience behaviour of the layered GR samples is presented in Fig. 14. Two samples of GR12 type (a) were prepared at different moisture contents, 70% and 100% of OMC. A positive correlation was found between the $M_r$ and the moisture content, which contrasted with some existing studies (Disfani *et al.* 2012; Azam and Cameron 2012).

## 6. SHEAR STRENGTH

A series of dynamic shear tests were conducted to assess the strength features of the homogenous and layered samples of R and different GR mixtures at a wide range of G percentages under dynamic shear loads. A range of factors that are considered to affect the stress-strain behaviour was investigated, and comparisons between the shear strength characteristics of the layered and homogeneous samples were presented. Figures 15 to 17 exhibit the maximum shear strength of homogenous and layered GR samples. It is apparent from Fig. 15 that all samples showed a positive correlation between the strain and shear stress until the peak shear point, while beyond that, the shear stress decreased with the shear strain increase. The peak shear strength of R was reduced from 1,110 kPa to 1,000 kPa as the G content increased to 12%. Figure 16 exhibits a series of stress-strain curves of layered samples with 12%, 24%, and 45% glass. At low G content (12%), the layered sample (R+GR12) showed the highest shear strength. In Fig. 17, it is worth noting that the GR12 sample type (a) showed the highest shear strength. The high interlocking between the G and the R particles around the interface layers could be the reason for that behaviour. Moreover, the high ability of fine materials to rotate under the shear forces impacts (Zhang *et al.* 2015) might reduce their susceptibility to breaking or crushing compared to coarse particles. Figure 17 also showed that the shear strength decreased when the GR ratio increased from 12% to 24%, while insignificant variations in the shear strength were noticeable when the percentage increased from 24% to 45%. It is essential to know that the coarse particles of G are easily crushed under the dynamic load's impacts (Disfani *et al.* 2009), and this causes an increase in the fine glass content within a sample, which causes a reduction in the shear strength of the sample at the high G content. Furthermore, coarse particles showed higher resistance to shear strength than fine particles (Wei *et al.* 2009), and that could be another reason for the dynamic shear strength reduction at high G content. Data from Fig. 17 shows a steady reduction in the shear strength of the sample type (a) as the thickness and G ratio increase. The response of the sample type (b) to dynamic shear seems to follow the same behaviour as the sample type (a). These results concluded that the interface layers between the GR and R layers could be an essential factor in the development of stress-strain behaviour of the samples.

Figure 18 characterises the effect of the moisture content on the shear strength of the GR24 sample type (a). Note that the R and GR24 layers were prepared at 100% and 70% of the OMC of each layer. It is worth noting that the shear strength of the sample increased with the moisture content increasing. This unexpected performance might be attributed to the effect of water lubricating around the interface layers at 100% OMC, which is caused by enhancing the soil fabric around the interface areas, which positively affected the shear strength characteristics of the GR24 sample.

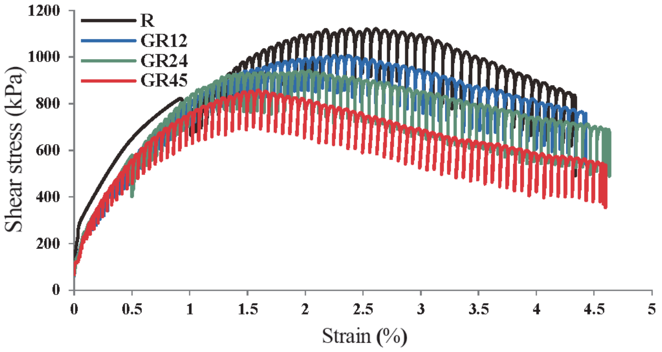


**Fig. 15** Stress-strain curves of the pure rock, GR12, GR24 and GR45 samples

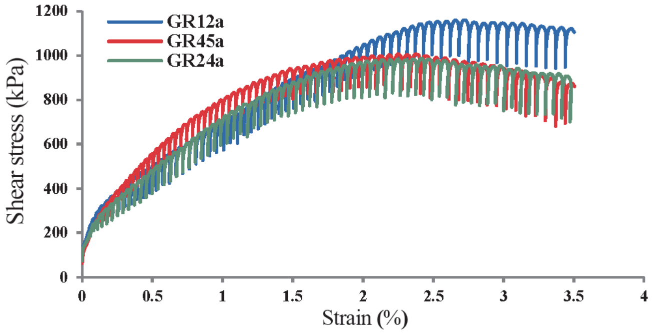


**Fig. 16** Stress-strain curves of layered samples with 12%, 24%, and 45% glass

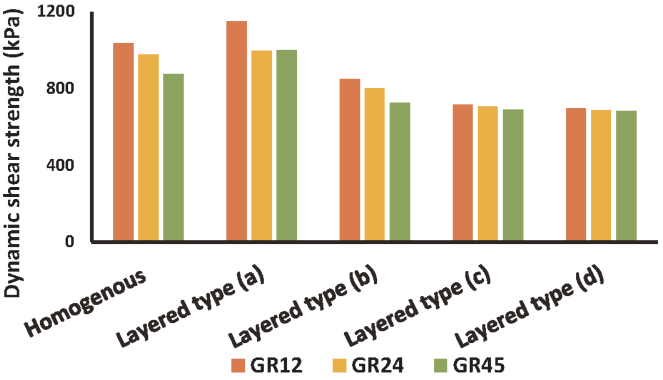


**Fig. 17** Dynamic shear strength of layered GR mixtures

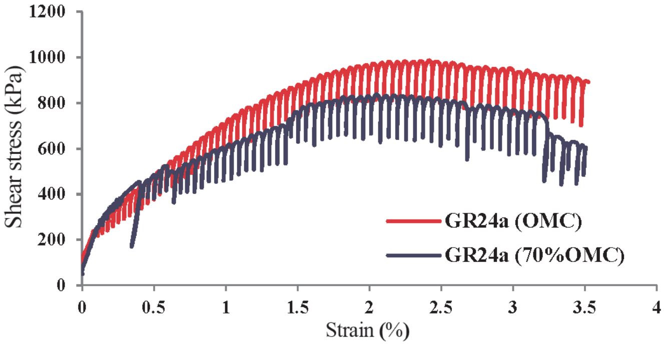


**Fig. 18** Effect of optimum moisture content on dynamic shear strength of the GR mixtures

## 7. CONCLUSIONS

This study set out to determine the effect of sample structure on the dynamic behaviour of the GR blends regarding their properties, gradation specifications, compaction parameters, resilient modulus, shear strength, and permanent deformation. The results of particle size distribution show that GR mixtures are appropriate for use in pavement applications. The modified compaction test results indicated that glass in the rock samples contributed to decreasing the MDD of the mixture. The increasing glass ratio caused a significant reduction in the OMC of the GR mixtures. Among the six types of specimens, which included layered and homogenous samples, the GR24 specimen showed the lowest values of deformation, and the highest $M_r$. What is interesting about the results is that the GR24h, GR45h, GR12(a), and GR45(a) samples showed higher $M_r$ values than the rock sample. In general, the homogenous samples of GR mixtures illustrated less $P_d$ and higher $M_r$ than the layered samples. Furthermore, the GR layer location played a crucial role in the stiffness and deformation susceptibilities of the layered samples. The samples at 70% of OMC showed the lowest $P_d$. The reduction in the moisture content by about 20% caused a decrease in the $P_d$ of the layered sample by about 15%. A positive correlation was reported between moisture content and the resilient modulus of the layered samples. The performance of the GR samples type (a) was affected by increasing the thickness of the GR layers. The GR45 sample type (a) showed higher $M_r$ values than other types of layered and R samples. It is worth noting that decreasing the R and the GR layer thickness of the layered samples is generally considered a factor strongly related to $M_r$ and $P_d$. Moreover, the $P_d$ of the layered samples was more sensitive to the GR ratios than that of the homogenous ones. The maximum $P_d$ of the homogenous specimens, about 0.85 mm, occurred at a 12% glass ratio, while the maximum $P_d$ of layered samples, about 1.9 mm, happened at a 12% G ratio. Fluctuations in the behaviour of specimens' modulus according to the GR rate, were observed in this research. In general, the highest $M_r$ of the homogenous samples, about 387.2 MPa, occurred at a 24% G content. In contrast, the highest one of the layered samples, approximately 355 MPa, happened at 12% G content. The results also showed that the thickness of the R and GR layers in the layered samples negatively affected the $P_d$ and $M_r$. In terms of shear strength, the results show that the highest shear strength appeared in the GR12 sample type (a). A positive correlation was found between the G ratio and the shear strength of the layered samples. What is interesting about the results of this study is that the layered sample at 12% G content showed higher shear strength than the R sample itself. On the other hand, there was a negative effect of the GR layer number on the shear strength. Unexpectedly, the layered sample at high moisture content, 100% OMC, showed higher shear strength than the sample at 70% OMC.

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## DATA AVAILABILITY

Data for figures in this paper are available from the corresponding author upon reasonable request.

## CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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