DYNAMIC PROPERTIES OF CRUSHED GLASS AND TYRE RUBBER IN UNBOUND PAVEMENT APPLICATIONS

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ABSTRACT

Flexible pavements consist of treated unbound materials between the surface, typically bituminous, and the natural subgrade layer. A laboratory study was conducted to assess the dynamic behavior under the influence of repeated loads of the two most common global waste materials for their performance as road materials. The study investigated the behavior and properties of crushed rock (R) blended with waste glass (G) and tyre rubber (T) and evaluated them as alternatives to natural unbound materials. Preliminary tests included Modified Proctor compaction and Particle Size Distribution tests (before and after the compaction stage), and a more specialised test to determine the resilient modulus (Mr) and the permanent deformation values; the Repeated Triaxial Load Test (RLTT). The mixtures were prepared at different percentages of the whole specimen's total dry weight: from 12 to 45 % waste glass, and from 5 to 15 % tyre rubber. To simulate typical in situ materials, the mixtures were also prepared at the lower target moisture contents of 70% and 80% of OMC. The moisture content and the dry density after the RLTT were measured. Results showed a positive correlation between permanent deformation and glass content, while glass content can improve Mr value of rock specimens by up to 50%. Under RLTT, the addition of tyre rubber to crushed rock decreased permanent deformation.

1 INTRODUCTION

Common global goals include a balanced, pollution-free ecosystem and the conservation of natural resources. To achieve these objectives, efforts and research is conducted to find inexpensive and safe methods of waste disposal to avoid damage caused by storage, moreover, to investigate these materials as a substitute for natural and abundant substances.

Waste materials are usually referred to any type of material which discarded after use in many activities including commercial, industrial and human activities. According to Australian Bureau of Statistics, Australian Government (2016), Australian waste production is about 1.5 tonnes per year per capita, including food waste, paper, and glass. The total amount of waste glass produced in Australia is about 1.36 million tonnes per year. Glass recycling fell by 6% between 2015 and 2016; this underscores the need to highlight the use of waste materials in road building which is one of the sectors with the potential to use the glass waste on an ongoing basis.

Increased road traffic in developing countries has led to an increase in the number of tyres produced, and ultimately discarded, with the potential to cause serious environmental and health problems. The Australian government estimated 51 million tyres are produced each year which are sources of environmental pollution and a direct threat to public health (Australian Government, Department of Environmental and Energy 2016). Moreover, waste materials play a major role in minimising the consumption of strategic inventories of natural resources through their direct and indirect use as an alternative to natural materials in several areas of civil engineering.

Base and subbase materials are one of the most widely used groups of unbound materials and have been extensively used in flexible pavements (Australian Road Research Board). Around Australia, One of the most important natural materials commonly used as unbound material is crushed rock, and success in utilising waste materials as a substitute for crushed rock will result in significant environmental and economic benefits.

In fact, the use of glass waste in the glass recycling industry is less expensive than using natural sand but separating the glass that has been collected according to colour is a major obstacle to its use and is considered to be an economically inefficient process. According to Ali *et al.*, (2011); Arulrajah *et al.*, (2012) and Wartman *et al.*, (2004) the behaviour of crushed glass is identical to natural soil and the presence of different colours of glass is not an obstacle to its use in different paving layers.

Previous researchers have studied the use of glass and stone blends for use in road construction. One such research in 2011 investigated the effects of blending differing proportions of glass and crushed rock. Laboratory results confirmed that the optimal percentage of glass in a glass/rock subbase material was 15% for 4.75 mm glass pieces. Moreover, there was a significant positive correlation between glass content and both workability and hydraulic conductivity of the mixture (Ali *et al.*, 2011). To review the similarity in the physical and mechanical properties of glass and aggregate, research presented by Disfani *et al*., (2011) has emphasised the similarities between them. The researchers conducted laboratory tests on samples containing glass at ratios ranging between 1- 100% of the total weight, the convergent results emerged between the mixture and raw material included particlel size distribution, specific gravity and shear strength.

Recently Gischig *et al.*, (2015) have examined the effects of glass content on the shear strength of base material. The results confirmed that there is a negative correlation between shear strength and glass content while 15% of glass content sized 4.75mm presented a good workability and high shear strength. In order to identify the effects of fine materials on the behaviour of road layers, Ali *et al.*, (2011) recorded a significant increase in water absorption and consolidation due to glass fines increase. On the other hand, a negative correlation was found between glass fines content and RLTT parameters.

Recycled tyre rubber has been used in civil engineering, and research regarding rubber-soil interactions has become available during the past decades. In her case study of tyre rubber, Bosscher *et al*., (1997) highlights the use of tyre rubber as virgin material in embankment works. Tyre rubber was also of interest for use as fill material in retaining walls, Humphrey *et al*., (1998; Humphrey, (2005) and Hazarika, (2007) have considered the effects of soil-rubber mixtures on soil cyclic responses and the results have indicated that a positive correlation between soil resistance and permanent deformations during shaking forces. A recent study on tyre rubber -subgrade soil mixture included resilient modulus, creep and consolidation (Cosentino *et al*., 2014). In asphalt layers, a positive relationship between tyre rubber and the elastic behaviour of gravel-rubber has been reported by Wang *et al*., (2006) and Estevez, (2009). In a study which set out to determine resilient modulus of tyre rubber, (Xiao *et al*., 2009) found a positive correlation between resilient modulus value and the size of rubber particles. Cabalar & Ali,(2011) investigated the differential impact of tyre rubber content on sand. Up to 50% of tyre rubber caused a significant reduction in the internal friction angle of the mixture. Data from several sources have identified the decreased Mr value associated with the inclusion of tyre rubber, there was also insignificant effects of the grain size on Mr (Speir &Matthew, 1996 and Warith & Sudhakar, 2006). Other studies have investigated the relationship between the use of rubber and soil density, There is an unambiguous reduction in soil density due to rubber inclusion (Speir & Matthew, 1996; Ghazavi, 2004 and Rao & Dutta, 2006).

2 MATERIAL SOURCES

Three materials were selected from different sources; crushed rock was obtained from Gosnells Quarry in Western Australia; glass was collected from Perth Bin Hire located in Duffy Street, Bayswater, Western Australia; and tyre rubber was obtained from Tyrecycle Pty Ltd at 30-56 Encore Avenue Somerton, Victoria. The materials were sampled stockpiles in accordance with American Society for Testing Materials (ASTM). The samples were kept in plastic bags and stored in the soil laboratory at Curtin University. Table1 illustrates some of the main characteristics of crushed rock and waste glass used in this research.

Table 1: Material Properties

Material Type	Unit	Crushed rock (Holcim, 2013)	Recycled glass (Benedict data sheet glass sand)	Rubber crumb tyre
Particle shape (Flakiness)	%	25	N/A*	N/A*
Specific gravity (Gs)	%	2.96	2.28	1.1
Bulk Density	t/m^3	1.82	1.37	1.153–1.198
Liquid Limit	%	22	------	N/A*
Linear Shrinkage	%	1.4	------	N/A*
Organic Content	%	0.47	0.98	0.25
pH		8.16	9.73	7.64
Electrical Resistivity	(Ø.m)	------	18	-------
Water absorption	%	7.9	0.4	0.957
Los Angeles	%	20	25	-------
MDD	kg/m^3	2.4	1.77	0.618 to 0.642
OMC	%	6	1.8	N/A*
California Bearing Ratio	%	198	41	N/A*

3 LABORATORY EXPERIMENTS

Sieve analyses were conducted as described by the Australian Soil Classification System (ACSS). The grading curves were plotted before and after the compaction process to compare the upper and the lower limits of 20 mm Class 2 base material (VicRoads 2008). Modified Proctor compaction tests following Australian Standard (2003) were used to establish the experimental values of OMC and MDD. Specimens were prepared and the procedure of compaction test was applied on specimens. The graphical relationship between water content and density was plotted and the MDD which accrues at OMC was established. In order to identify the elastic-plastic specimen's performance under repeated loads, a series of RLTT was conducted according to AASHTO T 307 (1999) as shown in Table 2.

The specimens were prepared in accordance with Gabr et al., (2013) and the most important parameters Mr and permanent deformation were established from two phases of RLTT. In order to prepare the specimen that consists of eight equal layers, the materials were carefully mixed at OMC and the weight of each layer was adjusted then compacted until it reached approximately the specified height. Other specimens were prepared at 80% and 70% of OMC to compare laboratory and field conditions (VicRoads 2010).

Table 2: Stress path design

Sequence #	Confining	Deviator	Cycles
Conditioning	103.4	93.1	1000
1	20.7	18.6	100
2	20.7	37.3	100
3	20.7	55.9	100
4	34.5	31	100
5	34.5	62	100
6	34.5	93.1	100
7	68.9	62	100
8	68.9	93.1	100
9	68.9	62	100
10	103.4	124.1	100
11	103.4	186.1	100
12	103.4	62	100
13	137.9	93.1	100
14	137.9	124.1	100
15	137.9	248.2	100

The RLTT apparatus used for this research is shown in Figure 1d; the apparatus consists of repeated load actuator, steel loading frame, load cell, loading ram, external Linear Variable Differential Transducers (LVDTs), confining pressure regulator, external air compressor equipment and computer. Before each test, the actuator and LVDTs were calibrated.

According to the stress paths shown in Table 2, the actuator applies the axial stress when the confining pressure reached the required value. Figure 1 from a to d presents photos that show the materials used in this research, the failed sample after RLT, and the RLT apparatus and all necessary equipment.

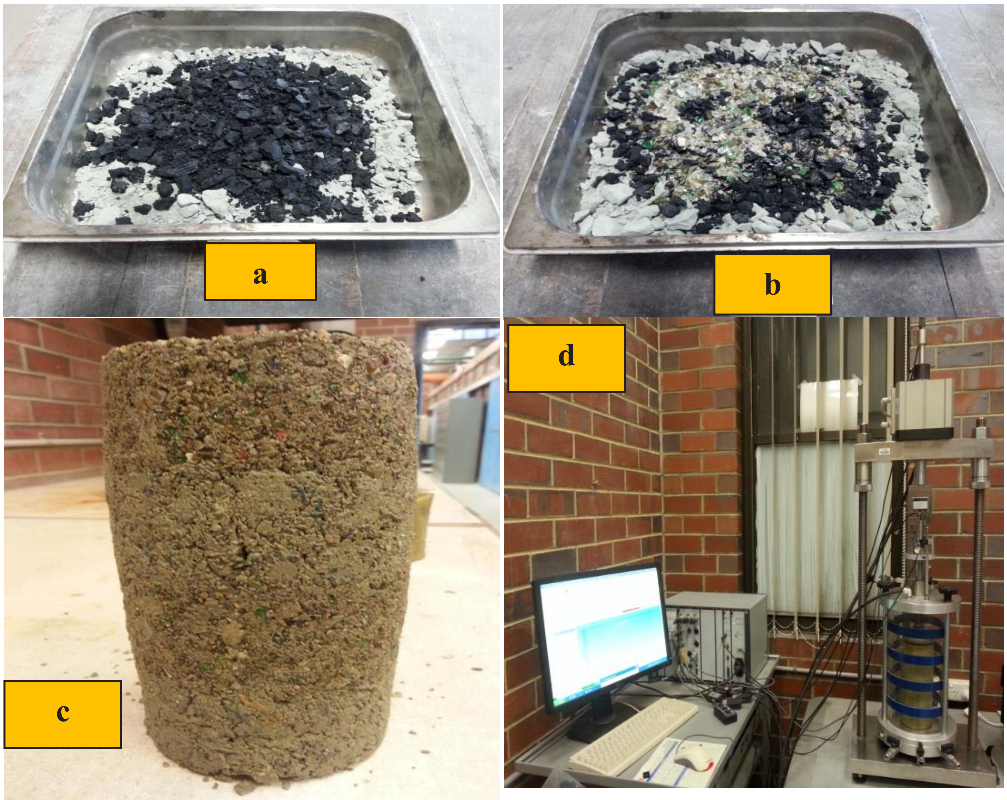


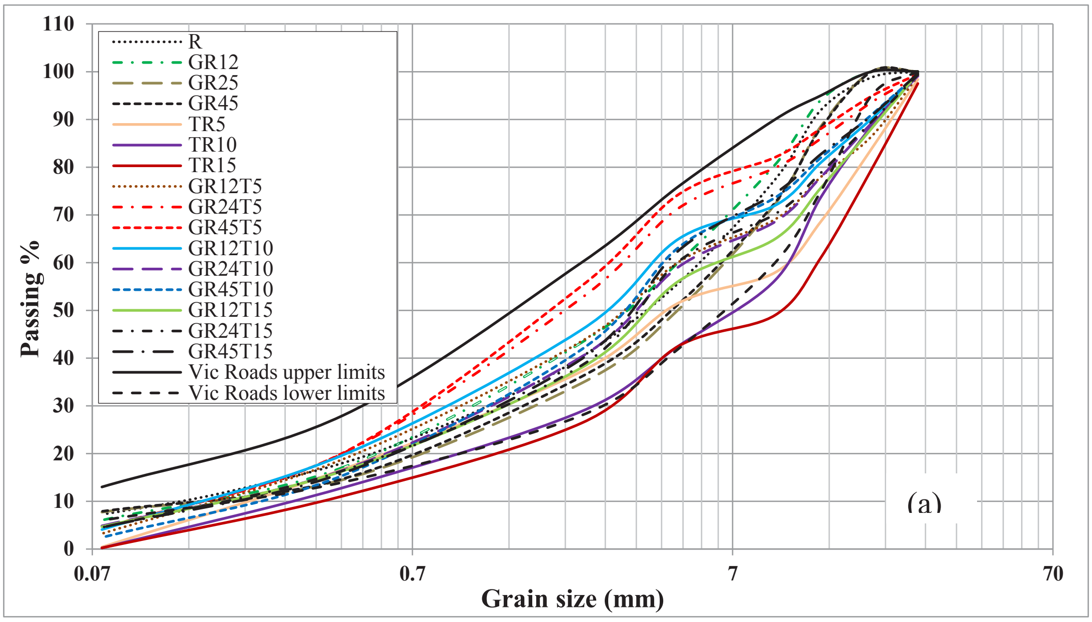
Figure 1: a) tray of tyre rubber and crushed rock b) tray of tyre rubber, crushed glass and crushed rock c) blended sample after RLTT d) fully sample inside the RLT apparatus.

4 CLASSIFICATION AND SELECTED PROPERTIES

The results of the sieve analysis test before and after compaction are presented in Table 3. The unbound materials classification is based on the percentage retained and passing through several sieves. According to ACSS, the particles larger than 2.36 mm are gravel while the smaller and retained on the No. 200 sieves are regarded as sand.

Table 3: Basic properties of the materials

Resource	Classification	Maximum particle size(mm)	Cu	Cc	Fine Content (%)	Gravel Content (%)	Sand Content (%)
Crushed Glass (G)	SW	5.2	12.1	1.345	3.2	39.5	57.3
Crushed Glass After Compaction	SW	4.75	13.6	1.4	4.5	35	60.5
Crushed Rock (R)	GW	20	42	2.38	6.3	61.2	32.5
Crushed Rock After Compaction	GW	20	60	2.6	7.6	54.4	38
Tyres rubber (T)	GP	16	2.7	0.67	0.02	96.79	3.19



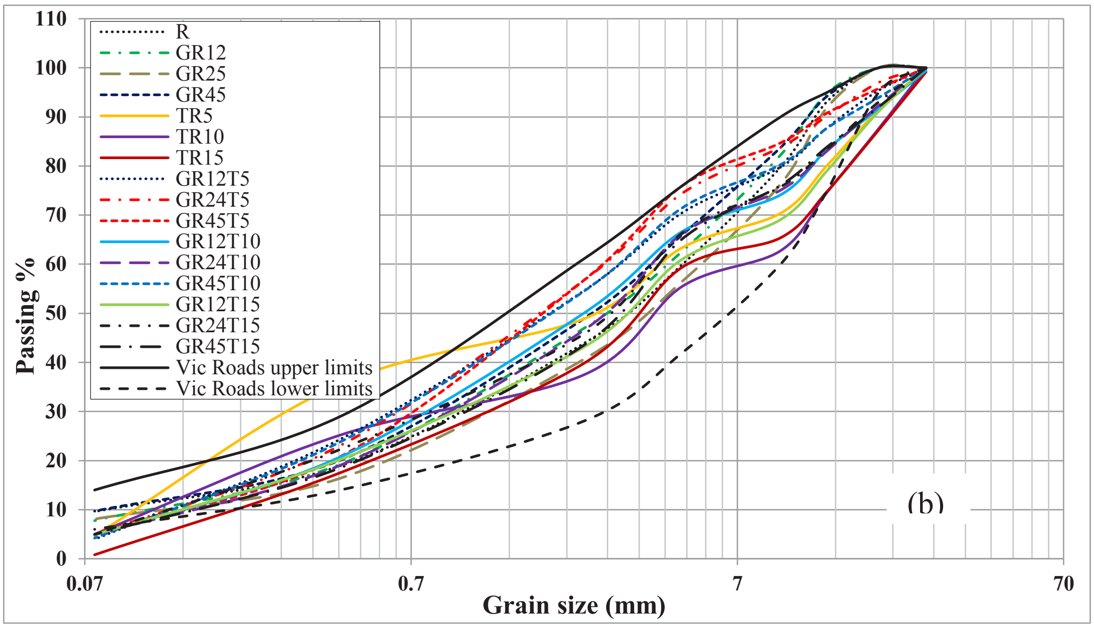


Figure 2: Gradation curves of all blends (a) before and (b) after, compaction stage

Figure 2(a) illustrates the gradient curves for crushed rock, as well as 15 samples at different proportions of glass-rock-rubber tyre before the compaction test. The figure presents the limitations for 20 mm Class 2 of base course material as was reported in the standard specifications for road and bridge works and per the methods of Disfani *et al*., (2011). Our findings show that the grading curves of GR12, GR24, GR45, GR45T5, and GR24T5 fall between the upper and the lower limits of base course material while the rest of the blends failed the lower limits requirements. Figure 2(b) presents the gradation curves of the blends after compaction. As expected, there was a significant increase in the fines content. It is clear that the ratio of coarse and medium particles are much smaller as a result of compaction impact.

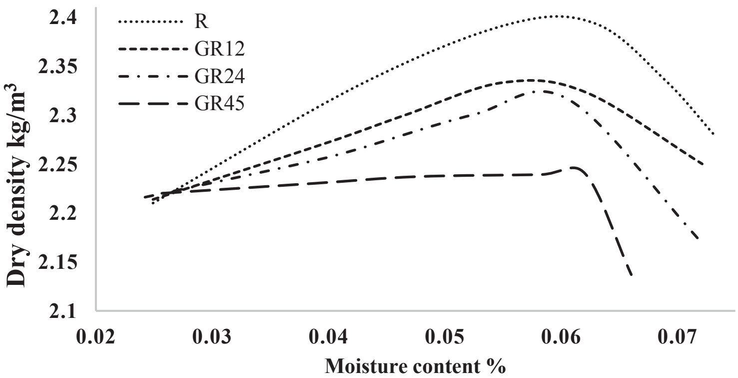
Table 4 shows the results obtained from sieve analysis results including classification, gravel content, sand content, fine content, D10, D30, D60, Cu and Cc.

Table 4: Basic properties of GR, TR and GRT blends

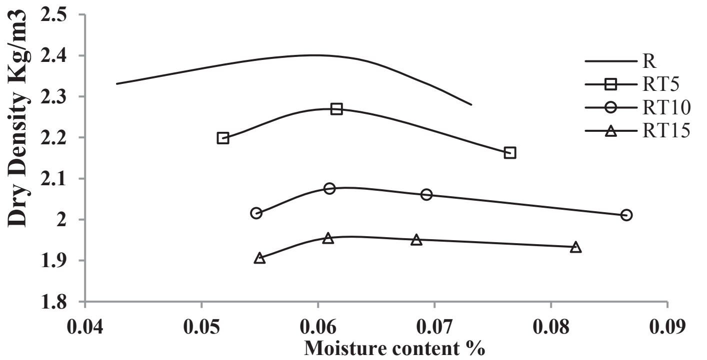
Mixture \ Properties	(G/R) ratio (%)	(T/R) ratio (%)	D10	D30	D50	D60	Cu	Cc	Classification	Gravel content %	Sand content %	Fine Content (%)
GR45T15 A.C	45	15	0.15	0.95	2.9	4	26.6	1.5	GW	56.5	38.4	5.0
GR45T15	45	15	0.17	1.4	3.2	4.5	26.4	2.56	GW	60.1	35.2	4.5
GR24T15 A.C	24	15	0.12	0.8	2	3.9	32.5	1.36	GW	54.3	40.7	5
GR24T15	24	15	0.17	1.4	3.5	4.9	28.8	2.35	GW	61.5	33.9	4.5
GR12T15 A.C	12	15	0.13	0.9	2	4.2	32.3	1.48	GW	56.9	38.1	4.9
GR12T15	12	15	0.15	1.25	3.7	5.5	36.6	1.89	GW	62	33.3	4.7
GR45T10 A.C	45	10	0.14	0.7	2	3	21.4	1.16	SW	45.6	50.1	4.2
GR45T10	45	10	0.2	1.2	3.2	4.5	22.5	1.6	GW	58.2	39.3	2.4
GR24T10 A.C	24	10	0.12	0.9	2.9	4	33.3	1.6	GW	53.5	41.6	4.9
GR24T10	24	10	0.18	1.2	3.5	5	27.7	1.6	GW	59.7	35.4	4.8
GR12T10 A.C	12	10	0.11	0.59	1.7	2.8	25.4	1.13	GW	50	45.1	4.8
GR12T10	12	10	0.14	0.85	2.8	4	28.5	1.29	GW	54	41.8	4.1
GR45T5 A.C	45	5	0.13	0.69	1.8	2.8	21.5	1.3	SW	43.4	51.6	5.0
GR45T5	45	5	0.15	0.75	2	3.3	22	1.13	SW	44.9	50.8	4.3
GR24T5 A.C	24	5	0.11	0.6	1.7	2.8	25.4	1.16	SW	43.4	51.7	4.9
GR24T5	24	5	0.15	0.7	2	3	20	1.08	GW	51	44.8	4.2
GR12T5 A.C	12	5	0.11	0.62	2.1	3.4	29	1.09	SW	45.5	50.5	3.9
GR12T5	12	5	0.16	1	3.3	5	31.2	1.25	GW	56.4	40.3	3.2
GR45 A.C	45	0	0.08	0.85	2.5	3.9	48.7	2.3	SW	57.5	32.8	9.7
GR45	45	0	0.185	1.7	4.3	6.4	35.1	2.44	SW	61.4	30.6	8
GR24 A.C	24	0	0.13	1.25	3.9	5.5	42.3	2.18	SW	54	37.8	8.2
GR24	24	0	0.18	1.8	4.5	6.5	36.1	2.76	SW	57.3	38	7.7
GR12 A.C	12	0	0.09	0.9	2.8	4.5	50	2	SW	53	39	8
GR12	12	0	0.17	1.2	4.75	3.4	27.9	1.78	SW	56.7	37.2	6
TR15 A.C	0	15	0.2	1.1	3.4	5	25	1.21	GW	60.2	39.3	0.4
TR15	0	15	0.35	2.8	7	9	25.7	2.5	GW	73.6	26.1	0.2
TR10 A.C	0	10	0.11	0.85	4	5.9	53.6	1.11	GW	62.6	32.4	5
TR10	0	10	0.3	2.4	6	7.1	23.66	2.70	GW	71.1	28.6	0.2
TR5 A.C	0	5	0.11	0.34	2.6	4	36.36	0.26	GW	51.2	44	4.7
TR5	0	5	0.22	1.35	4.5	7	31.8	1.18	GW	62.8	36.8	0.4

5 MODIFIED COMPACTION TESTS

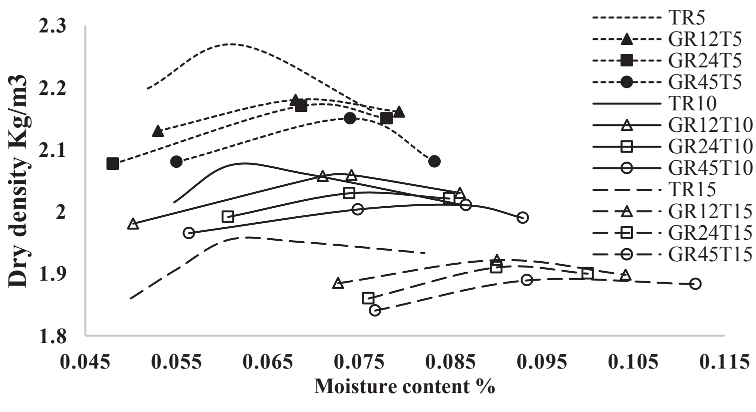
The results obtained from the compaction test of pure crushed rock as well as mixtures, GR12, GR24 and GR45 are presented Figure 3(a). There is a clear trend of decreasing density with increasing glass content. As expected, the dry density of the mix decreased as the percentage of glass increased. Overall, crushed rock gives GR specimens more stability against compaction efforts. Figure 3(b) details the results obtained from the compaction test of rock and tyre-rubber mixtures. The curves show that there is a steady decrease in dry density with rubber content increase. The values of density and OMC are expected to drop sharply due to tyre increase as mentioned in (Attom *et al*., 2007); Cabalar & Karabash, 2014). Figure 3(c) presents the effect of mixing glass and TR group on compaction parameters. Without exceptions, a significant reduction in dry density associated with glass inclusion. Moreover, a positive correlation was found between OMC and increased glass content in the specimens.



(a) Rock and GR blends.



(b) Rock and TR blends



(c) Effect of mixing glass and TR blends

Figure 3: Compaction curves

6 REPEATED LOAD TRIAXIAL (RLTT) TESTS

RLTT tests were performed to assess the dynamic behaviour of base coarse crushed rock material under traffic loads. Cyclical loads represented by deviator and confining stress were subjected to simulated traffic loads on prepared specimens. The results of accumulated permanent deformation and Mr against sequences number are present in the Figures below.

6.1 PERMANENT DEFORMATION

In this section, the findings on the impact of glass and tyre inclusion on permanent deformation of rock specimens are presented in Figures 4,5 and 6. The section also presents the effects of moisture content variations on the blend's deformation.

Figure 4 shows the impact of glass and tyre inclusion of rock specimens through loading sequences. As shown by Babiker, (2014), there is a sharp reduction in permanent deformation during the conditioning stage (sequence 0 to 1) which is represented by the initial stage of the RLLT process. It is difficult to distinguish between the deformation values of GR24 and GR45 specimen;, closer inspection of the figure revealed that GR24 specimen reported significantly less deformation than GR45 after the 5th sequence. In general ,the glass content gives the rock specimens more stability than tyre rubber against permanent deformation and there is a clear trend of decreasing deformation with glass increase. On the other hand, there is a clear negative correlation between permanent deformations and tyre inclusion, and that finding supports the conclusions of Papp *et al*., (1997) and Cosentino *et al*., (2014) that the rate of deformation resistance of unbound materials is anticipated to decline steadily due to tyre inclusion.

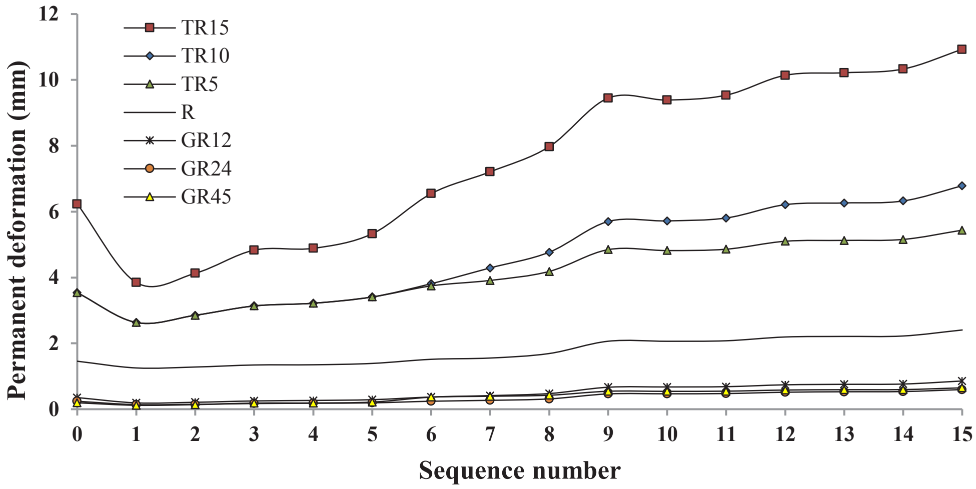


Figure 4: Effects of glass or tyre rubber inclusion on permanent deformation of

Figure 5 shows the effect of adding 12, 24, and 45% of glass to to the TR5 mixture. Overall, the new mixtures show the same resistent trends against permanent deformation during all sequences. These results confirm the above findings and contribute additional evidence that there is a significant positive correlation between the rate of deformation resistance and the glass content.

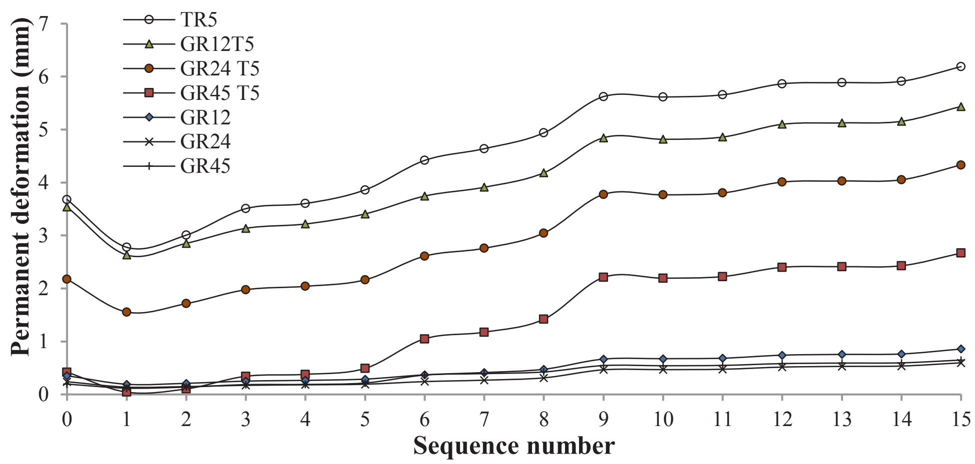


Figure 5: Effects of glass content on permanent deformation of TR

The results obtained from RLTTs of GRT group are compared in Figure 6 that shows how the permanent deformation of TR blends are influenced by glass inclusion. At 10% rubber ratio (TR10), the finding was expected and confirms the results above that the accumulated deformation decreases steadily with increasing glass content while GR45T10 resulted in the lowest value of deformation. At 15% of rubber ratio (TR15), similar behaviour was found in GR12T15 and GR24T15 blend considering the effect of glass content on deformation. One unanticipated finding was that a sharp reduction was seen in permanent deformation due to the mix 45% of glass with TR15 blends.

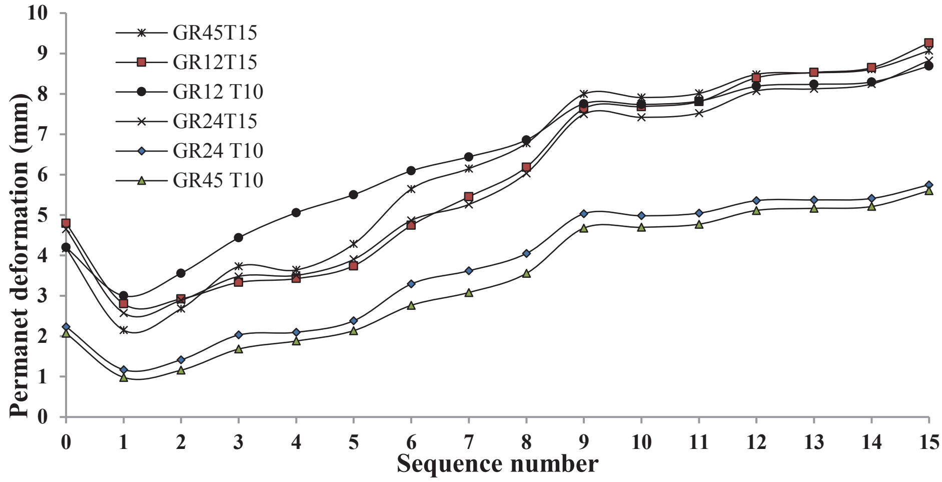


Figure 6: The impact of increasing the glass and tyre rubber ratio on permanent deformation

It would be of interest to assess the materials dry back which provides a more accurate value of compaction in the field as mentioned in Azam *et al*., (2012). Figure 7 compares the permanent deformation results of TR5, TR10, and TR15 during RLTTs. Each blend was tested twice, at OMC and 70% of OMC. The TR5 specimen provides additional support for the ideas of Kim *et al*., (2005 and Cosentino *et al*., (2014) who concluded a positive correlation between moisture content and deformation. In the initial stages of the test process, TR10 and TR15 specimens also provide a positive correlation between moisture content and deformation but contrary to expectations we found a negative correlation between moisture content and deformation in the final stages of this test. More details on correlation between moisture content and deformation of all blends are shown in the figure below.

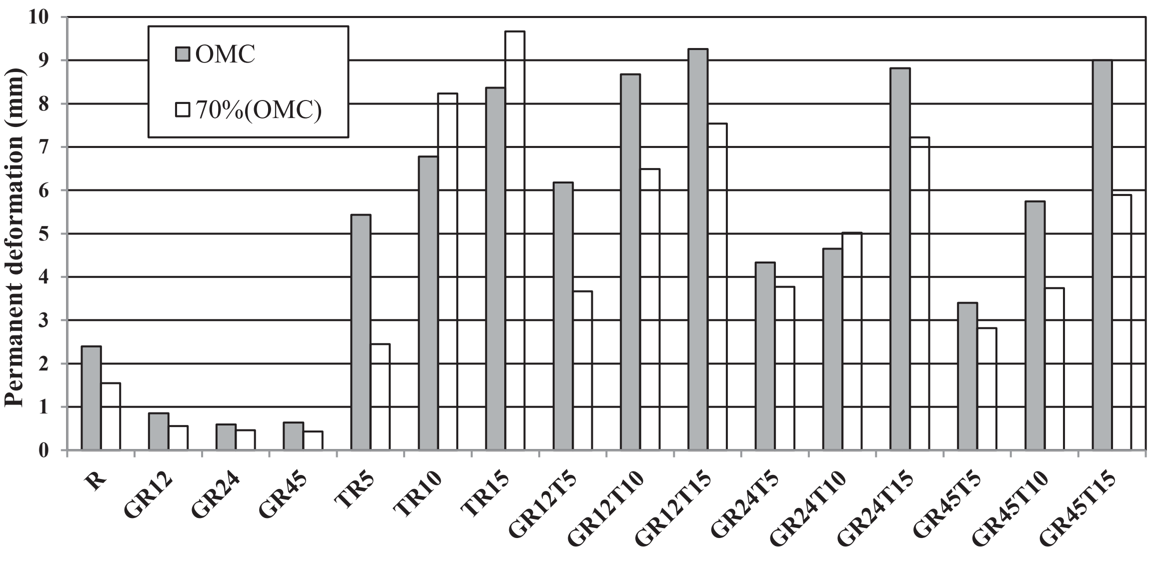


Figure 7: Effect the moisture content on permanent deformation

The correlation between permanent deformations and moisture content at the end of the test are presented in Figure 7. With a few exceptions, our results show that there is a significant correlation between moisture content and deformation while added glass to tyre exerts a powerful effect upon deformation by improving the behaviour of the TR group against deformation.

6.2 RESILIENT MODULUS

The findings on the impact of glass and tyre rubber inclusion on Mr of rock specimens are presented in Figures 8, 9 and 10. The effects of moisture content variations on the blend's Mr are also presented. As mentioned in Cosentino *et al*., 2014), Figure 8 confirms the previous findings and contributes additional evidence that the value of Mr decreases as the percentage of tyre rubber increases. Up to 24% of glass content, the figure also presents a significant positive correlation between glass and Mr value. On the other hand, there is unstable decline in Mr value at 45% G/R ratio. GR45 reported less Mr than the G24 during many stages and more than G24 in others. In general, Mr value of GR blends was found to be higher than 300 MPa and that satisfies the standard range of crushed rock (AustRoads, 2004).

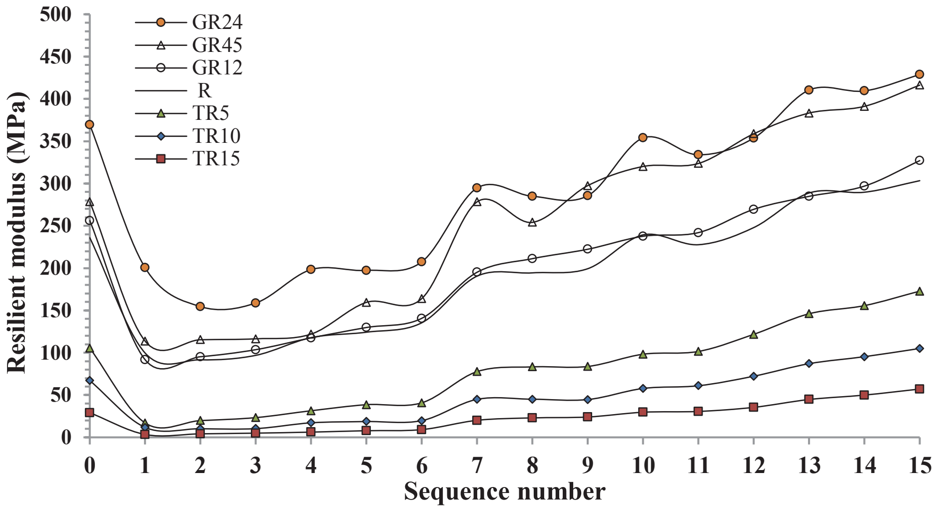


Figure 8: Effects of glass or tyre inclusion on Mr

The development of Mr values due to mixing glass with TR5 blends is represented in Figure 9. The graph shows a gradual increase in the Mr of TR5 as glass content increased and the increment ratio is 14.53%, 15.7% and 31.4% for mixes of 12%, 24% and 45% of ratios respectively.

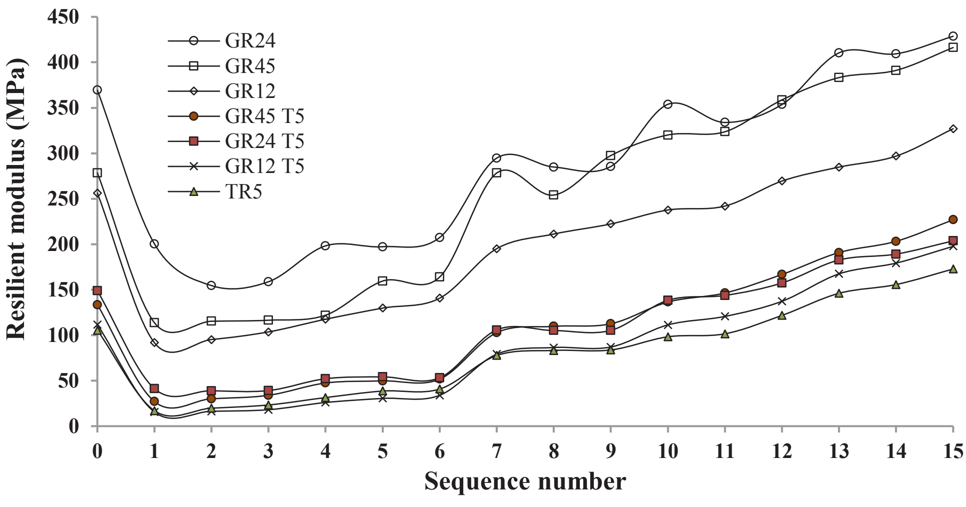


Figure 9: Effects of mixing glass with TR5 blends on Mr

Figure 10 presents the impact of increasing glass ratios on in TR specimens on Mr. For the TR10 and TR15 blends mixed with 12%, 24% and 45% of glass, the finding confirmed the previous result that Mr increases steady with increasing glass content. On the other hand, there is a steady drop in the Mr value of GR blends due toincreased quantity of tyre rubber.

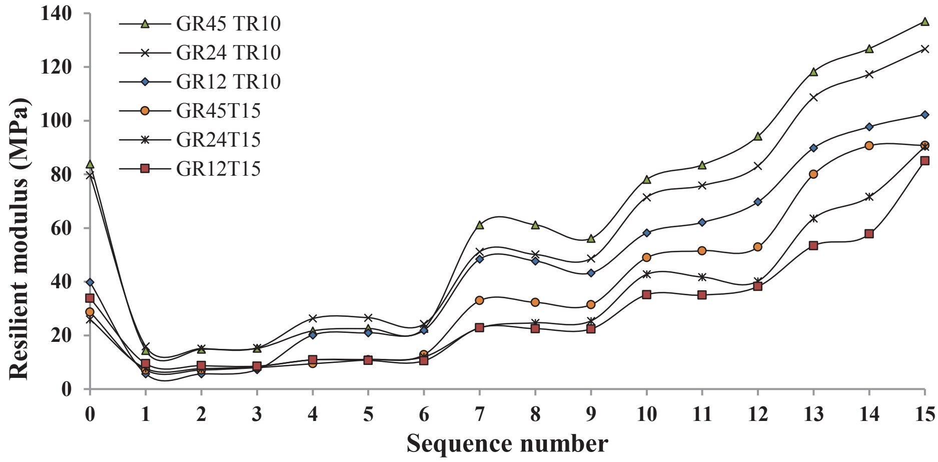


Figure 10: The impact of increasing glass ratios in TR specimens on

Figure 11 shows the comparison of the Mr results of TR5 and GR12T15 due to the variation in moisture content during RLTTs. During the last six stages of the test, TR5 prepared at 100 % OMC (TR5-100) showed significantly lower Mr than TR5 prepared at 70% OMC (TR5-70). From the 1st to the 13th sequence, we can see that the TR5-70 showed significantly higher Mr than the TR5-100 specimen. Moreover, TR5-70 was consistently harder than the TR5-100. By the 15th sequence, the Mr values of TR5-100 were 8.14% smaller than TR5-70.

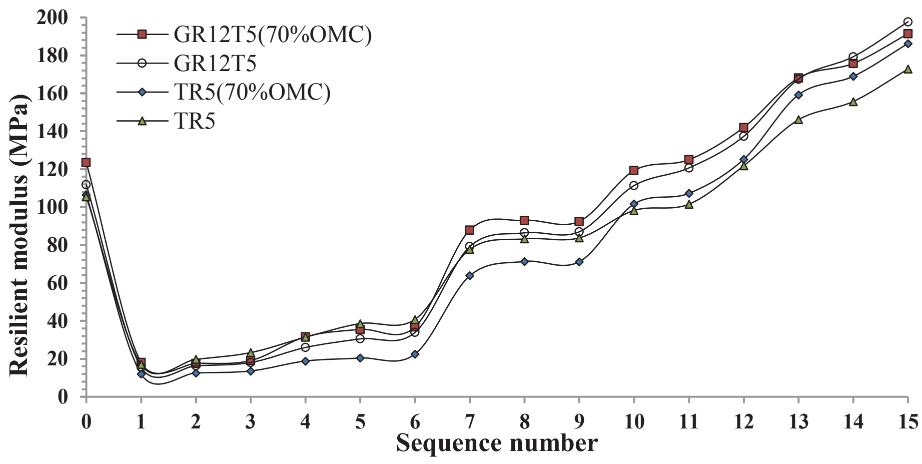


Figure 11: Effect of moisture content on Mr

The correlation between Mr and moisture content at the end of the test or at the 15th sequence is presented in Figure 12. The reduction in moisture content in many cases may have contributed to the increase in Mr. One unanticipated finding was that, in GRT12 group there is a clear trend of decreasing Mr due to decreasing moisture content, while other groups showed that mixing glass and tyre exerts a significant effect on Mr values at 70% OMC.

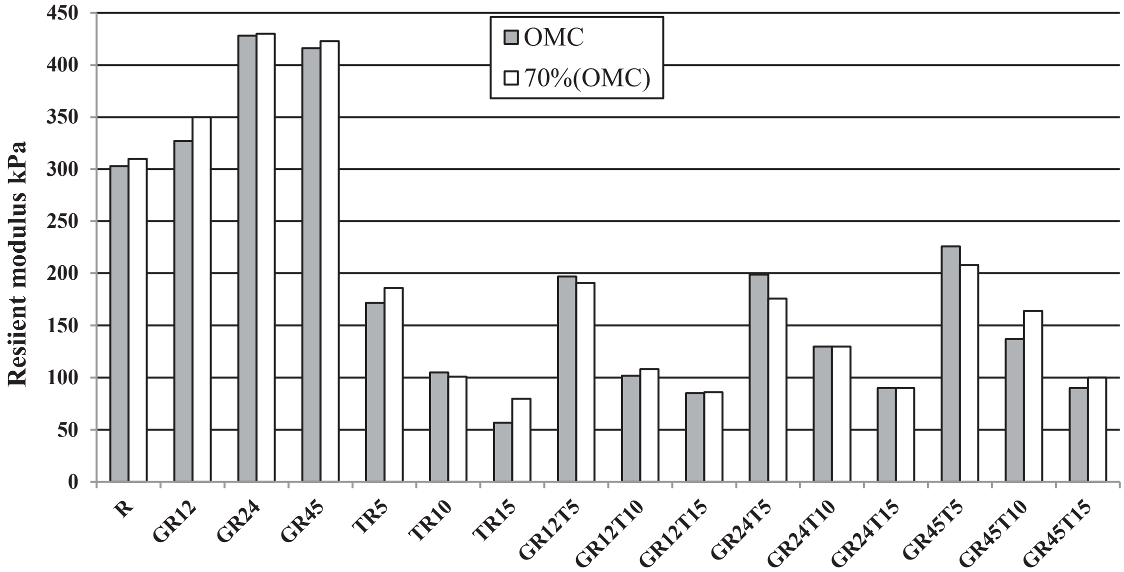


Figure 12: Effect of both G&T content in GRT blends on Mr

7 OPTIMUM MOISTURE CONTENT AND MAXIMUM DRY DENSITY AFTER RLTTS.

Compaction tests are among the most widely used methods to estimate dry density and optimum moisture content for unbound materials. To ensure that optimal density and moisture content for in situ soil, laboratory tests were carried out to compare typical and achieved values (Bowles, 1996). Further research is needed in this section to investigate the actual moisture content and the achieved density during the RLTTs. Figure 13 presents the ratio of actual moisture content/OMC (AMC/OMC) of each specimen prepared at 100% and 70% of OMC at the end of RLTT. It has been demonstrated that a high inclusion of glass and tyre in the specimens results in achieving the ideal ratio of the specimen's moisture content.

It should be noted that these data relate to the blended specimens and they show significantly more ability to retain water than the rock specimen. The reason for this phenomenon is not entirely clear but a probable explanation is that the variety of particles, which mixed with the rock specimen, resulted in more water being retained in the specimens. Moreover, the grains/water adhesion force may have played a role in the retention of water content during the drained test.

More details on the above explanations are presented in Figure 13. At the end of RLTT, The GR45T group reported a significantly higher rate of AMC/OMC than other groups and it is clear in the GR45T5, GR45T10, and GR45T15 specimens.

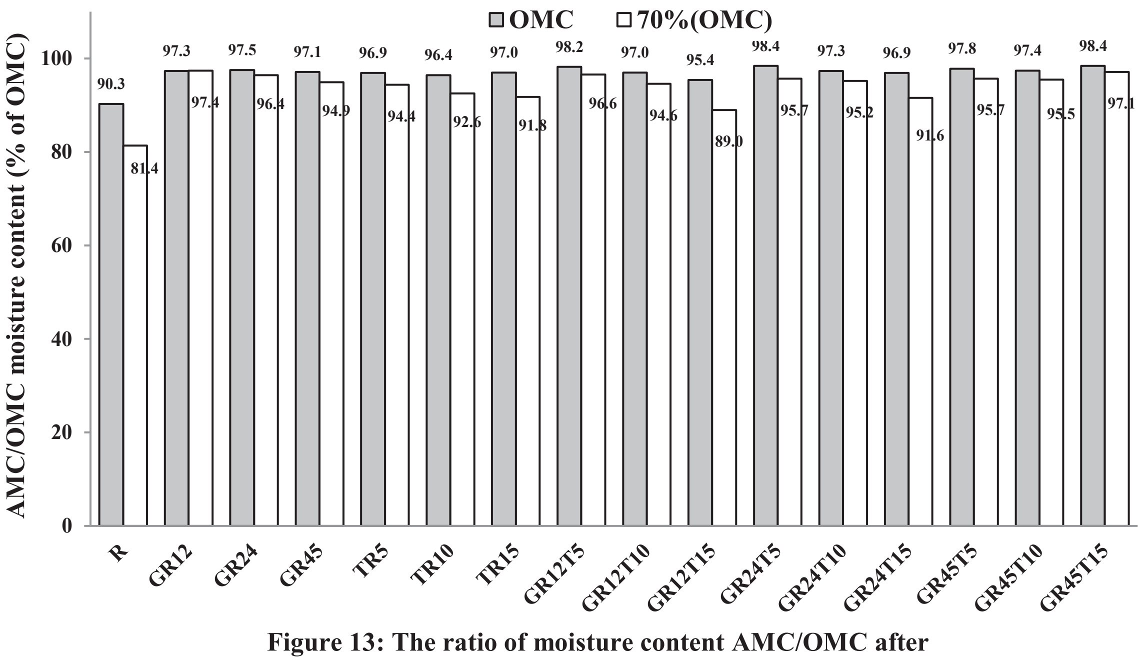


Figure 13: The ratio of moisture content AMC/OMC after

Figure 14 shows the ratio of AD/MDD of each specimen prepared at 100% and 70% of OMC at the end of RLTT. The figure reveals that there has been a marked increase in the AD/MDD ratio due to glass and tyre inclusion. Comparing the ratio of rock and GR results, it can be seen that a sharp increase in AD/MDD ratio as a result of the mix of waste materials. Furthermore, the ratio of GR12T5 is significantly greater than GR12, GR12T10, and GR12T15. Reduction in the moisture content from 100% to 70% of OMC generally exerts a powerful effect upon blends by improving the achieved density after the dynamic efforts of RLTTs.

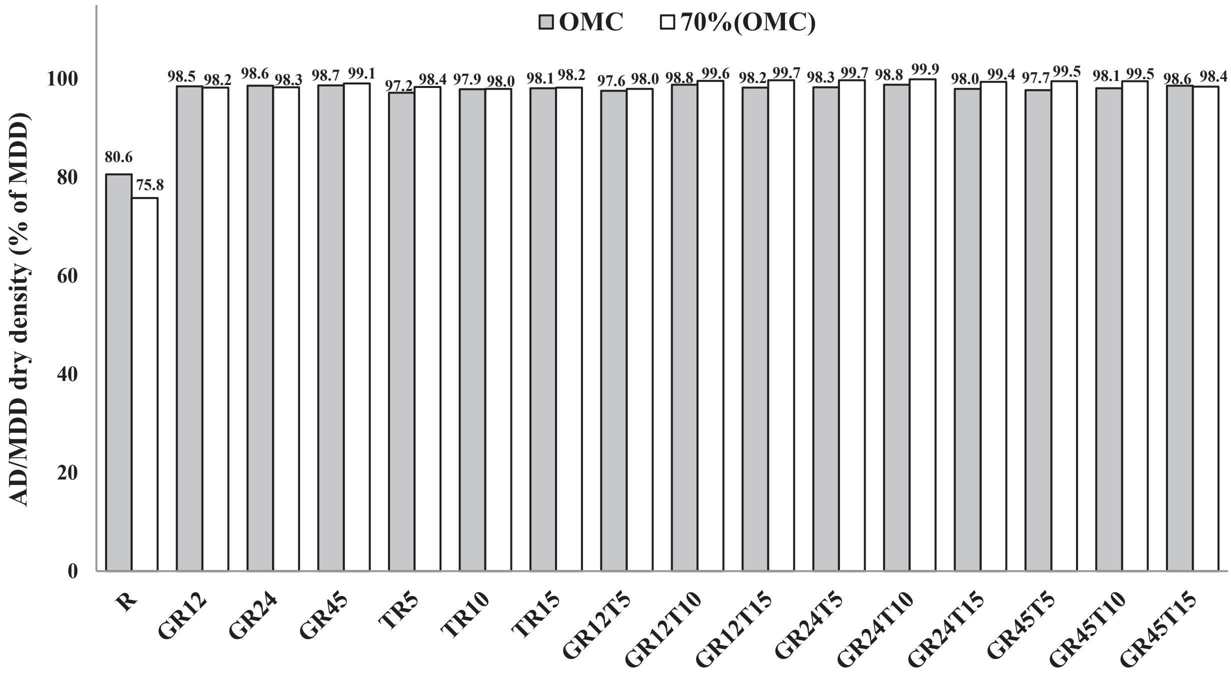


Figure 14: The ratio of dry density after RLTTs

8 CONCLUSIONS

The purpose of the current study was to determine the impacts of glass and tyre inclusion on the physical and dynamic behaviour of rock specimens. Laboratory tests included particle size distribution before and after compaction test, modified Proctor compaction test, and RLTT. The sieve analysis results show that the GR12, GR24, GR45, GR45T5, and GR24T5 specimens satisfied the crushed rock base material requirements. The observed increase in OMC was repeated on rock specimen as a result of G and T increase. The results also reveal that there has been a steady decline in MDD of rock caused by the glass increase, while a sharp reduction was found in MDD resulting from tyre increase.

At 100% of OMC, the GR group reported significantly less deformation than rock and TR groups. From the results of the analysis we can see that a negative correlation was found between permanent deformation and the glass ratio. On the other hand, a positive correlation was found between deformation and tyre inclusion. The mixing of glass and tyre exerts a powerful effect upon deformation through the reduction in deformation of rock and TR groups during RLTTs.

There is strong evidence that 70% of OMC may affect positively the deformation resistance of the GR group, while 5% of rubber caused an increase of 40% in the rock resistance against deformation. Moreover, the mixing of glass and tyre improved the performance of unbound material against permanent deformation by about 7-35 %.

At 100% of OMC, the GR group reported significantly more Mr than the rock specimen and the TR group. 12% to 45% of glass content can improve the Mr of the rock specimen by between 6.6 to 50%. On the other hand, there was a significant reduction in the Mr of the rock specimen as a result of tyre inclusion. The mixing of glass and TR groups exerted a powerful effect upon the GRT group through the increment of Mr under RLTTs. Reducing moisture content to 70% of OMC may have played a vital role in improving the resilient response of waste-rock mixtures.

In terms of evaluating the actual moisture content and the ability to achieve the ideal dry density of the specimens during and after the RLTTs, blended specimens became more able to achieve the optimum moisture content in both 100% of OMC and 70 % of OMC. At the same time, the group become more rigid by achieving the ideal moisture content condition.

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