



Review Article

Performance characteristics of recycled concrete aggregate as an unbound pavement material

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ABSTRACT

Use of recycled concrete aggregates (RCA) as a pavement material is one of the most sustainable engineering applications for the pavement industry. Investigation on the performance characteristics of RCA, such as elastic and plastic deformations of RCA is therefore, needed to assess RCA's application as an unbound pavement material. In this study, repeated load tri-axial (RLT) tests were conducted to investigate the response of RCA to elastic and plastic deformations under dynamic loads. The elastic and plastic properties were analysed through the 'resilient modulus' and the accumulation of plastic strain, respectively, at different confining stresses and moisture contents of the RCA specimens. The results from the tests revealed a steady gain of stiffness of the RCA specimens with an increase of load cycles at low moisture contents, high confining pressures and high vertical axial pressure.

1. Introduction

Aggregates from non-conventional material sources such as reclaimed glass, ash and fly ash, industrial slag, reclaimed asphalt and recycled concrete aggregates (RCA) are becoming very popular in the construction industry (Andrews and Rebbechi, 2009). Reuse of these materials helps address some of the current issues related to waste generation and mining of natural resources. Further benefits could be obtained by waste prevention, energy saving, conservation of natural mineral resources and avoiding of land filling (Ponte, 2016).

Production of RCA is a rapidly growing industry, since it has a much higher potential to be used as a construction material compared to many other recycled materials (Ismail and Ramli, 2013; Huang et al., 2007; Oikonomou, 2005). Utilization of RCA in granular layers in flexible pavements is a viable alternative since roads typically demand a huge volume of crushed aggregates (Recycling, 2004). The subsurface layers of flexible pavements should be constructed with adequate stiffness to sustain the traffic load and efficiently spread the load to avoid any damage to the sub-grade. Therefore, the compacted RCA should be demonstrated to have an adequate strength and stiffness as a subsurface pavement material and needs to be examined through its performance characteristics.

RCA have been subjected to many research studies to investigate their properties and ascertain their applicability as pavement materials over the past years (Jayakody et al., 2014; Gobieanandh and Jayakody, 2016). Many studies revealed that the strength properties of RCA were comparable to those of the conventional pavement aggregates even with constituents, such as asphalt, bricks and glass (Jayakody et al., 2017; Arulrajah et al., 2014). Further investigations on RCA are needed to determine their performance characteristics under repetitive loads since only a few research findings are available on this topic. The performance characteristics of RCA depend on the constituents and the quality of the parent concretes, and thus, can be examined by their response to elastic and plastic deformations under repetitive loads. The outcome of such a study is highly valuable in standardising RCA as an unbound pavement material and also in convincing the contractors of RCA's reliability.

Elastic property of a material under dynamic loads is reflected by its 'resilient modulus' which is used as a key parameter in pavement designing (Jameson and Group, 2008). Nataatmadja and Tan (2001) studied the elastic behaviour of RCA and emphasised the role of residual cement in the high resilient modulus of RCA. The physical properties of RCA, such as well-graded particle size distribution (Nataatmadja and Tan, 2001) and high compaction (Leite et al., 2011) have significantly contributed to its high resilient modulus. Arulrajah et al. (2012) further

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emphasised on the significance of compaction and observed the highest resilient modulus of RCA at a relative compaction of 98% based on the 'modified proctor compaction' method. [Gabr and Cameron \(2012\)](#) compared the resilient modulus of RCA with that of Quartzite aggregates and found a remarkable behaviour of RCA at a low moisture content which was 60% of the optimum moisture content (OMC). [Arulrajah et al. \(2013\)](#) further studied the influence of moisture on the resilient behaviour of RCA and showed that having high moisture content of about 75% of the OMC reduced the strength of RCA, possibly leading to their failure. Further studies by [Gabr and Cameron \(2012\)](#) and [Arshad and Ahmed \(2017\)](#) on RCA with alternative materials, such as reclaimed asphalt pavement (RAP) materials and clay fines have demonstrated high resilient properties which were comparable to those of high quality conventional pavement materials.

Determination of the plastic deformation characteristics of RCA helps estimate the rutting resistance when RCA are applied as unbound pavement materials. Rutting is one of the primary distress modes that diminish the performance of the unbound pavements ([Myers et al., 2005](#)). [Jr et al. \(1998\)](#) compared the plastic deformation of RCA with that of the RAP materials. Their results showed that RCA performed better than the RAP materials. Similar tests were carried out by [Bennert et al. \(2000\)](#) who further confirmed the above results. [Arulrajah et al. \(2012\)](#) observed that the strain gaining of compacted RCA specimens was at its minimum when the moisture content was 60% of the OMC. Further studies revealed that the presence of more residual cement in RCA adversely affected the formation of shrinkage cracks and reflective cracks in the compacted RCA specimens under loading ([Arulrajah et al., 2014](#)). [Gabr and Cameron \(2012\)](#) recorded lower plastic strain in the compacted RCA than in the conventional aggregates at low moisture contents. However, their study signified the role of well graded distribution of particle size in the range of standard specifications and high density after the compaction. On the other hand, [Arulrajah et al. \(2014\)](#) reported a greater plastic strain when more constituents were present, such as RAP materials in RCA.

Thus, further investigation on the performance characteristics of RCA is required to ascertain their behaviour in the base course and the sub-base course in pavements. Repeated load tri-axial (RLT) test is recognized as the preferred laboratory scale test to evaluate the performance of pavement materials through elastic and plastic deformation characteristics at different conditions of moisture content and stress with respect to repetitive loads. However, constitutive models are typically used to predict the non-linear resilient behaviour of granular materials since conducting the RLT test is not widely prevalent owing to its complexity, high cost and the time-required. Constitutive model equations available in literature were derived for particular materials. However, the application of such constitutive models could result in uncertainties for other materials owing to factors, such as the inconsistent behaviour of each material with its own constituents, differences in the inherent properties of each material source and simplification of the models (insufficient parameters). Therefore, it is necessary to validate the existing constitutive models for RCA. In this research, this was accomplished by conducting a comprehensive experimental program of RLT tests on RCA specimens. Resilient behaviour and plastic deformation characteristics were obtained from the RLT tests at different stress and moisture conditions and analysed to enhance the constitutive models, which were then used to estimate the resilient modulus of the RCA specimens, by taking their water content into account. The enhanced constitutive models were again validated by additional RLT tests and were used to estimate the resilient modulus of the RCA specimens under different stress and moisture conditions. In addition, the accumulation of plastic strain of the RCA specimens at different stress and moisture conditions was analysed in terms of "Shakedown concept" to assess the vulnerability of the compacted RCA by accumulating plastic deformation under repetitive loading.

2. Main text

2.1. Tests material

Commercially available RCA was employed in this experimental program. The RCA specimens were obtained from a leading concrete recycling company in Queensland, Australia and a representative sample is shown in [Fig. 1](#). The RCA samples were produced by crushing demolished concrete structures and separating out the attachable waste (such as bricks, glass, asphalt and wood) to avoid mixing. Therefore, the tested RCA samples were free from the constituents ([Alex Fraser Group, 2011](#)).

The particle size distribution (PSD), physical properties and strength properties of the RCA samples were determined and shown in [Fig. 2](#) and [Table 1](#) as a reference. These values were extracted from a previous research study by [Jayakody et al. \(2017\)](#) since the same lot of the RCA samples was used for this test program as well. The PSD of the RCA samples is plotted in [Fig. 2](#) along with the upper and lower boundaries of the PSDs of the base layer granular materials specified by the Department of transport and main roads in Queensland (QDTMR), Australia ([Main-Roads, 2010](#)). The PSD curve of the RCA samples shows that there were particles larger than 20 mm and smaller than 0.6 mm that did not conform to the standard specifications.

The physical properties of the RCA specimens in [Table 1](#) show that the 'Atterberg limits' of the samples were within the range of the standard specifications of high quality pavement materials as specified by QDTMR. However, the water absorption values of coarser and finer fractions of RCA specimens are high due to the presence of fines of cement mortar, bricks and tiles. The OMC was close to the upper margin of the high quality materials, while the maximum dry density (MDD) was below that of the high quality pavement material. This was due to the lack of coarser particles and high water absorption capacity of RCA compared to the standard granular pavement material. On the other hand, the California bearing ratio of the RCA samples reflected high strength that was greater than the minimum standard specifications of the base course material of high volume pavements.

2.2. Methodology

The elastic and the plastic deformation characteristics of the RCA specimens were determined by conducting a series of RLT tests on the compacted specimens at different moisture contents and stress conditions. The schematic of the RLT test apparatus is shown in [Fig. 3](#) which consisted of a cylindrical RCA specimen of 100 mm diameter and 200 mm height. The confining pressure was applied by pressurizing the air in the cell and it was continuously monitored by a transducer connected to the cell. The repeated vertical axial load was applied on top of the specimen by a pneumatic actuator which was connected to the vertical shaft. The maximum applicable load by the actuator was 12 kN with a



Fig. 1. Recycled concrete aggregate (RCA).

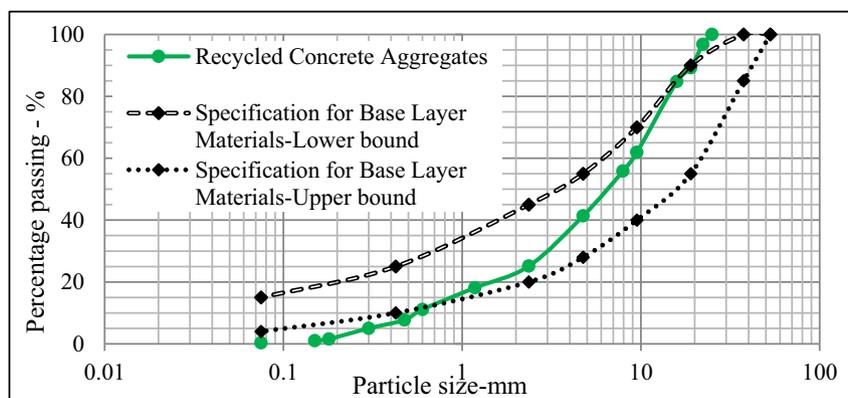


Fig. 2. PSD curves of the RCA samples with upper and lower limit curves of the standard base layer materials (Jayakody et al., 2017).

Table 1

Physical properties of RCA (Jayakody et al., 2017).

Property	Values	
	RCA	Standard granular pavement material
Liquid Limit (LL) [%]	21.00	Maximum: 25 (MainRoads, 2010)
Plasticity Index (PI) [%]	5.40	Maximum: 6 (MainRoads, 2010)
Linear Shrinkage (LS) [%]	1.00	Maximum: 3.5 (MainRoads, 2010)
Water absorption (particles <4.25 mm) [%]	7.35	<10 (Arulrajah et al., 2013)
Water absorption (particles >4.25 mm) [%]	6.50	<10 (Arulrajah et al., 2013)
Specific gravity (Gs)	2.64	2.85 (Vegas et al., 2008)
Maximum dry density (MDD) [g/cm ³]	1.75	>1.79 (Arulrajah et al., 2013)
Optimum moisture content (OMC) [%]	13.20	8-15 (Arulrajah et al., 2013)
California Bearing Ratio (4 days soaked) [%]	90-95	>80% (MainRoads, 2010)

maximum stroke of 30 mm. The vertical deformation of the specimen was calculated by averaging the measurements provided by two linear variable differential transformers (LVDTs) attached to the vertical shaft. Cell pressure transducers and the load cell were connected to a data logging system which collected the responses of the transducers at specified time intervals.

RLT tests were conducted according to the test method “Q137-Permanent deformation and resilient modulus of granular materials” of DTMR, Queensland (MainRoads, 2013). The RLT test programme is shown in Table 2. The tests were conducted for different confining pressures (σ_3) values, namely 25, 75, 125 and 175 kPa. Vertical stress (σ_1) was gradually increased to 300, 450, 600 and 750 kPa for a constant value of σ_3 in each test. σ_1 was changed after 10,000 load cycles. Thus, each RLT test was operated for 40,000 load cycles under a fixed constant σ_3 . Test specimens were prepared at four different water contents (w) and compacted to the MDD. The predetermined water contents were as per the corresponding degrees of saturation (DoS) — 60%, 68%, 75% and 80%. The 60% DoS represents the water content which is applied in the industry to compact the unbound granular pavement layers (Bodin et al., 2013). The 68% of DoS represents the OMC of RCA. DoS of 75% and 80% represent the water contents above the OMC of RCA.

2.2.1. Preparation of test specimens

Oven dried RCA samples were mixed with pre-determined water contents (i.e., 11.6, 13.2, 14.5 and 15.5 %) and left for 3 h to allow for the homogenization of the moisture (Jayakody et al., 2014). Then the samples were compacted to achieve an MDD of 1.75 g/cm³ in a split mould of 100 mm diameter and 200 mm height. The compacted samples were cured in sealed containers for four days to allow for strength gaining by

re-cementation (Gallage et al., 2014). The compacted specimens were then enclosed in a 0.8 mm thick rubber membrane and set in the RLT apparatus. The specimen was sealed at the top and the bottom and a predetermined σ_3 was applied and allowed to consolidate for about an hour, which was determined to be sufficient in the pre-tests.

2.2.2. Loading and data interpretation

The vertical axial load, σ_1 was repeatedly applied as a wave form on the consolidated sample under undrained conditions. Constant contact stress was applied (5% of σ_1) to ensure continuous and constant contact between the actuator piston and the top plate during the dynamic loading. Four different magnitudes of vertical stresses were applied — 300, 450, 600 and 750 kPa in each test under a constant confining pressure and each vertical load was run for 10,000 load cycles. Thus, each test specimen was subjected to 40,000 vertical axial repeated load cycles under a constant confining pressure.

The results of the RLT tests were analysed to estimate the plastic deformation characteristics and to enhance the chosen constitutive models to predict the resilient modulus of the RCA specimens. Three constitutive model equations were chosen from the literature and their model parameters were modified by non-linear regression analysis to develop a relationship between the resilient modulus and the variables, namely moisture content, mean stress and octahedral shear stress. Non-linear regression analysis was performed with the statistical software, MATLAB® version 7.1.

2.3. Results & discussion

The results of the RLT test series were analysed to enhance the constitutive models to predict the resilient modulus, taking w of the RCA specimens into account. The RLT test results were further analysed to estimate the accumulation of plastic strain of RCA at different values of w and stress conditions.

2.3.1. Resilient modulus of RCA

Fig. 4 presents the behaviour of the resilient moduli, M_r of the compacted RCA specimens as a function of load cycles at different values of w . M_r of the RCA specimens at each moisture level rapidly increased at the beginning of the load repetitions since the specimens were subjected to densification with initial vertical loadings. Conversely, the test results showed a reduction of M_r as w was increased. According to Thom and Brown (1987), water induces a lubricating effect on the particles when the moisture content is below the fully saturated condition in an aggregate assembly. Therefore, stiffness of the compacted material decreases due to the reduction of inter-particle bonds and consequently, M_r decreases with increasing moisture content. In our experiments, M_r of the compacted RCA specimens gradually increased with an increase of σ_1 and the number of repeated load cycles owing to the densification. However,

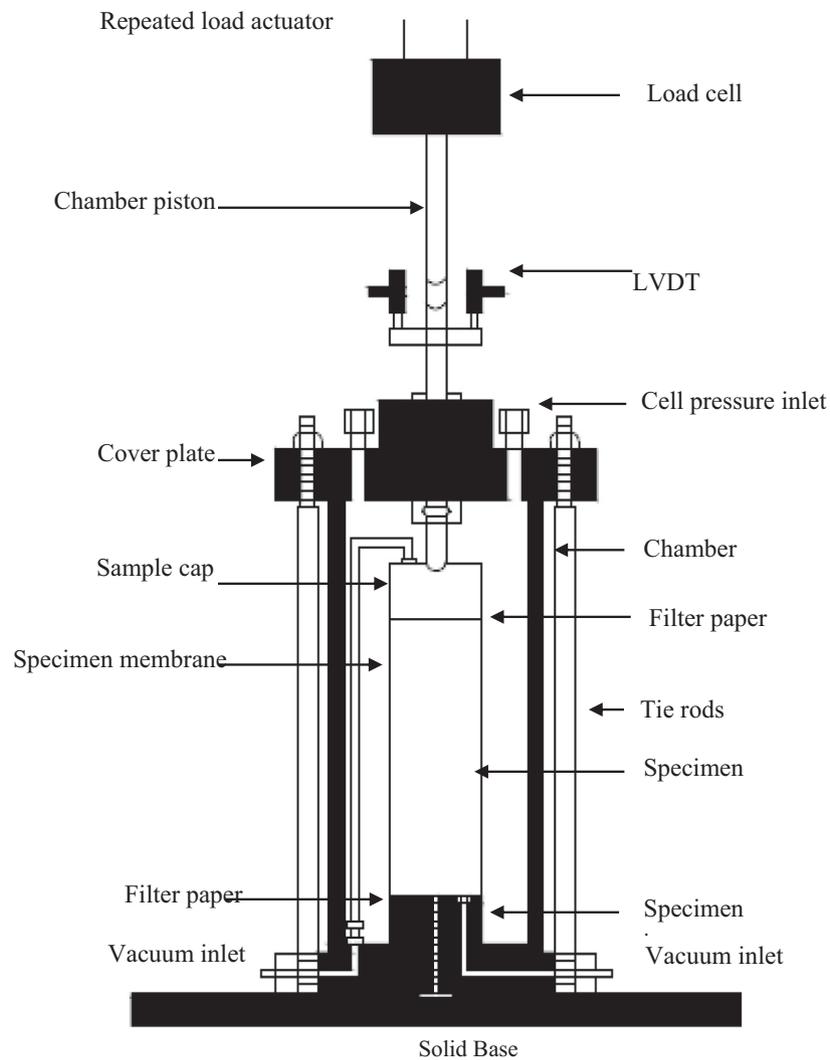


Fig. 3. Schematic of the RLT Chamber with a specimen.

Table 2
Summary of the RLT test programme.

Water content (<i>w</i> ; %)	Density (*MDD; g/cm ³)	*DoS (%)	Confining pressure (σ_3 ; kPa)	Vertical stress (σ_1 ; kPa)	Number of load cycles
11.62	1.75	60	25	300 450 600 750	10,000 for each vertical stress condition
			75		
			125		
			175		
13.2 (OMC)	1.75	68	25	300 450 600 750	
			75		
			125		
			175		
14.53	1.75	75	25	300 450 600 750	
			75		
			125		
			175		
15.5	1.75	80	25	300 450 600 750	
			75		
			125		
			175		

*DoS = Degree of saturation *MDD = Maximum dry density.

the rate of increase of M_r with the number of load repetitions gradually decreased, suggesting the onset of steady state conditions (i.e., no further change in M_r with loading cycles), which can be termed as “shakedown response” (Cerni et al., 2012). Once the samples achieved the

steady-state, neither plastic strain nor densification was accumulated in the material and M_r also attained a steady state due to the steadiness of the elastic deformation with the number of load cycles. Achieving the state of shakedown limit by the compacted RCA indicates the increase of

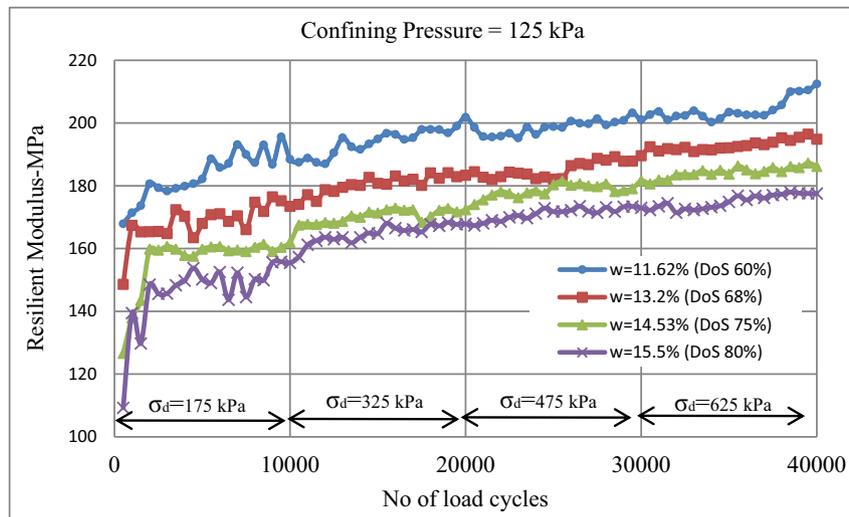


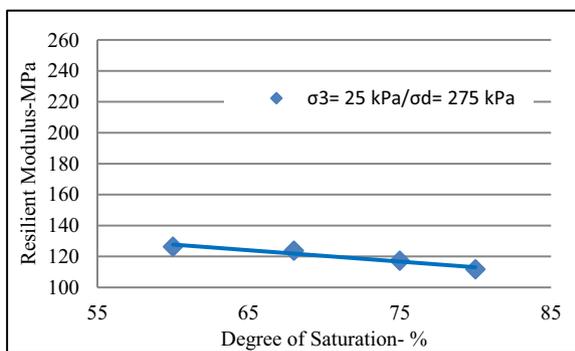
Fig. 4. Variation of M_r of the RCA specimens with number of load cycles at different amounts of w .

resistance to elastic deformation under continuous load repetitions similar to the case of high quality pavement materials which also show steadiness of M_r due to the increase of stiffness and approach the shakedown limit with an increase in the number of axial load cycles (Vuong and Hazell, 2003; Ekblad and Isacson, 2006). Achieving the shakedown limit with load repetitions reflects the stability of the stiffness of the compacted RCA and its ability to provide high quality unbound layers in the pavements.

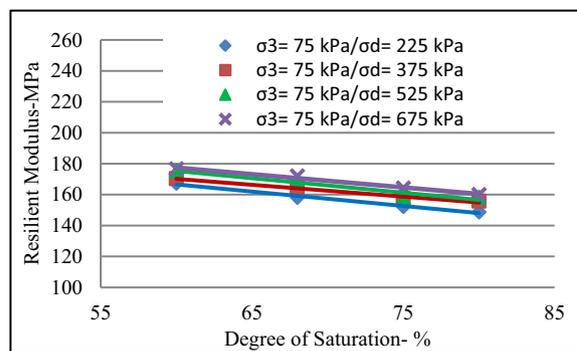
Fig. 5 shows the calculated M_r at different DoS and different stress conditions. The M_r values were obtained at the 10,000th load cycle corresponding to each deviator stress, $\sigma_d (= \sigma_1 - \sigma_3)$ at a constant σ_3 . The graphs illustrate the decrease of M_r with an increase in the DoS in the

compacted RCA specimens. Conversely, the M_r values slightly increased with an increase of the stress ratio, (σ_d/σ_3) and the bulk stress, $\theta (= \sigma_1 + \sigma_2 + \sigma_3)$.

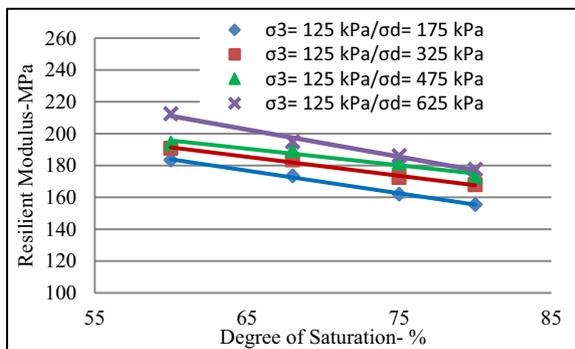
Water lubricates and reduces the frictional resistance between the particles, which in turn, caused a reduction of stiffness and M_r . Thus, the excess pore water pressure decreased the stiffness of the compacted RCA specimens and the best performance was achieved at the lowest moisture level, i.e., 60% DoS. However, the M_r values did not vary significantly as DoS varied from 60% to 80%. Water is more readily held in the pores of the cement mortar and crushed fines of RCA than in the conventional aggregates and the fines do not allow water to drain freely (Raad et al., 1992). This implies low sensitivity of the compacted RCA's resilient



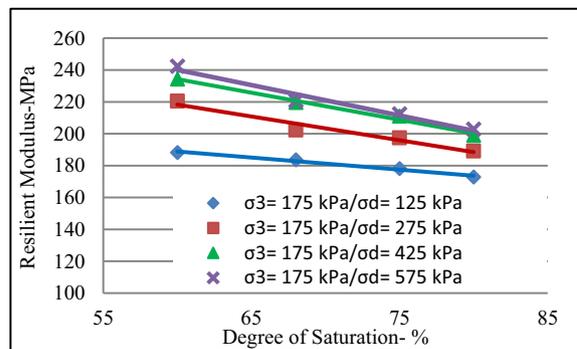
(a)



(b)



(c)



(d)

Fig. 5. M_r versus DoS of RCA at different vertical stresses and confining pressure (σ_3) of (a) 25 kPa, (b) 75kPa (c) 125 kPa (d) 175 kPa.

behaviour to moisture content.

Fig. 5a shows only one line graph for the variation of M_r at a σ_1 of 300 kPa ($\sigma_d = 275$ kPa), since the compacted RCA could not withstand σ_1 beyond 300 kPa under a low σ_3 of 25 kPa. The specimens failed when σ_1 was increased to 450 kPa where the stress ratio of the principal axial stress to the confining pressure (σ_1/σ_3) was as high as 12. The line graphs of Fig. 5b are very close which suggests that M_r increased only slightly even though σ_d was increased significantly at a constant σ_3 of 75 kPa. However, M_r decreased considerably with an increase of DoS. The plots in the figure reflect the poor response of the resilient deformation at low σ_3 even though σ_d was increased. It may be noticed that the four line graphs in Fig. 5c are scattered and more so in Fig. 5d, which represent 125 and 175 kPa of σ_3 , respectively. These plots depict the effect of σ_1 , which had more influence on M_r at high values of σ_3 (e.g., 125 and 175 kPa). Therefore, it can be concluded that RCA exhibited high M_r and high resistance to elastic deformation at high confining pressures much like the conventional granular materials (Rada and Witzczak, 1981). According to Maher et al. (2000), hardening of elastic strain can be expected due to the reorientation of the particles into a denser state. Therefore, the compacted specimens of RCA became stiffer with further load repetitions and this had the effect of gradually decreasing the resilient deformation and resulting in higher M_r .

RLT test was also performed on three types of high quality conventional aggregates under standard stress conditions and at 60% DoS. Their M_r values were 275, 290 and 450 MPa at the end of 50,000 load cycles (Jayakody, 2014) were greater than the M_r of the RCA specimens (which were in the range of 233–247 MPa at 60% DoS). Although, the tested RCA samples had lower M_r values than the high quality base layer materials, RCA exhibited a trend of continuously increasing M_r with more load cycles as shown in Fig. 4. Therefore, greater M_r could be predicted due to the continuous gaining of the stiffness of the compacted RCA.

2.3.1.1. Constitutive models for the M_r of RCA. Determination of the resilient characteristics of the pavement materials on a regular basis is not feasible since the RLT test facilities are not widely available. Therefore, constitutive models have been introduced by researchers (Seed et al., 1967; Witzczak and Uzan, 1988; Ooi et al., 2006) to predict the M_r of granular road materials. However, there is no such constitutive model available to estimate the M_r of RCA.

In this study, three constitutive model equations were selected from literature to be applied on RCA. These constitutive model equations have been developed based on conventional materials. Hence, modifications were required prior to their application on RCA for accurate estimation of the resilient properties under different stress and moisture conditions. The chosen equations are presented below as “Eqs. (1), (2), and (3)”. The model parameters (k_1 , k_2 , k_3) in these equations were modified based on the RLT test results (Hicks, 1970; Witzczak and Uzan, 1988; Main-Roads, 2009).

$$M_r = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \tag{1}$$

$$M_r = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} \right)^{k_3} \tag{2}$$

$$M_r = k_1 \left(\frac{\sigma_m}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} \right)^{k_3} \tag{3}$$

Where;

- M_r = Resilient Modulus,
- p_a = Atmospheric pressure (103.4 kPa),
- θ = Bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$),
- σ_m = Mean stress ($(\sigma_1 + \sigma_2 + \sigma_3)/3$),
- σ_1 = Principal axial stresses,

σ_3 = Confining pressure,
 σ_d = Deviator stress ($\sigma_1 - \sigma_3$),
 τ_{oct} = Octahedral shear stress = $\frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$,
 For the axisymmetric stress conditions in the RLT test “ $\sigma_2 = \sigma_3$ ” and “ $\sigma_1 - \sigma_3 = \sigma_d$ ”. Hence the octahedral shear stress is reduced to: $\tau_{oct} = \frac{\sqrt{2}}{3}(\sigma_d)$,
 k_1, k_2, k_3 are model parameters.

The extracted M_r values from the results of the RLT tests were analysed by non-linear regression analysis to develop correlations for the constitutive model parameters k_1, k_2 and k_3 in each equation. The obtained best fitting model curves derived the values for the k_1, k_2 and k_3 for different moisture contents of each equation and they are summarized in Table 3. Each constitutive model was multiplied by 10^3 to present the resilient modulus in “MPa”.

The obtained model parameters were then correlated with the moisture contents to define common expressions for the model parameters k_1, k_2 and k_3 in each constitutive model. The best fitting graphs for the model parameters in terms of “ k ” values versus moisture contents were drawn to correlate “ k ” with moisture content (w) and express it a function of water content. These correlations are shown below for Eqs. (1), (2), and (3) respectively with the corresponding R^2 values. The defined expressions of the model parameters in terms of w were successfully fitted to predict M_r of RCA.

Model parameters of Eq. (1) ($R^2 = 0.9611$ and 0.7 for k_1 and k_2 , respectively)

$$k_1 = (-0.0435) w + 1.3397$$

$$k_2 = (0.0088) w + 0.3009$$

Model parameters of Eq. (2) ($R^2 = 0.874, 0.944$ and 0.9983 for k_1, k_2 and k_3 , respectively)

$$k_1 = (0.0201) w^2 - (0.5517) w + 0.4008$$

$$k_2 = (-0.0216) w^2 + (0.5629) w - 3.1144$$

Table 3
 The k values in the three equations at different moisture contents.

For the Eq. (1), $M_r(\text{MPa}) = \left[k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \right] \times 10^3$							
DoS %	w %	k_1	Stand. Err	k_2	Stand. Err		
60	11.62	0.829	0.129	0.406	0.077		
68	13.20	0.782	0.108	0.408	0.068		
75	14.53	0.690	0.098	0.442	0.070		
80	15.50	0.673	0.129	0.431	0.095		
For the Eq. (2), $M_r(\text{MPa}) = \left[k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} \right)^{k_3} \right] \times 10^3$							
DoS %	w %	k_1	Stand. Err	k_2	Stand. Err	k_3	Stand. Err
60	11.62	0.695	0.123	0.520	0.097	-0.097	0.054
68	13.20	0.630	0.084	0.548	0.073	-0.118	0.041
75	14.53	0.601	0.101	0.531	0.092	-0.074	0.052
80	15.50	0.679	0.166	0.426	0.135	0.005	0.079
For the Eq. (3), $M_r(\text{MPa}) = \left[k_1 \left(\frac{\sigma_m}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} \right)^{k_3} \right] \times 10^3$							
DoS %	w %	k_1	Stand. Err	k_2	Stand. Err	k_3	Stand. Err
60	11.62	127.3	9.405	0.520	0.0966	-0.0969	0.0542
68	13.20	118.0	6.652	0.548	0.0729	-0.1175	0.0405
75	14.53	111.0	7.813	0.531	0.0917	-0.0739	0.0516
80	15.50	112.0	11.398	0.426	0.1348	-0.0052	0.0791

*w% = Moisture content in percentage (%).

$$k_3 = (0.0177) w^2 - (0.4531) w + 2.7834$$

Model parameters of Eq. (3) ($R^2 = 0.9807, 0.9437$ and 0.99 for k_1, k_2 and k_3 , respectively)

$$k_1 = (1.1099) w^2 - (34.264) w + 375.87$$

$$k_2 = (-0.0216) w^2 + (0.5639) w - 3.1221$$

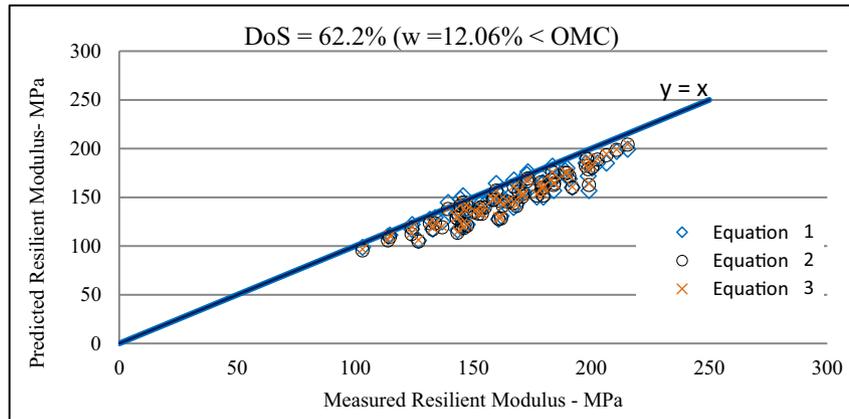
$$k_3 = (0.016) w^2 - (0.4111) w + 2.5162$$

Where

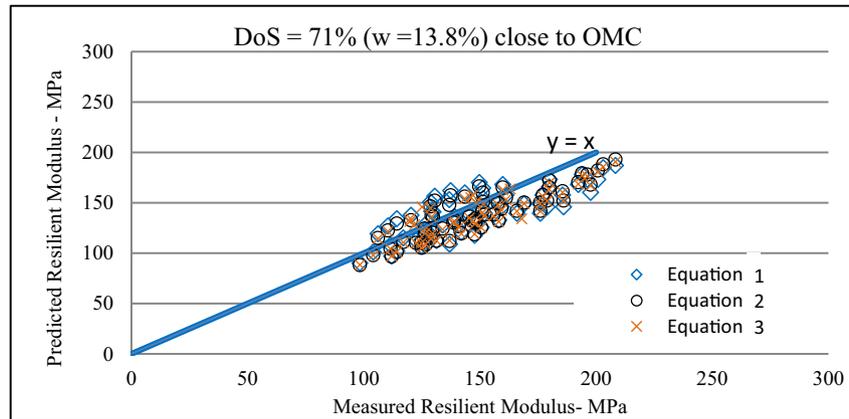
w = Moisture content in percentage (%).

k_1, k_2 and k_3 = Model parameters.

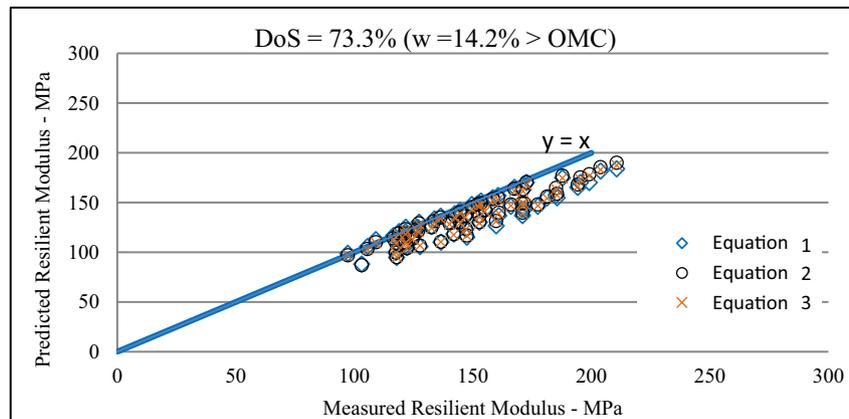
2.3.1.2. Validation of the model parameters. The enhanced constitutive models were validated by conducting additional RLT tests according to the standard method of Austroad APRG 00/33-2000 (Young and Brimble, 2000), at three different values of w that correspond to DoS of 62.2%, 71% and 73.3%. The w values of the validated samples were chosen both below and above the OMC of RCA. Fig. 6a–c presents the comparison of the laboratory measured M_r with the predicted M_r values by the



(a)



(b)



(c)

Fig. 6. Measured versus predicted M_r of RCA at different values of DoS: (a) 62.2%, (b) 71%, (c) 73.3%.

enhanced constitutive models at the three values of w . It was assumed that the laboratory measured M_r values represented the true M_r of the tested RCA. Three graphs illustrate a close fit of the measured and the predicted M_r values. Therefore, the defined constitutive model parameters of Eqs. 1, 2, and 3 are recommended to estimate the M_r of RCA taking w into account. It is important to highlight that the w values have been defined in the range of 60%–80% DoS, which represents the critical moisture variation in the real world.

Furthermore, the predicted M_r values from the three equations did not show significant deviations from one other and were comparable even though Eq. (1) considered only the bulk stress, while Eqs. (2) and (3) accounted for an additional variable — “octahedral shear stress”. However, it was found that the significance of the component of octahedral shear stress was minimal in predicting the M_r .

The predicted and measured M_r values showed minor deviations with an increase of w from below the OMC (62.2% of DoS) to above the OMC (73.3% of DoS) of the compacted RCA. The elastic deformation of RCA was not significantly affected even at a high moisture content (73.3% DoS). The softening effect of the compacted RCA specimens at high moisture levels, over the OMC was apparently low due to the high absorption properties of the fines and conglomerate cement mortar. The steady resilient behaviour of the compacted RCA at high moisture levels emphasizes its high stiffness even if the water table rises when RCA is used in the flexible pavement layers.

2.3.2. Plastic deformation of RCA

Accumulation of vertical plastic strain of the compacted RCA specimens with number of load cycles is shown in Fig. 7. This figure illustrates the effect of w and σ_d on the accumulation of the plastic strain at a constant σ_3 of 125 kPa.

The figure illustrates the increase of plastic strain with number of load cycles at various values of w . The higher the w , the higher the accumulated plastic strain was. Conversely, the rate of increase of plastic strain (plastic strain per loading cycle) diminished as the number of load cycles increased at a constant σ_d and σ_3 . The curves show a tendency towards attaining a steady-state of plastic response (i.e., no accumulation of plastic strain and each response is hysteretic) at the end of the 10000 load cycle range, especially, at the low values of σ_d i.e., 175 and 325 kPa. However, the shapes of the strain curves at high σ_d , i.e., 475, 625 kPa, also illustrate a decrease of accumulation of the plastic strain and a tendency to attain a steady state of plastic response with more load cycles beyond 10000. This implies high potential of energy absorption by RCA on each stress-strain excursion and its ability to withstand after gaining minor permanent deformations. Diminishing the plastic strain in RCA with the number of load cycles implies a state of “plastic shakedown

limit” (Cerni et al., 2012). High quality pavement materials indicate the hardening of the plastic strain after certain number of load cycles and deform only elastically thereafter (Werkmeister et al., 2001). Behaviour of the plastic strain of RCA depicts its approach to the region of plastic shakedown limit which establishes its high capacity for load bearing with the least permanent deformation and its suitability as a high quality granular pavement material.

The strain curves show the rise of plastic deformation with increasing w and the principal stress ratio (σ_d/σ_3). However, the magnitudes of the accumulated plastic strains were not much greater even when the moisture content increased in RCA. This is in contrast to many conventional pavement materials which exhibit a dramatic increase in plastic strain even with a relatively small increase in the water content (Thom and Brown, 1987). Excess water in the compacted specimens caused lubrication of the particle surfaces and facilitated their movement into air-voids, which consequently, lowered the stiffness and eventually increased the accumulation of plastic strain. Furthermore, the combined effect of high degree of saturation and low permeability resulted in high pore pressure due to the poor drainage of the compacted RCA specimens. The Excessive pore pressure reduced the effective stress and consequently, decreased the shear strength of the interlocked particles. However, the presence of adequate amount of moisture which was below the OMC of the RCA positively affected the strength and stiffness of the compacted RCA specimens, and lowered the accumulation of plastic deformation. On the other hand, RCA specimens did not collapse under repetitive loads even though the accumulated vertical strains were high at the moisture contents above the OMC. It is a significant performance characteristic of RCA which demonstrates high resistance against plastic deformation at high water contents without collapse.

Effects of σ_3 on the accumulation of permanent strain of the compacted RCA specimens at OMC are shown in Fig. 8. The figure illustrates high plastic deformation at low values of σ_3 and low deformation at the high values of σ_3 with increasing number of load cycles. Conversely, accumulation of plastic strain was increased with the increase of σ_1 .

The rate of accumulation of plastic strain of the compacted RCA specimens approached zero at the end of the first 10,000 load cycles, although the σ_3 values were not similar in each sample. However, the RCA specimens failed to carry the load, when σ_1 was increased to 450 kPa at a σ_3 value of 25 kPa, which signified the inability to carry a high load under low σ_3 . The accumulation of strain at the second stage of 10,000 load cycles also illustrated similar behaviour as the first stage for σ_3 values of 75, 125, and 175 kPa, when σ_1 was 450 kPa. The specimens exhibited the plastic shakedown limit (rate of strain accumulation decreases with number of cycles) under high σ_3 values of 125 and 175 kPa when σ_1 was 600 kPa at the third set of 10,000 load cycles. However, the

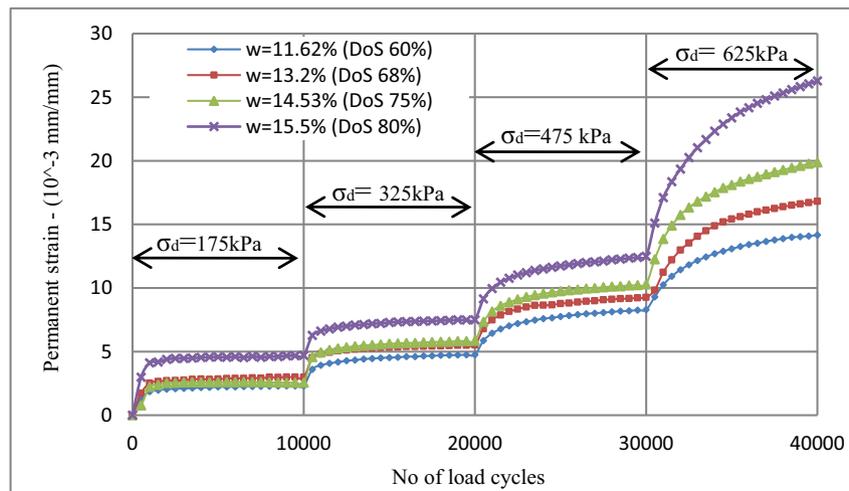


Fig. 7. Accumulation of vertical plastic strain of RCA with number of load cycles at a σ_3 of 125 kPa.

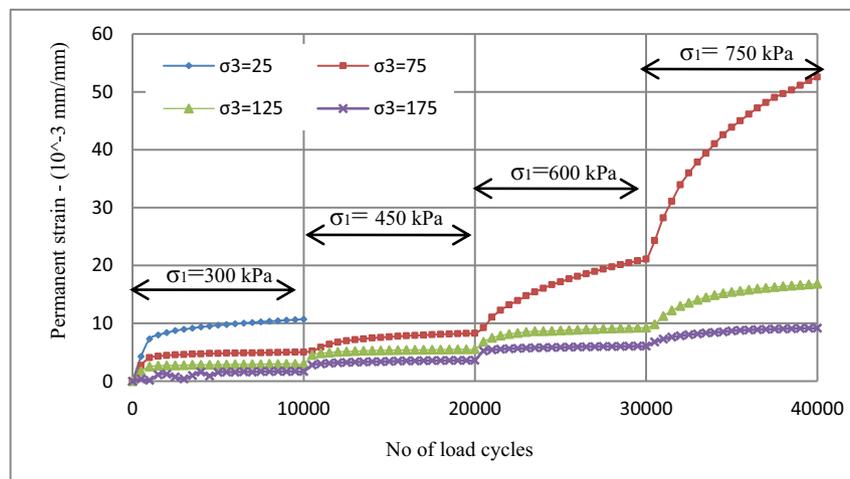


Fig. 8. Permanent strain of the compacted RCA at different value of σ_3 and at OMC = 13.2%

behaviour of plastic strain accumulation at $\sigma_1 = 75$ kPa has deviated away the other two curves and it continued the accumulation of plastic strain at high σ_1 values of 600 kPa and 750 kPa. The strain curve of corresponding to $\sigma_3 = 125$ kPa gained slightly more deformation than that for $\sigma_3 = 175$ kPa under $\sigma_1 = 750$ kPa at the last set of 10,000 load cycles. However, both curves illustrated gradual hysteresis in their strain gaining which suggested a behaviour of accumulation of plastic deformation within the plastic shakedown limit (Cerni et al., 2012).

The resultant plastic strain curves illustrate minor influence of σ_1 on the accumulation of plastic deformation of compacted RCA specimens at the OMC at high σ_3 values. The rate of deformation also decreased with increasing number of load cycles and approached zero when the stress ratio, σ_1/σ_3 was low.

3. Conclusions

The performance characteristics of RCA were investigated by conducting a series of RLT tests under different moisture and stress conditions and the following conclusions were drawn from this study:

- Moisture sensitivity on the resilient behaviour of the compacted RCA was low at high moisture contents (in the range of 60%–80% of DoS). Therefore, resilient modulus of RCA did not significantly vary within the range of moisture content which was below and above the OMC of RCA.
- Densification effect, which increases the resilient modulus of the compacted RCA, was significantly influenced by the increase of load cycles. Similarly, the principal axial stress at high confining pressures resulted in the decrease of the accumulation of the elastic strain and consequently, increased the resilient modulus of the compacted RCA specimens. Thus, the resilient modulus increased with the increase of confining pressure along the constant principal axial stresses.
- Increase of the stiffness of the compacted RCA was revealed by the plots of resilient modulus with continuous load cycles. Therefore, high resilient modulus can be predicted with more load cycles, even though the compacted RCA samples exhibited lower resilient modulus values (with 233–247 MPa at 60% of DoS) than high quality base layer materials (with 275–450 MPa).
- The close fit of the measured and the predicted resilient modulus values established that the enhanced correlation parameters of the chosen constitutive models (Eqs. (1), (2), and (3)) were successfully fitted for the prediction of the resilient modulus of the RCA by taking the moisture content and stresses into the account.
- Accumulation of plastic strain was not significantly affected by high moisture content over the OMC of the compacted RCA which revealed low sensitivity of the shear strength of the compacted RCA to

moisture. Conversely, the effect of the principal stress was dominant on the accumulation of plastic strain of RCA at low confining pressures.

- Accumulation of plastic deformation of RCA approached the range of “plastic shakedown limit” due to the hardening of the plastic strain with the increase of the load cycles. This is similar to the high quality pavement materials, which also undergo hardening of the plastic strain after a certain number of load cycles and then deform only elastically thereafter. However, very low confining pressures, i.e., below 75 kPa adversely affected the accumulation of plastic deformation and resulted in a behaviour that is seen above the plastic shakedown limit.

Declarations

Author contribution statement

Shiran Jayakody: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Chaminda Gallage: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jothi Ramanujam: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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