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
emphasized 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, 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.

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
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–Permanence 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 ($\sigma_3$) values, namely 25, 75, 125 and 175 kPa. Vertical stress ($\sigma_1$) was gradually increased to 300, 450, 600 and 750 kPa for a constant value of $\sigma_3$ in each test. $\sigma_1$ was changed after 10,000 load cycles. Thus, each RLT test was operated for 40,000 load cycles under a fixed constant $\sigma_1$. 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/cm$^3$ 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 $\sigma_1$ 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, $\sigma_1$ was repeatedly applied as a wave form on the consolidated sample under undrained conditions. Constant contact stress was applied (5% of $\sigma_1$) 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 $\sigma_1$ and the number of repeated load cycles owing to the densification. However,

Table 1

| Property                             | Values                                                                 |
|--------------------------------------|------------------------------------------------------------------------|
| 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) | <10 (Arulrajah et al., 2013)                                           |
| Water absorption (particles >4.25 mm) | <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)                                         |

Fig. 2. PSD curves of the RCA samples with upper and lower limit curves of the standard base layer materials (Jayakody et al., 2017).
the rate of increase of Mr with the number of load repetitions gradually decreased, suggesting the onset of steady state conditions (i.e., no further change in Mr 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 Mr 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

**Table 2**
Summary of the RLT test programme.

| Water content (w, %) | Density (*MDD; g/cm³) | *DoS (%) | Confining pressure (σ3; kPa) | Vertical stress (σ1; kPa) | Number of load cycles |
|---------------------|-----------------------|----------|-----------------------------|--------------------------|----------------------|
| 11.62               | 1.75                  | 60       | 25                          | 300 450 600 750          | 10,000 for each vertical stress condition |
| 13.2 (OMC)          | 1.75                  | 68       | 25                          | 300 450 600 750          |                      |
| 14.53               | 1.75                  | 75       | 25                          | 300 450 600 750          |                      |
| 15.5                | 1.75                  | 80       | 25                          | 300 450 600 750          |                      |

*DoS = Degree of saturation *MDD = Maximum dry density.
resistance to elastic deformation under continuous load repetitions similar to the case of high quality pavement materials which also show steadiness of Mr 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 Isacsson, 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 Mr at different DoS and different stress conditions. The Mr values were obtained at the 10,000th load cycle corresponding to each deviator stress, $\sigma_d = \sigma_1 - \sigma_3$ at a constant $\sigma_3$. The graphs illustrate the decrease of Mr with an increase in the DoS in the compacted RCA specimens. Conversely, the Mr values slightly increased with an increase of the stress ratio, $(\sigma_d/\sigma_3)$ 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 Mr. 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 Mr 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
behave to moisture content.

Fig. 5a shows only one line graph for the variation of Mr at a σf of 300 kPa (σg = 275 kPa), since the compacted RCA could not withstand σf beyond 300 kPa under a low σg of 25 kPa. The specimens failed when σf was increased to 450 kPa where the stress ratio of the principal axial stress to the confining pressure (σf/σg) was as high as 12. The line graphs of Fig. 5b are very close which suggests that Mr increased only slightly even though σg was increased significantly at a constant σf of 75 kPa. However, Mr decreased considerably with an increase of DoS. The plots in the figure reflect the poor response of the resilient deformation at low σf eventhough σg 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 σf, respectively. These plots depict the effect of σf, which had more influence on Mr at high values of σg (e.g., 125 and 175 kPa). Therefore, it can be concluded that RCA exhibited high Mr and high resistance to elastic deformation at high confining pressures much like the conventional granular materials (Rada and Witczak, 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 Mr.

RLT test was also performed on three types of high quality conventional aggregates under standard stress conditions and at 60% DoS. Their Mr values were 275, 290 and 450 MPa at the end of 50,000 load cycles (Jayakody, 2014) were greater than the Mr of the RCA specimens (which had more in granular road materials). However, there is no such constitutive model to predict Mr of RCA.

2.3.1.1. Constitutive models for the Mr 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; Witczak and Uzan, 1988; Ooi et al., 2006) to predict the Mr of granular road materials. However, there is no such constitutive model available to estimate the Mr 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 (k1, k2, k3) in these equations were modified based on the RLT test results (Hicks, 1970; Witczak and Uzan, 1988; Main-Roads, 2009).

\[
M_r = k_1 p_\text{atm} \left( \frac{\theta}{p_\text{atm}} \right)^{k_3} \quad (1)
\]

\[
M_r = k_2 p_\text{atm} \left( \frac{\sigma_\text{norm}}{p_\text{atm}} \right)^{k_3} \quad (2)
\]

\[
M_r = k_3 \left( \frac{\sigma_\text{norm}}{p_\text{atm}} \right)^{k_3} \quad (3)
\]

Where;

- Mr = Resilient Modulus
- \( p_\text{atm} \) = Atmospheric pressure (103.4 kPa),
- \( \theta \) = Bulk stress (σf + σs + σf),
- \( \sigma_\text{norm} \) = Mean stress ((σf + σs + σf)/3),
- \( \sigma_f \) = Principal axial stresses,

\( \sigma_3 \) = Confining pressure,
\( \sigma_d \) = Deviator stress (σf - σ3),
\( \tau_{oct} = \frac{1}{2} \text{Octahedral shear stress} = \frac{1}{\sqrt{3}} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)^{1/2} \) for the axisymmetric stress conditions in the RLT test and \( \sigma_2 = \sigma_3 \) and \( \sigma_1 = \sigma_3 \). Hence the octahedral shear stress is reduced to: \( \tau_{oct} = \frac{1}{\sqrt{2}} (\sigma_3) \).

k1, k2, k3 are model parameters.

The extracted Mr values from the results of the RLT tests were analysed by non-linear regression analysis to develop correlations for the constitutive model parameters k1, k2 and k3 in each equation. The obtained best fitting model curves derived the values for the k1, k2 and k3 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 k1, k2 and k3 in each constitutive model. The best fitting graphs for the model parameters in terms of “w” values versus moisture contents were drawn to correlate “w” with moisture content (w) and express it as a function of water content. These correlations are shown below for Eqs. (1), (2), and (3) respectively with the corresponding R² values. The defined expressions of the model parameters in terms of w were successfully fitted to predict Mr of RCA.

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

| DoS % | w % | k1 | Standard. Err | k2 | Standard. Err | k3 | Standard. Err |
|-------|-----|----|---------------|----|---------------|----|---------------|
| 60    | 11.62 | 0.829 | 0.129 | 0.406 | 0.077 | 0.016 | 0.037 |
| 68    | 13.20 | 0.782 | 0.148 | 0.408 | 0.068 | 0.021 | 0.050 |
| 75    | 14.53 | 0.690 | 0.098 | 0.442 | 0.070 | 0.006 | 0.012 |
| 80    | 15.50 | 0.673 | 0.129 | 0.431 | 0.095 | 0.012 | 0.017 |

For the Eq. (1), Mr (MPa) = \( k_1 p_\text{atm} \left( \frac{\sigma_\text{norm}}{p_\text{atm}} \right)^{k_3} \) \times 10^3

| DoS % | w % | k1 | Standard. Err | k2 | Standard. Err | k3 | Standard. 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. (2), Mr (MPa) = \( k_2 p_\text{atm} \left( \frac{\tau_{oct}}{p_\text{atm}} \right)^{k_3} \) \times 10^3

| DoS % | w % | k1 | Standard. Err | k2 | Standard. Err | k3 | Standard. 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 |

\(^{a}\text{w} = \text{Moisture content in percentage (%)}.\)
$k_1 = (0.0177) w^2 - (0.4531) w + 2.7834$

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

**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 Mr values represented the true Mr of the tested RCA. Three graphs illustrate a close fit of the measured and the predicted Mr values. Therefore, the defined constitutive model parameters of Eqs. 1, 2, and 3 are recommended to estimate the Mr 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 Mr values from the three equations did not show significant deviations from one another 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 Mr.

The predicted and measured Mr 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 σd on the accumulation of the plastic strain at a constant σ3 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 σd and σ3. 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 σ3 i.e., 175 and 325 kPa. However, the shapes of the strain curves at high σ3 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 (Werkeimer 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 (σd/σ3). 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 σ3 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 σ3 and low deformation at the high values of σ3 with increasing number of load cycles. Conversely, accumulation of plastic strain was increased with the increase of σ1.

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 σ3 values were not similar in each sample. However, the RCA specimens failed to carry the load, when σ1 was increased to 450 kPa at a σ3 value of 25 kPa, which signified the inability to carry a high load under low σ3. The accumulation of strain at the second stage of 10,000 load cycles also illustrated similar behaviour as the first stage for σ3 values of 75, 125, and 175 kPa, when σ1 was 450 kPa. The specimens exhibited the plastic shakedown limit (rate of strain accumulation decreases with number of cycles) under high σ3 values of 125 and 175 kPa when σ1 was 600 kPa at the third set of 10,000 load cycles. However, the
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 $\sigma_1$ values of 600 kPa and 750 kPa. The strain curve of corresponding to $\sigma_3$ of 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 $\sigma_1$ on the accumulation of plastic deformation of compacted RCA specimens at the OMC at high $\sigma_3$ values. The rate of deformation also decreased with increasing number of load cycles and approached zero when the stress ratio, $\sigma_1/\sigma_3$ 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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References
Alex Fraser Group, 2011. True and Practical Sustainability [Online]. Available: http://www.alexfraser.com.au/alex_frazer_2_read-only.pdf. Accessed 2014.
Andrews, B., Rebbechi, J., 2009. Guide to Pavement Technology 4E: Recycled Materials. Austroads Incorporated, Australia.
Arshad, M., Ahmed, M.F., 2014. Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pavements. Constr. Build. Mater. 83–97.
Arulrajah, A., Pirathiepan, J., Ali, M.M.Y., Bo, M.W., 2012. Geotechnical properties of recycled concrete aggregate in pavement sub-base applications. Geotech. Test. J. 35.
Arulrajah, A., Pirathiepan, J., Dishimi, M.M., 2014. Reclaimed asphalt pavement and recycled concrete aggregate blends in pavement subbases: laboratory and field evaluation. J. Mater. Civ. Eng. 26.
Arulrajah, A., Pirathiepan, J., Dishimi, M.M., Bo, M.W., 2013. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. J. Mater. Civ. Eng. 25, 1077–1088.
Bennett, T., Papp, W.J., Maher, A., Gucunski, N., 2000. Utilization of construction and demolition debris under traffic-type loading in base and subbase applications. Tranzp. Res. Rec. 33–39.
Bodin, D., Moffatt, M., Jameson, G., Group, A., 2013. Development of a Wheel-Tracking Test for Rut Resistance Characterisation of Unbound Granular Materials. Austroads Technical Report. Austroads Ltd, Sydney, NSW, Australia.
Cerni, G., Candoni, F., Virigli, A., Camilli, S., 2012. Characterisation of permanent deformation behaviour of unbound granular materials under repeated triaxial loading. Constr. Build. Mater. 28, 79–87.
Ekblad, J., Isacsson, U., 2006. Influence of water on resilient properties of coarse granular materials. Road Mater. Pavement Des. 7, 369–404.
Gabr, A.R., Cameron, D.A., 2012. Properties of recycled concrete aggregate for unbound pavement construction. J. Mater. Civ. Eng., American Society of Civil Engineers 24.
Gallage, C., Jayakody, S., Ramasujam, J., 2014. Effects of moisture content on resilient properties of recycled concrete aggregates (RCAs). In: Hossain, Z., Shiau, J. (Eds.), Construction Materials & Environment, 2014 Brisbane, Australia. The GEOMATE International Society, pp. 394–399.
Gobianandh, V., Jayakody, S., 2016. Evaluate the Strength of Cement Treated Recycled Concrete Aggregates as Granular Materials for Unbound pavements. Doctor of Philosophy, Queensland University of Technology, Australia. https://eprints.qut.edu.au/78131/.
Jayakody, S., 2014. Investigation on Characteristics and Performance of Recycled concrete Aggregates as Granular Materials for Unbound pavements. Doctor of Philosophy, Queensland University of Technology, Australia. https://eprints.qut.edu.au/78131/.
Jayakody, S., Gallage, C., Kumar, A., 2014. Assessment of recycled concrete aggregates as a pavement material. Geomechanics and Engineering. Int. J. 6, 235–248.
Jayakody, S., Gallage, C., Ramasujam, J., 2017. Effects of reclaimed asphalt materials on geotechnical characteristics of recycled concrete aggregates as a pavement material. Road Mater. Pavement Des. 1–19.
