Stiffness and strength characteristics of demolition wastes, glass and plastics i...

Stiffness and Strength Characteristics of Demolition Wastes, Glass and Plastics in Railway Capping Layers

Abstract

Increased generation of demolition waste has led to their successful implementation in civil engineering projects. Combination of recycled aggregates with supplementary materials can potentially improve the quality of geomaterials when constructing alternative railway capping layers. In this research, two types of demolition wastes, namely Recycled Crushed Aggregates (RCA) and Crushed Brick (CB) were studied in comparison with two Conventional Capping Materials (CCMs), which are currently used for railway track construction. Recycled Glass (RG) and Mixed Recovered Plastic (MRP) were also blended with RCA to assess their performance. All the materials and mixtures were evaluated in terms of both stiffness and strength. A new Repeated Load (RLT) triaxial testing protocol was introduced based on the induced stress in capping layer to determine the materials' stiffness. A comparison was made between the current resilient modulus prediction models to find a model better fits the results of demolition wastes and mixtures. Multistage triaxial test was also conducted to determine the strength, friction, stiffness and energy absorption capacity of materials. It was found from this research study that RCA, CB and mixtures of RCA with RG and MRP had equivalent or higher stiffness and strength than CCMs and are suitable alternatives for sustainable railway capping layer construction.

Keywords: Demolition waste; Recovered plastic; Railway capping layer; Sustainable subballast; Resilient modulus; Multistage triaxial test

1. Introduction

The usage of Construction and Demolition (C&D) wastes in civil engineering projects has become popular for the industrial sectors. This is predominantly due to the extensive pressure on natural resources, the increasing generation of C&D materials, their successful implementation in civil engineering projects, high disposal costs of landfilling, and enhancing environmental sustainability (Vieira and Pereira, 2015).

In Australia, the C&D waste generation increased by 20. 7% from 2007 to 2017 and formed a significant 30% of the waste stream produced in 2016-17 (Pickin et al., 2018). While the recycling rate increased from 60 to 67%, it is still lower than target recovery rate of 80-90% set by Australian states' authorities (Pickin et al., 2018). Recycled Concrete Aggregate (RCA) and Crushed Brick (CB) in particular, comprise more than 50% of C&D waste stored annually in Australia (Arulrajah et al., 2013). In addition, 1. 1 and 2. 5 million tons of glass and plastic waste were produced in Australia in 2017-18 respectively, which is approximately 8% and 18% of total generated municipal solid waste (Pickin et al., 2018). In the last decade, glass and plastic waste had a relatively stable recycling rate of around 57% and 12% in Australia respectively (Pickin et al., 2018). Plastic had the lowest recycling rate in all the key waste materials with almost all the rest of it was stockpiled in landfill (Pickin et al., 2018).

Extensive research has been conducted on RCA and CB, to determine their performance as road base/subbase layer and it was generally found that they can meet the requirements of pavement base/subbase layers (Vieira and Pereira, 2015). Previous studies also showed that Recycled Glass (RG) and recycled plastic, including LDPE and HDPE can be used reliably as additives in combination with other C&D materials in road construction (Arulrajah et al., 2014; Yaghoubi et al., 2017). Also, considering the importance of capping (also known as subballast) layer in reducing the generated train's load at the bottom of the ballast layer to a bearable threshold for the top of subgrade (Selig and Waters, 1994), some alternative materials including mixture of coarse aggregates with shredded waste tire rubber (Signes et al., 2015) and blend of coal wash, steel furnace slag and rubber crumb (Indraratna et al., 2018; Qi et al., 2018) have been introduced recently.

Earlier track foundation design methods for determining granular layers thickness do not consider the resilient modulus, M_r, of the granular layers (Li et al., 2016), however, more robust design methods are also introduced by Li and Selig (1998) and Indraratna and Ngo (2018). According to Li et al. (2016) and Indraratna and Ngo (2018), neglecting the different properties of individual layers will often result in inaccurate estimations of induced stresses in the subgrade, which subsequently influence the overall performance of the railway track significantly. Particularly, the most important factors governing track performance and induced stress on the subgrade are the M_r and thickness of ballast and subballast layer (Li and Selig, 1998; Li et al., 2016; Sayeed and Shahin, 2017). Shahu et al. (1999) and Smith et al. (2006) also reported that the M_r of subballast can have a major effect of induced vertical and horizontal stresses at the ballast-subballast interface. Although Repeated Load Triaxial (RLT) testing protocols have been used successfully for determining the M_r of pavement materials

(Arulrajah et al., 2013; Gu et al., 2015), no testing method has been introduced to date for determining the resilient response of capping materials under the induced loading of the train.

Sustainable utilization of C&D aggregates in railway track substructure has not been investigated, despite their successful implementation in pavement constructions. Although the conventional aggregates perform satisfactory in capping layer construction, there are limited regulations for designing these layers. In this research, the performance of alternative geomaterials was compared to the behavior of two types of Conventional Capping Materials (CCMs). Moreover, limited studies on the mixtures of C&D materials with additives such as RG and waste plastic are another motivation of this research to introduce alternative capping materials (Mohsenian Hadad Amlashi et al., 2018; Yaghoubi et al., 2017). According to Poulikakos et al. (2017), almost all the studies on aggregates with waste plastic, only focused on one or two individual types or mixtures of plastic, mainly for road or concrete construction. However, separating plastic requires further recycling operations and consequently is energy consuming which ultimately is not financially viable for construction activities. The Mixed Recovered Plastic (MRP) used in this research is the mixture of several types of plastic waste (including PET, HDPE, PVC, LDPE, PP, PS, and Other), with much lower processing costs. There has been limited study on civil engineering application of MRP to date, particularly in capping layer to utilize the energy absorption of MRP.

In this research, the feasibility of using C&D materials including RCA, CB, and blends of RCA/RG and RCA/MRP as alternative capping materials was investigated. Basic geotechnical properties of materials were compared to two CCMs currently being used in track constructions in Australia. In addition to basic geotechnical testing including Los Angeles (LA) aberration test and California Bearing Ratio (CBR), several specialized tests such as an adopted RLT testing protocol for determining the M_r of capping layer materials and multistage triaxial test have been conducted. The resilient and shear response of materials were compared with those of CCMs to evaluate the behavior of potential alternative capping materials.

2. Experimental Study

2. 1. Materials and Methods

In this research, four types of aggregates and two different supplementary materials were studied (Fig. 1). Aggregates with nominal size, d_{max}, of 20 mm, include Conventional Capping Materials of Victoria (CCM1), Conventional Capping Materials of New South Wales (CCM2), RCA and CB. RG and MRP were also utilized as supplementary materials in mixtures with RCA, having d_{max} of 4. 75 and 9. 5 mm, respectively. Traditional capping materials were obtained from two natural quarries of railway construction projects in Victoria and New South Wales, while recycled materials were collected from two recycling facilities in Victoria, Australia. MRP used in this research was the mixture of different types of plastic (including PET, HDPE, PVC, LDPE, PP, PS, and Other) which can neither be separated nor reprocessed into new products (Fig. 1). Sampling for all the materials has been undertaken according to ASTM D75/D75M (2014) to have a representative particle size.

Laboratory tests were also conducted on the mixtures of RCA blended with 10%, 20%, 30% and 40% of RG and 3% and 5% of MRP. RG contents were designated based on the study of Arulrajah et al. (2014) on RCA/RG mixture, while MRP percentages were chosen according to the results of Yaghoubi et al. (2017) on LDPE and HDPE blends with RCA. Mixture portions were calculated using dry weight measurement rather than volume fractions. This is mainly due to the fact that measurement of by weight percentage in both laboratory and field could be more accurate as the materials' volume is reliant on the specific gravity and may change by temperature and water content (Indraratna et al., 2018; Signes et al., 2015). Previous studies also used by-weight method in adding RG and waste plastic to RCA (Arulrajah et al., 2014; Yaghoubi et al., 2017).

Particle Size Distribution (PSD) test was conducted in accordance with ASTM D6913/D6913M (2017) using the washing method except for MRP which was sieved by dry method. ASTM D2487 (2017) was implemented to classify the materials based on the Unified Soil Classification System (USCS). Particle density and water absorption of all aggregates were determined based on ASTM C127 (2015); ASTM C128 (2015), while the specific gravity of RG and MRP were obtained following ASTM D854 (2014).

Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of all the aggregates and mixtures were determined using ASTM D698 (2012). Standard Proctor energy was used following ARTC ETC-08-03 (2017) for capping materials. Previous studies have also used standard Proctor energy in preparing samples of capping materials (Indraratna et al., 2019; Suiker et al., 2005).

In order to assess the degradation resistance of aggregates, LA abrasion test was conducted by ASTM C131/C131M (2014) test method. CBR tests were performed following ASTM D1883 (2012), using standard Proctor energy. Samples were submerged for 4 days by application of a 9 kg surcharge load as recommended by MTM L1-CHE-SPE-178 (2018) for capping materials.

RLT tests were conducted to measure the M_r of materials using a proposed testing protocol for capping layers. Multistage triaxial test was also performed at three confining pressures of 10, 40, and 80 kPa based on AS 1289. 6. 4. 1 (2016); DPTI TP184 (2015). For all the samples, ASTM C702/C702M (2018) was practiced carefully using both quartering and splitting method in reducing sample size.

2. 2. Adopted RLT testing Protocol

Different protocols of measuring the resilient response of granular pavement materials have been proposed based on the loading condition of pavement base/subbase layer using RLT test (AASHTO T307, 2012; CEN EN 13286-7, 2004; NCHRP 1-28A, 2004).

Stress state envelopes NCHRP 1-28A (2004) and AASHTO T307 (2012) for pavement base/subbase and CEN EN 13286-7 (2004) for Method B (High-stress level) are plotted in Fig. 2. In AASHTO T307 (2012) and CEN EN 13286-7 (2004), the confining pressure, σ_3, is kept constant at each stage and deviator stress follows a stress path inclined sharply toward the Mohr-Coulomb failure line till reaching a maximum value of principal Stress Ratio (SR) (Andrei et al., 2004). Thereafter, σ_3 is increased and the vertical stress, σ_1, is reset to a low level and is increased steeply again. Constantly experiencing low-stress to high-stress levels may result in either extensive deformation of weak materials even in the first stress path or disability of capturing enough data close to the failure line of strong materials. However, NCHRP-1-28A (2004) proposed harmonized loading protocol in which the initial stress combinations farthest from the line of failure are imposed to the sample, followed by more demanding stress paths (Andrei et al., 2004). This procedure enables capturing maximum number of M_r points over a larger stress state domain, comparing to the two other protocols.

The domain of applied confining pressure used in the three protocols is fairly similar and is approximately between 20 to 150 kPa (Fig. 2). Based on the discussions, numerical simulations, field measurements and laboratory investigations of Indraratna et al. (2015); Indraratna et al. (2018); Indraratna et al. (2019); Qi et al. (2018); Rose et al. (2004); Suiker et al. (2005), σ_3 of capping materials, particularly in Australia, is as low as 5 kPa especially at the edge of track to a maximum value of 75-80 kPa closer to centerline. This indicates the inefficiency of current pavement RLT testing protocols in capturing the M_r of capping materials at low σ_3. Hence, the confinement of the proposed testing regime was limited from 5 to 80 kPa.

Regarding the induced cyclic deviator stress ($\sigma_{d\text{-}cyclic}$) at top and bottom of capping layer, field studies of Indraratna et al. (2010) determined a range of around 30 to 80 kPa for passenger train and 60 to 120 kPa for coal train at Australia. Based on the analytical and numerical investigations, $\sigma_{d\text{-}cyclic}$ of capping layer interface with ballast or subgrade was reported to be between 50 to 150 by Adegoke et al. (1979), 70 to 90 by Selig and Waters (1994), 60 to 90 by Li and Selig (1998), 30 to 90 by Shahu et al. (1999), 50 to 150 by Rose et al. (2004), 30 to 60 by Sayeed and Shahin (2017). While different loading condition and individual layer characteristics, such as layer thickness and M_r values were assumed in these studies, the reported range of most of the studies was consistent with the field studies reported by Indraratna et al. (2010) in Australia. Also, concerning laboratory studies, Indraratna et al. (2015) applied cyclic sinusoidal stress of 41 to 166 kPa on the subballast-ballast interface. Qi et al. (2018) used the maximum cyclic axial stress of 16 to 116 kPa (corresponding to the σ_3 of 10 to 70 kPa).

Based on the aforementioned in-situ and induced loading condition of capping layers, and the characteristics of current RLT testing protocols, a new RLT testing protocol was adopted using the NCHRP 1-28 A (2004) approach. As presented in Table 1 and Fig. 2, the range of confining pressures and cyclic axial stresses was determined based on the previous studies discussed earlier, considering the in-situ anisotropy of materials (ν = 0. 3), emphasizing on field studies in Australia. Unlike NCHRP 1-28A (2004) which uses a constant principal stress ratio in each stress path, *SR* varies in the newly proposed protocolat different confinement levels. In other words, higher *SR* was imposed at lower confining pressures, which is a more realistic condition of an element of soil under moving wheel load when considering in-situ anisotropy and thickness of different sections of track. The same methodology was used in CEN EN 13286-7 (2004) and the proposed protocol of Gu et al. (2015).

For RLT test with constant σ_3, the resilient modulus is defined as a ratio of the applied repeated deviator stress to the induced recoverable axial strain (AASHTO T307, 2012), which is a measure of material's stiffness:

$$M_r = \frac{\sigma_1 - \sigma_3}{\varepsilon_1} = \frac{\sigma_d}{\varepsilon_1} \quad (1)$$

where M_r is resilient modulus, σ_1 and σ_3 are major and minor principal stresses (axial and confining stresses), ε_1 is the major principal or axial recoverable strain, and σ_d is deviator stress. Since this parameter is stress dependent (Andrei et al., 2004), many researchers have introduced resilient modulus models in terms of stress state parameters, as presented in Table 2. Some of the models presented in this table were reformulated by changing σ_3 to θ (bulk stress) and/or σ_d to τ_{oct} (octahedral shear stress), to capture the sensitivity of the models to input parameters (Andrei et al., 2004).

3. Results and Discussion

Geotechnical properties of the aggregates and supplementary materials are presented in Table 3 and the results will be discussed in the following sections.

3. 1. Geotechnical Properties

Fig. 3 illustrates the PSD of recycled materials in comparison to the requirement of Australian agencies (ARTC ETC-08-03, 2017; MTM L1-CHE-SPE-178, 2018) for capping materials. The PSD of CB, CCM1 and CCM2 is within the specified limit of ARTC ETC-08-03 (2017), while RCA has less fine content in the range of 0. 15 mm to 0. 075 mm than the lower limit of both specifications. Both CCM1 and CCM2 have more fine contents than the limit of MTM L1-CHE-SPE-178 (2018), whereas the fine content of CB is slightly below the upper limit. Also, none of the supplementary materials (RG and MRP) satisfy the recommended range of both specifications. As presented in Table 3, RCA and CCM1 have similar gravel content (well-graded gravel with sand), while CB and CCM2 have more sand than gravel (well-graded sand with gravel).

Based on Table 3, particle density of both coarse and fine particles of RCA and CB are similar to the CCMs. While specific gravity of RG is similar to the measured value of Arulrajah et al. (2013), that of MRP is higher than the HDPE and LDPE used in Yaghoubi et al. (2017). Also, RCA and CB have higher water absorption than both CCMs.

As presented in Table 3, MDD of both capping materials is more than (2 Mg/m ^{3}). MDD of CB is marginally below 2 Mg/m ^{3} and that of RCA is 1. 83 Mg/m ^{3} . As plotted in Fig. 4, adding RG up to 30% reduces the MDD and increases the OMC of the RCA/RG blends, which is similar to results of Arulrajah et al. (2014). However, by adding 40% RG, the MDD of mixture increases significantly. According to Vallejo (2001), this is due to transition in fabric of the mixture from coarse grain supported matrix to fine grain supported matrix, in which the sand-sized particles of RCA and RG fill the voids between coarse particles and reduce the porosity of mixture. The MDD of RCA/MRP blend also decreases significantly by increasing the MRP content (Fig. 4), which is expected due to the low specific gravity of plastic (Yaghoubi et al., 2017).

An LA abrasion of less than 50 is usually adopted for capping materials (Li et al., 2016; Selig and Waters, 1994). While RCA and CB show higher degradation than CCMs, all the aggregates meet this maximum criterion.

Following the Australian agencies (ARTC ETC-08-03, 2017; MTM L1-CHE-SPE-178, 2018), the CBR value of capping materials should be more than 50%. All the tested aggregates except for RG meet the required limit (Table 3). As presented in Fig. 5, inclusion of both RG and MRP in RCA has resulted in CBR value reduction. Lower strength of RG to the RCA (Arulrajah et al., 2014) and softer surface of plastics (Arulrajah et al., 2017) to the RCA particles can contribute to this trend. The only strength parameter that has been set by Australian agencies to evaluate the feasibility of using any materials in capping layer is CBR value. Hence, 5% MRP can be blended confidently with RCA for capping layer construction while the usage of RG should be limited to 40% (Fig. 5).

3. 2. Resilient Response of Materials

In order to better compare the response of conventional capping materials with the alternative recycled products, the obtained M_r of materials has been re-ordered in accordance with the applied confining pressure and maximum applied cyclic stress from the lowest to highest value as presented in Fig. 6.

Fig. 6(a) shows that the M_r of both CCM1 and CCM2 is approximately in the range of 50 to 150 corresponding to the bulk stress of 37. 5 to 560 kPa. The M_r of CCM1 is higher than that of the CCM2, from around 3 MPa at the lowest θ to 15 MPa at the last cycle. Limited studies have reported on the measurement of M_r for railway capping materials. Selig and Waters (1994) used a range of 55 to 125 MPa in their analytical calculations. Shahu et al. (1999) assumed a range of 60 to 100 MPa corresponding the induced major principal stress of 82 to 92 kPa at the subballast-ballast interface. Qi et al. (2018) used the same limit in evaluating the M_r of coal wash, steel furnace slag and rubber crumb mixture as an alternative subballast layer. Their cyclic triaxial test results showed that the M_r of coal wash and steel furnace slag blend with zero and 10% rubber crumb is approximately between 35 MPa ($\theta = 46$ kPa) and 140 MPa ($\theta = 322$ kPa). Li et al. (2016) proposed a required range of 55 to 105 MPa for subballast materials. Based on the available data in literature, the M_r range of both CCM1 and CCM2 falls between the required ranges of this layer (Fig. 6(a)).

The M_r of CB was observed to commence from a lower value than CCMs till σ_3 of 40 kPa (Fig. 6(a)). Subsequently, this falls between the ranges measured for CCMs. Also, the M_r of CB is in the range of M_r presented by other researchers for capping materials, as discussed earlier. Therefore, CB can be a suitable alternative material to the capping materials, in terms of M_r. Nevertheless, RCA shows higher M_r compared to the other aggregates used in this study (Fig. 6(a)) showing a 1. 4 to 1. 9 times higher M_r of CCMs and CB. This superior resilient response of RCA can result in lower induced vertical and horizontal stresses and deformations of track substructure (Shahu et al., 1999; Smith et al., 2006).

Superior resilient response of RCA provides the potential for sustainable utilization of alternative recycled capping materials. Based on Fig. 6(b) and (c), inclusion of both RG and MRP has resulted in decreasing the M_r of the RCA/RG and RCA/MRP mixtures, which is expected as the shear strength of both additives is lower than RCA (Fig. 5) and consistent with the previous observations (Arulrajah et al., 2014; Arulrajah et al., 2017; Mohsenian Hadad Amlashi et al., 2018; Yaghoubi et al., 2017). Particle shape and low particle roughness of recycled plastic can contribute to this trend as well (Arulrajah et al., 2017).

Although by increasing the RG percentage the M_r of the RCA/RG mixtures decreases, the M_r of RCA60/RG40 is still higher than that of CCMs (Fig. 6(b)). The M_r of both mixtures of RCA97/MRP3 and RCA95/MRP5 falls between the M_r values of RCA and CCMs. Fig. 6(c) also shows that at the same σ_3, some levels of shear softening have occurred for the RCA/MRP mixtures by increasing the σ_d even for the inclusion of 3% MRP. This can be related to high *SR* applied to the sample compared to the other protocols discussed earlier. Attia and Abdelrahman (2011) also observed a similar trend for recycled C&D materials that experienced shear softening under a loading condition with relatively high-stress ratio.

3. 3. Comparison of M_r Models

Predictions of all the models in Table 2 were compared with the measured M_r, to determine a more robust model which could be used with the newly proposed protocol for capping materials, especially for the blend of RCA/MRP which experienced shear softening. This was done by measuring S_e/S_y ratio, which is defined as the ratio of the standard deviation of the errors (S_e) to the standard deviation of the measured M_r of sample (S_y) (Andrei et al., 2004). S_e/S_y ratio was given higher priority than the well-known determination coefficient, R^2, in evaluating the models as this parameter applies only to linear, unbiased models based on its statistical definition (Andrei et al., 2004).

As presented in Table 2, the models have been categorized based on the number of regression coefficients into 4 groups and S_e/S_y ratio for all the samples was calculated for the models of each group and presented in Fig. 7. For some models (like Model 3 and 4), changing the set of stress parameters (like from σ_d to τ_{oct}) does not result in different goodness of fitting parameters. However, since the correlation coefficients are different, it was decided to evaluate all the models.

Fig. 7(a) shows that in the 2-parameter models, confining pressure (Model 1) is the best single-variable predictor and can predict more accurately than some of the 2-parameter models such as model 21 and 22 (Fig. 7(b)). Other single-variable models (Model 2, 3, 4, 5, and 6) has S_e/S_y more than 0. 2, which shows a low level of their accuracy. For RCA/MRP mixture, increasing σ_d at the same σ_3 has an adverse influence on the M_r (shear softening in Fig.

6(c)). Therefore, Model 7, in 2-parameter models, better fits the results than Model 1 since parameter J_2 in this model takes into account the effect of stress ratio. Also, using bulk stress as a single predictor (Model 2) will result in inaccuracy for RCA/MRP mixture as this parameter simultaneously accounts for σ_3 and σ_d.

Fig. 7(b) and (c) also illustrate the S_e/S_y ratio of 3 and 4-parameter models. Model 11/12 (3-parameter) and 23/24 (4-parameter) have the best goodness of fit (S_e/S_y below 0. 06) for CB, CCM1, and CCM2 respectively. However, Model 13/14 or 17/18 in 3-parameter models and Model 26/27 in 4-parameter models generally perform better for RCA and its mixtures (RG or MRP).

For the RCA/RG and RCA/MRP mixture, the R^2 of Models 13/14 and 17/18 in 3-parameter models are very close. Therefore, unlike the results reported by Andrei et al. (2004) on unbound natural pavement materials, using σ_3 and σ_d instead of θ and τ_{oct} can increase the accuracy of the models especially in the RCA/RG and RCA/MRP blends. This is consistent with the results of Attia and Abdelrahman (2011) on recycled C&D materials, where the samples experienced some levels of shear softening. Therefore, in the 5-parameter model (Model 32), only the pair stress parameters of σ_3 and σ_d were considered with special emphasize on recycled C&D materials and their mixtures.

Since Model 32 as a 5-parameter model takes into account the effect of suction (k_4), failure of material, and instability of equation (k_5), for the most of the samples gives the highest goodness of fitness in comparison to the other models (Fig. 7(c)). Although the S_e/S_y ratio of this model in most of the samples is low, it is slightly lower than some of the 3 and 4-parameter models including 13/14 or 17/18 and 26/27 for RCA and its mixtures.

While Model 32 needs many trial and errors to find the best parameters with the highest goodness of the fit, Models 17 and 26 provide a good balance between accuracy, ease of calculation, and computational stability for recycled materials as a sustainable alternative for capping layer construction with the newly proposed RLT testing protocol. Therefore, the regression parameters of these two models for tested samples are presented in Table 4.

3. 4. Stress-strain characteristics

Fig. 8(a)-(c) present the results of multistage triaxial test on RCA, CB and CCMs and the mixtures of RCA with supplementary materials. For all the samples, the deviator stress, q, initially rises with accumulation of axial strain, ε_1, until it reaches the peak strength, q_{peak}, and in the post-peak zone, the q decreases with increasing ε_1. This is generally known as strain softening behavior in which the yield surface in stress space contracts with continuous shearing and is a typical characteristic of dense granular materials and a similar trend was observed for capping materials (Indraratna et al., 2019; Suiker et al., 2005).

As plotted in Fig. 8(a), RCA has the highest strength followed by CCM1. CB has an intermediate strength between the two CCMs, and q_{peak} of CCM2 at each stage is around half of the RCA, which is the lowest recorded strength among all the aggregates and also mixtures. A similar trend was observed in resilient response of the materials and signifies the superior strength of RCA and intermediate behavior of CB in comparison to the CCMs. Also, CB and CCMs mainly show a relatively ductile behavior as compared to that of RCA which can be related to the higher particle breakage and high amount of cohesive fine content.

According to Fig. 8(b) and (c), adding either RG or MRP content leads to the reduction of q_{peak} of the mixtures, mainly due to the lower shear strength of both materials (especially MRP) compared to that of RCA. Moreover, the axial strain corresponding to the q_{peak} has increased by inclusion of RG and MRP. While for RCA/RG mixtures, this increase is insignificant especially below 30% RG content, addition of MRP noticeably increases the ductility of the RCA/MRP blends. Similar observations have been reported in Mohsenian Hadad Amlashi et al. (2018) for the crushed limestone and recycled glass blends and unconfined compression strength results of Yaghoubi et al. (2017) on RCA and plastic mixture.

In terms of RCA/RG mixtures (Fig. 8(b)), up to 20% RG reduces the peak strength of RCA to about 20%. The rate of reduction has increased significantly by increasing the RG content and q_{peak} has decreased to 45% in the RCA60/RG40 mixture. Ultimately, the shear strength of the highest RG inclusion, RCA60/RG40, is within the range of the two tested CCMs. Similarly, both RCA97/MRP3 and RCA95/MRP5 show 25% and 15% more strength than CCM1.

In order to better assess the behavior of the recycled C&D materials and mixtures, the peak friction angle, ϕ_{peak}, Young's modulus, E, and Energy Absorption Capacity (EAC) of mixtures were calculated and compared with the range of results of two capping materials, as presented in Fig. 9. Based on CBR values, resilient response, and stress-strain behavior, CCM1 has higher strength than CCM2. Hence, the upper and lower range of CCMs plotted in Fig. 9 is related to CCM1 and CCM2, respectively.

Similar to the Indraratna et al. (2019), ϕ_{peak} of the samples was calculated for the second stage of loading (σ_3 of 40 kPa) and is presented in Fig. 9(a). The value of ϕ_{peak} reduces approximately linearly with increasing both RG and MRP content. Since the ϕ_{peak} of RCA is about 20% higher than that of CCM1, the ϕ_{peak} of RCA70/RG30 is still higher than the plotted range for conventional materials, while RCA60/RG40 has similar value to CB and falls within the CCMs range. Also, Both RCA97/MRP3 and RCA95/MRP5 has higher friction angle than capping materials (> 50°). Similar results were also observed for other confining pressures, which are not presented herein.

The reduction in Young’s modulus (initial tangent modulus at the first stage of loading) of RCA with addition of RG and MRP is plotted in Fig. 9(b). Low stiffness of RG and especially MRP is the main factor contributing to this trend, but, generally, due to the high stiffness of RCA, all its mixtures have relatively higher E than the range of CCMs. According to Indraratna et al. (2019), the reduction in E is corresponding to the increase of sample’s ductility as can be seen in Fig. 8(b) and (c). RCA/MRP mixtures show higher ductility compared to RCA/RG mixtures, which results in their lower stiffness. The E of CB is also about 17% higher than CCM1.

Energy absorption capacity of capping materials can enhance the overall stability of railway track structure, reduce track degradation and maintenance costs (Indraratna et al., 2018). The total energy per unit volume absorbed by soil sample can be calculated based on the area of stress-strain curve (Fig. 8) to a given value of strain (Babu and Vasudevan, 2008):

$$U^{*} = \int_{0}^{\varepsilon} \sigma d\varepsilon \qquad (2)$$

where U^* is EAC, σ and ε are deviator stress and axial strain in triaxial test. Generally, it is expected for capping materials to not to experience an axial strain of more than 2% (Indraratna et al., 2018). More axial strain or reaching post-peak regime of this layer may result in extensive deformation of track structure and development of undesirable differential and total settlements (Suiker et al., 2005). Consequently, the area under stress-strain curve of samples up to q_{peak} or 2% axial strain, whichever reached first, was calculated at each stage of loading. Fig. 9(c) illustrates the average U^* of samples, which has a similar trend to the U^* at each stage of loading. While increasing RG content increases the ductility of RCA/RG mixture, the reduction in deviator stress outweighs the increase in axial strain and hence the reduction in U^*. Based on the general trend line of RCA/RG mixtures, after 30% RG, the EAC of mixture is lower than the range of CCMs. However, inclusion of MRP enhances the energy absorption of the matrix such that even by adding 3% MRP, the U^* of RCA increases by 22% which is around 45% higher than CCM2. This is due to the increase in dissipation of energy by plastic particles rather than the frictional resistance of the sample. This substantial increase in energy absorption as well as higher strength and stiffness of RCA/MRP mixtures (Fig. 6(c) and Fig. 8(c)) than CCMs, provide the opportunity of introducing an energy-absorbing capping layer with superior performance to virgin aggregates. CB also shows an EAC in the range of two tested capping materials.

4. Conclusions

In this research, the feasibility of using recycled C&D materials including RCA, CB, and blends of RCA/RG and RCA/MRP, with up to 40% RG and 3 to 5% MRP as railway capping layer was studied and results compared to two types of CCMs. Stiffness and strength characteristics of materials and mixtures were evaluated based on the proposed RLT loading protocol for capping layers and multistage triaxial tests. The following conclusions can be drawn:

- Generally, basic geotechnical properties of RCA and CB including PSD, specific gravity, water absorption and LA were fairly similar to the CCMs and complied with the requirement of Australian standards for capping layer. Also, in terms of CBR value, RCA, CB and mixture of RCA with up to 40% RG and 5% MRP fulfilled the limit recommended by Australian agencies.
- M_r and shear strength of materials showed that RCA had approximately two times higher stiffness and strength than CCMs, while M_r and strength of CB were approximately in the range of tested natural capping materials.

- Higher stiffness of RCA provided the opportunity for adjusting the sensitivity of the layer to repeated loading by inclusion of supplementary materials such as MRP and RG. Based on the test results, both blends of RCA with up to 40% RG and 5% MRP had higher M_r than the two CCMs.
- For the RCA/MRP mixture which experienced some levels of shear softening during RLT testing, resilient modulus models taking into account both σ_3 and σ_d performed better than θ and τ_{oct}.
- Based on the results of multistage triaxial test, addition of both RG and MRP reduced the peak strength, peak friction and Young’s modulus of RCA/RG and RCA/MRP mixture. However, in the case of up to 30% RG and 5% MRP, their values were generally higher than CCMs. The values of RCA60/RG40 and CB also were either higher or in the range of CCMs results.
- RCA blended with up to 20% RG and 5% MRP are a viable replacement for CCMs with superior performance in terms of stiffness and strength. Although addition of RG decreased the energy absorption capacity of RCA/RG mixture, RCA/MRP blends showed a significant enhancement in energy dissipation compared to CCMs. Therefore, higher content of RG up to 40% can be utilized considering the comparatively lower EAC of the final product.