



Effects of reclaimed asphalt materials on geotechnical characteristics of recycled concrete aggregates as a pavement material

S. Jayakody, C. Gallage & J. Ramanujam

To cite this article: S. Jayakody, C. Gallage & J. Ramanujam (2019) Effects of reclaimed asphalt materials on geotechnical characteristics of recycled concrete aggregates as a pavement material, Road Materials and Pavement Design, 20:4, 754-772, DOI: [10.1080/14680629.2017.1417151](https://doi.org/10.1080/14680629.2017.1417151)

To link to this article: <https://doi.org/10.1080/14680629.2017.1417151>



Published online: 21 Dec 2017.



Submit your article to this journal [↗](#)



Article views: 290



View Crossmark data [↗](#)



Effects of reclaimed asphalt materials on geotechnical characteristics of recycled concrete aggregates as a pavement material

S. Jayakody*, C. Gallage and J. Ramanujam

School of Civil Engineering & Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Australia

(Received 8 June 2017; accepted 8 December 2017)

The use of recycled concrete aggregates (RCAs) as an unbound pavement material is a perfect alternative to effectively manage the construction and demolition (C&D) wastes. However, the presence of constituents in RCA is led for inconsistent properties. The reclaimed asphalt pavement (RAP) material is one of the major constituents that can be mixed at the recycling process of demolished concrete. Therefore, this study aims to investigate the effects of RAP as a constituent in RCA, on its characteristic properties as an unbound pavement material. To achieve the objectives of the study, five RCA samples were produced by mixing different percentages of RAP by weight. A series of standard laboratory tests were conducted on each sample. The results were then compared with the properties of standard granular pavement materials specified by Queensland Department of Transport and Main Roads (QDTMR), Australia. The analysis depicted that the presence of RAP as a constituent in RCA up to 15% was not significantly affected on the physical properties of RCA as an unbound pavement material.

Keywords: pavement material; recycled concrete aggregates; reclaimed asphalt pavement

Introduction

Construction and demolition (C&D) waste cannot be eliminated from the industry as long as there are upcoming constructions every day. Recycling is the prominent option for C&D waste management and to gain benefits by reducing the demand upon new resources. According to the “Construction and demolition waste status report-October 2011”, a total of 8.5 million tonnes of C&D wastes disposed in Australia in 2008–2009 financial year and recovered only 55%. The recovered percentage of C&D in the state of Queensland was only 37%, lower than Australian national recovery (Hyder Consulting, 2011). Therefore, some states in Australia like Queensland have to increase their contribution to come up with more recycling of C&D waste to achieve the national target. C&D wastes carry over 50% of waste concrete in Australia (Tam, 2009). Therefore, recycling waste concrete to produce the crushed aggregates is one of the sustainable outcomes of C&D waste management. Meanwhile, the potential engineering applications of the recycled concrete aggregates (RCAs) have to be investigated to enhance and maintain consistent demand on it. Therefore, engineering properties of RCA need to be investigated to promote as a construction material in the industry.

Characterisation studies of RCAs have been conducted in recent years around the world. The shear strength characteristics of RCA were discussed by Bhuiyan, Ali, and Salman (2014) to

*Corresponding author. Current address: Department of Civil Engineering, South Eastern University of Sri Lanka, Oluvil, Sri Lanka. Email: jshiran@gmail.com

evaluate the potential use of RCA as a granular infill in hollow segmental block systems in Malaysia. The results showed a great shear strength of RCA comparable to the fresh aggregates. Studies on RCA to reuse in concrete structures made successful outcomes as a partial or complete substitution of natural aggregates and combining with other recycled materials such as fly ash, bricks, glass and cement mortar (Evangelista & De Brito, 2007; Ismail & Ramli, 2013; Katz, 2003; Kou, Poon, & Agrela, 2011; Manzi, Mazzotti, & Bignozzi, 2013; Rizvi, Tighe, Henderson, & Norris, 2010). Some of the researchers aimed to use the RCA as an aggregate in hot mix asphalt productions (Arabani & Azarhoosh, 2012; Mills-Beale & You, 2010). Successful outcomes of those investigations were came up with introducing the best mixing portion of RCA with natural aggregates and other recycled materials for concrete and asphalt productions.

Promoting the RCA in pavement industry is an extensive remedy to decline the excessive demand on natural aggregates. The past studies on the characterisation of RCA for pavement applications revealed the potential use of RCA in unbound road applications under different conditions. Those studies have been focused to characterise the properties of RCA as a treated material by adding substitutes such as crushed rock, sand, limes and crushed bricks. Strength properties of RCA with traditional limestone were tested by Behiry (2013) for base and subbase applications, and the California bearing ratio (CBR) and unconfined compressive strength (UCS) tests results revealed a significant improvement of the strength of RCA with a small quantity of limestone. A comprehensive laboratory evaluation was conducted by Arulrajah, Piratheepan, Bo, and Sivakugan (2012) to observe the classification and strength properties of recycled materials, including RCA and the results were found to have appreciable properties equivalent to typical natural granular subbase materials. Properties of RCA without constituents were investigated by Arulrajah, Piratheepan, Ali, and Bo (2012) to apply in pavement subbase layers and the strength was found to satisfy with high durability. Boudlal and Melbouci (2009) obtained high CBR values for the specimens which were the mixtures of RCA with cement, sand and brick, and found that treatment with cement and sand has certainly very appreciable results at CBR tests ($> 100\%$ of CBR). The feasibility of blending crushed clay bricks from recycled C&D with RCA was investigated to be applied as an unbound subbase material (Poon & Chan, 2006). The soaked CBR values of crushed bricks and RCA mixtures were satisfied the requirements of the specifications in Hong Kong. The self-cementing properties of RCA were investigated by Poon, Qiao, and Chan (2005) to describe the strength gaining of compacted RCA and the results indicated that the size fractions of less than 0.15 mm and 0.3–0.6 mm (active fractions) were most likely to be the principal cause of the self-cementing properties. Therefore, high strength could be accepted in the compacted layers in pavements by increasing the quantity of active fraction in RCA.

Jiménez, Ayuso, Agrela, López, and Galvín (2012) studied the property of recycled C&D waste that comprised RCA as the major component. The materials were evaluated in unpaved rural roads. The structural performance of the road was determined by the “Falling Weight Deflectometer” and concluded that the recycled C&D material is an alternative to natural aggregates in unpaved roads without environmental impact. A similar material (recycled C&D) was evaluated in pavement applications by Leite, Motta, Vasconcelos, and Bernucci (2011). The study aimed to investigate the influence of PSD on the densification of recycled C&D materials and observed improvement of bearing capacity, resilient modulus and resistance to permanent deformation while increasing the percentage of cubic grains in the specimens.

Reclaimed asphalt pavement (RAP) material is one of the major products of recycled C&D waste. However, investigations of the properties of RAP materials as an unbound pavement material are very limited. Arulrajah, Piratheepan, and Disfani (2014) conducted a comprehensive study on blended samples of RCA and RAP to apply as an unbound pavement material in subbase layers. The laboratory and field test results together identified the adequate portion of

RAP as 15% to be mixed in RCA to assure the required performance and great performance was observed at the water content below the respective optimum moisture content (OMC). The study was further exposed insufficient strength requirement when 100% RAP was used in subbase layers. The results of this study were confirmed by the findings of Kazmee, Tutumluuer, and Beshears (2017). This investigation was focused on field tests for various applications of 100% RAP in base, subbase and subgrade layers and observed more rutting accumulation in unsurfaced pavements and sinkage documented during the hot-mix asphalt paving operation. Taha, Al-Harthy, Al-Shamsi, and Al-Zubeidi (2002) introduced cement fines as a binding agent to increase the performance characteristics when RAP mixed with conventional aggregates in pavement layers. Gobieanandh and Jayakody (2016) also observed an extremely high strength in CBR index values when a little portion of cement fines used with recycled C&D aggregates. However, alkalinity of cement fines, particularly in the presence of water percolating through the particles, generates a corrosive solution with an increase in pH value (Rahman, Imteaz, Arulrajah, & Disfani, 2014). Therefore, the consequences of using more chemical substances with recycled aggregates in pavement applications are against the natural environment (Vegas, Ibañez, San José, & Urzelai, 2008).

RAP has been noticed as the major constituent mixed with RCA at the recycling process. Therefore, many investigations are needed to determine the effect of RAP as a constituent on the properties of RCA and, limited past studies are recorded. Therefore, this study focused to investigate the influence of RAP on the physical properties of RCA as a granular pavement material under a comprehensive test programme. The RAP particles are temperature sensitive thus could be more cohesive at high temperature. The cohesion of bitumen-coated RAP materials is therefore influenced by the sample preparation temperature; consequently, the standard sample preparation temperature of each test procedure which is 105°C could be caused to alter the inherent properties revealed by the laboratory tests. Therefore, this study programme further extended to conduct three test series based on the sample drying temperature to investigate the effect of sample preparation temperature on the laboratory test results of RAP mixed RCA. In addition, the study aimed to determine the feasible RAP content that can be blended with RCA to be used as an unbound pavement material without deficiency of performance.

Test materials

The materials of the study, RCAs and RAPs, were obtained from a concrete recycling plant in Queensland, Australia. Pictures of the samples of RCA and RAP are shown in Figure 1(a) and (b), respectively.

Figure 2 shows the particle size distribution (PSD) curves of RAP and RCA materials. The maximum particle size of the RAP is below 16 mm and the majority of particles (about 75%) are within the size range of 4.75–0.18 mm. The RCA has the maximum particle size of 25.4 mm. The coefficient of uniformity (C_u) and coefficient of curvature (C_z) values are 21.7 and 2.8, respectively, depict the reasonably well-graded distribution of RCA.

The physical properties of the RCA are summarised in Table 1. The liquid limit (LL) and plasticity index (PI) of the RCA samples are within the range of the standard limits of high-quality base layer materials recommended by Queensland Department of Transport and Main Roads (QDTMR). In addition, they are within the range of high-quality crushed aggregates such as Rhyolite (PI = 6) and crushed Hornfels (PI = 8) (Jameson, Voung, Moffatt, Martin, & Lourensz, 2010). The adequate plastic properties of the RCA avoid the excess deformations at the compacted state and reflect their stability as granular pavement materials (Rizvi et al., 2010). The linear shrinkage (LS) was observed at around 1% in RCA which is within

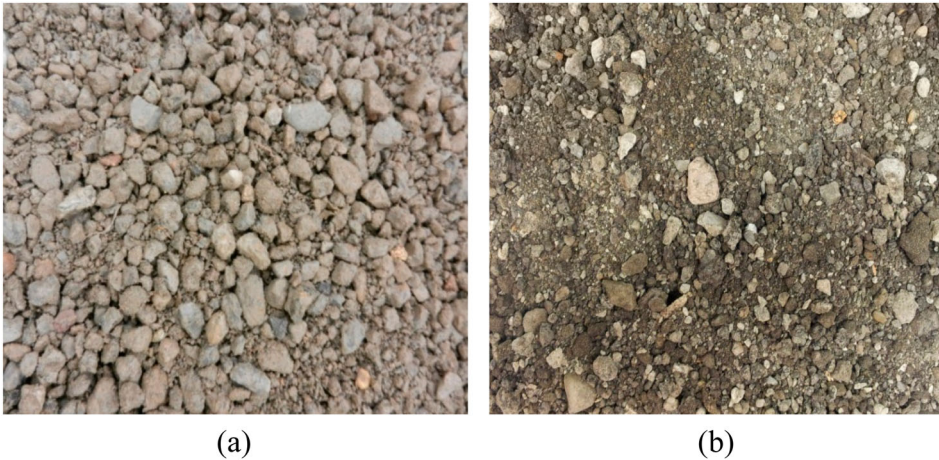


Figure 1. (a) Recycled concrete aggregates – RCAs (Scale 1:5). (b) Reclaimed asphalt pavement – RAP (Scale 1:3.2).

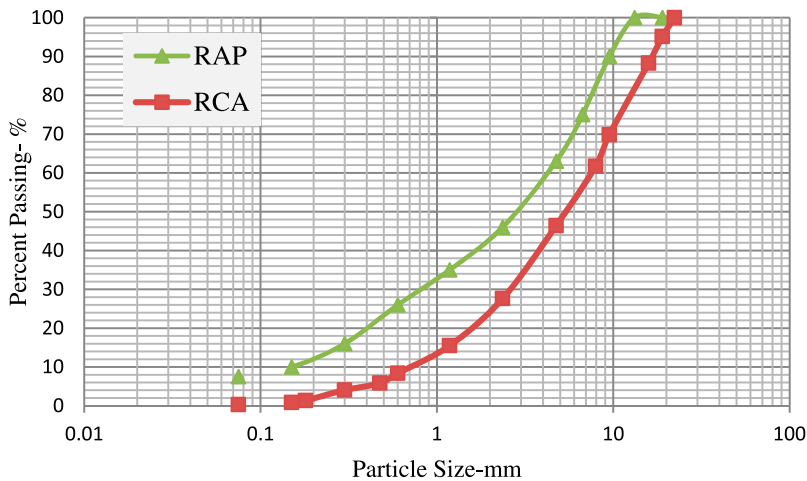


Figure 2. Particle size distribution (PSD) of reclaimed asphalt pavement (RAP) materials and recycled concrete aggregates (RCAs).

the maximum limited value 3% as standardised by the QDTMR. Low shrinkage property of the RCA avoids the damages to the pavement structures that could be caused by shrinking and swelling when going through wet and dry climate seasons. The obtained flakiness index (FI) value of RCA is 11% that is under the maximum of standard specification. Therefore, desirable particle shapes of the RCA avoid difficulties in workability and minimise the tendency to break down during compaction and under vehicular loads (Voung, Jameson, Sharp, & Fielding, 2008).

Water absorption values of RCA, 7.35% in fine fraction and 6.5% in coarse fraction, were observed. The values are much higher than the natural aggregates whose absorption is about 0.5–1% (Rao, Jha, & Misra, 2007). High porosity of the adhering cement mortar around the original aggregates and the presence of cement fines were caused for the high water absorption.

Table 1. Physical properties of RCA.

Property	Value	Test method
Liquid limit (LL) (%)	21.00	AS 1289.3.9.1-2002
Plasticity index (PI)	5.40	AS 1289.3.2.1-2000
Linear shrinkage (LS) (%)	1.00	Q106-QDTMR
Flakiness index	11.00	Q 201-QDTMR
Water absorption (particles smaller than 4.25 mm) (%)	7.35	Q214A-QDTMR
Water absorption (particles greater than 4.25 mm) (%)	6.50	Q214B-QDTMR
Specific gravity (G_s)	2.64	Q109A,B-QDTMR

Note: AS: Australian standard; QDTMR: Queensland Department of Transport and Main Roads.

Water absorption affects the other properties of the materials particularly increases the workability. On the other hand, high water absorption adversely affects the demand on RCA, since it is not accepted for the applications in arid zones where the water sources are scarce (Padmini, Ramamurthy, & Mathews, 2009). The specific gravity (G_s) of the RCA is 2.64 and it is relatively lower than crushed rock aggregates, whose G_s is around 2.85 (Vegas et al., 2008). The presence of crushed and uncrushed parent aggregates coated with cement mortar and small pieces of hardened mortar cause for low G_s value of RCA.

The basic properties of the RAP materials were determined prior to the test programme. The binder (bitumen) content in RAP was determined following two test methods, solvent extraction (MainRoads, 2011a) and ignition methods (MainRoads, 2011b), and results were 3.87% and 4.81% by weight, respectively. The result under the ignition test method represents the presence of all the organic material including bitumen in RAP, thus indicated 0.96% higher value than the result of solvent extraction method. The specific gravity of the RAP was determined (MainRoads, 2011c) as 2.59, which is a relatively low value compared to RCA. The presence of small size particles and low density of the bitumen in RAP aggregates marginally reduce the G_s of RAP compared to granular materials. Water absorption tests were performed according to the test method Q214A (MainRoads, 2011d) and Q214B (MainRoads, 2011e) of QDTMR for the fine fraction (particle size < 4.75 mm) and coarse fraction (particle size > 4.75 mm), respectively. The water absorption of the finer RAP particles (< 4.75 mm) and coarser particles (> 4.75 mm) are 2.85% and 2.81%, respectively. The values show a significant reduction than the corresponding values 5.35% and 6.50% of RCA due to the hydrophobic bitumen coat around the RAP materials.

Testing methodology

Test samples and testing programme

Five RCA samples were prepared in the laboratory by adding different percentages (by mass) of RAP and mixed ratios are shown in Table 2. The new samples were thoroughly mixed in a concrete mixture. Blending the RAP materials with the RCA is controlled at the production process and QDTMR is not recommended over 20% of RAP in RCA (MainRoads, 2010a). Therefore, the maximum percentage of RAP was used as 20% in the test samples since; it is the highest possible amount that could be mixed with RCA at the production process.

The RAP-mixed RCA samples (Table 2) were subjected to classification test programme in three test series. The test series were designed to investigate the effect of sample preparation temperature on the results of classification and strength property tests. The bitumen-coated RAP materials are sensitive on the temperature; consequently, the sample preparation temperature at

Table 2. New blended samples with the material mix ratios.

Blended sample name	RCA (% by mass)	RAP (% by mass)
RM1-100/RAP0	100	0
RM1-95/RAP5	95	5
RM1-90/RAP10	90	10
RM1-85/RAP15	85	15
RM1-80/RAP20	80	20

each test could be affected on the output of test results. However, those materials are not being subjected such temperature in the real world applications; thus, the laboratory results would be misled to reveal the inherent properties of the RAP-mixed RCA samples. Therefore, sample drying temperature at the sample preparation prior to the tests was concerned to define the three test series as described below and in Table 3.

Series I (Not Oven Dried Samples – <i>NODSs</i>)	Samples were dried 2–4 days in room temperature prior to the tests.
Series II (Oven Dried Samples – <i>ODSs</i>)	Samples were dried 24 h in an oven at 100–105°C.
Series III (Ignited Samples – <i>ISs</i>)	Samples were ignited up to 540°C in a furnace.

Drying the samples prior to the tests in the oven at 105°C is the standard test procedure to remove moisture. This temperature could be affected on the heat-sensitive materials, thereby could alter the inherent attributes of the original materials. The bitumen coat of the asphalt particles in blended samples could be sensitive to melt at the oven temperature and the melted bitumen would be influenced on the inter-particle bonds causing alteration of the engineering properties. Though drying the materials in the oven is not practised in real applications, it was required to reveal the influence of oven temperature on the laboratory test results of RAP-mixed RCA samples. The results of the “oven dried samples (*ODSs*)” in test series II and “not oven dried samples (*NODSs*)” in test series I were then compared to assess the impact of sample preparation temperature (oven temperature) on the test results. Test series III was defined for the materials after ignition at 540°C in a furnace to evaporate the bitumen and organic materials. The objective of test series III was to determine the properties of RAP-mixed RCA samples in the absence of bitumen and organic materials, however, keeping the same material gradation of the samples.

Table 3. Sample names with their tags in three test series.

Primary sample name (from Table 2)	Sample name with the tag of test series		
	Test series I – <i>NODSs</i>	Test series II – <i>ODSs</i>	Test series III – <i>ISs</i>
RM1-100/RAP0	RM1-100/RAP0/ <i>NODS</i>	RM1-100/RAP0/ <i>ODS</i>	RM1-100/RAP0/ <i>IS</i>
RM1-95/RAP5	RM1-95/RAP5/ <i>NODS</i>	RM1-95/RAP5/ <i>ODS</i>	–
RM1-90/RAP10	RM1-90/RAP10/ <i>NODS</i>	RM1-90/RAP10/ <i>ODS</i>	RM1-90/RAP10/ <i>IS</i>
RM1-85/RAP15	RM1-85/RAP15/ <i>NODS</i>	RM1-85/RAP15/ <i>ODS</i>	–
RM1-80/RAP20	RM1-80/RAP20/ <i>NODS</i>	RM1-80/RAP20/ <i>ODS</i>	RM1-80/RAP20/ <i>IS</i>

Only three samples were tested in test series III since it required a large quantity of samples to be ignited.

Testing procedure

The classification and strength characterisation tests which were conducted in this research study: PSD, FI, Atterberg limits, LS, proctor compaction, CBR, ten percent fines (TPF) value test and UCS tests. Evaluation of the materials was then done following the QDTMR specifications to identify the maximum allowable amount of RAP in RCA which meets the required specification of the unbound pavement material.

The PSD of the specimens was determined in dry sieve analysis according to the Australian standards, AS1289.3.6.1-2009 (Australia, 2009a). Particle shape of the RCA was examined through the FI test, following the test methods Q201 (MainRoads, 2011f) of Department of Transport and Main Roads (DTMR). Atterberg limit of the specimens was determined following AS 1289.3.2.1-2009 (Australia, 2009b) for the plastic limit (PL), AS 1289.3.9.1-2002 (Australia, 2002) for the LL and the test method Q106 of DTMR (MainRoads, 2011g) for one-dimensional shrinkage limit tests. The water content versus dry density relationships for the blended samples were determined by the standard proctor compaction method as per Australian standards, AS1285.5.1-2003 (Australia, 2003). OMC and maximum dry density (MDD) values of each sample were obtained from the density–moisture graphs.

Strength properties of the blended samples were then evaluated with the TPF value test, CBR and UCS tests.

TPF value test

The TPF value test was conducted to determine the resistance of the aggregates to crushing under compressive load. Therefore, the TPF test is employed in assessing the durability of aggregates for highway constructions (Shen, Zhou, Ma, Hu, & Cai, 2009). The test aimed to determine the force required to produce 10% of fines of the aggregates size between 9.5 and 13.2 mm. The test was performed under dry and wet conditions according to the QDTMR test methods Q205A (MainRoads, 2011h) and Q205B (MainRoads, 2011i), respectively. Under the dry condition, NODSs were dried at 30°C for 2–3 days, since it was required to ensure no surface water on the aggregates and ODSs were dried in the oven at 105°C until a constant weight. Under the wet conditions, the samples were submerged in water overnight and the test was performed for the saturated surface aggregates. Test specimens prepared by filling aggregates in the cylindrical mould (115 mm diameter and 180 mm height) within three layers and each layer was tamped 25 times to appropriately compact the materials. It was required to conduct trial tests to estimate the applicable rates of loading to produce 10% of fines in each specimen. Therefore, pre-determined loads are applied in a uniform rate for each specimen through a plunger on top of the specimen by means of a compression machine.

California bearing ratio

CBR of the specimens was determined to evaluate the stability of RCA with respect to shear deformation with an increase in the load (Voung et al., 2008). CBR test results relatively measure the mechanical strength and moisture durability of pavement materials. Therefore, CBR index issued to rank the RAP mixed with RCA samples as it is one of the foremost factors in material selection for the structural design of pavements (MainRoads, 2009).

Australian standard AS1289.6.1.1-1998 (Australia, 1998) was followed to determine the CBR values of the specimens. Tests were conducted under the unsoaked conditions and then conducted

soaked CBR tests to examine the moisture effect on the load sustained of RCA samples. Sample preparation was done at corresponding OMC to achieve MDD of each compacted specimen. The water mixed materials were cured for 3 h in sealed containers prior to the compaction as it is the sufficient time period for moisture homogenisation for RCAs (Jayakody, Gallage, & Kumar, 2014). Cured samples were compacted in a standard compaction effort. The compacted samples were cured in sealed containers for 4 days for the unsoaked test, since it required a specific time period for strength gaining by the re-cementing process of compacted RCA specimens (Jayakody et al., 2014). For the soaked CBR test, a similar method was followed for the sample preparation up to the compaction and compacted specimens were inundated in water for 4 days. Then, tests performed in the loading machine named “Instron-series 5000” and the load was applied with a uniform rate of 1.00 mm/min and data were acquired through a software program “Bluehill3”.

Unconfined compressive strength

UCS is generally recognised as an important indicator of blending quality of treated aggregates in pavement industry. Untreated granular materials such as crushed rocks are not possible to be tested in UCS without the addition of binding agents due to non-cohesiveness (Vidal, Moliner, Martínez, & Rubio, 2013). UCS test is even not a common test for untreated pavement aggregates, the RCA samples were tested to investigate the binding effect of cement mortar in loads sustained under unconfined conditions.

UCS test was performed as specified in AS 5101.4-2008 (Australia, 2008b). Cylindrical shape specimens with 105 mm diameter and 115 mm height were prepared at their respective OMC and MDD with the standard compaction effort. A split cylindrical mould was used to extrude the sample without damages after the compaction. Water mixed materials were cured in a sealed container for 3 h for moisture homogenisation and the compacted specimens were cured for 4 days for strength gaining in sealed containers prior to the tests. Three hours curing period for the water mixed RCA samples and 4 days curing period for the compacted RCA specimens were applied to optimise the strength gaining as similar to the sample preparation of unsoaked CBR test by following previous research findings of Jayakody et al. (2014). UCS tests were performed on the specimens with a uniform loading rate of 1.00 mm/min in the same loading machine used for CBR test.

Results and discussion

Detailed investigation of physical and strength properties of RCA was needed to assess and classify them according to their applications in different pavement layers for different traffic volume roads. The obtained results describe the inherent attributes of RCA with and without RAP materials as a constituent. The physical properties and strength properties of the samples in three test series are discussed below.

Particle size distribution

PSD curves of ODS and NODS samples are shown in Figure 3, and Figure 4 shows the PSD curves of ODSs with ISs. The PSD curves of the ODSs were drawn as the references in both figures for comparison, since the standard PSD test is conducted for oven-dried materials.

The comparison of the ODSs and NODSs depicts that NODSs are consisted of slightly more coarse particles than ODSs. The conglomerate particles are easily separated once moisture is completely removed at the oven temperature 105°C, thus ODSs showed slightly lower coarser materials than NODSs. A similar trend of PSD curves observed in Figure 4 which was the ODSs

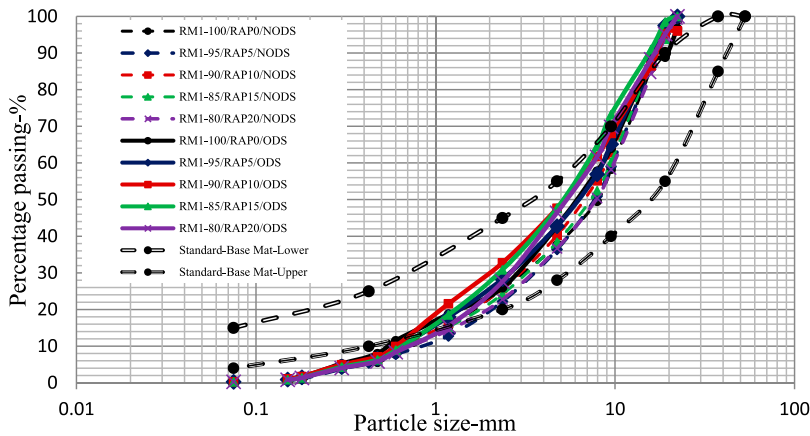


Figure 3. Particle size distribution curves of the “Not oven-dried samples (NODSs) and Oven-dried samples (ODSs)” with minimum and maximum curves of standard base layer materials.

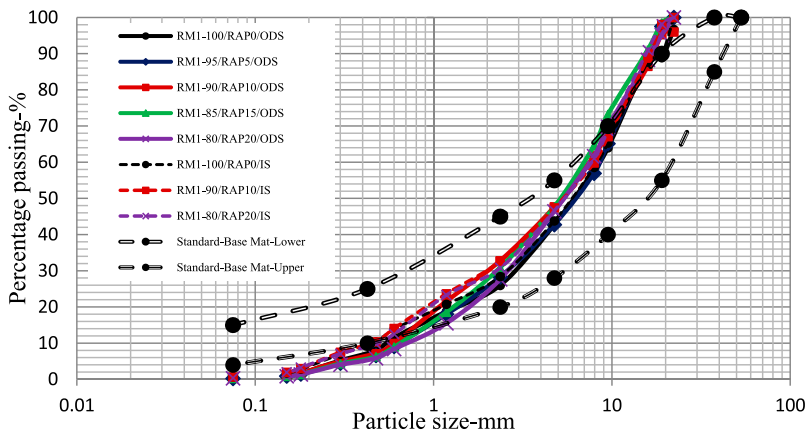


Figure 4. Particle size distribution curves of the “Oven-dried samples (ODSs) and Ignites samples (ISs)” with minimum and maximum curves of standard base layer materials.

show relatively higher coarser particles than ISs. The furnace temperature of 540°C has removed the bitumen coat of the RAP particles. Further, the sticky and conglomerate particles are easily segregated under such high temperature. Therefore, PSD curves illustrate comparatively more fine particles in ISs than in ODSs.

The lower and upper boundary levels of standard base layer material specified by QDTMR were drawn in both figures for the comparison. Two figures show that all the samples are unlike the standard specification and do not fulfil the required amount of coarser fraction as well as fines (< 0.425 mm). A greater percentage (> 50%) of materials is laid between 0.425 and 10.00 mm indicating low coarser and finer fractions and high amount of medium-size particles. This adversely affects the strength of the materials in two ways when they are compacted in a pavement structure. (1) Lack of coarser aggregates builds poor grain-to-grain contact and decreases the shear resistance due to low stiffness. (2) Lack of fines in materials leads to poor compaction with more unfilled voids, thereby deforming readily when increasing the load. The shear strength and stiffness of the compacted specimens decrease with more medium-size particles due to the increase in surface area in an equal volume.

Table 4. Physical properties of RAP mixed with RCA samples of three test series.

Test series	Sample name	LL (%)	PI (%)	LS (%)	FI (%)	OMC (%)	MDD (t/m ³)
NODS	RM1-100/RAP0	23	6.8	Around 1%	11	9.4	1.764
	RM1-95/RAP5	23	5.2		–	9.6	1.745
	RM1-90/RAP10	22	7.7		11	8.8	1.763
	RM1-85/RAP15	22	6.4		–	9.0	1.770
	RM1-80/RAP20	22	7.3		11	9.7	1.778
ODS	RM1-100/RAP0	21	5.4	Around 1%	12	13.2	1.748
	RM1-95/RAP5	25	7.1		–	13.2	1.785
	RM1-90/RAP10	24	7.4		11	13.7	1.785
	RM1-85/RAP15	23	7.2		–	13.3	1.789
	RM1-80/RAP20	23	6.8		12	12.9	1.789
IS	RM1-100/RAP0	18.8	–	Around 1%	–	9.4	1.808
	RM1-90/RAP10	19.3	–		–	8.4	1.788
	RM1-80/RAP20	17.7	–		–	7.5	1.807
Standard granular pavement material	Max: 25 (MainRoads, 2010b)	Max: 6 (MainRoads, 2010b)	3.5% (MainRoads, 2010b)	Max: 35 (MainRoads, 2010b)	8–15 (Arulrajah, Piratheepan, Disfani, & Bo, 2013)	> 1.79 (Arulrajah et al., 2013)	

Note: Max = Maximum.

Gradation of the blended samples could be modified by adding fines and coarser particles to meet the specifications of base layer materials. However, these samples can exhibit relatively better strength and performance characteristics due to the presence of residual cement fines in RCA.

Physical properties

Physical properties of the RAP-mixed RCA samples of the three test series are summarised in Table 4. Plastic properties of the samples were presented with LL, PI and LS test results. LL values of NODSs and ODSs are varying in a small range with almost similar results and do not appear the effect of oven temperature on ODSs. The influence of RAP is not significant since the amount of finer particles (> 0.425 mm) in RAP is very low. According to the PSD curve of RAP material in Figure 2, the portion of fines (< 0.425 mm) in RAP is about 10%. Further, RAP materials represent 0–20% by weight in RCA samples. Therefore, RAP contributes a negligible amount of fines on RCA samples and insufficient to affect on plastic properties of RAP-mixed RCA samples. However, the LL of the ISs was slightly lower than the samples of NODS and ODS test series. It was difficult to conduct PL test on the fines of ISs due to the presence of non-cohesive fines, thus no PI values. It was appeared a mineralogical change of the fines of materials after ignition at 540°C.

The LLs of the samples are within the range of the standard limit of high-quality base layer materials recommended by QDTMR. The PI values are deviating around the maximum limit. However, the samples of NODS and ODS are within the range of high-quality crushed aggregates such as Rhyolite (PI = 6) and crushed Hornfels (PI = 8) (Jameson et al., 2010). The adequate plastic properties of the RAP mixed with RCA samples avoid the excess deformations at the compacted state and reflect their stability as granular pavement materials (Rizvi et al., 2010). Fines with plastic properties positively affect on the strength gaining of compacted RCA than natural crushed rocks as some of conventional aggregates are non-plastic (Horpibulsuk, Suddepong, Chamket, & Chinkulkijniwat, 2013).

The LS of the specimens indicates almost similar values around 1% which is below the maximum standard limit 3.5%. The results suggest that sample preparation temperature and the presence of RAP in RCA have no significant effect on the linear contraction. Therefore, the low shrinkage property guarantees low swell potential of the blended RCA samples and avoids the damages to the pavement structures that could be caused by shrinking and swelling when going through wet and dry climate seasons.

The FI was determined only in six specimens and did not require conducting for all the samples since it exhibited similar values. The presence of RAP in RCA has not affected since the FI depends on the shapes of the materials used in parent concretes and parent asphalt layers. Further, the impact of crushing at the recycling process has not significantly affected to be produced more flaky shape particles. The obtained FI values are well below the maximum limit of standard specification. The particles of the samples are thus not accepted as flaky shape and have a desirable particle shape for the pavement material. Therefore, the test results illustrated that the particle shape does not work in support to break down under heavy compaction loads at the construction and under traffic loads (Voung et al., 2008).

The results of the proctor compaction test exhibited a minor impact of RAP likewise similar values of MDDs of 13 samples, varying in a small range of 1.745–1.808 t/m³. Mixing of RAP up to 20% in RCA and the sample preparation temperature did not significantly affected on the MDD values. However, the values of MDDs are lower than high-quality crushed rocks such as Hornfels (2.32 t/m³), Limestone (2.34 t/m³), Rhyolite (2.34 t/m³) (Jameson et al., 2010). Lack of high-quality crushed aggregates and lack of coarser materials lead to lower the densities in blended samples. Tatsuoka, Tomita, Iguchi, and Hirakawa (2013) investigated the properties of RCA with respect to the level of compaction and observed a high strength of well-compacted RCA similar to the natural aggregates. Therefore, it could be expected high strength characteristics of RCA when meet their corresponding maximum dry densities under the well compaction state. In contrast, OMC values revealed high water demand of RCA than high-quality crushed rocks such as Hornfels (6.5%), Limestone (6.5%) and Rhyolite (5.85%) (Jameson et al., 2010). The presence of cement mortar increases the demand of water at the compaction. The presence of the RAP materials in the samples was insignificant on the OMC values. However, the sample preparation temperature shows a significant effect on OMCs of the ODSs.

The ODSs exhibited higher OMC than NODSSs. It can be expected to scatter the conglomerate particles with evaporation of water during the oven drying and facilitate more surface area to absorb more water. However, ISS showed low OMC values than ODSs. It was appeared a mineralogical change in the particles to reduce water demand after being subjected to 540°C temperature. However, the OMC values of all the specimens are above the average than the standard materials. The high water demand adversely affects on the RCAs not to be recommended for the applications in arid zones where the water sources are scarce (Padmini et al., 2009).

Strength characteristics

Strength characteristics of the RCA samples were evaluated with TPF value test, CBR and UCS tests.

TPF value test

TPF value test was conducted only on six samples since a large quantity of materials were required for a single test. TPF values of the tested specimens and their wet/dry strength variation values are shown in Figure 5 and Table 5, respectively.

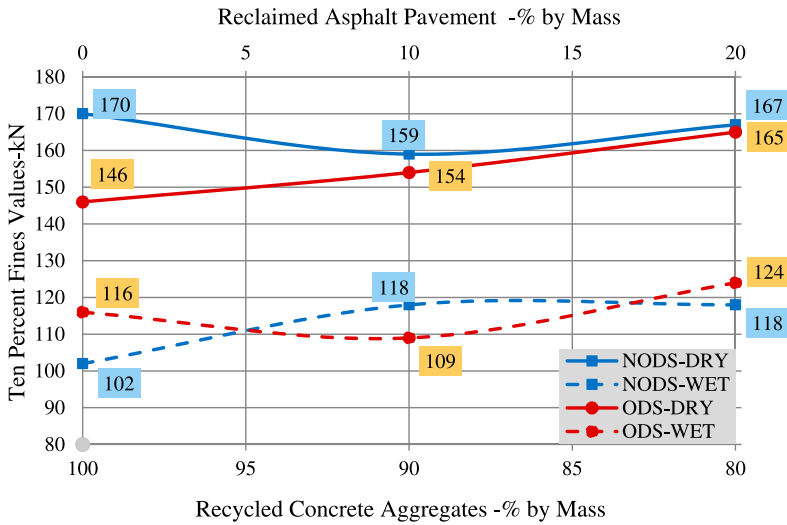


Figure 5. Ten percent fine (TPF) values at dry and wet conditions.

Table 5. Wet/dry strength variation values of TPF test.

Sample name	Ten Percent Fines Value; Wet/Dry strength variation (%)	
	NODS	ODS
RM1-100/RAP0	40	21
RM1-95/RAP5	26	29
RM1-90/RAP10	26	29
RM1-85/RAP15	29	25
RM1-80/RAP20	29	25

The obtained TPF values at the wet condition were always lower than the dry condition since excess water absorption weakens the bond of adhering mortar around the aggregates and separate from the attached aggregates. The effect of RAP was negligible on the TPF results since the standard particle size for the TPF test is 9.5–13.2 mm. The presence of particles in the above range is less than 4% in RAP materials (see PSD curve of RAP in Figure 2) and this further reduces when the maximum mixed portion of RAP is 20% in RCA.

The TPF values of the samples were above 100 kPa and exhibit the ability to sustain an appreciable load against crushing and abrasion. The QDTMR, Australia has included the TPF values as one of the specifications for pavement materials. According to them, the required minimum TPF values at the wet condition lie between 115 and 135 kN for the high-quality pavement materials and their specifications for the maximum wet/dry strength variation are 30–40% (MainRoads, 2010b). The obtained TPF values for the RCA specimens were observed below and above the minimum margin of standard specifications. The results did not show a regular correlation with neither the amount of RAP portion nor the sample preparation temperature. The main reason for the inconsistency results was the conglomerate particles and the adhering cement mortar around the aggregates which are easily crushed and contribute more fines instead of crushing the aggregates while load increases on the specimens. Therefore, the required load to produce the 10% of fines affected by the existing quantity of cement mortar attached in aggregates and the presence of hardened mortar in the test samples. It is thus difficult to assess the crushing resistance of

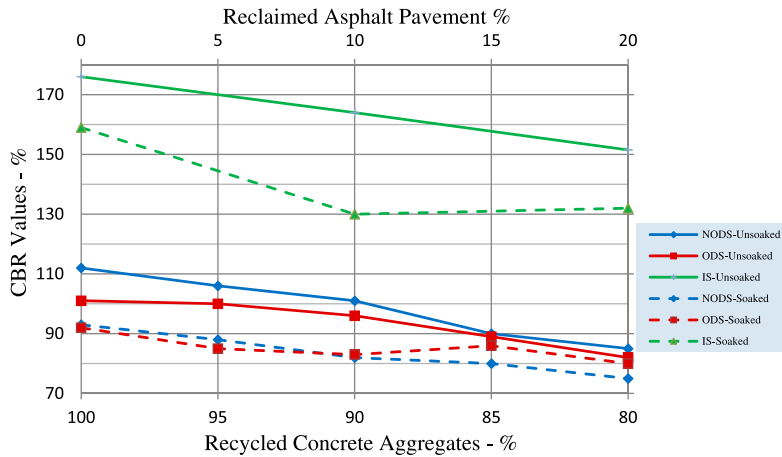


Figure 6. Unsoaked and soaked CBR values of the samples in three test series.

RCA with the TPF value test. Therefore, evaluation of RCA based on TPF test results is not reliable.

California bearing ratio

The load-bearing capacity of the samples in three test series was examined by the CBR index, under unsoaked and soaked conditions.

Unsoaked CBR. Figure 6 shows the unsoaked and soaked CBR values together for the 13 samples of three test series. The results show up a common trend in the three test series, which was a slight decrease in CBR indices with the increase in RAP in crushed concrete. This can be explained by three aspects:

- (1) Cement fines in crushed concrete aggregates react with water and harden the mixture of recycled aggregates. When the RAP replaces the RCA, the re-cementing process is weakened resulting in low stiffness due to the decrease in cement fines.
- (2) The quantity of coarser particles is decreased with the replacement of RCA by RAP. RAP presents more medium-size particles; consequently, more surface area available in an equal volume of specimen and cause more shearing by facilitating high deformation with an increase in the load.
- (3) The bitumen-coated RAP particles build poor interlocking between particles due to slipping the hydrophobic wet surfaces. This leads to weakening the load imparting to the contiguous aggregates; thus, lower the stiffness and then load sustained.

The sample preparation temperature has not considerably affected on CBR indices of NODSs and ODSs. However, unsoaked CBR values of ODSs are slightly behind those of the NODSs. The ODSs demand more water for compaction since the oven temperature (105°C) expands the porous between the recycled aggregates and adhering mortar. The retained water in the porous spaces leads for a slight reduction of the shear strength and marginally reduces the load bearing in ODSs than in NODSs.

The ignited samples (ISs) showed outstanding results in CBR. This explicates two attributes of the RCA after the ignition at 540°C:

- (1) Ignited temperature removed all the organic composition and consequently reduced the demand of water for the compactions at MDDs. Compacted specimens with low moisture contents strengthen the inter-particle bonds by increasing the shear resistance.
- (2) Mineralogical change of materials (particularly, in fines) after the ignition, facilitated for high degree of compaction and greater stiffness.

The above two factors caused to enhance the load sustained of the ignited materials by increasing the frictional resistance of the compacted specimens.

Soaked CBR. The soaked CBR values of materials are the key index for the selection of materials in pavement designing (MainRoads, 2010b). The water immersed samples simulate a water content adjustment roughly equivalent to which would occur if the water table rises during the rainy season. Therefore, evaluation of CBR indices of inundated samples is highly recommended to assess the strength of pavement materials.

The soaked CBR results of the samples of three test series are shown in Figure 6. Low CBR values are exhibited under the soaked condition than the unsoaked condition due to the increase in pore-water pressure in the compacted specimens. The presence of water weakens the shear strength by reducing the inter-particle bonding and consequently demotes the load-bearing capacity.

The effect of RAP on the soaked CBR values followed a similar behaviour to the unsoaked values. The maximum CBR was achieved by the samples with 100% crushed concrete (RM1-100/RAP0) and gradually decreased with the increase in RAP. It was a common behaviour of decreasing the CBR values with increasing the RAP in three test series. The possible reasons were discussed under the unsoaked CBR results which were similarly applied under the soaked condition as well. Samples in the NODS and ODS test series indicated almost similar soaked CBR values. Therefore, drying the samples in an oven at a temperature of 105°C prior to the sample preparation does not expose a significant impact on the results of soaked CBR.

ISs showed an appreciable CBR value alike the unsoaked test series. However, the achieved moisture content of RM1-90/RAP10/IS sample was greater than the corresponding OMC. It was 110% of OMC, thereby the CBR result was affected by excess water and consequently low CBR value was resulted in the RM1-90/RAP10/IS sample than in the RM1-80/RAP20/IS sample. However, greater soaked CBR values could be predicted in the RM1-90/RAP10/IS sample than the obtained value at the exact OMC level.

The RM1-100/RAP0 sample which represents clean RCA (no constituents) depicted the highest CBR value at the unsoaked and soaked conditions in three test series. The bearing capacity marginally reduced with the increase in RAP portion up to 15%. The trend of decreasing the load sustained is appeared with the substitution of RAP over 15% in RCA. The samples showed appreciable soaked CBR values when compared with the standard specifications of QDTMR shown in Table 6. Except the RM1-80/RAP20 sample, all samples in the three test series exhibited soaked CBR values higher than 80%, which is the lower margin for base layer materials in high traffic volume roads. Therefore, conclusion can be made with the soaked CBR results that the load sustained by RCA as a base layer material is unlikely to be a problem in high traffic volume roads when RAP materials present up to about 15%.

Unconfined compressive strength

The UCS is a comparable indicator for the stabilised and bound pavement materials. Even though it is not a common test for untreated pavement aggregates, the blended RCA samples were tested to investigate the binding effect of residual cement in load sustained under unconfined conditions.

Table 6. Standard pavement material groups with CBR specifications and descriptions (MainRoads, 2010b).

Material type	Pavement layer	CBR (soaked) – minimum	Description
2.1	Base	80	Roads with design traffic equal to or exceeding 10^6 equivalent standard axle (ESA) repetitions
2.2	Base	60	Roads with design traffic less than 10^6 ESAs
2.3	Subbase	45	Roads with design traffic equal to or exceeding 10^6
2.4	Subbase	35	Roads with design traffic less than 10^6 ESAs
2.5	Lower Subbase	15	Roads with design traffic less than 10^6 ESAs

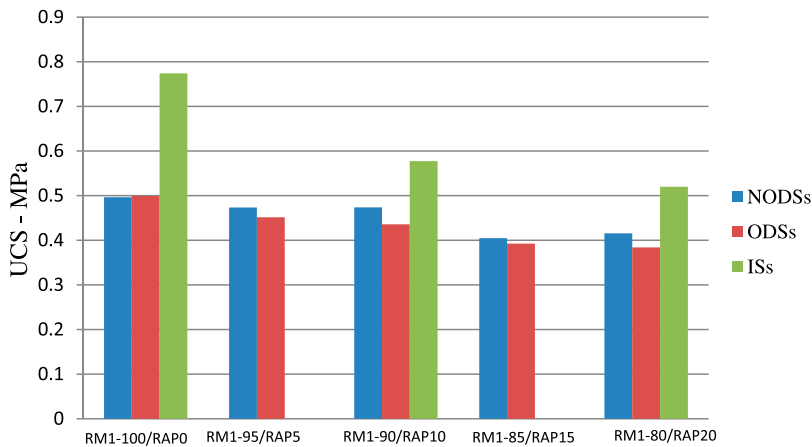


Figure 7. Summary of unconfined compressive strength of the RAP-mixed RCA samples.

Figure 7 presents the results of UCS values of the samples of the three tests series. The residual cement has reacted as a binder to enhance the inter-particle bonding in compacted specimens. Conversely, the presence of residual cement decreases with the increase in the RAP portion and the compressive strength was gradually decreased with the increase in the RAP. Additions of the bitumen-coated asphalt particles further reduce the cohesion due to the slippery surfaces. The hydrophobic wet surfaces of bitumen-coated particles reduced the UCS values by decreasing the inter-particle friction and shear resistance.

The results of NODSs and ODSs did not show a significant variation and it emphasised the negligible impact of material drying in the oven prior to the UCS tests. Curing periods of the water-mixed samples and compacted specimens might be softening the effect of the sample preparation temperature (105°C). In contrast, the ISs behaved as binder-treated materials. They appeared to have greater inter-particle bonds due to the high friction of inter-locking particles. The sample RM1-100/RAP0 in IS series has the highest UCS value comparatively all the other samples. The target OMC value of this sample could not be achieved and it was less than OMC (about 85% OMC) even though other samples were tested at their corresponding OMC values. However, it was revealed the potential of having greater UCS values of the RCA specimens below the corresponding OMCs.

The residual cements subject to the re-cementation process and behave as a binder agent in the compacted RCA specimens and showed high load sustained under unconfined conditions.

The required minimum UCS value for the modified stabilised materials for base layer material is 0.7 MPa, after the addition of cementitious binders, lime or chemical binders (Australia, 2008a). The modified materials are assumed to behave like bound granular materials with the maximum 1.5 MPa limit on the UCS (Andrews & Group, 2006). The first three samples of NODS and ODS test series (RM1-100/RAP0, RM1-95/RAP5 and RM1-90/RAP10) had their UCS over 0.45 MPa and appeared the possibility to improve their UCS beyond 0.7 MPa by adding the least quantity of binders as required. The next two samples, RM1-85/RAP15 and RM1-80/RAP20, were exhibited appreciable UCS values around 0.4 MPa even the RAP portion is greater. The UCS values indicate the potential use of RCA as a promising stabilised pavement material with the least quantity of binding agents. Improvement of the compressive strength of RCA by increasing the binding properties could be done by adding the chemicals such as Calcium phosphate compound which were introduced as environmental friendly binding agents for the unbound construction materials (Kawasaki & Akiyama, 2013).

Conclusions

This study aimed to evaluate the potential use of RCA materials when the RAP presents as a constituent for the unbound pavement constructions. Classification tests and strength property tests were conducted on the RCA samples by varying the presence of RAP portion on the samples. The laboratory test programme was conducted under three test series for a detailed characterisation of the RAP-mixed RCA samples. The three test series based on the sample preparation temperature examined the effect of the “temperature-sensitive bitumen-coated asphalt materials” on the test results of blended samples. The obtained results were then compared with the specifications of pavement materials specified by DTMR, Queensland, Australia which are shown in Table 6. The established conclusions based on the classification and strength property tests are summarised below:

- The PSD curves exhibit slightly less coarse and fine particles in RCA than the specifications of standard granular base layer material. However, the obtained PSD of the specimens did not adversely affect on the compaction and strength properties of the RCA samples.
- Plastic properties of RCA samples are comparable to the high-quality granular pavement materials.
- The RCA specimens indicated low MDDs and high OMCs relative to the high-quality granular pavement materials. Samples demand more water at the MDDs when they dried in the oven at 105°C.
- The TPF values of RCA specimens did not show a regular correlation, with neither the amount of RAP portion nor the sample preparation temperature. The TPF results are affected on the attached cement mortar in the aggregates and conglomerate mortar particles. Therefore, the TPF value test is not recommended for evaluating the RCA materials.
- The UCS values of the samples at corresponding OMCs were gradually decreased with the increase in the RAP portion from 0% to 20% in RCA. However, RCA samples showed appreciable UCS due to the effect of cement mortar.
- The high strength of RCA samples was indicated by greater CBR values at their corresponding OMCs and MDDs. RCA samples showed the tendency to lower the soaked CBR when the RAP beyond the 15%. Therefore, the substitution of RAP exceeding 15% leads to lower the load-bearing capacity below the standard limit of high-quality base layer material.

- RCA with RAP up to 15% is technically viable to use as a base material in unbound structural layers of high traffic volume roads. RCA with 20% of RAP is appropriate to use either as a subbase material in high volume roads (equivalent standard axle, ESA > 10⁶) or as a base layer material in low volume roads (ESA < 10⁶) where the required minimum soaked CBR is 60%.
- The ISs exhibited remarkable strength properties at the CBR and UCS tests. The ignited temperature (540°C) altered the consistency of the materials and significantly increased the shear strength of ISs at their corresponding OMCs and MDDs. Therefore, great load-bearing capacity was observed due to the high compaction and stiffness.

Acknowledgements

The authors acknowledge Queensland University of Technology (QUT) for giving the opportunity to conduct the research. The authors gratefully acknowledge Alex Fraser Queensland for providing Recycled Concrete Aggregates (RCA) for this experimental program. Queensland Department of Transport and Main Roads (QDTMR) and Brisbane City Council (BCC) are greatly acknowledged for providing some of the testing facilities. Acknowledge Glen's support.

References

- Andrews, B., & Group, A. (2006). Guide to pavement technology part 4d: Stabilized materials. In R. t. a. t. authorities (Ed., pp. 3–6). Sydney: Austroads incorporated, Robell house.
- Arabani, M., & Azarhoosh, A. R. (2012). The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures. *Construction and Building Materials*, 35(0), 1–7.
- Arulrajah, A., Piratheepan, J., Ali, M. M. Y., & Bo, M. W. (2012). Geotechnical properties of recycled concrete aggregate in pavement sub-base applications. *Geotechnical Testing Journal*, 35(5), 743–751.
- Arulrajah, A., Piratheepan, J., Bo, M. W., & Sivakugan, N. (2012). Geotechnical characteristics of recycled crushed brick blends for pavement sub-base applications. *Canadian Geotechnical Journal*, 49, 796–811.
- Arulrajah, A., Piratheepan, J., & Disfani, M. M. (2014). Reclaimed asphalt pavement and recycled concrete aggregate blends in pavement subbases: Laboratory and field evaluation. *Journal of Materials in Civil Engineering*, 26(2), 349–357.
- Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2013). Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering*, 25(8), 1077–1088.
- Australia, C. C. A. (2008a). *Stabilized and modified road base materials*. Retrieved from <http://www.concrete.net.au/publications>
- Australia, C. o. S. (1998). *Methods of testing soils for engineering purposes*. Method 6.1.1: Soil strength and consolidation tests-determination of the California Bearing Ratio of a soil-standard laboratory method for a remoulded specimen. AS 1289.6.1.1.
- Australia, C. o. S. (2002). *Methods of testing soils for engineering purposes*. Method 3.9.1: Soil classification tests-determination of the cone liquid limit of a soil. AS 1289.3.9.1-2002.
- Australia, C. o. S. (2003). *Methods of testing soils for engineering purposes*. Method 5.1.1: Soil compaction and density tests-determination of the dry density/moisture content relation of a soil using standard compactive effort. AS 1289.5.1.1.
- Australia, C. o. S. (2008b). *Methods for preparation and testing of stabilized materials*. Method 4: Unconfined compressive strength of compacted materials. AS 5101.4-2008.
- Australia, C. o. S. (2009a). *Methods of testing soils for engineering purposes*. Method 3.6.1: Soil classification tests-determination of the particle size distribution of a soil-standard method of analysis by sieving. AS 1289.3.6.1-2009.
- Australia, C. o. S. (2009b). *Methods of testing soils for engineering purposes*. Method 3.2.1: Soil classification tests-determination of the plastic limit of a soil-standards method. AS 1289.3.2.1-2009.
- Behiry, A. E. A. E.-M. (2013). Evaluation of steel slag and crushed limestone mixtures as subbase material in flexible pavement. *Ain Shams Engineering Journal*, 4(1), 43–53.
- Bhuiyan, M. Z. I., Ali, F. H., & Salman, F. A. (2014). Application of recycled concrete aggregates as alternative granular infills in hollow segmental block systems. *Soils and Foundations*, 55(2), 296–303.

- Boudlal, O., & Melbouci, B. (2009). *Study of the behavior of aggregates demolition by proctor and CBR tests. Paper presented at the material, design, construction, maintenance, and testing of pavement*, Changsha, Hunan, China.
- Evangelista, L., & De Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 29(5), 397–401.
- Gobianandh, V., & Jayakody, S. (2016). *Evaluate the strength of cement treated recycled construction and demolition aggregates as a pavement material. Paper presented at the 7th International Conference on Sustainable Built Environment*, Kandy, Sri Lanka.
- Horpibulsuk, S., Suddeepong, A., Chamket, P., & Chinkulkijniwat, A. (2013). Compaction behavior of fine-grained soils, lateritic soils and crushed rocks. *Soils and Foundations*, 53(1), 166–172.
- Hyder Consulting, E. C. S. R. S. (2011). Construction and demolition waste status report. In e. Department of sustainability, water, population and communitie & Q. d. o. e. a. r. management (Eds.). Melbourne, Australia.
- Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44(0), 464–476.
- Jameson, G., Voung, B., Moffatt, M., Martin, A., & Lourensz, S. (2010). *Assessment of rut resistance of granular bases using the repeated load triaxial test*. Sydney: Austroads Ltd.
- Jayakody, S., Gallage, C., & Kumar, A. (2014). Assessment of recycled concrete aggregates as a pavement material. *Geomechanics and Engineering, An International Journal*, 6(3), 235–248.
- Jiménez, J. R., Ayuso, J., Agrela, F., López, M., & Galvín, A. P. (2012). Utilisation of unbound recycled aggregates from selected CDW in unpaved rural roads. *Resources, Conservation and Recycling*, 58(0), 88–97.
- Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research*, 33(5), 703–711.
- Kawasaki, S., & Akiyama, M. (2013). Enhancement of unconfined compressive strength of sand test pieces cemented with calcium phosphate compound by addition of various powders. *Soils and Foundations*, 53(6), 966–976.
- Kazmee, H., Tutumluer, E., & Beshears, S. (2017). Using accelerated pavement testing to evaluate reclaimed asphalt pavement materials for pavement unbound granular layers. *Journal of Materials in Civil Engineering*, 29(2), 04016205-1–13.
- Kou, S.-c., Poon, C.-s., & Agrela, F. (2011). Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. *Cement and Concrete Composites*, 33(8), 788–795.
- Leite, F. d. C., Motta, R. d. S., Vasconcelos, K. L., & Bernucci, L. (2011). Laboratory evaluation of recycled construction and demolition waste for pavements. *Construction and Building Materials*, 25(6), 2972–2979.
- MainRoads, Q. D. o. (2009). Pavement design manual. In D. o. MainRoads (Ed.), *Supplement to 'part 2: Pavement structural design' of the Austroads guide to pavement technology* (pp. 163–165). Brisbane: Queensland Department of Main Roads.
- MainRoads, Q. D. o. T. a. (2010a). Main roads technical standard: MRTS35 - recycled materials for pavements. In Q. D. o. T. a. MainRoads (Ed.), *Technical specification* (pp. 5–15). Brisbane: Queensland Department of Main Roads.
- MainRoads, Q. D. o. T. a. (2010b). Main roads technical standards: MRTS05 - unbound pavements. In Q. D. o. T. a. MainRoads (Ed.), *Technical specification* (pp. 4–16). Brisbane: Queensland Department of Main Roads.
- MainRoads, Q. D. o. T. a. (2011a). *Material testing manual*. Test method Q308A, Binder content and aggregate grading of asphalt (refluxing). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011b). *Material testing manual*. Test method Q308D-2002, Binder content and aggregate grading of asphalt (Ignition oven). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011c). *Material testing manual*. Test method No Q109A-1996, Apparent particle density of soil (Fine fraction). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011d). *Material testing manual*. Test method Q214A-1996, Particle density and water absorption of aggregates (Fine fraction). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.

- MainRoads, Q. D. o. T. a. (2011e). *Material testing manual*. Test method Q214B-1996, Particle density and water absorption of aggregates (Coarse fraction). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011f). *Material testing manual*. Test method Q201-2012, Flakiness index. Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011g). *Material testing manual*. Test method No.Q106-1989 Linear shrinkage. Department of Transport and Main Roads, Queensland Government. Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011h). *Material testing manual*. Test method No.Q205A-1986, Determination of the ten percent fines value (Dry). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- MainRoads, Q. D. o. T. a. (2011i). *Material testing manual*. Test method No.Q205B-1986, Determination of the ten percent fines value (Wet). Brisbane: Department of Transport and Main Roads, Queensland Government, Australia.
- Manzi, S., Mazzotti, C., & Bignozzi, M. C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites*, 37(0), 312–318.
- Mills-Beale, J., & You, Z. (2010). The mechanical properties of asphalt mixtures with recycled concrete aggregates. *Construction and Building Materials*, 24(3), 230–235.
- Padmini, A. K., Ramamurthy, K., & Mathews, M. S. (2009). Influence of parent concrete on the properties of recycled aggregate concrete. *Construction and Building Materials*, 23(2), 829–836.
- Poon, C. S., & Chan, D. (2006). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials*, 20, 578–585.
- Poon, C. S., Qiao, X. C., & Chan, D. (2005). The cause and influence of self-cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base. *Waste Management*, 26, 1166–1172.
- Rahman, M. A., Imteaz, M., Arulrajah, A., & Disfani, M. M. (2014). Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials. *Journal of Cleaner Production*, 66, 75–84.
- Rao, A., Jha, K. N., & Misra, S. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling*, 50, 71–81.
- Rizvi, R., Tighe, S., Henderson, V., & Norris, J. (2010). Evaluating the use of recycled concrete aggregate in pervious concrete pavement. *Transportation Research Record: Journal of the Transportation Research Board*, 2164, 132–140.
- Shen, W., Zhou, M., Ma, W., Hu, J., & Cai, Z. (2009). Investigation on the application of steel slag–fly ash–phosphogypsum solidified material as road base material. *Journal of Hazardous Materials*, 164(1), 99–104.
- Taha, R., Al-Harthy, A., Al-Shamsi, K., & Al-Zubeidi, M. (2002). Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases. *Journal of Materials in Civil Engineering*, 14(3), 239–245.
- Tam, V. W. Y. (2009). Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. *Journal of Cleaner Production*, 17, 688–702.
- Tatsuoka, F., Tomita, Y.-I., Iguchi, Y., & Hirakawa, D. (2013). Strength and stiffness of compacted crushed concrete aggregate. *Soils and Foundations*, 53(6), 835–852.
- Vegas, I., Ibañez, J. A., San José, J. T., & Urzelai, A. (2008). Construction demolition wastes, Waelz slag and MSWI bottom ash: A comparative technical analysis as material for road construction. *Waste Management*, 28(3), 565–574.
- Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling*, 74(0), 101–114.
- Voung, B., Jameson, G., Sharp, K., & Fielding, B. (2008). *Guide to pavement technology part 4A: Granular base and subbase materials*. (D. o. T. a. M. Roads, Trans.). Sydney: Austroads Incorporated.