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Evaluation of Mechanical Properties of Recycled Material for Utilization in Asphalt Mixtures

Farzaneh Tahmoorian [1,*], Bijan Samali [1], Vivian W.Y. Tam [2,3] and John Yeaman [4]

1 Centre for Infrastructure Engineering, Western Sydney University, Kingswood, NSW 2751, Australia; B.Samali@westernsydney.edu.au
2 School of Computing, Engineering, and Mathematics, Western Sydney University, Kingswood, NSW 2751, Australia; V.Tam@westernsydney.edu.au
3 College of Civil Engineering, Shenzhen University, Shenzhen 518060, China
4 Faculty of Science, Health, Education and Engineering, University of Sunshine Coast, Sippy Downs, Queensland 4556, Australia; jyeaman@usc.edu.au
* Correspondence: F.Tahmoorian@westernsydney.edu.au; Tel.: +61-2-4736-0866

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Abstract: With an expanding world, the demand for extensive road networks is increasing. As natural resources become scarce, the necessity of finding alternative resources has led to the idea of applying recycled material to pavement construction including asphalt pavements. Amongst all asphalt components, aggregate constitutes the largest part of asphalt mixtures. Therefore, the utilization of recycled material for aggregate will represent an important opportunity to save virgin material and divert material away from landfills. Because of the large amount of construction waste generation around the world, using recycled construction aggregate (RCA) in asphalt mixtures appears to be an effective utilization of RCA. However, as aggregate plays an important role in the final performance of the asphalt mixture, an understanding of their properties is essential in designing an asphalt mixture. Therefore, in this research, the properties of RCA have been evaluated through laboratory investigations. Based on the test results, it is required that combination of RCA with some other targeted waste materials be considered in asphalt mixture. This paper presents the results of an experimental study to evaluate the RCA properties as an alternative for virgin aggregate in asphalt mixture under different percentages and combination with other aggregates, such as reclaimed asphalt pavement (RAP) and basalt.

Keywords: asphalt; basalt; reclaimed asphalt pavement; recycled construction aggregate; recycled aggregate; pavement

1. Introduction

The increasing amount of waste all over the world has shown that effective measures have to be implemented to reduce their negative environmental impact. Landfilling of waste is not a solution, due to danger of leaching and soil impregnation with potential subsequent contamination of underground water.

On the other hand, there are important sustainability benefits associated with the use of recycled material in pavement industry. Recycling helps the environment by reducing resource extraction and the use of virgin material, thereby reducing energy and water use, reducing harmful gas emissions and helping reduce waste to landfills. Buying recycled products also in some cases can reduce cost.

Therefore, the idea of using recycled material in pavement construction has attracted the attention of many researchers (e.g., Karlsson and Isacsson, 2006; Huang et al., 2007; Widyatmoko, 2008; Ahmedzade and Sengoz, 2009; Rafi et al., 2011; Khan and Gundaliya, 2012; Menaria and Sankhla, 2015;

Chandh and Akhila, 2016) in the pavement industry to investigate feasibility of the application of some of waste materials as alternative material in pavement construction [1–8].

Among different layers of flexible pavements, asphalt surface layer plays a fundamental role in flexible pavement structure systems as it should withstand varying traffic loads and constantly changing environmental conditions. Moreover, the asphalt surface layer is critical for safe and comfortable driving. Due to the composition nature of asphalt surface layer, application of solid waste in asphalt layer reduces not only environmental issues associated with waste disposal but also the demand for virgin aggregate which will subsequently result in cost savings and economic advantages, representing a value add application for waste material.

However, the selection of waste material to be used for pavement construction, particularly asphalt surface layer, is of high importance as the application of waste should not adversely influence the structural and functional aspects of the pavements [9–12].

Among different asphalt components, coarse aggregate properties are identified by the researchers (e.g., Vavrik, 2009; Zaniewski and Srinivasan, 2004; Husain, 2014; Al-Mosawe et al., 2015) as the second most important parameter after gradation for the performance of hot-mix asphalt (HMA) because coarse aggregate often forms the skeleton of the asphalt structure and transfers traffic and environmental loads to the underlying base, subbase, and subgrade layers [13–16]. Therefore, the behaviour and performance of asphalt mixture and eventually the asphalt surface layer are directly affected by the material properties and composition of this aggregate skeleton. In fact, the low stiffness of the asphalt mixtures and the excessive rutting in hot-mix asphalt (HMA) pavement surfaces are often attributed to the poor asphalt mixture designs which is primarily controlled by the asphalt binder and aggregate properties [17]. Therefore, except for the fine mixes, the selection of coarse aggregate greatly influences the asphalt layer behaviour.

In addition, since the aggregate represents the major portion of the asphalt mix, from the viewpoint of environmental preservation and effective use of resources, a comprehensive understanding of the engineering properties of the recycled aggregate can provide enormous benefits. Recognizing this fact, the reported studies and research on the utilization of recycled aggregate such as reclaimed asphalt pavement (RAP), recycled construction aggregate (RCA), recycled glass, etc. have increased all over the world over the past two decades [18–29]. Among the recycled aggregates that can be utilized in asphalt mixture, RCA obtained from construction and demolition waste constitute a major part of generated solid waste as a result of renovation and construction projects. Referring to literature survey (e.g., Arulrajah, 2012; Bennert et al., 2000; Blankenagel, 2005; Conceicao et al., 2011; Jayakody et al., 2014; Jimenez et al., 2012; Papp et al., 1998; Nataatmadja and Tan, 2001), although RCA has been used effectively as a base course and subbase course material [30–37], but, few research studies (e.g., Celaura et al., 2010; Hossain et al., 1993; Pereira et al., 2004; Rebbechi and Green, 2005; Berthelot et al., 2010; Wu et al., 2013) have reported the use of RCA in hot-mix asphalt [38–42]. Accordingly, in this research, the properties of RCA have been thoroughly evaluated through the laboratory investigation and tests. The results of these tests have showed that RCA has some shortcomings in satisfying design requirements as asphalt mixtures aggregate, in terms of some properties such as absorption and wet/dry strength variation. Therefore, utilization of RCA in asphalt mixture on its own, can result in less efficient asphalt mixtures and it is, hence, required that combination of RCA with some other targeted and acceptable waste materials and aggregates in certain percentages be considered in designing the asphalt mixture. Accordingly, RCA, RAP, and basalt have been considered as coarse aggregate in this research, and various tests have been conducted on each individual component and in combination. The paper will demonstrate the results of the conducted tests leading to the selection of most acceptable combination of aggregates for designing asphalt mixtures.

It should be noted that because of the diversity in quality and composition of the recycled construction aggregates, this research has been performed on aggregate samples which are collected from a recycling unit in Sydney over a period of one year.

2. Aggregate Properties and Their Relationship to Asphalt Performance

The high proportion of aggregate materials in volumetric design of asphalt mixes inherently links aggregate properties to the strength, stiffness, and generally the performance of the asphalt surface layer.

Because of the important impact of aggregate on the properties of asphalt mixture, a better understanding of the aggregates characteristics is essential in selecting the appropriate materials to optimize the asphalt mixture for strength and durability, and subsequently design a pavement with enough resistance to permanent deformation and cracking.

The most important physical and mechanical characteristics of aggregates include size and gradation, shape and angularity, surface texture, absorption, particle density, durability, toughness and hardness, resistance to polishing, soundness, cleanliness and the deleterious materials contained. Many research studies (e.g., Dahir, 1979; Brown et al., 1989; Brown and Bassett, 1990; Button et al., 1990; Elliot et al., 1991; Krutz and Sebaaly, 1993; Oduroh et al., 2000; Chen and Liao, 2002; Sengoz et al., 2014; Masad et al., 2009; Wu and King, 2011) have been conducted to link the properties of the aggregates to the performance of asphalt concrete pavement [43–53].

The results of these studies have shown that the physical and mechanical properties of the aggregates significantly affect the performance of the asphalt pavements.

Referring to the literature and the research conducted to relate aggregate properties and HMA performance, Figure 1 is generated to illustrate a generalized pattern and a summary of the effects of aggregate properties on the asphalt performance. The figure is the result of extensive literature review during the course of this research study and could be used by the practicing engineers as well as researchers to further improve their understanding of the effects of aggregate constituents on asphalt system performance. The reported relations and correlations shown in Figure 1 exemplify the complexities of mix design issues and considerations involved. This is certainly not unexpected considering the heterogeneity of the asphalt mixes. For example, as shown in this figure, different aggregate properties affect different aspects of asphalt mixture performance, which consequently define pavement service life. Accordingly, in order to design asphalt mixtures with longer service lives and lower production and maintenance costs, the aggregate must have appropriate characteristics.

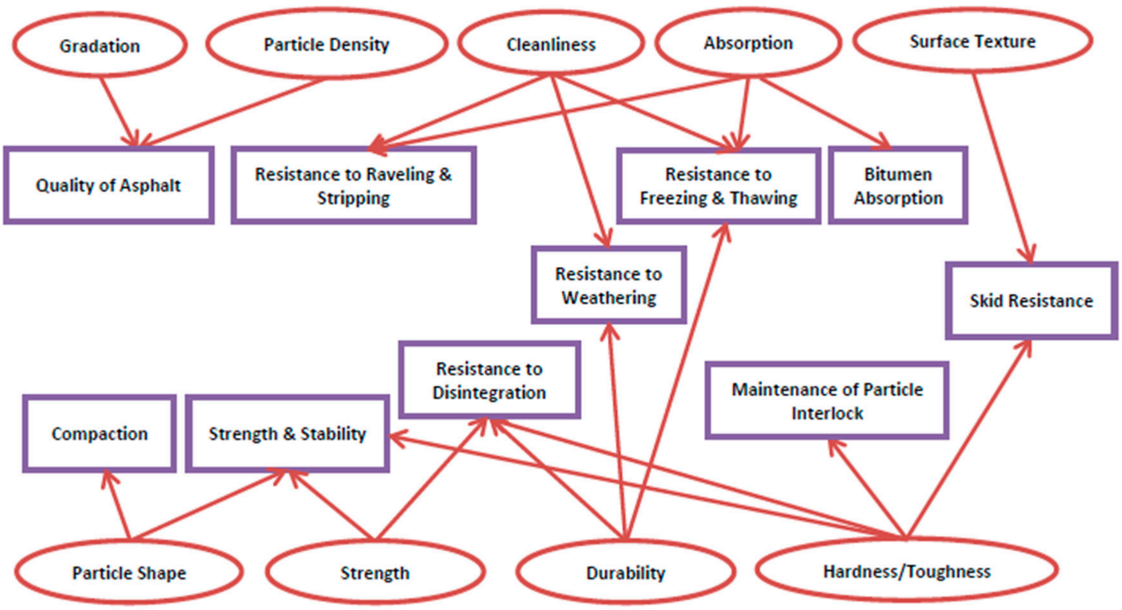


Figure 1. A Summary of the Effects of Aggregate Properties on the Asphalt Performance.

Therefore, the following section describes the experimental work carried out on selected coarse aggregates in order to evaluate the feasibility of using RCA as a part of coarse aggregates in asphalt mixture, and to produce an economical and sustainable asphalt mixture with adequate strength and good workability.

3. Experimental Work

3.1. Materials

In the present study, RCA, RAP, and basalt passing through 20 mm and retained on 4.75 mm I.S sieve have been used throughout the experiments. RAP material used in this research was stockpiled RAP collected from Boral Asphalt Plant (Prospect, NSW, Australia) which is generated from milling and being used in their asphalt projects. It was plant-screened material retained on 19 mm sieve size. The crushed virgin basalt aggregate was obtained from a local supplier. These virgin aggregates were transported from a local quarry (Nepean Quarries) in the vicinity of Sydney. In addition, RCA was collected from a local recycling centre called Revesby Recycling Centre (Revesby, NSW, Australia), a licensed waste facility and transfer station which accepts all construction and demolition waste from both the residential and commercial waste streams. In this centre, RCA is produced through the first sorting process for removing of contaminants such as wood, plastic, metal and glass, then crushing of construction wastes, and finally screening for removal of contaminants such as reinforcement, wood, plastics and gypsum.

3.2. Laboratory Tests

This section reports the laboratory investigation on RCA, RAP and basalt, in order to obtain comprehensive information and data of their properties and to compare these properties with the requirements specified in the standards as well as with the properties of the virgin aggregate. The key properties investigated in this experimental study are presented in Table 1.

Table 1. The Key Properties Investigated in the Experimental Study.

Property	Test Method	Test Name
Gradation and particle size distribution	AS 1141.11.1	Particle Size Distribution (Sieving Method)
Flakiness index of aggregate	AS 1141.15	Flakiness Index
Proportion of misshapen particles	AS 1141.14	Particle Shape by proportional calliper
Water absorption of aggregate	AS1141.6.1	Particle Density and Water Absorption of coarse aggregate
Variation in strength of aggregate in wet/dry condition	AS 1141.22	Wet/Dry Strength Variation
Particle density of aggregate	AS 1141.6.1	Particle Density and Water Absorption of coarse aggregate
Strength and crushing value of aggregate	AS 1141.21	Aggregate Crushing Value
Percentage of weak particles in coarse aggregate	AS 1141.32	Weak particles (including clay lumps, soft and friable particles) in coarse aggregates

In addition, based on the test results on the individual aggregates, necessary tests were conducted on different combinations of these aggregates. The results of these tests are shown in the following sections. It should be noted that three samples were performed for each test and the average of the three samples was reported as the test result.

3.2.1. Particle Size Distribution Test

The gradation of aggregate to be used in asphalt mixtures are evaluated through Particle Size Distribution Test (Figure 2).

Figure 2. Aggregate Gradation by Particle Size Distribution Test.

This test is conducted in accordance with AS 1141.11.1 (2009) and the gradation curves obtained from this test for different coarse aggregates considered in this research, including RCA, RAP and basalt, are shown in Figure 3.

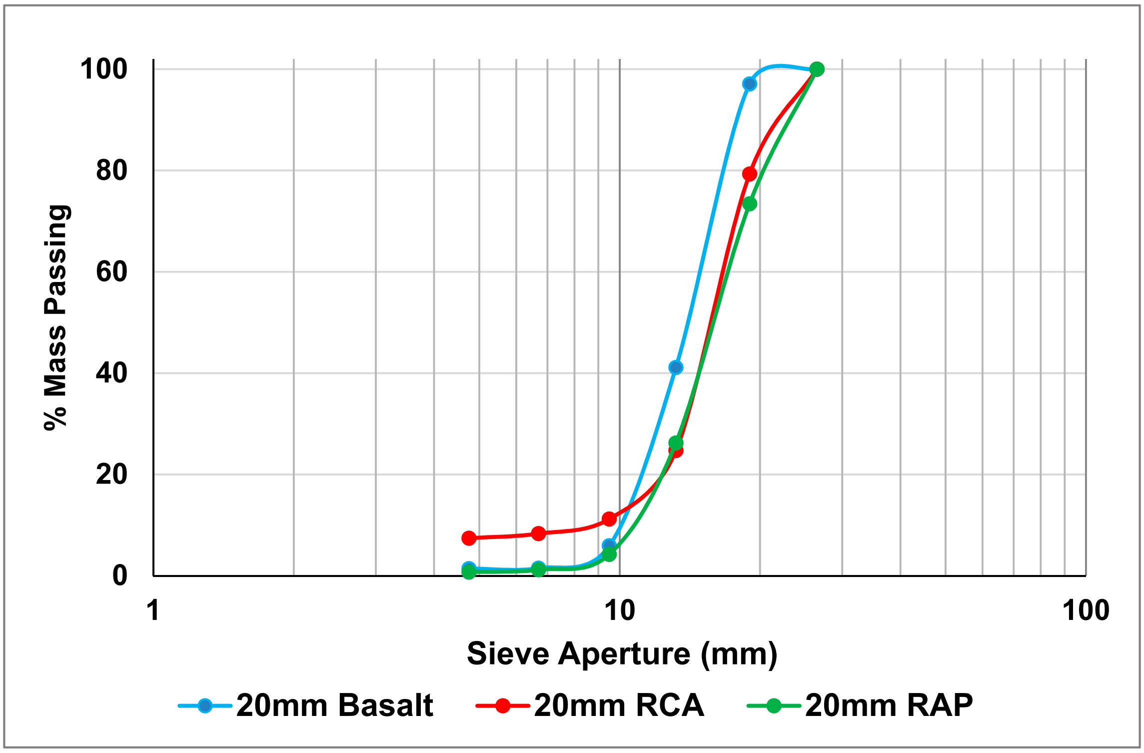


Figure 3. The Results of Particle Size Distribution Test for Coarse Aggregate; RCA: recycled construction aggregate; RAP: reclaimed asphalt pavement.

3.2.2. Particle Shape Test

The results of the studies on aggregate have shown that the aggregate physical shape properties significantly affect both the strength and stability of asphalt mixes [54]. Therefore, in order to design asphalt mixtures with long service lives, the aggregate must have the proper gradation and shape. The particle shape of aggregate substantially influences the mechanical stability of asphalt mix. The presence of excessive flaky and elongated particles is undesirable in asphalt mixtures as they tend to break down during the production and construction, and thus affect the durability of HMAs. Therefore, it is preferable to have rough and angular aggregates rather than smooth and round aggregates.

In this study, the proportion of misshapen aggregates, including the flat particles, elongated particles and, flat and elongated particles found in coarse aggregate is evaluated through the Particle Shape Test (Figure 4). The particle shape test is carried out by proportional caliper, using a 2:1 calliper ratio and based on AS 1141.14 (2007). The results of this test on three samples for each aggregate type (i.e., RCA, RAP and basalt) and the average value are given in Table 2.

Figure 4. Classification of Aggregate Based on Particle Shape Test.

Table 2. The Results of Particle Shape Test for Coarse Aggregates and Misshapen Percentage Limits for Dense Graded Asphalt Based on Australian Standards.

Sample Number	Misshapen Particles (%)			Australian Standards Misshapen Percentage Limits (%)
	RCA	RAP	Basalt	
Sample 1	5.3	12.0	19.4	35% (max) For heavy and very heavy traffic
Sample 2	6.2	7.7	18.3	
Sample 3	7.0	8.7	17.3	
Average Misshapen Particles Percentage (%)	**6.2**	**9.5**	**18.3**	

As presented in Table 2, basalt materials show more of misshapen particles than RAP and RCA while still below the 35% limit of the Australian standard.

3.2.3. Flakiness Index Test

Some aggregates, on account of their shape, would be unsuitable for asphalt mixture as they would have low potential for developing inter-particle interlock. The percentage by mass of this type of aggregates, namely flaky aggregates is determined by the most commonly used test, called Flakiness Index Test (Figure 5). In this test, the flakiness index is determined by direct measurement using a special slotted sieve, from the ratio of the mass of material passing the slotted sieve to the total mass of the size fraction.

Figure 5. Conducting Flakiness Index Test for Coarse Aggregate.

The flakiness index test is performed based on AS 1141.15 (1999) and the results of this test on three samples for each aggregate type (i.e., RCA, RAP and basalt) and the average flakiness index for each aggregate type are given in Table 3.

Table 3. The Results of Flakiness Index Test for Coarse Aggregates and Flakiness Index Limits for Dense Graded Asphalt Based on Australian Standards.

Sample Number	Flakiness Index (%)			Australian Standards Flakiness Index Limits (%)
	RCA	RAP	Basalt	
Sample 1	5.6	12.8	21.3	25% (max) For heavy and very heavy traffic
Sample 2	8.1	10.1	21.1	
Sample 3	7.1	8.4	14.7	
Average Flakiness Index (%)	**6.9**	**10.4**	**19.0**	

The results of flakiness index test shows that RCA has less flakiness index than basalt and RAP which can positively affect the inter-particle interlock in asphalt mixture.

3.2.4. Particle Density and Water Absorption Test

The absorption is an indication of porosity in aggregate which demonstrates the pore structure of the aggregate. In asphalt mixtures, a porous aggregate increases the binder absorption, resulting in a dry and less cohesive asphalt mixture. In addition, the particle density of the aggregate is an essential property of the aggregate which plays an important role in the whole procedure of asphalt mix design. Therefore, in this research, the particle density and water absorption test is conducted on coarse aggregates (i.e., RCA, RAP and coarse basalt) based on the procedure described in AS 1141.6.1 (2000), as presented in Figure 6.

In this test, the amount of water which a dried sample will absorb is measured. This test is performed on three trials and the related test results on RCA, RAP and basalt are given in Table 4, under apparent, dry, and saturated surface dry (SSD) conditions.

Figure 6. Evaluation of Particle Density of Coarse Aggregate.

Table 4. The Results of Particle Density and Water Absorption Test on Coarse Aggregates and Water Absorption Limits for Dense Graded Asphalt Based on Australian Standards.

Sample Name	Apparent Particle Density (g/cm^3)	Particle Density on a Dry Basis (g/cm^3)	Particle Density on a SSD Basis (g/cm^3)	Water Absorption (%)	Australian Standards Limits for Water Absorption (%)
RCA 1	2.375	2.211	2.352	6.39	2% (max) For heavy and very heavy traffic
RCA 2	2.375	2.211	2.352	6.39	
RCA 3	2.361	2.214	2.349	6.12	
Average Values for RCA	**2.370**	**2.212**	**2.351**	**6.30**	
RAP 1	2.539	2.422	2.468	1.89	
RAP 2	2.544	2.437	2.479	1.72	
RAP 3	2.540	2.433	2.475	1.73	
Average Values for RAP	**2.541**	**2.431**	**2.474**	**1.78**	
Basalt 1	2.635	2.528	2.568	1.60	
Basalt 2	2.630	2.521	2.562	1.64	
Basalt 3	2.654	2.542	2.584	1.67	
Average Values for Basalt	**2.640**	**2.530**	**2.571**	**1.64**	

The results of the particle density and water absorption test on different coarse aggregates (i.e., RCA, RAP and basalt) and their average value, as presented in Table 4, indicate the high absorption of RCA in comparison with RAP and basalt. The RCA water absorption exceeds the limit set by the Australian Standard.

As this research aims to investigate the feasibility of the application of RCA as a recycled material for potential partial replacement of coarse virgin aggregate (basalt) in asphalt mixtures, the particle density and water absorption test is also conducted on the mix of coarse aggregates (i.e., RCA, RAP and coarse basalt) considering different percentages of these materials. Such undertaking was needed in order to get a better understanding of an acceptable range of mix proportions in terms of water absorption.

The results of Particle Density and Water Absorption test on six different mixes of RCA, RAP and basalt and the average water absorption and particle density for each mix are given in Table 5. Despite the fact that above mixes (except when there is no RCA) have water absorption of more than 2%, the use of RCA is still a viable option as discussed in Section 3.3.

Table 5. The Results of Particle Density and Water Absorption Test for the Mix of Coarse Aggregates.

Sample Name		Apparent Particle Density (g/cm^3)	Particle Density on a Dry Basis (g/cm^3)	Particle Density on a SSD Basis (g/cm^3)	Water Absorption (%)
75% Basalt and 25% RCA	1	2.579	2.394	2.466	2.98
	2	2.589	2.406	2.476	2.94
	3	2.601	2.420	2.489	2.88
Average Values for 75% Basalt and 25% RCA		**2.590**	**2.407**	**2.477**	**2.93**
50% Basalt and 50% RCA	1	2.520	2.296	2.385	3.86
	2	2.535	2.322	2.406	3.62
	3	2.527	2.313	2.397	3.65
Average Values for 50% Basalt and 50% RCA		**2.527**	**2.310**	**2.396**	**3.71**
25% Basalt and 75% RCA	1	2.477	2.224	2.326	4.57
	2	2.471	2.207	2.313	4.84
	3	2.480	2.234	2.333	4.44
Average Values for 25% Basalt and 75% RCA		**2.476**	**2.222**	**2.324**	**4.62**
80% Basalt and 20% RAP	1	2.727	2.607	2.651	1.68
	2	2.719	2.600	2.644	1.68
	3	2.724	2.596	2.643	1.80
Average Values for 80% Basalt and 20% RAP		**2.723**	**2.601**	**2.646**	**1.72**
25% Basalt and 25% RCA and 50% RAP	1	2.579	2.411	2.476	2.70
	2	2.581	2.401	2.471	2.89
	3	2.585	2.412	2.479	2.78
Average Values for 25% Basalt and 25% RCA and 50% RAP		**2.582**	**2.408**	**2.475**	**2.79**
25% Basalt and 50% RCA and 25% RAP	1	2.606	2.380	2.466	3.63
	2	2.592	2.356	2.447	3.85
	3	2.596	2.355	2.447	3.94
Average Values for 25% Basalt and 50% RCA and 25% RAP		**2.598**	**2.364**	**2.453**	**3.81**

3.2.5. Crushing Value Test

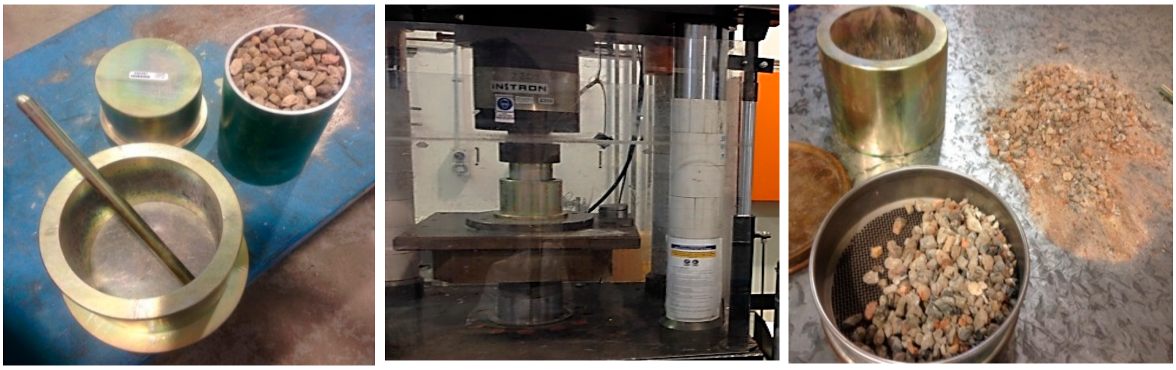
Aggregates used in road construction should be strong enough to resist crushing under traffic wheel loads [55]. The strength of the coarse aggregates can be evaluated by the Aggregate Crushing Value Test. In this test, the aggregate were crushed by a compression testing machine with a load rate of 40 kN/min to reach the peak load of 400 kN. The percentage of particles produced when the aggregate is crushed under this load and which pass a 2.36 mm sieve is called Aggregate Crushing Value.

The aggregate crushing value provides a relative measure of resistance to crushing under a gradually applied compressive load. To achieve a high quality pavement, it is preferred to utilize the aggregate possessing low crushing value.

In this research, the crushing value of RCA, RAP and basalt is assessed through the Aggregate Crushing Value Test in accordance with AS 1141.21 (1997), as presented in Figure 7. This test was performed in two trials, as required in the standard, and the related test results on RCA, RAP and basalt and the average crushing values for each aggregate type are given in Table 6.

Table 6. The Results of Aggregate Crushing Value Test for Coarse Aggregates and Crushing Value Limits for Dense Graded Asphalt Based on Australian Standards.

Sample Number	Crushing Value (%)			Australian Standards Aggregate Crushing Value Limits (%)
	RCA	RAP	Basalt	
Sample 1	29.53	7.04	9.32	35% (max) For heavy and very heavy traffic
Sample 2	28.88	7.76	8.51	
Average Crushing Value (%)	**29.21**	**7.40**	**8.91**	



(a) (b) (c)

Figure 7. Crushing Value Test for Coarse Aggregates. (**a**) apparatus to crush aggregate; (**b**) compression machine ; (**c**) aggregates after crushing and sieving.

3.2.6. Weak Particle Test

The aggregate cleanliness refers to the presence of foreign or deleterious substances such as soft particles, weak and weathered materials, friable particles, clay lumps, and organic matters. The presence of these materials in the used aggregate can lead to stripping and ravelling in HMAs, as these materials adversely affect the bond between the aggregate and asphalt, and subsequently the stability of the pavement structure. Moreover, these substances disintegrate under traffic loading and wetting and drying cycles.

The cleanliness of aggregate can be evaluated based on the Weak Particles Test. In this test, the percentage of weak particles in coarse aggregate is determined. These particles will deform under finger pressures when wet. In this study, the percentage of weak particles in RCA, RAP and basalt are determined through the Weak Particle Test in accordance with AS 1141.32 (2008).

The weak particle test is conducted on two samples, as specified in the related standard, and the results of this test on RCA, RAP and basalt and the average weak particle percentage for each type of aggregate are presented in Table 7. The test results show that RCA and basalt have higher percentage of weak particles. However, all aggregates still meet the Standard's requirements.

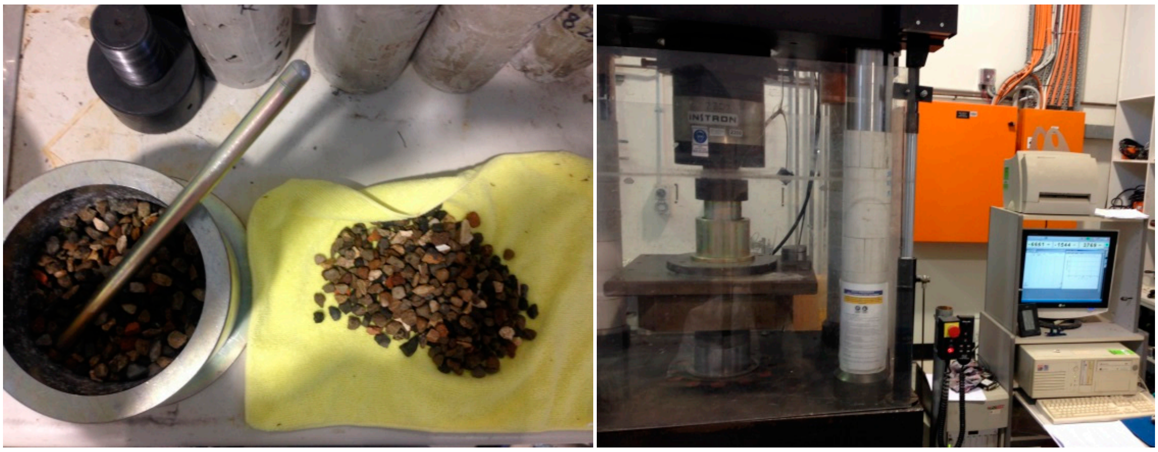
Table 7. The Results of Weak Particle Test for Coarse Aggregates and Weak Particles Percentage Limits for Dense Graded Asphalt Based on Australian Standards.

Sample Number	**Weak Particles (%)**			**Australian Standards Aggregate Crushing Value Limits (%)**
	RCA	**RAP**	**Basalt**	
Sample 1	0.21	0.05	0.29	1% (max) For heavy and very heavy traffic
Sample 2	0.25	0.03	0.16	
Average Weak Particles Percentage (%)	**0.23**	**0.04**	**0.23**	

3.2.7. Wet/Dry Strength Variation Test

Strength is an important aggregate property which is related to the satisfactory resistance to crushing under the roller during construction, and adequate resistance to surface abrasion under traffic [56]. Therefore, aggregates used in pavement construction should be strong enough to resist crushing during mixing, laying process, compaction, consolidation and during its service life period when they are subjected to various loads applied by traffic [57].

In this research, the variation in strength of aggregate is evaluated by conducting the Wet-Dry Strength Variation Test on RCA, RAP and basalt in accordance with AS 1141.22 (2008), as shown in Figure 8.



(**a**) (**b**)

Figure 8. Conducting the Wet/Dry Strength Variation Test on Coarse Aggregate. (**a**) apparatus to crush aggregate; (**b**) compression machine.

This test determines the variation in strength of the aggregates tested after drying in an oven and then saturated yet with a dry surface. Based on the available standards, the wet/dry strength variation of less than 35% indicate a durable material but values as high as 60% could be used in undemanding circumstances.

In this research, the wet/dry strength variation test was conducted on the RCA, RAP and basalt fraction passed through 13.2 mm and retained on 9.5 mm I.S sieve. Different loading was used in order to adjust the applied load for providing the fines within the range of 7.5% and 12.5%. The results of these tests for coarse aggregates are illustrated in Figures 9 and 10 under dry condition and saturated surface dry condition (SSD), respectively. The wet and dry strengths can be inferred from the test results shown in these figures. Based on the obtained data, the wet/dry strength variation was calculated as follows:

$$\text{Wet/dry strength variation} = \frac{D - W}{D} \times 100 \quad (1)$$

where D is the dry strength in kilonewtons, and W is the wet strength in kilonewtons.

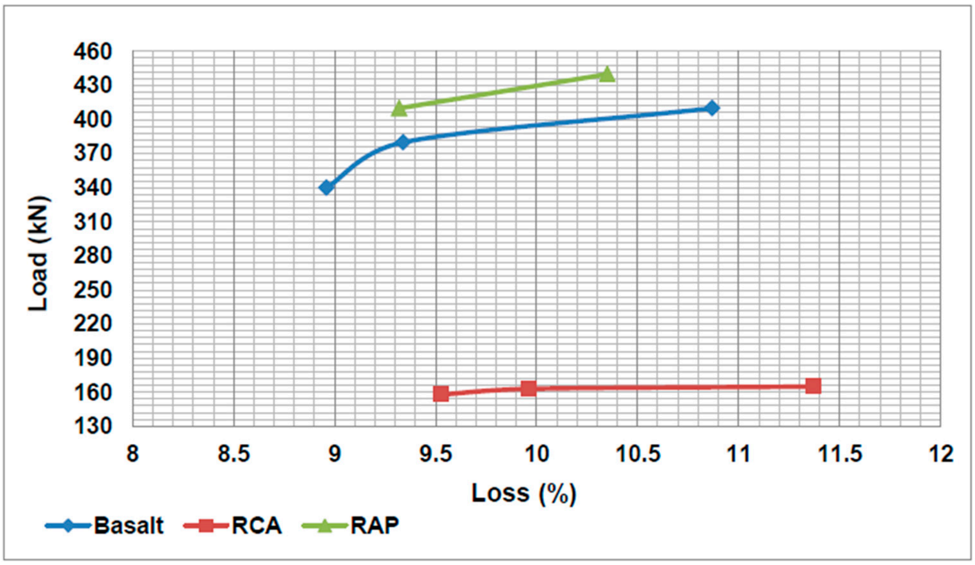


Figure 9. Results of Wet/Dry Strength Test for Coarse Aggregate (Dry Strength).

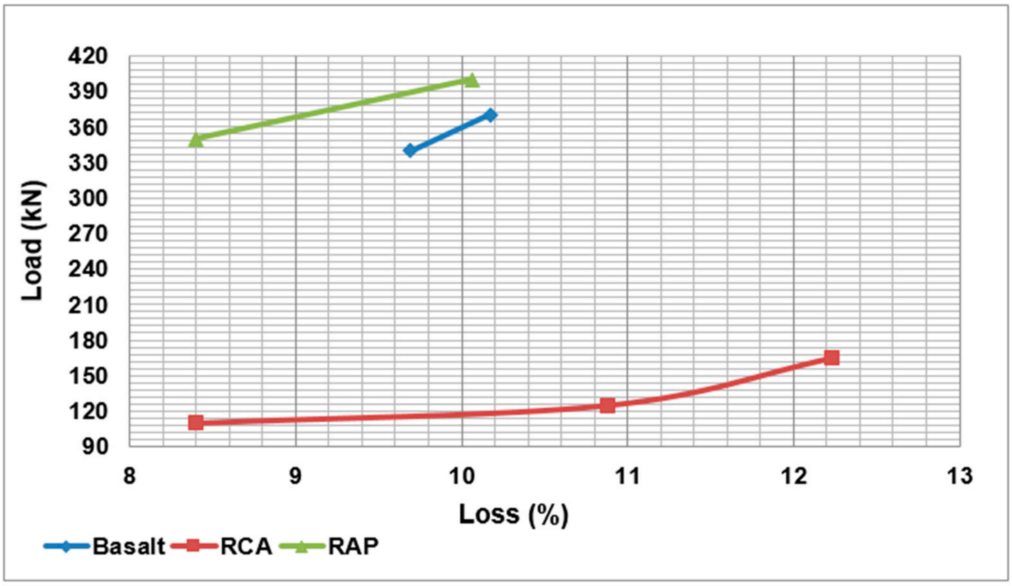


Figure 10. Results of Wet/Dry Strength Test for Coarse Aggregate (Wet Strength).

The results of the calculations for wet strength, dry strength, and wet/dry strength variation for basalt, RAP and RCA are presented in Table 8.

Table 8. The Results of Wet/Dry Strength Variation Test for Aggregates and Strength Limits for Dense Graded Asphalt Based on Australian Standards.

Material	Dry Strength, D (kN)	Wet Strength, W (kN)	Wet/Dry Strength Variation (%)	Australian Standards Wet/Dry Strength Limits (%)
RCA	163.1	119.7	26.6	35% (max) For heavy and very heavy traffic
RAP	429.8	398.2	7.4	
Basalt	392.9	359.4	8.5	

As the results of wet/dry strength test shows, the wet/dry strength variation of RCA is substantially more than the corresponding values for RAP and basalt. Therefore, as mentioned previously, it appears plausible to further investigate the feasibility of the application of RCA for the replacement of part of basalt in asphalt mixtures.

Accordingly, the wet/dry strength variation test was also conducted on different mix of coarse aggregates (i.e., RCA, RAP and coarse basalt) considering different percentages of these materials. Figures 11 and 12 illustrate the results of the wet/dry strength test for several mixes of RCA, RAP and basalt in dry condition and saturated surface dry condition respectively.

Based on the obtained results from these graphs, the wet strength (W) and the dry strength (D) can be determined and subsequently the wet/dry strength variation can be calculated as shown previously. The results of the calculations for wet strength, dry strength, and wet/dry strength variation on different mix of RAP, basalt and RCA are presented in Table 9. The results indicate that all mixes satisfy the maximum 35% limit set by the Australian Standards.

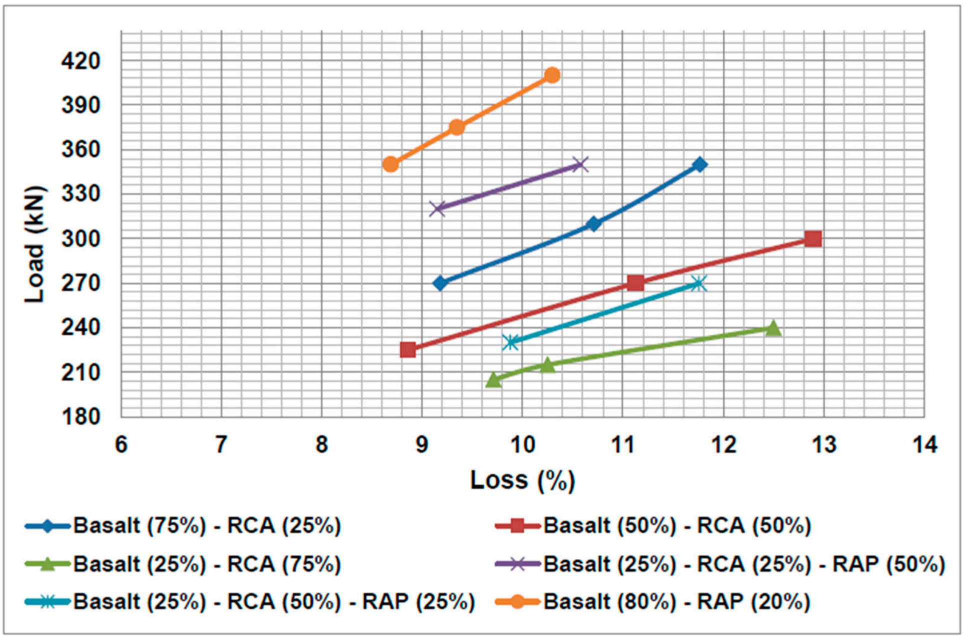


Figure 11. Results of Wet/Dry Strength Test for Mix of Coarse Aggregates (Dry Strength).

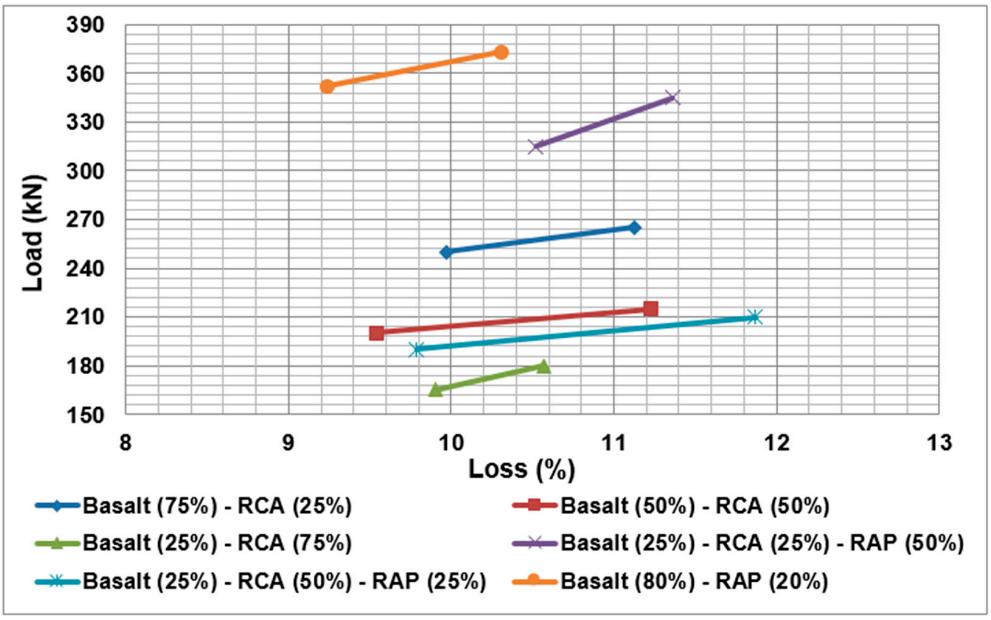


Figure 12. Results of Wet/Dry Strength Test for Mix of Coarse Aggregates (Wet Strength).

Table 9. The Results of Wet/Dry Strength Variation Test for Different Mix of Coarse Aggregates.

Material	Dry Strength, D (kN)	Wet Strength, W (kN)	Wet/Dry Strength Variation (%)	Australian Standards Wet/Dry Strength Limits (%)
Basalt (75%) and RCA (25%)	291.4	250.4	14.1	35% (max) For heavy and very heavy traffic
Basalt (50%) and RCA (50%)	247.6	204.1	17.6	
Basalt (25%) and RCA (75%)	210.4	167.2	20.5	
Basalt (80%) and RAP (20%)	398.9	366.9	8.0	
Basalt (25%), RCA (25%) and RAP (50%)	337.8	296.4	12.3	
Basalt (25%), RCA (50%) and RAP (25%)	232.6	192	17.5	

3.3. Results and Discussions

As presented in the previous sections, in this research, the properties of RCA, RAP, basalt and mix of these aggregates were evaluated by conducting a series of tests. The test results are summarized in Table 10.

Table 10. Summary of the Test Results for the Evaluation of Coarse Aggregate Properties.

Test	Test Method	Aggregate			Typical Limit Based on Australian Standards
		RCA	RAP	Basalt	
Particle Distribution Test	AS 1141.11.1	As presented in relevant Figures and Tables			-
Flakiness Index Test	AS 1141.15	6.91	10.42	19.03	25% (max)
Particle Shape Test	AS 1141.14	6.16	9.47	18.34	35% (max)
Water Absorption	AS 1141.6.1	**6.30**	1.78	1.64	2% (max)
Particle Density	AS 1141.6.1	2.370	2.541	2.640	-
Particle Density on Dry Basis	AS 1141.6.1	2.212	2.431	2.530	-
Particle Density on SSD Basis	AS 1141.6.1	2.351	2.474	2.571	-
Aggregate Crushing Value	AS 1141.21	29.21	7.40	8.91	35% (max)
Weak Particles	AS 1141.32	0.23	0.04	0.23	1% (max)
Wet/Dry Strength Test	AS 1141.22	26.6	7.4	8.5	35% (max)
Wet Strength	AS 1141.22	**119.7**	398.2	359.2	150 kN (min)
Dry Strength	AS 1141.22	163.1	429.8	392.9	-

In addition, to have better comparisons between the aggregate properties, the test results on different aggregates as well as the standard limits are also illustrated in Figure 13.

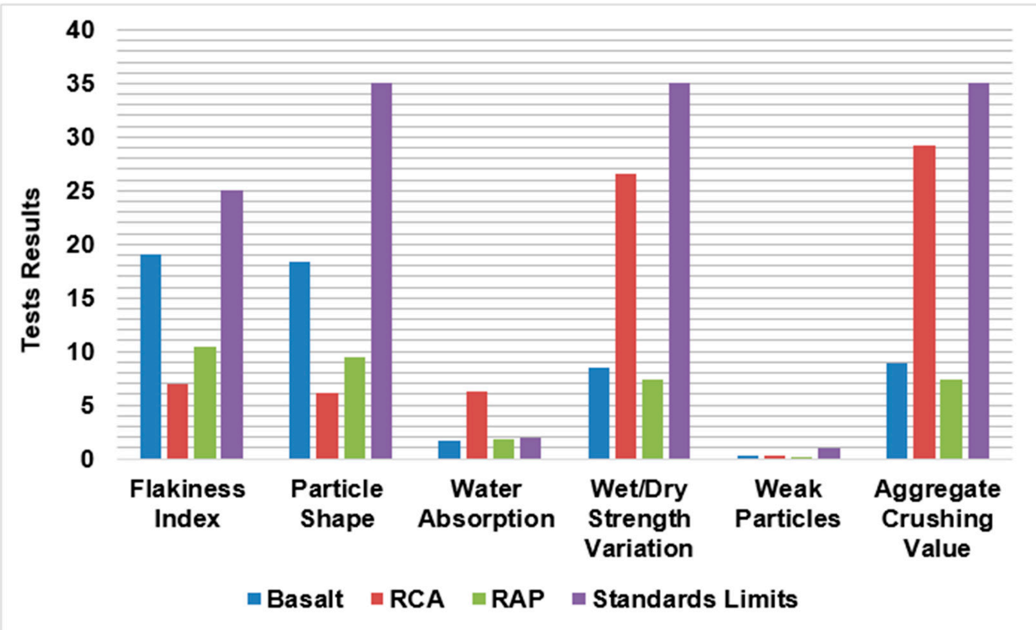


Figure 13. Comparison of Different Aggregate Properties with Standard Limits.

As shown in Figure 13, the results of preliminary tests on coarse aggregates indicate that all properties of RCA, except for water absorption and wet strength (which are shown in bold in Table 10), are within the limits specified by relevant Australian Standards and hence deemed appropriate for use as aggregate in the asphalt mixture. However, for some parameters such as Flakiness Index and Particle Shape which are two dominant characteristics having significant impact on asphalt mixture strength and stability; RCA displays smaller value in comparison with basalt and RAP. This can be one of the strong points of RCA as flakiness index and particle shape are the two important properties for proper compaction, deformation resistance, and workability of asphalt mixture [58].

In addition, as can be observed in Table 10 and Figure 13, the water absorption of RCA is higher than the corresponding value of RAP and basalt and the Australian Standards limit, because it is well known that water absorption requires linked and open cracks in the structure of aggregate and RCA contains cracks due to the crushing processes. Moreover, the great amounts of impurities in RCA can increase the water absorption of RCA. The high water absorption of RCA may result in high bitumen absorption in asphalt mixtures, and hence plays an important role in asphalt mixture design.

Accordingly, since this research aims to investigate the feasibility of the application of RCA for the partial replacement of coarse virgin aggregate (basalt) and in combination with other recycled aggregate (RAP) in asphalt mixtures, the particle density and water absorption tests were conducted on different mix of coarse aggregates while considering different percentages of these materials. The results of these tests are presented in Figure 14.

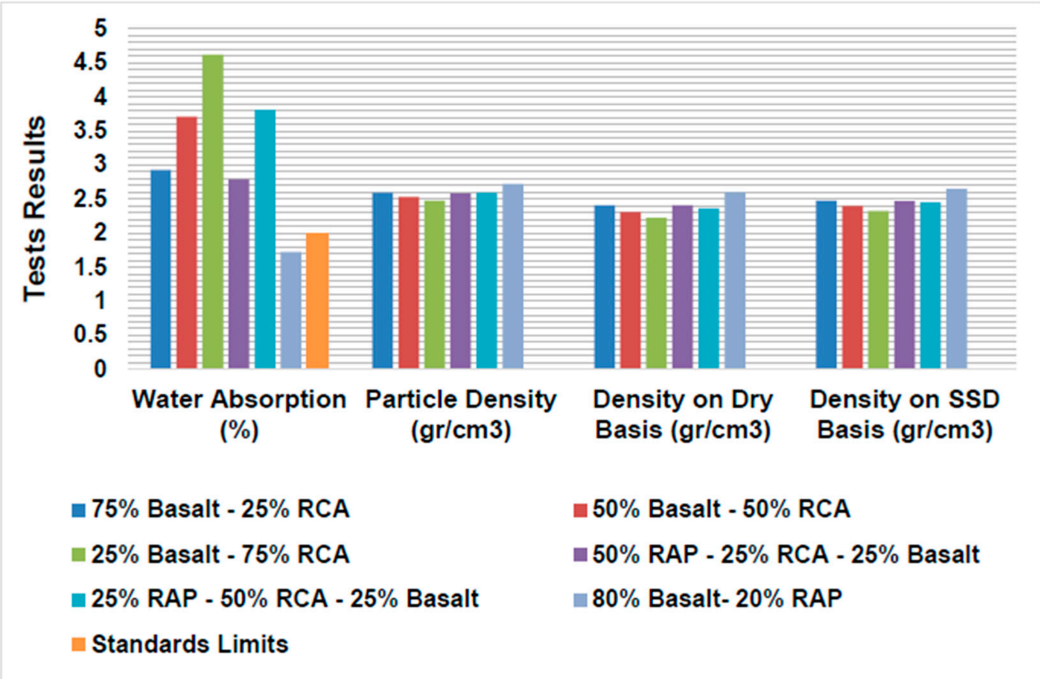


Figure 14. Comparison of Water Absorption and Particle Density of Different Mixes of Coarse Aggregates.

As can be observed in Figure 14, increasing RCA in the mix does not make any substantial change in mix density in comparison with water absorption. In other words, by increasing RCA from 0% to 100% in the mix, the density decreases by 7%, whereas water absorption increases by 74%.

In addition, although wet/dry strength variation of RCA meets the requirements of Australian standards, the test results show that this value is higher than the corresponding value of RAP and basalt. As the wet/dry strength variation is related to the principal mechanical properties which are required for asphalt aggregate, it is of high importance in asphalt mixture design. Therefore, wet/dry strength variation test was also conducted on different mixes of coarse aggregate. Figure 15 shows the comparison of wet strength, dry strength, and wet/dry variation in different mixes of RCA, RAP and basalt.

As illustrated in this figure, the wet/dry strength variation of mix of RCA/basalt increases by increase of the percentage of RCA in the mix, so that the increase of RCA from 0% to 100% will result in 20% increase in wet/dry strength variation. The results of these two tests (i.e., water absorption and particle density test, and wet/dry strength variation test) on mix of coarse aggregates are summarized in Table 11.

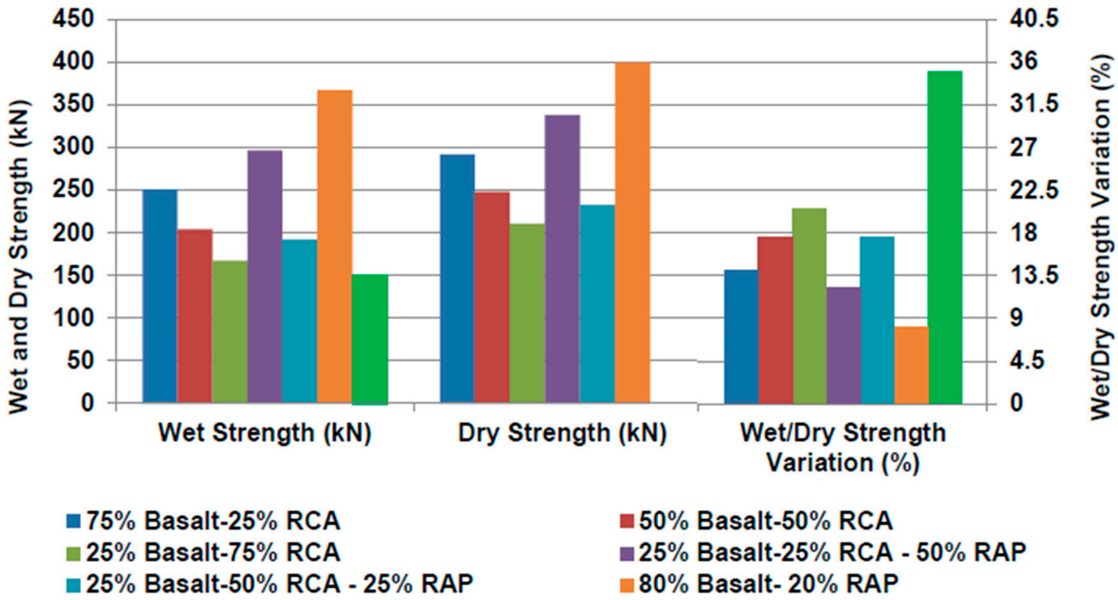


Figure 15. Comparison of the Wet Strength and Dry Strength of Different Mixes of Coarse Aggregates.

Table 11. Summary of Tests Results for Evaluation of Mix of Coarse Aggregates Properties.

Mix	Test Method	Water Absorption	Particle Density	Wet/Dry Strength Variation
Basalt (75%), RCA (25%)	AS 1141.15	2.93	2.590	14.1
Basalt (50%), RCA (50%)	AS 1141.14	3.71	2.527	17.6
Basalt (25%), RCA (75%)	AS 1141.6.1	4.62	2.476	20.5
Basalt (80%), RAP (20%)	AS 1141.6.1	1.72	2.723	8.0
Basalt (25%), RCA (25%), RAP (50%)	AS 1141.21	2.79	2.582	12.3
Basalt (25%), RCA (50%), RAP (25%)	AS 1141.32	3.81	2.598	17.5

The results of tests on mix of coarse aggregate showed that in all cases of RCA ratios, RCA increase causes a decrease in wet and dry strength and an increase in water absorption. This will necessitate the proper selection and optimum combination of RCA and other aggregates.

The coefficient of variation is used as an indication to measure the heterogeniety of test results. The results of calculation of standard deviation (SD) and coefficient of variation (CV) for each set of aggregate mixes are presented in Table 12.

Table 12. Coefficient of Variation and Standard Deviation for Mix of Coarse Aggregates.

Mix	Coefficient of Variation	Standard Deviation
Basalt (100%) + RCA (0%)	2.14	0.035
Basalt (75%) + RCA (25%)	1.71	0.050
Basalt (50%) + RCA (50%)	3.52	0.131
Basalt (25%) + RCA (75%)	4.42	0.204
Basalt (0%) + RCA (100%)	2.47	0.156

As can be observed in Table 12, the coefficient of variation for each data set reveals that the test results dispersion is low and the tests are conducted consistently.

Furthermore, regression analysis is typically applied to the water absorption test results for different combination of RCA and basalt, to show the typical amount of RCA and basalt in a blend to give 2% water absorption which is the standard limit of water absorption based on Australian standards (Figures 16 and 17).

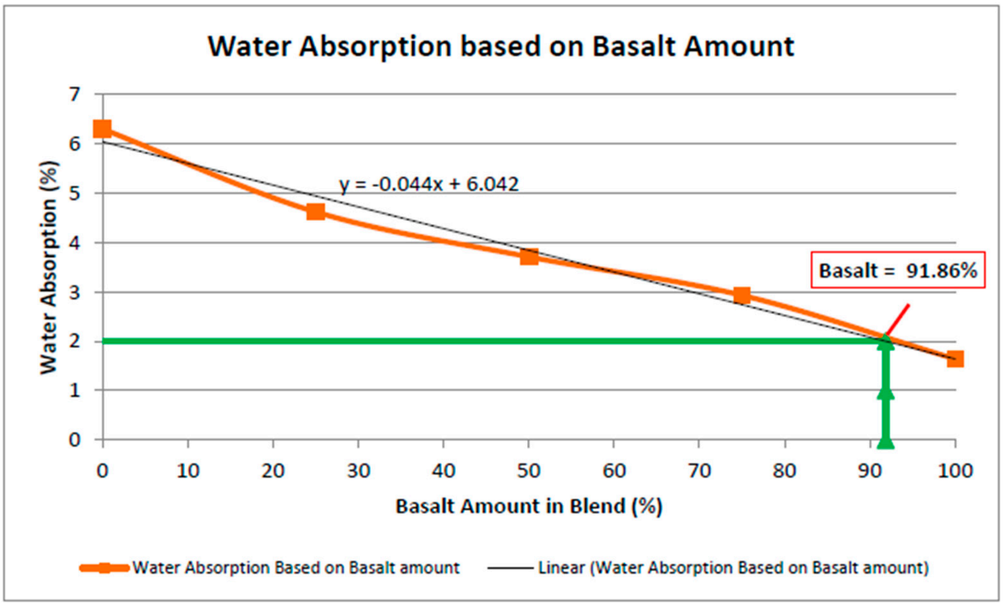


Figure 16. Regression Analysis for Determination of Optimum Basalt Amount.

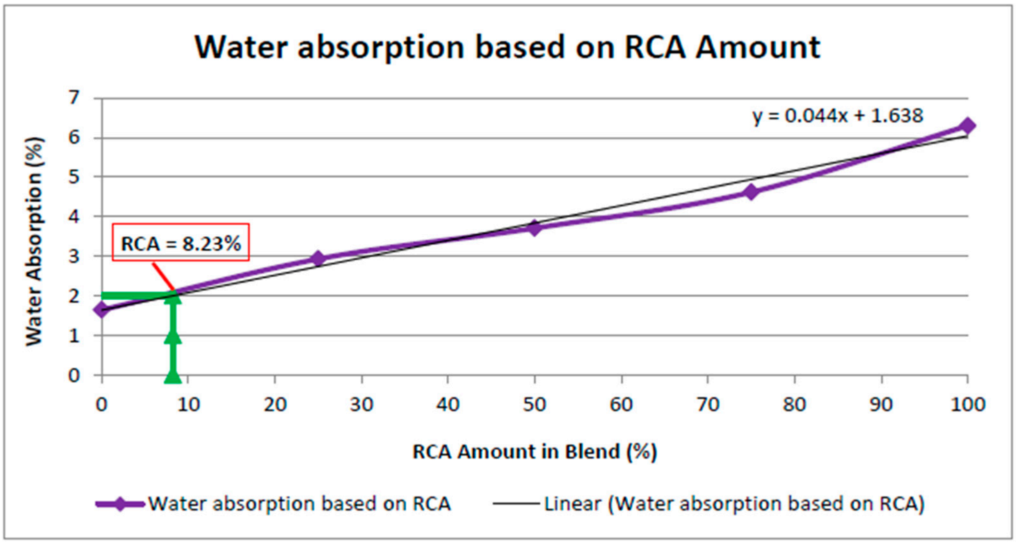


Figure 17. Regression Analysis for Determination of Optimum recycled construction aggregate (RCA) Amount.

As illustrated in Figures 16 and 17, the standard water absorption limit of 2% can be achieved by mixing of almost 8% and 92% of RCA and basalt, respectively. However, based on the available references [59], typically, the amount of binder absorbed by aggregate is 0.3 to 0.7 times the water absorption of the aggregate. In addition, according to this standard, if the sample absorbs between 2% and 4% of its mass, it should be carefully examined by other tests. If the sample absorbs in excess of 4% of its mass, it will rarely prove to be an adequate aggregate for asphalt production. Based on the water absorption results, it can be observed that the combination of 25% RCA and 75% basalt would provide water absorption of 2.93%, and also water absorption of the combination of 50% RCA and 50% basalt would be 3.71%, which are still in the range of aggregate water absorption that suggest further research.

4. Conclusions

Since the coarse aggregate properties are identified by current research as the second most important parameter after gradation for the performance of HMA [49], therefore, in this research, attempts were made to assess the properties of RCA for use in asphalt mixture as coarse aggregate, and this paper presented the summary results of a comprehensive set of preliminary tests on RCA, RAP and basalt as well as different mixes of these aggregates to evaluate their basic mechanical and physical properties. It was argued that information on these fundamental properties were paramount in designing a durable and sustainable asphalt mixtures. To this end, different aggregate and aggregate mixes containing different percentages of RCA, RAP, and basalt were investigated in this research to assess its suitability as coarse aggregate in asphalt. This paper presented the results of this experimental work conducted as a component of a broader research project for designing an asphalt mixture. Based on this research, it was concluded that:

(1) RCA has lower value of flaky and misshapen particles in comparison with RAP and basalt. This implies that asphalt mixtures containing a certain amount of RCA can have better workability, deformation resistance and compaction.
(2) RCA exhibits comparatively more absorption and wet/dry strength variation than conventional aggregate and RAP, while the results of other tests show that RCA still meets the requirements for aggregate in asphalt mixtures. Cracks and adhering mortar and cement paste can be significant reasons for the high water absorbtion of RCA which needs to be compensated for during mix design.
(3) The results of water absorption and particle density test on different mix of coarse aggregates revealed that RCA increase will increase water absorption of the mixture. Therefore, the selection of optimum combination of RCA and other aggregates is required to satisfy the relevant standards requirements.
(4) Regression analysis applied to the results of water absorption test on different combination of RCA and basalt, as illustrated in Figures 16 and 17, indicates that mixing of almost 8% of RCA with natural aggregates will provide the standard water absorption limit of 2%.
(5) Since, according to Austroads (2014), the aggregates with water absorption of between 2% and 4% of their mass should be carefully examined by other tests [59]. This standard limit will allow further investigation of the application of up to 50% of RCA in mixtures because based on the water absorption results, it can be observed that the combination of 25% RCA and 75% basalt would provide water absorption of 2.93%, and the combination of 50% RCA and 50% basalt would provide water absorption of 3.71%, which are still in the range of aggregates that require further research for their water absorption properties.

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