Laboratory Investigations on the Utilization of Recycled Construction Aggregates in Asphalt Mixtures

Farzaneh Tahmoorian, Bijan Samali, John Yeaman

***Abstract*—**Road networks are increasingly expanding all over the world. The construction and maintenance of the road pavements require large amounts of aggregates. Considerable usage of various natural aggregates for constructing roads as well as the increasing rate at which solid waste is generated have attracted the attention of many researchers in the pavement industry to investigate the feasibility of the application of some of the waste materials as alternative materials in pavement construction. Among various waste materials, construction and demolition wastes, including Recycled Construction Aggregate (RCA) constitute a major part of the municipal solid wastes in Australia. Creating opportunities for the application of RCA in civil and geotechnical engineering applications is an efficient way to increase the market value of RCA. However, in spite of such promising potentials, insufficient and inconclusive data and information on the engineering properties of RCA had limited the reliability and design specifications of RCA to date. In light of this, this paper, as a first step of a comprehensive research, aims to investigate the feasibility of the application of RCA obtained from construction and demolition wastes for the replacement of part of coarse aggregates in asphalt mixture. As the suitability of aggregates for using in asphalt mixtures is determined based on the aggregate characteristics, including physical and mechanical properties of the aggregates, an experimental program is set up to evaluate the physical and mechanical properties of RCA. This laboratory investigation included the measurement of compressive strength and workability of RCA, particle shape, water absorption, flakiness index, crushing value, deleterious materials and weak particles, wet/dry strength variation, and particle density. In addition, the comparison of RCA properties with virgin aggregates has been included as part of this investigation and this paper presents the results of these investigations on RCA, basalt, and the mix of RCA/basalt.

***Keywords*—**Asphalt, basalt, pavement, recycled aggregate.

I. Introduction

With an expanding world and the remarkable growth of freight volumes, the demand for extensive road networks and adequately designed pavements is increasing. As available natural resources become scarce, utilization of recycled materials for construction purposes, including flexible pavement construction, has become increasingly common. Over the past decade, there has been a significant increase in the application of waste materials in different layers of flexible pavements, including asphalt surface layer, base layer, and subbase layer. Today, many waste materials such as tires, plastics, waste glass, etc. are used for construction of different layers of flexible pavements.

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. According to the nature of asphalt surface layer, application of solid wastes in the asphalt layer reduces not only environmental issues associated with waste disposal but also the demand for virgin asphalt binder, as well as the coarse and fine aggregates, which will subsequently result in cost savings and economic advantages. Moreover, using the recycled materials in asphalt surface layer can contribute to further improvement of engineering characteristics of the asphalt pavement materials as well as the pavement performance, representing a value add application for solid wastes. However, the selection of waste materials to be used for pavement construction, particularly the asphalt surface layer, is of high importance as the application of wastes should not adversely influence the structural and functional aspects of the pavements. This paper presents the results of an experimental work which is conducted as a component of a broader research project for designing an asphalt mixture. As designing the asphalt mixture involves the process of selecting suitable ingredients of asphalt and determining their relative amounts with the objective of producing an asphalt mixture with enough resistance to permanent deformation and cracking as well as the required strength, durability, and workability as economically as possible, the better understanding of the characteristics of the materials used in different asphalt components, including coarse and fine aggregates, filler, and binder, will help avoid the use of improper materials in asphalt mixture, and hence improve the asphalt pavement performance.

Among different asphalt components, coarse aggregate often forms the skeleton of the asphalt structure and transfers the traffic and environmental loads to the underlying base, subbase, and sub-grade layers. Therefore, the behavior 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

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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. Therefore, except for the fine mixes, the selection of coarse aggregate greatly influences the asphalt layer behavior [12].

In addition, since the aggregates represent the major portion of the asphalt mix, from the viewpoint of environmental preservation and effective use of resources, focus on the recycled aggregates can provide enormous benefits. Accordingly, due to the importance of the aggregates in asphalt mix, the studies on the utilization of recycled aggregates such as reclaimed asphalt pavement (RAP), RCAs, glass, etc. have increased all over the world over the past two decades. Among the recycled aggregates that can be utilized in asphalt mixture, RCA obtained from construction and demolition wastes constitute a major part of generated solid wastes as a result of renovation and construction projects. Referring to literature survey, RCA has been used effectively as a base course and subbase course materials [1], [2], [4], [10], [15], [16], [17], [23]. However, a few documents have reported the use of RCA in hot mix asphalt [3], [8], [14], [24], [26]. Therefore, the aim of this laboratory investigation is to perform a precise evaluation of the RCA characteristics, including the physical and mechanical properties through a series of tests on RCA and the mix of RCA and basalt, in order to use RCA as part of coarse aggregates in dense graded asphalt.

II. Aggregate Properties and Their Relationship to Asphalt Performance

Aggregate materials constitute the aggregate structure and subsequently the largest proportion by weight of asphalt mixture, as they contribute up to 90% to 95% of the mixture weight. The high proportion of aggregate materials in the volumetric design of asphalt mixes inherently links aggregate properties to the strength, stiffness, and generally the performance of the asphalt surface layer.

According to the important role of aggregates in the properties of asphalt mixture, including the load bearing and strength characteristics of the mixture, better understanding of the aggregates characteristics will be essential in selecting the appropriate materials to optimize the asphalt mixture, and subsequently the pavement performance with enough resistance to permanent deformation and cracking. It is, therefore, a necessity to evaluate the properties of the aggregates precisely.

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. [11]; [5]-[7]; [13]; [19]; [9]; [22]) have been conducted to link the properties of the aggregates to the performance of asphalt concrete pavement [5]-[7], [9], [11], [13], [19], [22]. The results of these studies proved that the physical and mechanical properties of the aggregates significantly affect the performance of the asphalt pavements [20]. However, it is difficult to isolate the effects of different properties of aggregate on asphalt performance. 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 aggregates must have appropriate characteristics.

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

III. Experimental Work

A. Materials Used

In the present study, RCA and basalt passing through 20 mm and retained on 4.75 mm IS sieve have been used throughout the experiments.

B. Laboratory Tests

In any construction, the physical properties of constituent structural components have to be known so that accurate analysis and relevant design can be performed in order to ensure the stability of that construction. In constructing an asphalt surface layer, the properties of the aggregates must be known because it influences the stability and the overall behavior of the asphalt layer. Therefore, in the present work, attempts have been made to evaluate the basic engineering properties of RCA and the mix of RCA and basalt to compare these properties with the requirements specified in the Australian Standards as well as the properties of the virgin aggregates. The key properties investigated in this experimental study included:

1) Gradation and particle size distribution in accordance with AS 1141.11.1
2) Particle shape based on AS 1141.14
3) Water absorption according to AS 1141.6.1
4) Wet/dry strength based on AS 1141.22
5) Flakiness index in accordance with AS 1141.15
6) Particle density based on AS 1141.6.1
7) Aggregate crushing value in accordance with AS 1141.21
8) Cleanliness according to AS 1141.32

C. Particle Shape Test

The results of the studies on aggregates have shown that the aggregate physical shape properties significantly affect both the strength and stability of asphalt mixes [18]. Therefore, in order to design asphalt mixtures with long service lives, the aggregates must have the proper gradation and shape. The particle shape of aggregates substantially influences the mechanical stability of an 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 they affect the durability of HMAs. Therefore, it is preferable to have rough and angular aggregates rather than smooth and round aggregates.

TABLE I
THE RESULTS OF PARTICLE SHAPE TEST FOR RCA AND BASALT

Property	RCA	Basalt
Particle Shape (%)	6.16	18.34

In this research, the proportion of misshapen aggregates, including the flat particles, elongated particles and, flat and elongated particles found in coarse aggregates is evaluated through the Particle Shape Test in accordance with AS 1141.14 (2007) by proportional caliper, using a 2:1 caliper ratio. Three samples have been considered for the particle shape test on RCA and basalt, and the results of these tests are given in Table I.

D. Water Absorption and Particle Density Test

The absorption of aggregates demonstrates the pore structure of the aggregates and can be considered as an indication of porosity. The aggregates used in an asphalt mixture should be dense and of low porosity, as the large volumes of pores make the aggregate more susceptible to degradation or breakage under the repeated cycles of freezing and thawing or wetting and drying. Moreover, in HMAs, a porous aggregate increases the binder absorption, resulting in a dry and less cohesive asphalt mixture. In addition, the porous aggregate will cause the selective absorption of binder, which refers to the absorption of oily constituents of the asphalt into the aggregate, leaving the harder residue on the surface. This may cause the raveling and stripping of asphalt binder from aggregates. Furthermore, the particle density of the aggregates plays an important role in the whole procedure of asphalt mix design. Particle density is not just an aggregate property, but an essential property of the aggregates.

TABLE II
THE RESULTS OF WATER ABSORPTION TEST FOR RCA AND BASALT

Property	RCA	Basalt
Water Absorption (%)	6.30	1.64
Apparent Density (gr/cm3)	2.476	2.640
Density on Dry Basis (gr/cm3)	2.212	2.530
Density on SSD Basis (gr/cm3)	2.324	2.571

In this research, the water absorption and particle density test was conducted on RCA, basalt, and the mix of RCA/basalt based on the procedure described in AS 1141.6.1 (2000). In this test, the amount of water a dried sample will absorb, the apparent particle density, particle density on a dry basis, and particle density on a saturated surface dry (SSD) basis of RCA and basalt are measured. This test is performed on three trials and the related test results on RCA and basalt are given in Table II. Furthermore, due to the high value of water absorption for RCA in comparison with natural aggregates and as this research aims to investigate the feasibility of the application of RCA as part of coarse virgin aggregates (i.e. basalt) in asphalt mixtures, the water absorption test is also conducted on the mix of coarse aggregates (i.e. RCA and coarse basalt) considering different percentages of these materials, and the related test results on different mix of RCA and basalt are given in Table III.

TABLE III
THE RESULTS OF WATER ABSORPTION TEST FOR MIX OF RCA AND BASALT

Property	75% Basalt + 25% RCA	50% Basalt + 50% RCA	25% Basalt + 75% RCA
Water Absorption (%)	2.94	3.71	4.62
Apparent Density (gr/cm3)	2.590	2.570	2.527
Density on Dry Basis (gr/cm^3)	2.407	2.310	2.222
Density on SSD Basis (gr/cm^3)	2.477	2.396	2.351

E. Crushing Value Test

The principal mechanical properties which are required for asphalt aggregates are satisfactory resistance to crushing under the roller during construction, and adequate resistance to surface abrasion under traffic [27]. Therefore, aggregates used in pavement construction should be strong enough to resist crushing during mixing, laying process, compaction, consolidation and during its service life span when they are subjected to various loads applied by traffic forces. This property is an essential characteristic in providing the proper resistance of the coarse aggregates to crushing and impact forces under the applied loads. Generally, the aggregates with a higher degree of resistance to crushing and impact forces are desired for most construction applications, and especially pavement construction, as the aggregates must be able to withstand the crushing and impact forces during manufacture, placing, and compaction of asphalt mixtures. This characteristic of the coarse aggregates can be evaluated by the Aggregate Crushing Value Test. In this test, the aggregates were crushed by a compression testing machine with a load rate of 40 kN/min for about 10 minutes to reach the peak force 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 of pavement, it is preferred to utilize the aggregates possessing low crushing value. In this research, the crushing value of RCA and basalt are assessed through the Aggregate Crushing Value Test in accordance with AS 1141.21 (1997). This test is performed on two trials, as specified in the related standard, and the related test results on RCA and basalt are given in Table IV.

TABLE IV
THE RESULTS OF CRUSHING VALUE TEST FOR RCA AND BASALT

Property	RCA	Basalt
Crushing Value (%)	29.21	16.91

F. Flakiness Index Test

Some aggregates, on account of their shape, would be unsuitable for asphalt mixture as they would have a low potential for developing inter-particle interlock. In addition, flat and elongated aggregates, namely flaky aggregates, impede compaction and may produce a mix with high in situ air voids, which subsequently lack strength and are more prone to deterioration due to ageing of the binder and stripping.

In this research, the percentage by mass of flaky aggregates is determined by the most commonly used test, called Flakiness Index Test, in accordance with AS 1141.15 (1999). In this test, the flakiness index is determined by the direct measurement using a special slotted sieve, from the ratio of the mass of material passing slotted sieve to the total mass of the size fraction. The results of this test on RCA and basalt are presented in Table V.

TABLE V
THE RESULTS OF FLAKINESS INDEX TEST FOR RCA AND BASALT

Property	RCA	Basalt
Flakiness Index (%)	6.9	19.1

G. Wet/Dry Strength Variation Test

Strength is an important aggregate property which is related to the resistance of the particles to degradation due to loading stress in the pavement layers. This characteristic of aggregates is an essential property in the assessment of asphalt subjected to high traffic intensity, high tire pressures or heavy wheel loads. In general, aggregate strength and stiffness have been used as indicators of aggregate resistance to degradation. Strength is quantified by the maximum tensile or compressive stress that aggregate sample can sustain prior to failure. It is important to utilize the aggregates with higher degree of stiffness in pavement construction, particularly the upper pavement layers where the stresses are very high. Furthermore, durability is another important aggregate characteristic which can be related to the aggregate resistance to disintegration, mainly caused by the temperature changes and the presence of moisture, as they result in changes in the volume of aggregates, and subsequently the breakage of the aggregate.

In this research, the strength of RCA and basalt and the variation in their strength in both dry and wet conditions are evaluated by conducting the Wet-Dry Strength Variation Test in accordance with AS 1141.22 (2008).

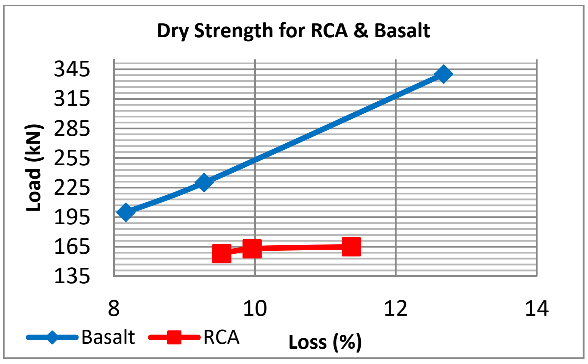

Fig. 1 Results of Wet/Dry Strength Test for RCA and Basalt (Dry Strength)

This test uses the variation in strength of the aggregate tested after drying in an oven and when saturated but with a dry surface. Based on the available standards, the values obtained from this test, which are about 35% or less; indicate a durable material and values as high as 60% are used in undemanding circumstances.

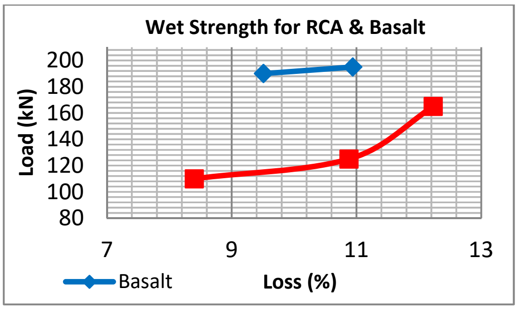

Fig. 2 Results of Wet/Dry Strength Test for RCA and Basalt (Wet Strength)

The wet/dry strength variation test is conducted on the RCA and basalt fraction passed through 13.2 mm and retained on 9.5 mm IS sieve, with different loading in order to adjust the applied force for providing the fines within the range of 7.5% and 12.5%. The results of these tests for RCA and basalt are illustrated in Figs. 1 and 2 in dry condition and saturated surface dry condition (SSD), respectively.

The wet and dry strengths can be inferred from the test results shown in Figs. 1 and 2. The results of the calculations for wet strength, dry strength, and wet/dry strength variation for basalt and RCA are presented in Table VI. Furthermore, as mentioned previously, to investigate the feasibility of the application of RCA for the replacement of part of basalt in asphalt mixtures, the wet/dry strength variation test is also conducted on the mix of coarse aggregates (i.e. RCA and coarse basalt) considering different percentages of these materials.

TABLE VI
THE RESULTS OF WET/DRY STRENGTH VARIATION TEST FOR RCA AND BASALT

Property	RCA	Basalt
Dry Strength (kN)	163.1	390.1
Wet Strength (kN)	119.7	315.2
Wet/Dry Strength Variation (%)	26.6	21.3

TABLE VII
THE RESULTS OF WET/DRY STRENGTH VARIATION TEST FOR MIX OF RCA AND BASALT

Property	75% Basalt + 25% RCA	50% Basalt + 50% RCA	25% Basalt + 75% RCA
Dry Strength (kN)	347.1	269.4	210.4
Wet Strength (kN)	289.1	220.7	157.6
Wet/Dry Strength Variation (%)	22.4	23.7	25.2

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

H. 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 aggregates can lead to stripping and raveling in HMAs, as these materials adversely affect the bond between the aggregate and asphalt. Moreover, these substances disintegrate under traffic loading or wetting and drying process.

The cleanliness of aggregates can be evaluated based on the Weak Particles Test. In this test, the percentage of weak particles in coarse aggregates is determined. These particles will deform under finger pressures when wet. The presence of high percentage of weak particles in the aggregates which are used for pavement construction will adversely affect the stability of the pavement structure. In this study, the percentage of weak particles in RCA and basalt are determined through the Weak Particle Test in accordance with AS 1141.32 (2008).

TABLE VIII
THE RESULTS OF WEAK PARTICLE TEST FOR RCA AND BASALT

Property	RCA	Basalt
Weak Particle (%)	0.23	0.23

The weak particle test is conducted on two trials, as specified in the related standard, and the results of this test on RCA and basalt are presented in Table VIII.

IV. RESULTS AND DISCUSSIONS

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

As can be observed in this table, all properties of RCA, excluding water absorption, are within the limits specified by relevant Australian Standards and hence deemed appropriate for use as aggregate in the asphalt mixture. However, in some cases such as flakiness index and particle shape, RCA has less value in comparison with basalt. This can be one of the strength points of RCA as flakiness index and particle shape are the two important properties for proper compaction, deformation resistance, and workability of asphalt mixture [21].

According to the test results presented in Table IX, as mentioned previously, the absorption of RCA is higher than the corresponding value of 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. In addition, 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 play an important role in asphalt mixture design. In addition, although wet/dry strength variation of RCA meets the requirements of Australian standards, the test results show that this value is higher that the corresponding value of basalt. As the wet/dry strength variation is related to the principal mechanical properties which are required for asphalt aggregates, it is of high importance in asphalt mixture design because aggregates should have satisfactory resistance to crushing under the roller during construction, and adequate resistance to surface abrasion under traffic.

TABLE IX
THE RESULTS OF TESTS FOR EVALUATION OF PHYSICAL AND MECHANICAL PROPERTIES OF RCA

Property	RCA	Basalt	Specification
Particle Shape (%)	6.16	18.34	35% (max)
Water Absorption (%)	6.30	1.64	2% (max)
Aggregate Crushing Value (%)	29.21	16.91	35% (max)
Flakiness Index (%)	6.9	19.1	25% (max)
Particle Density (gr/cm^3)	2.570	2.640	-
Particle Density on Dry Basis (gr/cm^3)	2.212	2.530	-
Particle Density on SSD Basis (gr/cm^3)	2.351	2.571	-
Wet Strength (kN)	119.7	315.2	-
Dry Strength (kN)	163.1	390.1	-
Wet/Dry Strength Variation (%)	26.6	21.3	35% (max)
Weak Particles (%)	0.23	0.23	1% (max)

TABLE X
THE RESULTS OF TESTS FOR MIX OF RCA AND BASALT

Property	75% Basalt + 25% RCA	50% Basalt + 50% RCA	25% Basalt + 75% RCA
Water Absorption (%)	2.94	3.71	4.62
Apparent Density (gr/cm3)	2.590	2.570	2.527
Density on Dry Basis (gr/cm3)	2.407	2.310	2.222
Density on SSD Basis (gr/cm3)	2.477	2.396	2.351
Dry Strength, D (kN)	347.1	289.1	210.7
Wet Strength, W (kN)	269.4	220.7	157.6
Wet/Dry Strength Variation (%)	22.4	23.7	25.2

Accordingly, the amount of RCA in the asphalt mixtures and its combination with other aggregates should be carefully investigated in order to design an adequate asphalt mixture. To this end, different mixes containing different percentage of basalt and RCA have been investigated in this research for these two properties (i.e. water absorption and wet/dry strength variation) and the results of these tests are summarized in Table X.

As can be observed, 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, 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.

V. CONCLUSIONS

Aggregates make up between 80% and 90% of the total volume or 90% to 95% of the mass of hot mix asphalt (HMA). With such a big proportion in asphalt mixture, the aggregate would have important effects on the performance of asphalt mixtures. On the other hand, sources of natural aggregates are becoming depleted all over the world, and hence utilization of recycled aggregates can provide a welcomed opportunity to reduce the problems of waste disposal and the aggregate scarcity. For these reasons, it is important to substitute the natural aggregates by the recycled aggregates, and to maximize the quality of the aggregates to ensure the performance of the roadways. Referring to NCHRP, Report 539 (2005, the quality of aggregates for road paving materials has been specified by the toughness, soundness (durability), cleanliness, particle shape, angularity, surface texture, and absorption. In addition, coarse aggregate properties are identified by the researches as the second most important parameter after gradation for the performance of HMA [25]. Therefore, in this research, attempts have been made to assess the properties of RCA for use in asphalt mixture as coarse aggregates.

The utilization of RCA as coarse aggregate is particularly promising, since 65% of asphalt mixtures are made of coarse aggregates, and enormous quantities of construction and demolition wastes are available at various construction sites. In light of this, research efforts have been made towards characterizing the fundamental properties of RCA. However, the existing research and experimental works still have some deficiencies and weaknesses in order to integrate all required tests for evaluation of RCA properties. Therefore, in this study, a series of tests have been selected for evaluation of physical and mechanical properties of RCA and basalt to assess its suitability as coarse aggregate in asphalt mixtures, and their results analysis are presented in this paper.

Based on this research, it is concluded that RCA has lower value of flaky and misshapen particles in comparison with basalt. This implies that asphalt mixtures containing the certain amount of RCA can have better workability, deformation resistance and compaction. In addition, the test results reveal that RCA exhibits comparatively more absorption and wet/dry strength variation than conventional aggregates, because of cracks and adhering mortar and cement paste. This needs to be compensated for during mix design. The results of other tests show that RCA still meets the requirements for aggregates in asphalt mixtures.

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