

# Dense-Graded Hot Mix Asphalt with 100% Recycled Concrete Aggregate Based on Thermal-Mechanical Surface Treatment

**Peerapong JITSANGIAM**, B.Eng., M.Eng., Ph.D. (*corresponding author*)

*Assistant Professor*, Center of Excellence in Natural Disaster Management, Department of Civil Engineering, Faculty of Engineering, Chiang Mai University, Huai Kaew Road, Mueang, Chiang Mai, 50200, Thailand

E-mail: [peerapong@eng.cmu.ac.th](mailto:peerapong@eng.cmu.ac.th); Tel: +66 053 944 157; Fax: +66 053 892 376

**Korakod NUSIT**, B.Eng., M.Eng., Ph.D.

*Lecturer*, Center of Excellence on Energy Technology and Environment, Department of Civil Engineering, Faculty of Engineering, Naresuan University, Tha-Po, Mueang, Phitsanulok, 65000, Thailand, [korakodn@nu.ac.th](mailto:korakodn@nu.ac.th)

**Hamid NIKRAZ**, B.Eng., M.Sc., Ph.D.

*Emeritus Professor*, Department of Civil Engineering, Curtin University, Perth, Western Australia, Australia; [h.nikraz@curtin.edu.au](mailto:h.nikraz@curtin.edu.au)

**Zhen Leng**, B.Eng., M.Eng., Ph.D.

*Associate Professor*, Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, [zhen.leng@polyu.edu.hk](mailto:zhen.leng@polyu.edu.hk)

**Jitinun PROMMARIN**, B.Eng.

*Research Assistant*, Department of Civil Engineering, Faculty of Engineering, Chiang Mai University, Huai Kaew Road, Mueang, Chiang Mai, Thailand, [jitinun\\_pr@cmu.ac.th](mailto:jitinun_pr@cmu.ac.th)

**Prinya CHINDAPRASIRT**, B.Eng., M.Eng., Ph.D.

*Professor*, Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Thailand, [prinya@kku.ac.th](mailto:prinya@kku.ac.th)

# Dense-Graded Hot Mix Asphalt with 100% Recycled Concrete Aggregate Based on Thermal-Mechanical Surface Treatment

## Abstract

This study examined the use of recycled concrete aggregate (RCA) as a full replacement for natural aggregate (NA) in a hot mix asphalt (HMA) mixture for a heavy-duty asphalt surface. A modified thermal–mechanical beneficiation method was employed to improve the RCA abrasion resistance to meet the Los Angeles abrasion (LAA) requirements for HMA aggregates. Then, the heavy-duty dense-graded HMA was mixed with beneficiated RCA (BRCA) (HMA-BRCA). The HMA mixture with NA (HMA-NA) was utilised as a benchmark. A series of laboratory performance tests on the Marshall stability and flow, resilient modulus (MR), dynamic modulus, and tensile strength ratio (TSR) were performed in conjunction with x-ray diffraction (XRD) analysis. The test results revealed that HMA-BRCA provided larger Marshall stability, lower Marshall flow, and larger MR than HMA-NA, and both demonstrated similar dynamic modulus characteristics. Nevertheless, HMA-BRCA was more susceptible to moisture than HMA-NA, indicated by the sub-standard TSR of HMA-BRCA. Further analysis showed that the breakage of BRCA particles during the mixing and compaction processes led to tighter packing of the HMA aggregate matrix, which was the cause for the improved strength, modulus, and deformation characteristics of HMA-BRCA. Furthermore, a relatively thinner asphalt binder film and the presence of calcite (retained from the original mortar) lead to the poor moisture damage resistance of HMA-BRCA. Therefore, moisture susceptibility is an issue when RCA is used in an HMA mixture, even though the RCA was treated to meet all HMA aggregate requirements.

Keywords: Recycled concrete aggregate; hot mix asphalt; beneficiation; utilisation; Los Angeles abrasion

## **1. Background and introduction**

The construction and demolition rate of infrastructures is increasing every year owing to population growth. These rapid changes have led to a shortage of natural resources and issues with waste management. The waste produced by the construction industry generally comprises concrete, wood, glass, and metallic objects. Further, previous literature has estimated that seven to ten billion tons of solid waste (SW) are generated annually by households, commercial factories, and the construction industry. Of this amount of SW generated worldwide, 13–30% is construction and demolition (C&D) waste [1]. However, the reuse and recycling rates of this type of waste are extremely low [1]. The reuse of C&D waste not only reduces the consumption of virgin materials but also decreases the carbon emissions produced from quarry operations. Moreover, the integration of recycled C&D aggregate into road pavement decreases the quantity of waste added to landfills each year. Recently, landfills have become very environmentally unfriendly or unsustainable for waste disposal. Lopez and Lobo [2] report that the disposal of C&D waste in landfills could lead to the leaching of hazardous compounds – such as sulphates, gypsum, and heavy metals – into the ground. Demolished concrete is a major component of C&D materials from buildings and other types of infrastructure. To recycle C&D materials, concrete rubble is conveyed to C&D processing plants where it is crushed, screened, and stockpiled. After completing this process, recycled concrete aggregate (RCA) is obtained and can be used for various purposes.

The potential for using RCA has been studied in various fields of engineering. Extensive research work on has been conducted on RCA applications in infrastructure [3–6], road bases and subbases [7,8], and pavement surface courses [9–13]. When using RCA as a hot-mix asphalt (HMA) aggregate, it is generally blended with natural aggregate (NA) prior to being properly mixed with an asphalt binder [9,14]. The HMA mixture is then compacted to form a relatively dense pavement layer in the field.

According to pavement design guidelines, road pavement aggregate requires good wear characteristics, especially against abrasion, in order to withstand cyclic loading from traffic. Previous research has reported that the presence of cement mortar in RCA material is the main cause of weak and low-quality aggregates [12,13,15,16]. Therefore, to increase the abrasion resistance of RCA aggregates the weak matrix (i.e. mortar and crushed brick) must be removed [15,17]. To accomplish this, various beneficiation methods have been developed and implemented in the past [12]. These methods include mechanical beneficiation, thermal beneficiation, thermal–mechanical beneficiation, acidic beneficiation, and microwave beneficiation [3,4,18]. The beneficiation process leaves only the solid matrix in the blended aggregates, which is expected to improve the quality of RCA materials.

The beneficiation method studied by Akbarnezhad et al. [12] and Bastidas-Martínez et al. [19] relied on mechanical processes. The mortar and crushed brick were either ground or crushed and rubbed away to produce fine particles. These soft and weak fractions were later screened out; therefore, the treated RCA comprised only the strong and hard matrix. Akbarnezhad et al. [12] also reported that heating the RCA up to 500 °C could fracture and unbind weak mortar fractions from strong aggregate particles owing to thermal stress. Furthermore, when the heated RCA was immediately submerged in cold water, the thermal stresses resulting from the temperature difference further improved the

process of removing mortar from the hard matrix [12]. According to Shima et al. [18], cement mortar becomes brittle because of dehydration resulting from the mechanical beneficiation process. This could ease the removal of the cement mortar from RCA. However, most previous research on the utilisation of RCA for pavement applications has focused on using RCA as an HMA aggregate, along with how to use RCA as unbound granular materials for road bases. This HMA research has employed both untreated RCA [9,13,20] and beneficiated RCA [21–23] as only a portion of the total HMA aggregates. It should be noted that there is a paucity of research on entirely replacing commonly used aggregates with RCA for HMA mixtures. Muniz de Farias et al. [24], Bastidas-Martínez et al. [19], and Bhusal and Wen [25] reported the use of RCA with full replacement of NA in HMA as a reference HMA mixture in a series of test programs. Furthermore, in previous research, the performance of HMA incorporating RCA has mostly been evaluated from laboratory test results regarding various properties, such as the dynamic modulus, phase angle, resilient modulus (MR), tensile strength ratio (TSR), and stability and flow numbers. According to the laboratory performance of HMA that incorporates untreated RCA [9,13,20,26], its use would not be recommended heavy-duty pavement because of its inadequate properties. Consequently, it is important to consider whether RCA can be used as an NA replacement in HMA for heavy-duty pavement if RCA is treated to meet all requirements for HMA aggregates. Therefore, the goal of this study is to examine HMA that incorporates 100% RCA based on modified beneficiation processes, along with a series of laboratory performance tests.

Applying a combination of high-temperature and mechanical processes to improve the quality of RCA could be an efficient means for removing weak mortar fractions from RCA in the most simple, economical, and widely accessible manner. Therefore, this study attempted to produce RCA with satisfactory abrasion resistance for

HMA aggregates based on more practical beneficiation processes. In many countries, the abrasion resistance of pavement aggregates is commonly measured using the Los Angeles abrasion (LAA) test. Suitable aggregates for pavement construction material should have lower LAA values than those specified by design guidelines [5]. Accordingly, in this study, a hybrid thermal–mechanical beneficiation method was used to improve the abrasion resistance of RCA and allow it to meet the LAA requirements for HMA aggregates. Subsequently, a dense-graded HMA mix design of the 14 mm nominal aggregate size for an intersection pavement surface (i.e. one type of heavy-duty pavement surface) was utilised to examine the use of RCA treated by this thermal–mechanical beneficiation process in conjunction with a series of laboratory performance tests on the Marshall stability and flow, MR, dynamic modulus, and TSR.

## **2. Materials**

### ***2.1 Natural aggregate (NA)***

Figure 1 shows the NA used as an HMA aggregate in this research. This type of NA is classified as granite, with a nominal size of 14 mm (for the intersection mix) [27], which is a commonly used HMA aggregate and was readily available from a local quarry in Western Australia. The particle size distribution (PSD) of this NA complied with the HMA gradation recommended by the Western Australia Main Road Standards [27] and Standards Australia [28].



Figure 1. Natural (granite) aggregates used in this study

## ***2.2 Recycled concrete aggregate (RCA)***

The RCA for the research work was supplied by a local RCA supplier in Perth, Western Australia. RCA generally consists of crushed concrete, rocks, bricks, and rubble. The raw RCA was processed from C&D waste. The nominal aggregate size of the produced RCA ranged between 20 mm and 25 mm. The weak particles – i.e. cement mortar and crushed brick – were a significant portion of the raw RCA, as shown in Figure 2(a). Two forms of cement mortar observed in the RCA are shown in Figure 2(b): (1) an individual chunk and (2) a conglomeration between aggregates and mortar. A preliminary sieving test of a sample showed that the RCA particles were retained in 26.5 to 13.2 mm sieves.

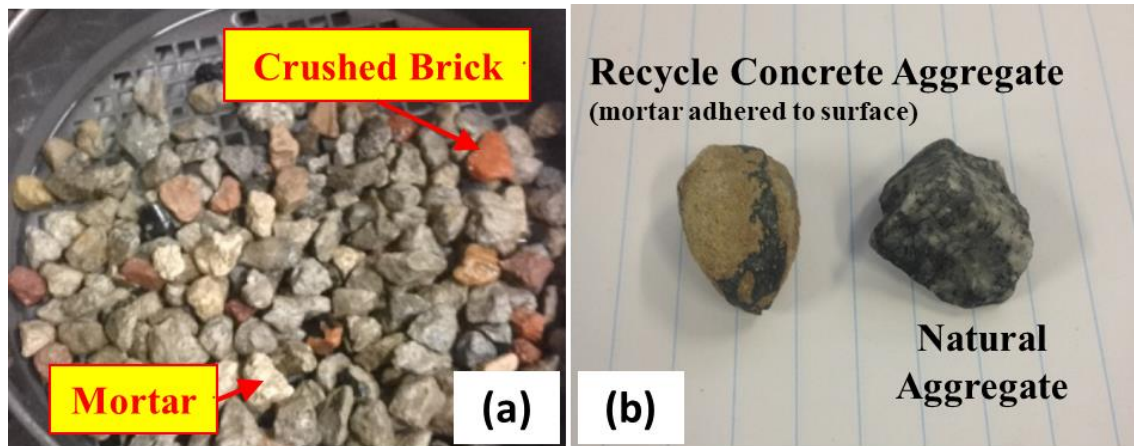


Figure 2. RCA with (a) the mortar chunks, bricks, and natural aggregates and (b) a conglomeration between aggregate and mortar

The supplier classified the RCA as a high-grade concrete blend compliant with Main Roads Western Australia (MRWA) specifications 501 standards [27]. To ensure that the gradation of the RCA met this MRWA specification, the RCA supplier blended the remanufactured C&D aggregate using a controlled ratio. Pre-determined amounts of crushed concrete, bricks, limestone, and rubble were added in each batch to provide some degree of uniformity. The produced RCA is regularly tested every month to meet quality control standards.

### 2.3 Asphalt binder

Class 320 asphalt binder was used in this study. The selected asphalt binder has a flashpoint higher than 300 °C and a density of 1040 kg/m<sup>3</sup>. The properties of the selected Class 320 asphalt binder complied with Standards Australia [29] as shown in Table 1.



Table 1. Asphalt Class-320 specifications [30]

Property	Requirement	
	min	max
Viscosity at 60 °C, Pa·s	260	380
Viscosity at 135 °C, Pa·s	0.40	0.65
Viscosity at 60 °C after RTFO <sup>1</sup> , Pa·s	Report <sup>2</sup>	
Penetration at 25 °C, mm	40	-
Flashpoint, °C	250	-
Viscosity of residue at 60 °C, % of the original	300	-
Density at 15 °C, kg/m <sup>3</sup>	Report <sup>2</sup>	
<b>Remarks</b> 1 - Rolling thin-film oven test. 2 - No conformity criteria exist but test results must be reported.		

### 3. Research methodology

The research methodology is shown in Figure 3. It was divided into two stages: (1) examining the beneficiation process for RCA and the material characterisations, and (2) performance tests of HMA prepared from the treated RCA. The first stage of this study was used to determine a practical and suitable beneficiation method. Accordingly, mechanical beneficiation and thermal–mechanical beneficiation were investigated at this stage. The RCA was treated using both beneficiation processes. In this study, the LAA value was used to indicate the suitability of an HMA aggregate. Therefore, the LAA results of the treated and untreated RCAs from both beneficiation processes were compared. Subsequently, a so-call beneficiated RCA (BRCA) was established based on the best LAA results. Finally, the study aggregates of NA, RCA, and BRCA (BRCA) were characterised to determine some crucial properties required for being an appropriate HMA aggregate. The second stage of this research includes: (1) the mix design of HMA with BRCA derived from a suitable beneficiation process and (2) its performance tests as the validation process. The test results of the BRCA asphalt mixtures were then analysed

and examined in Stage 3 of this study. The details of each research stage are shown in Figure 3.

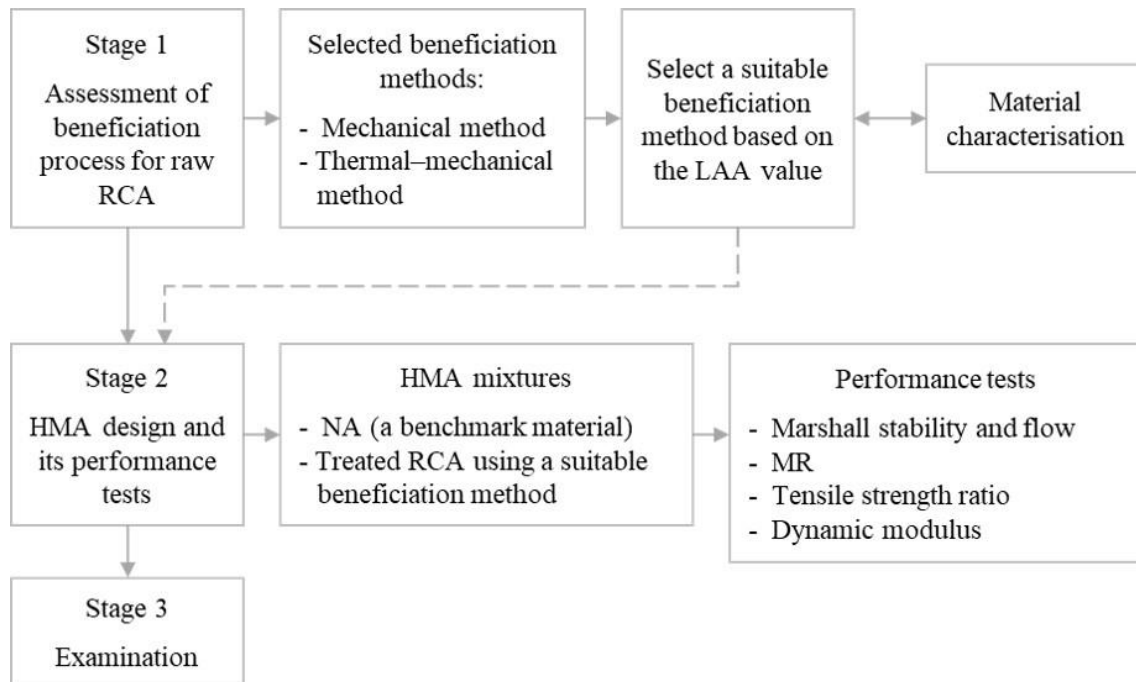


Figure 3. Research methodology

### 3.1 Beneficiation processes of RCA

In the first stage, as shown in Figure 4, the beneficiation processes were conducted in conjunction with the LAA tests [31] to determine the suitability of using the treated RCA as an HMA aggregate – using the abrasion resistance as measured by its LAA value. First, the LAA tests were performed to determine the abrasion resistance of the so-called untreated RCA. Next, the mechanical and modified thermal–mechanical beneficiation processes were carried out. A temperature of 180 °C was selected to activate the thermal reaction on the RCA because this temperature is generally used as the mixing temperature for HMA mixtures. This means that the generation of hot aggregates at 180 °C is practical based on normal HMA mixing processes. Table 2 compares both beneficiation methods.

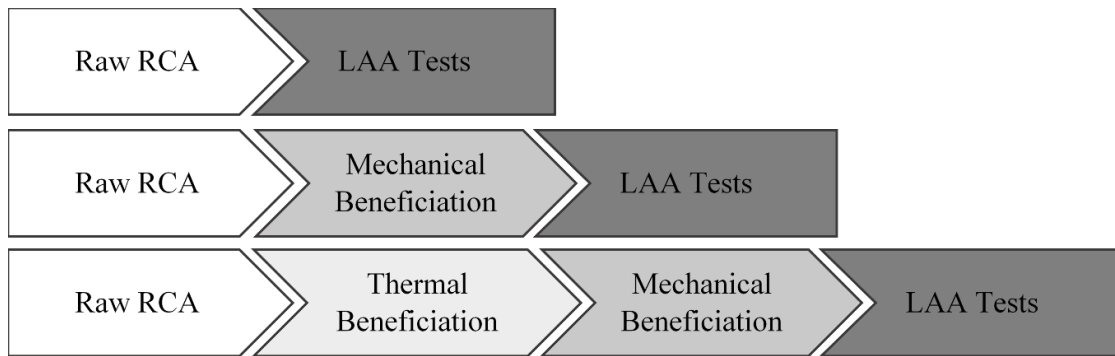


Figure 4. Beneficiation and LAA test process

Table 2. Details of the mechanical beneficiation method and the modified thermal–mechanical beneficiation method

Mechanical beneficiation	Modified thermal–mechanical beneficiation
<ol style="list-style-type: none"> <li>1. Untreated RCA was sieved to collect the target grading of 13.2–19.0 mm.</li> <li>2. Untreated RCA with the target grading was placed in an LAA drum and 500 revolutions were completed.</li> <li>3. Re-sieving, washing, and drying processes were carried out.</li> <li>4. LAA tests were performed to determine the LAA value after treatment.</li> </ol>	<ol style="list-style-type: none"> <li>1. Untreated RCA was sieved to collect the target grading of 13.2–19.0 mm.</li> <li>2. Untreated RCA with the target grading was placed in an oven and heated at 180 °C for 24 hours.</li> <li>3. The hot RCA was rapidly cooled in water.</li> <li>4. The process was repeated a total of three times.</li> <li>5. Re-sieving, washing, and drying processes were carried out.</li> <li>6. LAA tests were performed to determine the LAA value after treatment.</li> </ol>

### 3.2 Material characterisation

Because RCA and BRCA are not standard HMA aggregates, some characterisation tests must be conducted to determine their essential properties. Table 3 shows the essential properties of these aggregates, which were characterised using established test standards. It should be noted that, apart from routine tests according to

Austroads' guide to pavement technology: Part 4B [32], the tests of aggregate impact value (AIV) and aggregate crushing value (ACV) were conducted to determine the impact and crushing resistances of the aggregates. Furthermore, the soundness test, which indicates the durability of aggregates under certain environmental conditions, was also used for material characterisation in this study.

Table 3. Characterisation tests for aggregates

Test	Standard method
Gradation	AS 1141.11.1
Specific gravity/water absorption (coarse aggregate)	AS 1141.6.1
Specific gravity/water absorption (fine aggregate)	AS 1141.5
LAA (300 revolutions)	AS 1141.23-2009
Soundness (magnesium sulphate)	ASTM C 88-99a
Aggregate impact value (AIV)	BS 812:112
Aggregate crushing value (ACV)	BS 812-110

### ***3.3 HMA mix design***

In this study, the HMA mix was designed in accordance to the Austroads guideline [32] using two HMA aggregates of NA and BRCA to form HMA-NA and HMA-BRCA, respectively. The dense-graded HMA with a nominal size of 14 mm was selected. In Western Australia, such dense-graded HMA is generally used for paving at the intersections, where relatively high traffic loads exist – this could unequivocally prove whether the beneficiated RCA could replace NA as the HMA aggregate entirely in such heavy-duty pavement surfaces at intersections.

Theoretically, the HMA mix design involves the process of selecting proper aggregates in terms of types, gradations, and binder types, along with determining the optimal binder content. At this optimal binder content, an HMA mixture would have appropriate engineering properties, which would lead to desirable HMA behaviour in-service. The Australia HMA mix design follows the volumetric design concept. This uses

gyratory compaction in conjunction with a series of performance-related tests. Figure 5 shows the HMA mix design procedure for the dense-graded mixes used in this study, based on the Austroads guideline. An outcome of this HMA mix design is to obtain an optimum binder (asphalt cement) content, which could be graphically determined based on the values of certain parameters, as follows.

- Air voids
- Void in mineral aggregate (VMA)
- Bulk density
- Maximum density
- Voids filled with asphalt (VFA)
- Marshall stability
- Marshall flow

These parameters are used to choose a final binder, at which an HMA mixture must have air voids after compaction within a specified range, including a VMA value close to a specified minimum point. Furthermore, in terms of the mix performance that would indicate a satisfying in-service state, the maximum values of stability and bulk density must be achieved with a specific range of flow values. In this study, the values used for HMA mix assessment are in accordance with the Western Australia Mainroads's specifications [30], shown in Table 4.

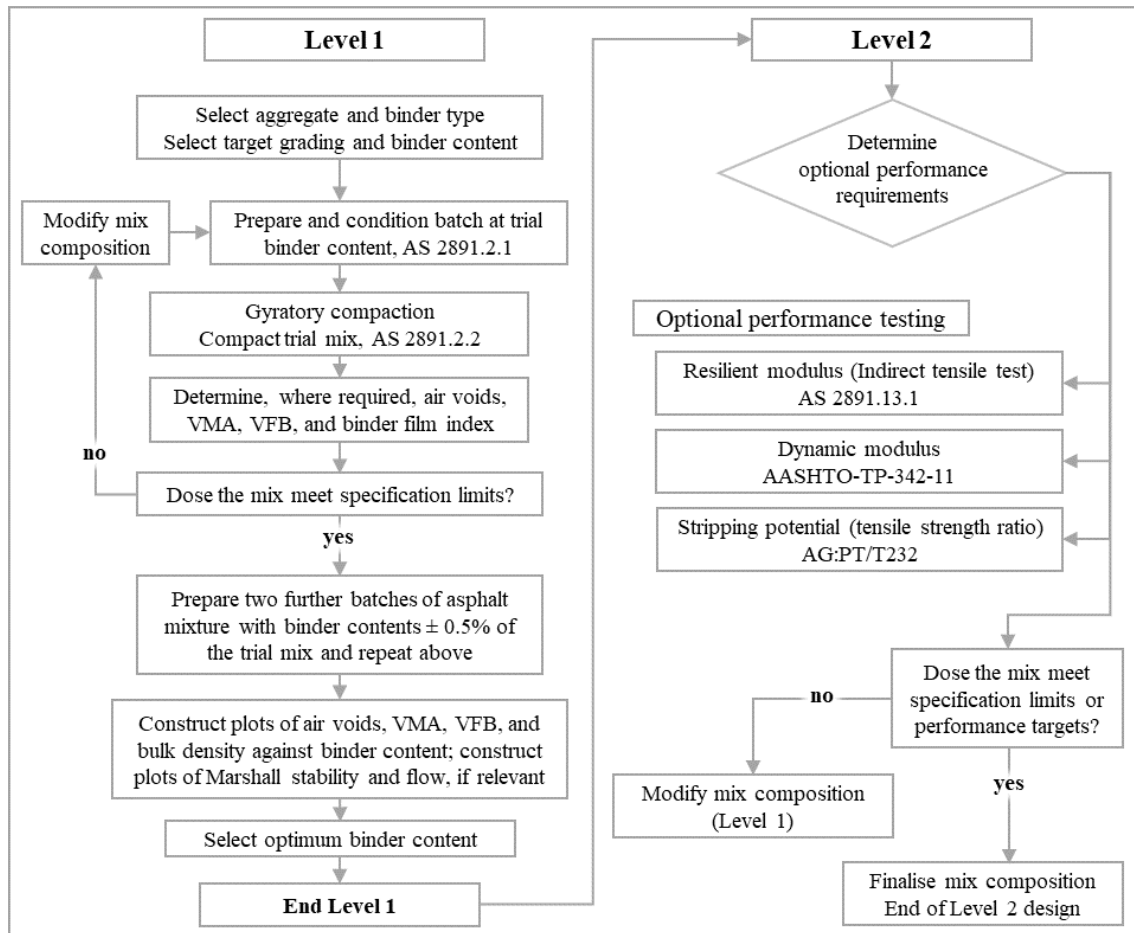


Figure 5 Mix design procedures used in this study

Both NA and BRCA were prepared to meet the specified particle size distribution (PSD) recommended by AS 2758.2 [28], as shown in Figure 6.

Table 4 Parameters and the values used for the mix assessment in this study

Parameter	Min	Max
Marshall stability, kN	8.0	-
Marshall flow, mm	2.00	4.00
Air void, %	4	7
VMA, %	14	-
Binder content (by percentage mass of a whole mixture)	4.7% $\pm$ 0.3% (Class 320)	
Gradation Australian Standard (AS 1152) Sieve mm	Nominal 14 mm Granite (Intersection mix)	
19.00	100	
13.20	93–100	
9.50	79–89	
6.70	63–73	
4.75	49–59	
2.36	33–41	
1.18	22–32	
0.600	15–23	
0.300	10–18	
0.150	6–11	
0.075	2–5	

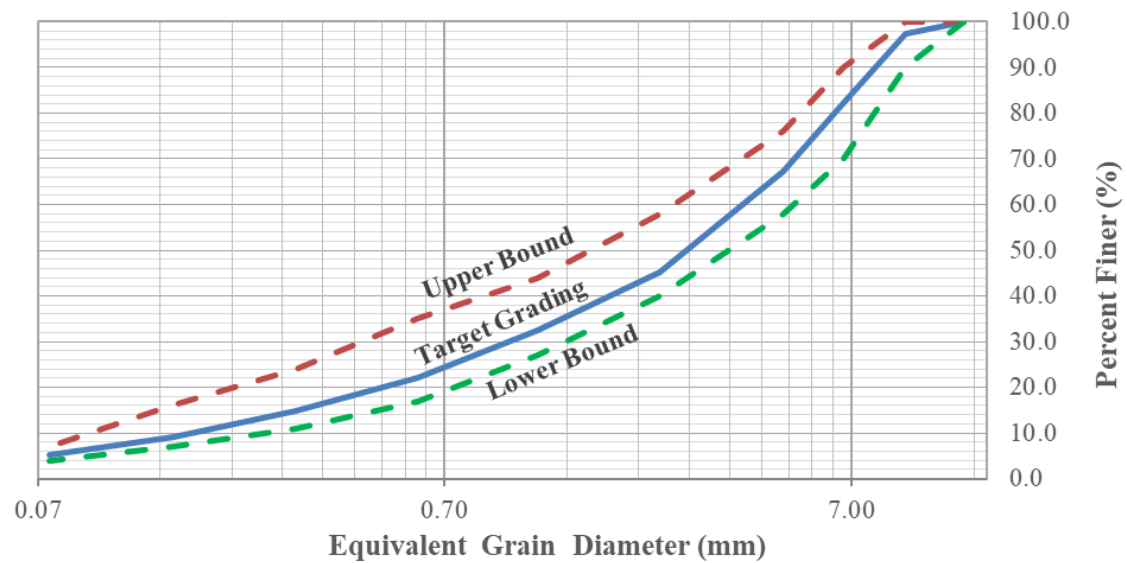


Figure 6. PSD of HMA aggregates in this study

Two series of HMA samples were manufactured based on two types of aggregates (NA and BRCA). Both aggregates were oven-heated overnight at a temperature of  $100 \pm 5^\circ\text{C}$  to reach a fully dry condition. A mixing temperature of  $150 \pm 5^\circ\text{C}$  was targeted when heating an asphalt binder of C320 and HMA aggregates in an oven. The hand-mixing method was selected to avoid the coarse aggregate degradation that could occur if machine mixing was used. After the mixing process was completed and a consistent mixture texture was obtained, an HMA mixture was cured in an oven at a compaction temperature of  $135^\circ\text{C}$  for at least 2 hours to ensure further absorption of asphalt binder into the aggregates. The gyratory compactor, based on the Survopac machine [32], was used to compact the HMA sample in accordance with the Standards Australia [33]. It should be noted that a trial process was undertaken to obtain the relationship between the number of gyrations and void ratios of the HMA mixture – then, the target number of gyrations can be specified for use in compacting a corresponding HMA mixture until reaching a target air void ratio. The volumetric measurements were conducted after a 24-hour curing time of the HMA samples, followed by Marshall stability and flow tests.



### 3.4 HMA performance tests

The HMA performance tests in this study were conducted in a repeatable manner to ensure reliability. Table 5 shows the repeatability scheme of HMA performance tests against the coefficient of variation (COV) of each test. All test results fall within an acceptable range of COV, which indicates their reliability. Furthermore, all test results present in the next session are the average values, which are representative results for each test.

Table 5 The repeatability scheme of HMA performance tests of this study

Tests	Repeatability in terms of the number of test specimens per test	Coefficient of variation* (COV), %
Marshall stability and flow	5	11
MR	3	18
Dynamic modulus	2	8**
Tensile strength ratio	5	12
Remarks: * Averaged values. ** COV depended on the testing frequency; higher COVs were observed for specimens with higher loading frequencies.		

The performance tests for both HMA mixtures used in this study are as follows.

#### 3.3.1 The Marshall stability and flow tests

The Marshall stability and flow tests were conducted in accordance with the MRWA standards [34]. The test specimens were fabricated using the Australian standard for HMA sample preparation procedures [35]. The maximum load capacity of the compacted HMA specimen at 60 °C is defined as the Marshall stability, and the vertical deformation of the HMA specimen measured at the maximum load capacity is defined as the flow number. However, owing to variations in the sample height – depending on various factors, such as the level of compaction energy, binder content, and sample mass

– height correction factors were used to generalise the values of the Marshall stability. The corrected Marshall stability of the HMA specimen, therefore, can be calculated based on Eq. 1 [36].

$$S = LF \quad (1)$$

where  $S$  is the corrected Marshall stability (kN),  $L$  is the maximum load at failure (kN), and  $F$  is the height correction factor (see Table 6).

Table 6. Height correction factors for the stability of HMA [34]

Height of the specimen (mm)	Correction factor
57	1.19
58	1.16
59	1.13
60	1.10
61	1.07
62	1.04
63	1.01
64	0.99
65	0.96
66	0.94
67	0.92
68	0.90
69	0.88
70	0.86

### 3.3.2 MR tests

The MR tests were carried out in accordance with Standards Australia [37]. A repeated tensile load was continually applied to an HMA specimen during MR measurement. The test specimens were prepared such that they consisted of  $5.0\% \pm 0.5\%$  air voids, which is similar to the specimen requirements for the dynamic modulus test [38]. According to the test standard, this repeated tensile stress was indirectly applied to the HMA specimen at 25 °C, with a rest period. A sinusoidal load pulse with a 100-ms

loading time was employed to obtain a horizontal strain between 30 and 70 micro-strains. A repetition period of 3,000 ms is recommended by the standards, which corresponds to a 2,900-ms rest period. To obtain the MR of the test specimen, five load pulses are required for both the conditioning stage and the testing stage. The recovered horizontal deformation or elastic deformation after each load pulse was recorded and used to calculate the modulus. Consequently, the resilient modulus of the asphalt mixture can be determined using Eq. 2.

$$MR = P(\nu + 0.27)/(H + h_c) \quad (2)$$

where  $MR$  is the resilient modulus (MPa),  $P$  is the peak load (N),  $\nu$  is Poisson's ratio,  $h_c$  is the height of the specimen (mm), and  $H$  is the recovered horizontal deformation after application of the load (mm). The MR, therefore, can be determined by averaging the elastic moduli obtained from five consecutive loads.

### 3.3.3 The dynamic modulus tests

The dynamic modulus of the HMA specimens was tested in accordance with the AASHTO guidelines [38]. Figure 7 shows the asphalt mixture performance tester (AMPT) machine used in this study. The AMPT was used to evaluate the aspects of HMA performance that are essential for the mechanistic-empirical pavement design framework. The dynamic modulus, flow number, and flow time are the key performance parameters determined by the AMPT. The rutting performance and creep behaviour of HMA were evaluated from the flow number and flow time, respectively. The dynamic modulus is also a necessary parameter used to analyse the material responses of pavement. Figure 7 illustrates the major components of the AMPT. The machine consists of the conditioning chamber, the controller, the data acquisition system, and the dynamic actuator. The test specimens were required to have air void percentages equal to  $5.0\% \pm 0.5\%$  [38]. Three

linear variable differential transformers (LVDTs) were attached to each specimen during testing (Figure 7(b)). After the LVDTs were installed, the specimen was placed in the conditioning chamber overnight. The temperature in the chamber was set to 4.4 °C. A seating load equivalent to 5% of the applied dynamic load was employed prior to measuring the dynamic modulus. Sinusoidal loading was then applied to the specimen in a cyclic manner. The applied dynamic load should induce axial strains between 50 and 150 microstrains. Six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz) were employed at each tested temperature. Next, the dynamic moduli at different loading frequencies were measured and the temperature in the conditioning chamber was increased to the next level. Four test temperatures were employed for each specimen: 4.4, 21.1, 37.8, and 54 °C. According to the standard [38], different curing times are required for each tested temperature. Accordingly, the same set of test parameters was employed for the dynamic modulus measurement of each mixture.



Figure 7. The dynamic modulus test setup, showing (a) the AMPT and (b) LVDTs attached to the sides of a test specimen

### 3.3.4 Tensile strength ratio (TSR) tests

The tensile strength ratio tests were conducted in accordance with the Australian guidelines [39]. The stripping potential of asphalt aggregates owing to moisture ingress was determined by comparing the indirect tensile strengths (ITDs) of test specimens under soaked and unsoaked conditions. According to the standard, six test specimens are required for each HMA mixture. The air void percentage of a specimen prepared for the TSR test should be equal to  $8\% \pm 1.0\%$ . To obtain the TSR of each mixture, six specimens were split into two groups with three specimens in each group. The first group of specimens was submerged in a desiccator filled with warm water at  $50 \pm 5$  °C. A vacuum pump was attached to the desiccator and a vacuum of 80 kPa was applied for 10 minutes. The soaked specimens were then removed from the desiccator, patted dry, and weighed. The saturation degree of the specimen was later determined using Eq. 3 [39].

$$SP = \left( \frac{m_{ps} - m_d}{V_a} \right) \times 100 \quad (3)$$

where  $SP$  is the degree of saturation (%),  $m_{ps}$  is the mass of the partially saturated specimen (g),  $m_d$  is the mass of the dry specimen (g), and  $V_a$  is the volume of air in the compacted specimen (cm<sup>3</sup>).

The standard referred to requires that the degree of saturation for soaked specimens be between 50% and 80%. The specimens that did not have an appropriate degree of saturation were discarded. After the saturation stage, the soaked specimens were immersed in water at 60 °C for 24 hours. Subsequently, the soaked specimens were transferred to a water bath at 25 °C for two hours prior to the IDT test. The second group of specimens represented dry conditions and were unsoaked but were also submerged in a water bath at 25 °C for 2 hours prior to the IDT test. After temperature conditioning, the soaked and unsoaked specimens were tested to obtain the IDT results according to

Austrroads guidelines [39]. Figure 8(a) shows the IDT test, while the fractured specimen is shown in Figure 8(b).



Figure 8. Images of the tensile strength ratio test, including (a) the IDT test apparatus and (b) specimens after failure.

## 4. Results and discussion

### 4.1 *Thermal–mechanical beneficiation processes*

The average values of LAA loss, calculated from the five specimens per aggregate type, are summarised in Figure 9. These values were then compared to the abrasion resistance requirements given in the specifications [27].

The abrasive force during the numerous revolutions involved in the LAA test can crack weaker portions of the mortar on untreated RCA. Therefore, the weight of the untreated RCA specimens was reduced after the tests. Figure 9 shows that the average LAA value of the untreated RCA is five absolute per cent higher than the LAA cut-off value required for lightly trafficked roads. Therefore, raw RCA is unsuitable for use as an HMA aggregate based on its relatively high LAA value. However, the mechanical beneficiation process can increase the abrasion resistance of RCA, as indicated by the drop in LAA value, from 35% to 27%. Therefore, mechanically beneficiated RCA can be

employed as an HMA aggregate for light-traffic roads. The modified thermal–mechanical beneficiation process used in this study can further reduce the LAA by 25%, which was the best LAA value obtained from all tests. It should be noted that the improved abrasion resistance of this RCA mainly stemmed from the mechanical beneficiation process. This process could alone provide an absolute improvement in the LAA value of 8%. Additionally, the modified thermal–mechanical beneficiation process used in this study can provide further enhancements to the LAA value derived from the mechanical beneficiation process by an absolute reduction of 2%. Consequently, the beneficiated RCA produced using the modified thermal–mechanical beneficiation process – with the best LAA test result of 25% – can be used as an HMA aggregate suitable for light- and medium-traffic roads. This beneficiated RCA was selected to represent the treated RCA and then used as the HMA aggregate in the asphalt mix design in this study.

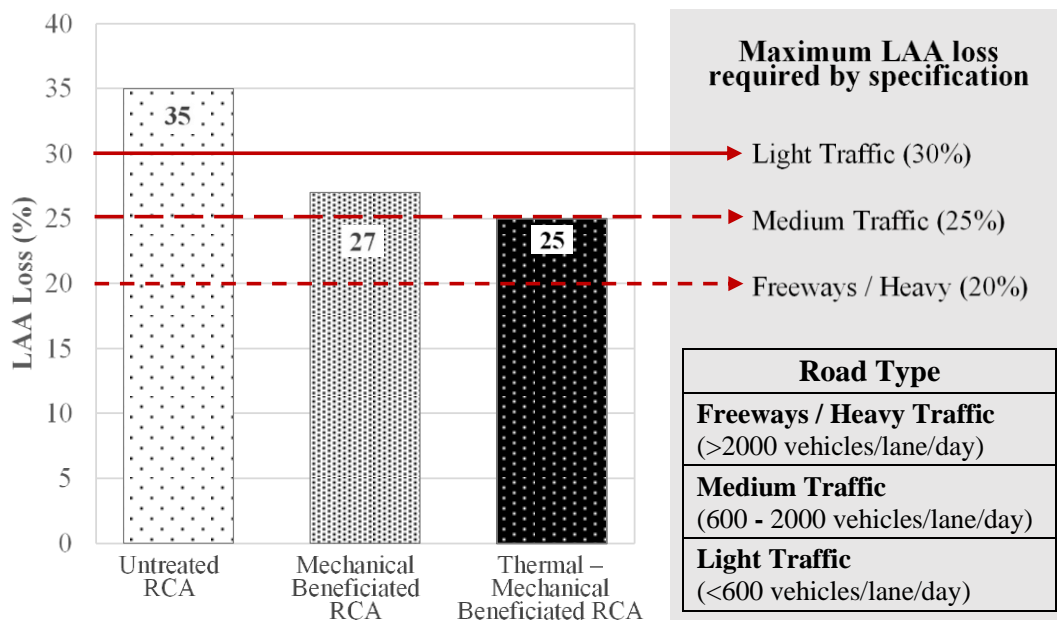


Figure 9. Average LAA values of untreated RCA and RCA treated with the beneficiation processes, along with standard specifications [27]

## **4.2 Material characterisations**

Table 7 shows the relevant properties of the aggregates used in this study. Firstly, through a visual inspection, it was clear that the NA of granite had a clean texture with no signs of deleterious particles – irregular and angular manners were mostly seen (see Figure 1). As seen in Figure 2, RCA is a combination of the parent aggregate as a core and the adhered cement mortar. For BRCA, there is far less adhered cement mortar than RCA, as expected. With less adhered cement mortar, BRCA has a higher specific gravity (SG) than RCA, exhibiting less water absorption for both types of RCA. However, among the three types of aggregates in Table 7, NA shows the highest SG with the least water absorption. LAA tests, aggregate impact tests, and aggregate crushing tests were used to assess the mechanical degradation of aggregates under impact and crushing actions. Further, soundness tests using magnesium sulphate were undertaken to assess the environmental degradation of aggregates. These durability properties are crucial contributors to the performance of HMA, because HMA aggregates must withstand degradation and disintegration to maintain appropriate fine content in a mixture. If weak aggregates with lower durability are used, excessive fine generation with a relatively high level of degradation would be expected, resulting in a poor-quality HMA mixture in general. The LAA values for BRCA are slightly better than those for NA. When considering degradation caused by impacting and crushing actions, NA obviously has better mechanical degradation resistance in terms of AIV and ACV than BRCA. Furthermore, NA also demonstrates better soundness resistance than BRCA. As expected, RCA has the lowest degradation resistance of all three aggregates used in this study. However, all the values for BRCA still satisfied the Western Australia Main Roads standards [27] for HMA mixtures. Based on the properties in Table 7, it should be noted that the LAA values of NA and BRCA are almost identical, but the ACV and AIV values



of NA and BRCA differ. This indicates that BRCA has virtually the same abrasion resistance, but the lower impact and crushing strength in comparison to NA.

Table 7. Relevant properties of aggregates used in this study for HMA

Tests	Standard methods	Materials		
		RCA	NA	BRCA
Gradation	AS 1141.11.1	NA.	See Figure 6	
Specific gravity/water absorption, % (coarse aggregate)	AS 1141.6.1	2.23/8.93	2.63/0.44	2.58/2.88
Specific gravity/water absorption, % (fine aggregate)	AS 1141.5	2.42/7.82	2.60/0.41	2.61/2.81
LAA, %	AS 1141.23	35	26	25
Soundness (magnesium sulphate), %	ASTM C 88-99a	8.7	4.2	4.8
Aggregate impact value (AIV), %	BS 812:112	31	20	24
Aggregate crushing value (ACV), %	BS 812-110	36	25	29

#### 4.3 Mix design

Table 8 shows the HMA mix design results obtained in this study. Both HMA-NA and HMA-BRCA were formulated based on the 14-mm dense-graded HMA criteria [30] – with the asphalt binder type of C320 – and NA and BRCA aggregates, respectively.

For the mix design volumetric analysis, the results shown in Table 8 confirm that the mix design parameters meet the mix design criteria for both HMA-NA and HMA-BRCA. However, it should be noted that HMA-BRCA has a higher binder content and a lower air void content than HMA-NA. With the same reproduced grading curve for both HMA mixtures before the compaction process, the VMAs of both mixtures should theoretically be identical because VMA is the total air void content within a matrix of a compacted aggregate and is strongly dependent on its nominal size and gradation curve. However, in Table 7, it can be seen that the VMA of HMA-NA is larger than the VMA

of HMA-BRCA, leading to different VFAs for both mixtures. This could be caused by the higher asphalt binder absorption of BRCA, indicated by its higher water absorption than NA (see Table 7). This relatively higher asphalt binder absorption rate of BRCA reduces the effective asphalt binder content in the HMA mixture. Consequently, the VFA decreases because the actual air voids in both HMA mixtures did not differ much.

HMA-BRCA provides better mechanical performance in the mix design owing to its higher stability and smaller flow values than HMA-NA. Conversely, HMA-NA has a higher density than of HMA-BRCA, which is contributed to by the higher SG value of NA.

Table 8. HMA mix design results from this study

Mix design parameters	14 mm dense-graded HMA		Mix design criteria	
	HMA-NA	HMA-BRCA	Min	Max
Binder content, % (by percentage mass of a whole mixture)	4.5	4.7	4.7% $\pm$ 0.3 (Class 320)	
Density, (kg/m <sup>3</sup> )	2430	2390	-	-
Marshall stability, kN	15.40	17.50	8.0	-
Marshall flow, mm	3.6	2.6	2.00	4.00
Air void, %	4.3	4.1	4	7
VMA, %	17	14	14	-
VFA*, %	71	67	65	80

\*Note: VFA is not a mix design criterion according to MRWA's HMA mix design, but the normal range of VFA for a dense-graded HMA is between 65 and 80%, based on Austroads' guide to pavement technology: Part 4B [32].

### ***4.3 Mechanical performance tests***

#### ***4.3.1 Marshall stability and flow***

The Marshall stability and flow test results are shown in Table 7. These Marshall values empirically indicate the performance of an HMA mixture in regard to external stress, which causes distortion and displacement. These results indicate that the HMA-BRCA exhibited higher stability than HMA-NA, by 12%. On the other hand, the flow number of HMA-BRCA is 16% lower than that for HMA-NA.

#### ***4.3.2 MR***

In this study, the MR was used for comparing material moduli under different mix conditions and the cyclic loading regime. The asphalt mixture specimens for the MR test were prepared to have an air void percentage of  $5.0\% \pm 0.5\%$ . This specified air void range was adopted from the value recommended in the dynamic modulus determination standard [38]. The air void percentage is in accordance with the Australian standard method for determining the MR [37]. The resilient moduli of HMA-NA and HMA-BRCA specimens determined in this study are shown in Figure 10. The results indicate that the MR of HMA-BRCA is higher than that of HMA-NA by 16.20%.

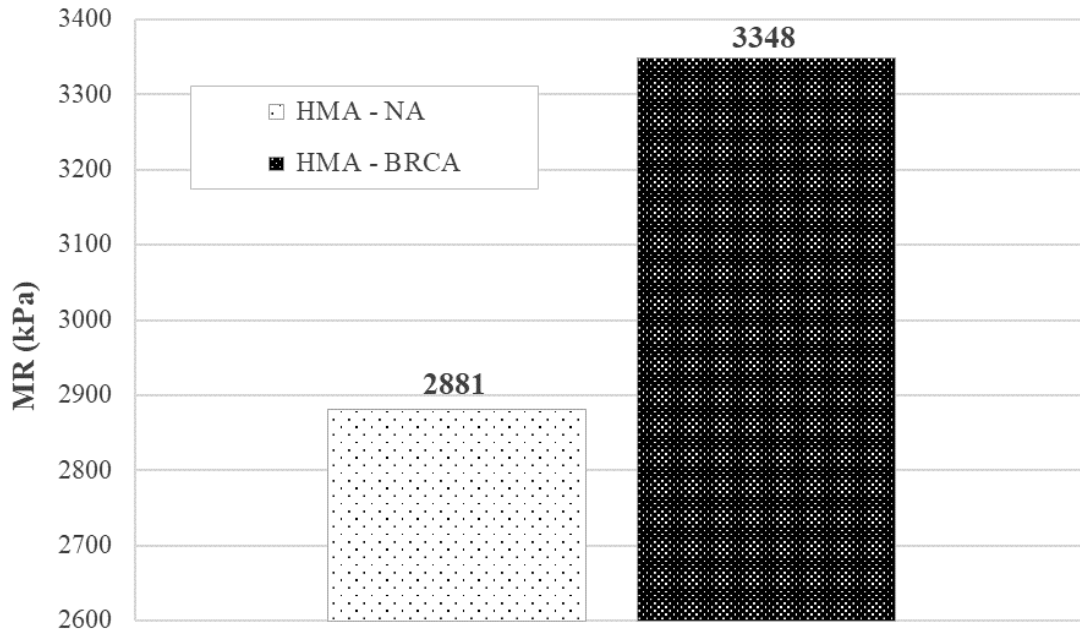


Figure 10. Resilient moduli of HMA-NA and HMA-BRCA

#### 4.3.3 Dynamic modulus test results

The specimens for the dynamic modulus tests were prepared to have an air void percentage of  $5.0\% \pm 0.5\%$  [38]. According to the time–temperature superposition principle, the moduli measured at different temperatures were shifted horizontally to form a dynamic modulus master curve [40]. Figure 11 shows the dynamic modulus master curves of HMA-NA and HMA-BRCA obtained from the AMPT tests. The results clearly show that the dynamic moduli of both mixtures increased with increases in reduced frequency. An increase in reduced frequency physically represents a reduction in temperature or a rise in loading frequency. Figure 12 presents the variations in phase angle with the changes in reduced frequency, which can be categorised into two stages. First, when the reduced frequency is lower than 0.1 Hz (higher testing temperature), the phase angle increases with a rise in reduced frequency. In the second stage, when the reduced frequency is greater than 0.1 Hz (lower testing temperature), the increase in reduced frequency leads to a drop in phase angle values.

Figures 11 and 12 further illustrate the similarity between the AMPT test results measured using HMA-NA and HMA-BRCA specimens. The dynamic modulus master curves and phase angle curves for both mixtures are almost identical. However, a difference in the MR values of the mixtures was observed in the previous section; this indicates a fundamental difference between the characteristics of the dynamic modulus test and the MR test. Continuous cyclic loading was employed for dynamic modulus measurement, while a pulse load with a rest period was applied to the specimen during the MR test. Moreover, the specimen size and test configurations of both tests are not the same. The cylindrical specimen is axially loaded by the AMPT during the dynamic modulus measurement, while the splitting force is applied to the side of the specimen during the MR test. However, it is important to note that – in the range of temperature and frequency of the dynamic modulus tests in this study – HMA-NA and beneficiated HMA-BRCA specimens performed almost identically under cyclical loading, which more accurately represents moving traffic.

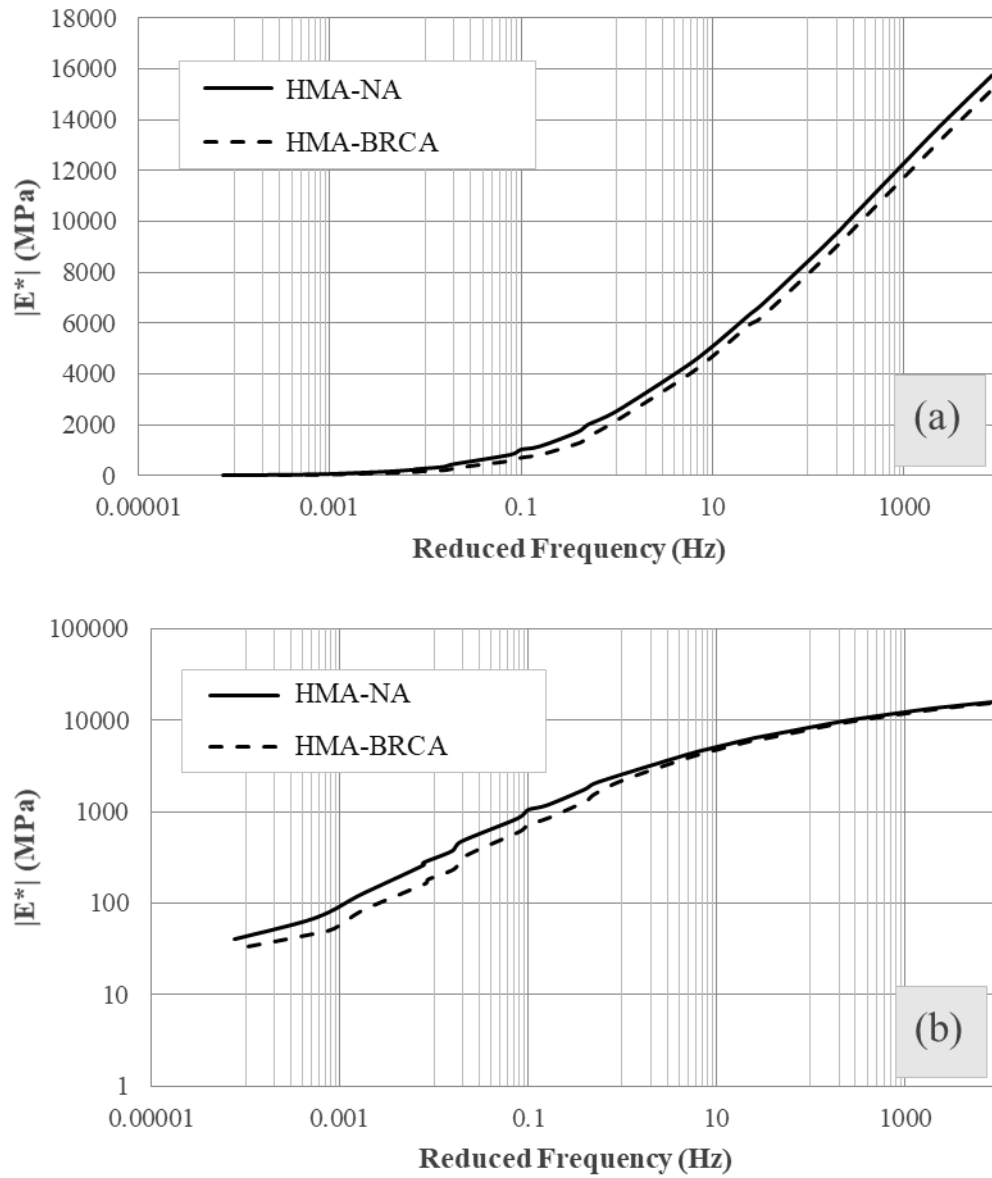


Figure 11. Dynamic modulus master curves of HMA-NA and HMA-BRCA in (a) arithmetic scale and (b) logarithmic scale

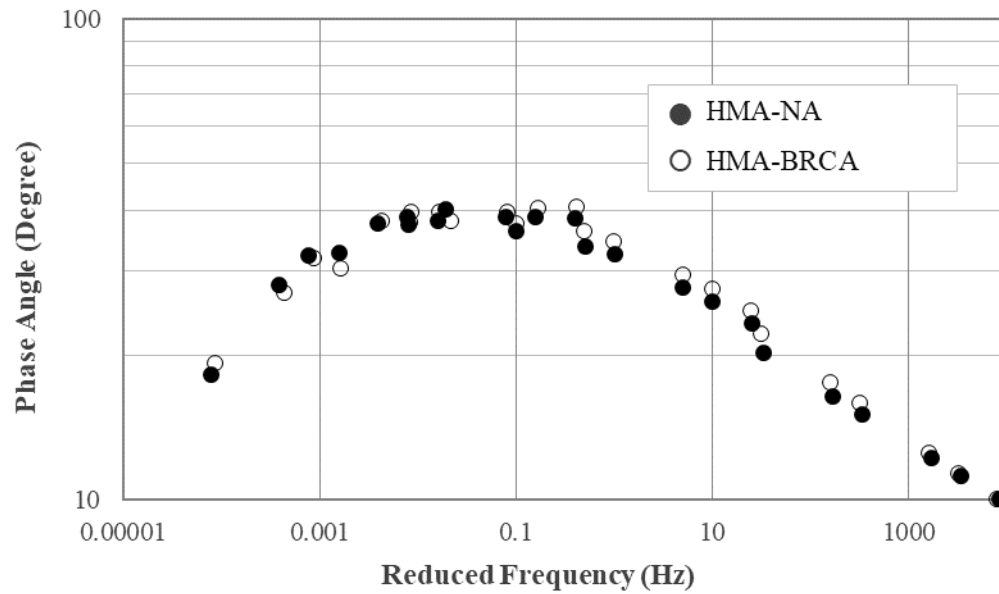


Figure 12. Phase angle master curves of HMA-NA and HMA-BRCA

#### 4.3.4 Tensile strength ratio (TSR)

The results of the IDT and TSR tests are shown in Figure 13. The IDT values obtained from soaked (wet) specimens were lower than those from the unsoaked (dry) specimens. This difference in IDT values indicates the adverse effect of moisture ingress. However, the IDT values of both soaked and unsoaked HMA-NA specimens were higher than those of HMA-BRCA specimens. In addition, HMA-NA demonstrates a TSR value above 80%, while a TSR value of 67.5% was obtained for HMA-BRCA. According to Austroads [39], a TSR greater than 80% is required for a good quality HMA mixture that can withstand moisture-induced damage. Therefore, based on this TSR value, the HMA-BRCA used in this study is susceptible to moisture and does not meet the moisture damage resistance requirements of the HMA mix design.

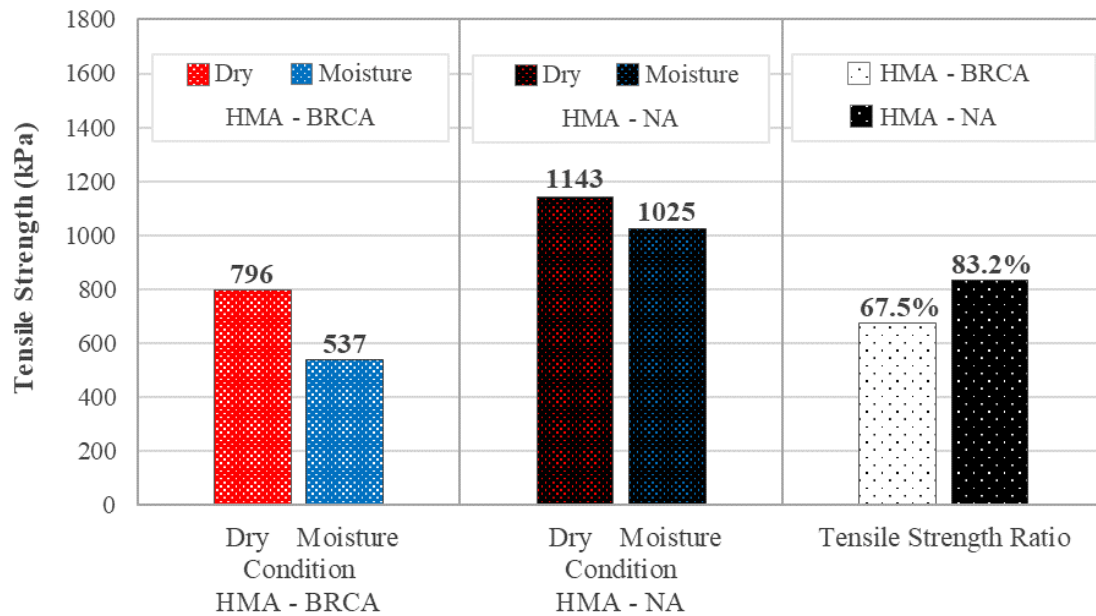


Figure 13. Indirect tensile strength (IDT) and tensile strength ratio (TSR) test results

#### 4.4 Examination and discussion

As mentioned before, RCA has two main components – the parent aggregate as a core and the cement mortar adhered to this core. Generally, untreated RCA fails to meet the requirements for abrasion resistance for an HMA aggregate owing to its weak mortar portions. The presence of adhered cement mortar also affects the overall performance of RCA. In this study, thermal–mechanical beneficiation was employed to treat raw RCA to meet abrasion-resistant requirements based on the LAA value. In line with HMA mix design perspectives, beneficiated RCA with a satisfactory LAA value could be used as the aggregate in a 14 mm-dense graded HMA mixture with no NA, based on MRWA’s HMA mix design specifications [27]. The performance test results of HMA-BRAC reveal better Marshall stability and flow, and MR values, along with almost identical dynamic modulus characteristics, in comparison to HMA-NA. Notably, HMA-BRAC exhibited relatively weak moisture damage resistance, demonstrated by its TSR value of 67.5%, which is significantly lower than the 80% minimum requirement for this purpose. For the general Marshall mix design, TSR is not a compulsory test. Therefore, it should be noted



that, when using any RCA in HMA, the moisture damage resistance of HMA incorporating RCA should be considered. Additionally, mechanical crushing and impacting during the production and construction processes of HMA could affect the degradation of RCA or even treated RCA through the generation of more fine particles in the HMA matrix. This higher proportion of fine aggregate in the HMA mixture alters its performance.

The following subsections examine why HMA-BRCA yields better strength, deformation, and stiffness than HMA-NA, with substandard moisture damage resistance.

#### *4.4.1 A denser mixture matrix due to RCA breakage*

In this study, the laboratory aggregate tests to determine AIV and CIV were used to identify the impacting and crushing resistance of aggregates used in HMA. Although RCA was treated to become BRCA with a satisfactory LAA value, BRCA was still prone to degrade under impacting and crushing actions, based on its relatively high AIV and CIV (see Table 7). Furthermore, for the mix design results in this study, a lower VMA of HMA-BRCA could theoretically indicate that, under the HMA-BRCA mix structure, a denser BRCA structure is formed. The breakage of BRCA during the mixing and compacting processes could alter the aggregate gradation through the generation of more fine content. Coarse particles of BRCA would break into smaller particles, simplifying the reorientation and filling of void matrices within a mixture. Consequently, less air void space – in terms of VMA – in an HMA mixture can be expected. As shown in Table 7, the calculated VMA of HMA-BRCA is less than that of HMA-NA. Therefore, HMA-BRCA has greater absorption levels for asphalt binders, but a lower amount of asphalt binder would be required to fill VMA voids. This would explain why HMA-BRAC has less VFA than HMA-NA, as shown in Table 7, but both mixtures have similar asphalt binder content. Therefore, a denser mixture of HMR-BRAC, with tighter aggregate

packing, could provide better strength, stiffness, and deformation characteristics. Therefore, the higher Marshall stability and resilient modulus, along with the lower Marshall flow of HMA-BRCA could be attributed to this denser mix structure. Figure 14 shows evidence of BRCA breakage (see Figure 14(b)) in the HMA-BRCA mixture after the TSR tests, in comparison to the same results for HMA-NA.

For the dynamic modulus tests, HMA-BRCA and HMA-NA yield similar dynamic modulus master curves. The dynamic modulus test was designed to capture the behaviour of asphalt concrete materials, having intrinsic viscoelastic properties. To this end, a specific range of temperature and applied loading frequencies were assigned to test a relatively small strain amplitude. This small applied strain was specified to assure that, under the assigned test conditions, asphalt concrete performs within its range of viscoelasticity. Within this range of applied low-strain amplitude, the difference in VMA and VFA owing to such breakages between HMA-BRCA and HMA-NA would not be significant enough distinguish the dynamic moduli of both mixtures under a specified range of temperatures and frequencies.

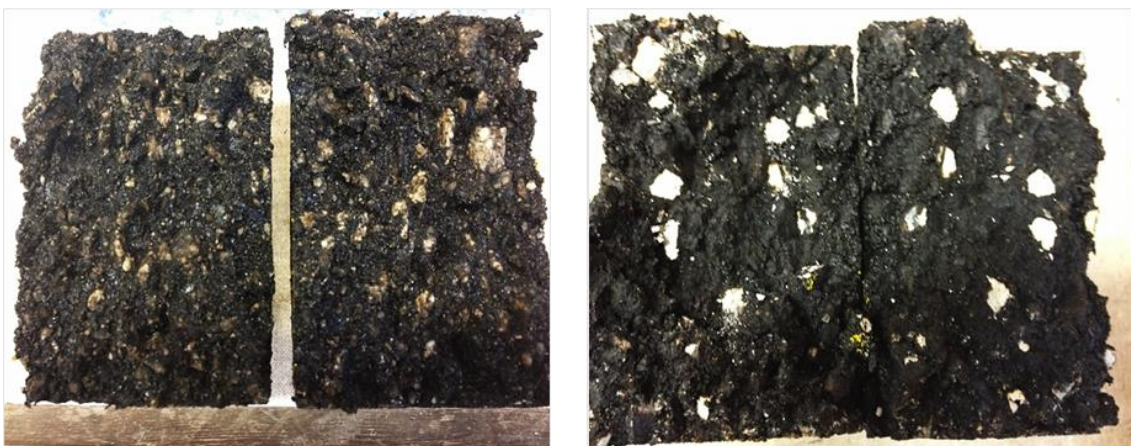


Figure 14. The soaked (a) HMA-NA specimen and (b) HMA-BRCA specimen after the  
TRs tests

#### *4.4.2 Role of asphalt binder film thickness*

As mentioned before, a lower asphalt binder film thickness was expected for HMA-BRCA, in accordance with its lower VMA and the higher asphalt absorption of BRCA. This thinner film of the effective asphalt binder layer could lower the moisture damage resistance. However, when considering the internal shear friction within an HMA mixture, a thinner asphalt binder film could facilitate improved sliding resistance between nearby aggregate particles upon loading. Thus, with the thinner asphalt binder film of HMA-BRCA, improved strength characteristics and deformation resistance can be expected; however, it is more susceptible to moisture damage. It is suspected that the asphalt binder may not completely coat some parts of the broken BRCA particles illustrated in Figure 14 (b). Imperfectly coated surfaces of BRCA could be seriously damaged under loading in the presence of a certain level of moisture. Furthermore, these defective surfaces could also attract moisture, deteriorating asphalt binder–aggregate bonding, leading to the occurrence of a stripping effect.

#### *4.4.3 The presence of calcite in BRCA*

Information on the dependence of the quality of the aggregate and asphalt binder bonding on surface chemical activities is known, which could play a key role in the moisture damage resistance of HMA. During the mixing process, hot asphalt binder is incorporated with hot aggregate in the liquid form; subsequently, upon cooling, the asphalt binder hardens and binds aggregates together in an asphalt concrete mixture or HMA. Therefore, the chemical interactions between the asphalt binder and aggregate significantly affect these bonding properties. For asphalt binders, they can be acid-based binders (pH values less than 7) or caustic-based binders (pH values more than 7), depending on sources of crude oil [41]. In this study, the NA of granite is classified as an acid rock with high silica content. It must have a good affinity with a caustic-based binder.

Based on the acceptable moisture damage resistance through a relatively high TSR value of HMA-NA, the asphalt binder batch of C320 used in this study could be caustic with good bonding to the positive charges on the surface of the NA particles. On the other hand, this caustic-based asphalt binder does not have sound affinity with limestone – which is mostly caustic in nature owing to its high content of calcite. After obtaining a sub-standard TSR result for HMA-BRCA, NA and BRCA were re-examined using x-ray diffraction (XRD). Figure 15 shows the XRD results for NA and BRCA, through which calcite was detected in BRCA. The appearance of calcite in BRCA relates to the original cement mortar adhered to the surfaces of the raw RCA particles. Consequently, the presence of calcite in HMA-BRCA could enhance the moisture susceptibility of HMA-BRCA.

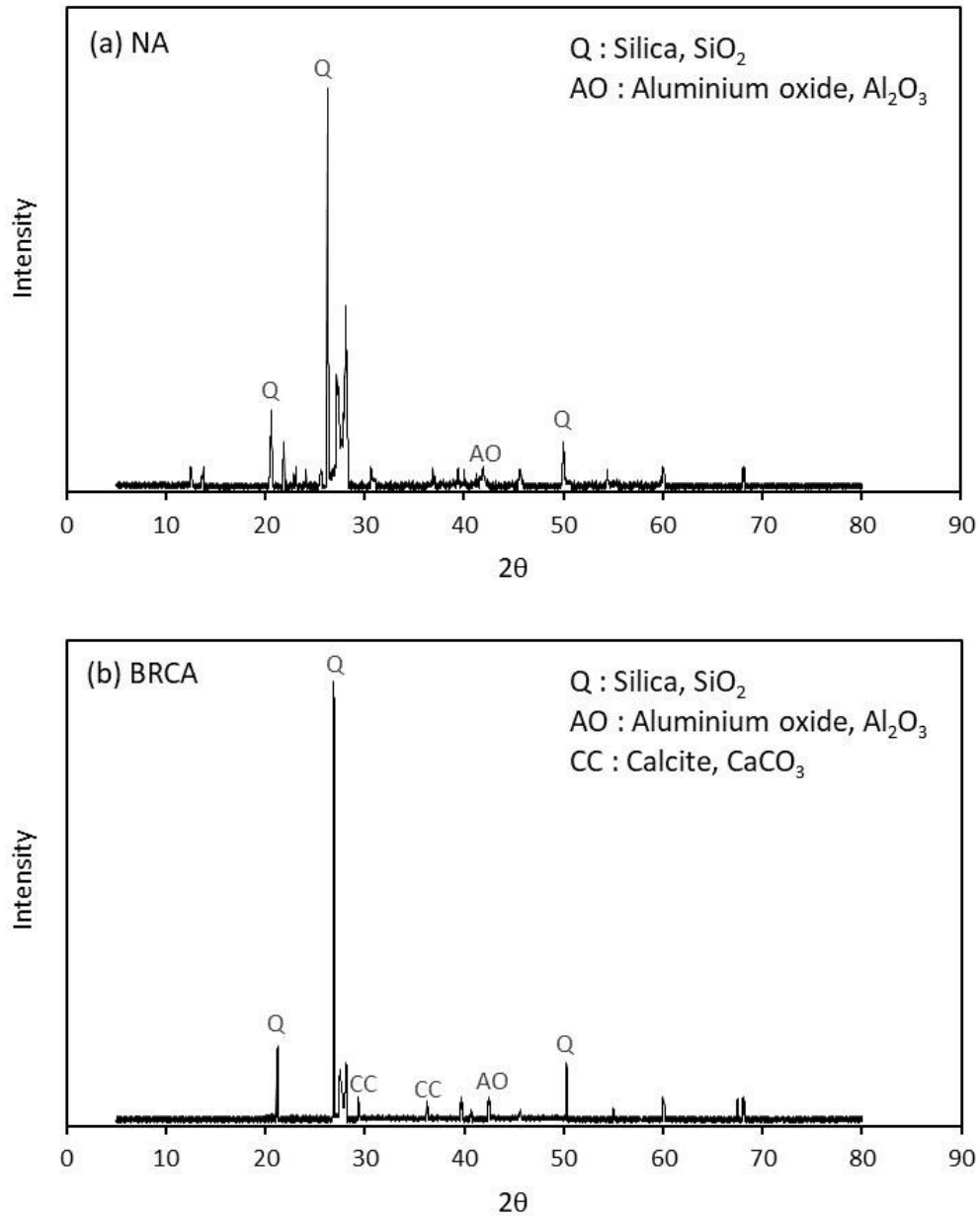


Figure 15. XRD results for (a) NA and (b) BRCA

## 5. Concluding remarks

This study examines the possibility of employing BRCA as a suitable HMA aggregate in HMA mixtures. The abrasion resistance of RCA was focused on because it has been highlighted as a significant limitation regarding the use of RCA as an HMA aggregate based on previous research. Consequently, this study employed a modified

thermal–mechanical beneficiation process to improve the abrasion resistance of RCA. A series of performance tests on HMA-BRCA and HMA-NA (a benchmark material) were conducted to examine the complete replacement of NA by BRCA in the HMA mixture. This study intended to examine the mix design and laboratory performance of HMA using 100% beneficiated RCA to replace NA. The concluding remarks of this study are as follows:

1. The modified thermal–mechanical beneficiation process used in this study removed a large amount of the weak matrix from the RCA. The LAA value of 25% indicated this and met the requirements for HMA aggregates.
2. BRCA also provided satisfying LAA result, complying with HMA aggregate requirements. Further, its AIV and ACV, indicating the impacting and crushing resistance, respectively, were relatively high. These high AIVs and ACVs of BRCA indicate a significant possibility of breakage under mixing and compacting processes of BRCA fabrications.
3. Based on the Marshall mix design used to validate the use of BRCA in the 14 mm dense-graded HMA mixture, HMA-BRCA addressed all mix design criteria as the benchmark of HMA-NA. for both HMA mixtures with similar asphalt binder contents (4.5% for HMA-NA and 4.7% for HMA-BRCA), HMA-BRCA exhibited lower air void content, VMA, VFA, and density than HMA-NA. However, HMA-BRCA provided larger Marshall stability and smaller Marshall flow than HMA-NA.
4. The results of a series of performance tests on MR and dynamic modulus confirm that HMA-BRCA shows superior MR performance than HMA-NA, which was used as a benchmark material for this study. However, it should be noted that, based on the advanced dynamic modulus tests – which represent the best replication of conditions in the field – the dynamic moduli of HMA-BRCA and HMA-NA were almost

identical. This resulted from a slight application of the strain amplitude of the dynamic modulus tests to maintain default viscoelastic behaviour of the HMA test sample. However, HMA-BRCA, on the other hand, was more susceptible to moisture than HMA-NA, indicated by the sub-standard TSR value of HMA-BRCA.

5. An investigation was made to clarify why HMA-BRCA yielded better strength, deformation, and stiffness than HMA-NA, with sub-standard moisture damage resistance. It could be that the breakage of BRCA during mixing and compacting led to finer aggregate content in the entire HMA mixture matrix, resulting in tighter aggregate structure packing. This better packing with lower VMA of BRCA would play a role in the increased strength, stiffness, and deformation characteristics of HMA-BRCA. The thinner asphalt binder film thickness of HMA-BRCA could further enhance these engineering properties. However, it would have an adverse effect on the moisture damage resistance by simplifying moisture ingress. The presence of calcite, which would be a retained cement mortar, in HMA-BRCA is another crucial factor affecting the moisture susceptibility of HMA-BRCA. Calcite, with a negative surface charge, must push over with the same negative charge of the asphalt binder of C320, which leads to a poor quality of bonding between BRCA and C320, enhancing the moisture susceptibility of HMA-BRCA.
6. Although the engineering characteristics of HMA-BRCA are sound, concerns regarding the mix design performance criteria of HMA with RCA are inevitable owing to its moisture susceptibility. Durability in terms of moisture susceptibility should be an important criterion to be assessed for the HMA mix design – through the TSR test – having RCA as the aggregate.
7. Based on the results of this study, some suggestions can be made. Although RCA was treated to meet all the basic requirements of HMA aggregates, simple strength and

stiffness evaluations in the laboratory are not sufficient for the HMA mix design. In addition, the stripping potential of HMA must be focused on because of the potential of RCA to break. The relatively thin asphalt film thickness and retained calcite in HMA with RCA can enhance moisture ingress into the HMA matrix.

## **6. Acknowledgement**

Chiang Mai University and Curtin University mainly supported the work. Special thanks are extended to the Department of Civil Engineering at Curtin University, Australia, for the relevant information, and the laboratory works in this study. Mr. Lachlan Maddams and Mr. Nabil Rahman should be strongly acknowledged and thankful to their main contributions to the laboratory experiment of this study. The last author would like to acknowledge the financial support of the Thailand Research Fund (TRF) under the TRF Distinguished Research Professor Grant No. DPG6180002. Moreover, the research teams of the Civil Engineering Department at Curtin University, Australia, Chiang Mai University, and Naresuan University, Thailand, are also gratefully acknowledged for providing guidance and valuable input into this work.

## **References**

- [1] A. Turkyilmaz, M. Guney, F. Karaca, Z. Bagdatkyzy, A. Sandybayeva, G. Sirenova, A comprehensive construction and demolition waste management model using PESTEL and 3R for construction companies operating in Central Asia, *Sustainability*. 11 (2019) 1593. <https://doi.org/10.3390/su11061593>.
- [2] A. López, A. Lobo, Emissions of C&D refuse in landfills: A European case, *Waste Manag.* 34 (2014) 1446–1454.



- <https://doi.org/https://doi.org/10.1016/j.wasman.2014.04.004>.
- [3] A. Arulrajah, J. Piratheepan, M. M. Disfani, M. W. Bo, Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications, *J. Mater. Civ. Eng.* 25 (2013) 1077–1088.  
[https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000652](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000652).
- [4] S. Ismail, M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications, *Constr. Build. Mater.* 44 (2013) 464–476. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.03.014>.
- [5] P. Saravanakumar, K. Abhiram, B. Manoj, Properties of treated recycled aggregates and its influence on concrete strength characteristics, *Constr. Build. Mater.* 111 (2016) 611–617.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.02.064>.
- [6] K.K. Sagoe-Crentsil, T. Brown, A.H. Taylor, Performance of concrete made with commercially produced coarse recycled concrete aggregate, *Cem. Concr. Res.* 31 (2001) 707–712. [https://doi.org/https://doi.org/10.1016/S0008-8846\(00\)00476-2](https://doi.org/https://doi.org/10.1016/S0008-8846(00)00476-2).
- [7] P. Taesoon, Application of construction and building debris as base and subbase materials in rigid pavement, *J. Transp. Eng.* 129 (2003) 558–563.  
[https://doi.org/10.1061/\(ASCE\)0733-947X\(2003\)129:5\(558\)](https://doi.org/10.1061/(ASCE)0733-947X(2003)129:5(558)).
- [8] F. da C. Leite, R. dos S. Motta, K.L. Vasconcelos, L. Bernucci, Laboratory evaluation of recycled construction and demolition waste for pavements, *Constr. Build. Mater.* 25 (2011) 2972–2979.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2010.11.105>.

- [9] J. Mills-Beale, Z. You, The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates, *Constr. Build. Mater.* 24 (2010) 230–235.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2009.08.046>.
- [10] A.R. Pasandín, I. Pérez, Laboratory evaluation of hot-mix asphalt containing construction and demolition waste, *Constr. Build. Mater.* 43 (2013) 497–505.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.02.052>.
- [11] M.J. Chen, Y.D. Wong, Porous asphalt mixture with 100% recycled concrete aggregate, *Road Mater. Pavement Des.* 14 (2013) 921–932.  
<https://doi.org/10.1080/14680629.2013.837839>.
- [12] A. Akbarnezhad, K.C.G. Ong, M.H. Zhang, C.T. Tam, T.W.J. Foo, Microwave-assisted beneficiation of recycled concrete aggregates, *Constr. Build. Mater.* 25 (2011) 3469–3479.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2011.03.038>.
- [13] S. Paranavithana, A. Mohajerani, Effects of recycled concrete aggregates on properties of asphalt concrete, *Resour. Conserv. Recycl.* 48 (2006) 1–12.  
<https://doi.org/https://doi.org/10.1016/j.resconrec.2005.12.009>.
- [14] S. Bhusal, X. Li, H. Wen, Evaluation of effects of recycled concrete aggregate on volumetrics of hot-mix asphalt, *Transp. Res. Rec.* 2205 (2011) 36–39.  
<https://doi.org/10.3141/2205-05>.
- [15] A. Arulrajah, S. Horpibulsuk, F. Maghool, Recycled construction and demolition materials in pavement and footpath bases, in: *Sixth Int. Symp. Rural Roads*, Bangkok, Thailand, 2016: pp. 1–14.

- [16] M. Aboutalebi Esfahani, Evaluating the feasibility, usability, and strength of recycled construction and demolition waste in base and subbase courses, *Road Mater. Pavement Des.* 21 (2020) 156–178.  
<https://doi.org/10.1080/14680629.2018.1483259>.
- [17] Y.C. Gokhale, R.S. Shukla, P.K. Jain, Beneficiation of shale aggregate and production of artificial aggregate, *Bull. Int. Assoc. Eng. Geol.* 30 (1984) 391–393.
- [18] H. Shima, H. Tateyashiki, R. Matsushashi, Y. Yoshida, An advanced concrete recycling technology and its applicability assessment through input-output analysis, *J. Adv. Concr. Technol.* 3 (2005) 53–67.  
<https://doi.org/10.3151/jact.3.53>.
- [19] J.G. Bastidas-Martínez, H.A. Rondón-Quintana, C.A. Zafra-Mejía, Study of hot mix asphalt containing recycled concrete aggregates that were mechanically treated with a Los Angeles machine, *Int. J. Civ. Eng. Technol.* 10 (2019) 226–243.
- [20] Y.-H. Cho, T. Yun, I.T. Kim, N.R. Choi, The application of Recycled Concrete Aggregate (RCA) for Hot Mix Asphalt (HMA) base layer aggregate, *KSCE J. Civ. Eng.* 15 (2011) 473–478. <https://doi.org/10.1007/s12205-011-1155-3>.
- [21] Y.D. Wong, D.D. Sun, D. Lai, Value-added utilisation of recycled concrete in hot-mix asphalt, *Waste Manag.* 27 (2007) 294–301.  
<https://doi.org/https://doi.org/10.1016/j.wasman.2006.02.001>.
- [22] N.K. Bui, T. Satomi, H. Takahashi, Enhancement of recycled aggregate concrete properties by a new treatment method, *Int. J. GEOMATE.* 14 (2018) 68–76.

- [23] C.-H. Lee, J.-C. Du, D.-H. Shen, Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt, *Constr. Build. Mater.* 28 (2012) 66–71.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2011.08.025>.
- [24] M. Muniz de Farias, F. Quiñonez Sinisterra, H.A. Rondón Quintana, Behavior of a hot mix asphalt made with recycled concrete aggregate and crumb rubber, *Can. J. Civ. Eng.* 46 (2018) 544–551. <https://doi.org/10.1139/cjce-2018-0443>.
- [25] S. Bhusal, H. Wen, Evaluating recycled concrete aggregate as hot mix asphalt aggregate, *Adv. Civ. Eng. Mater.* 2 (2013) 252–265.  
<https://doi.org/10.1520/ACEM20120053>.
- [26] Z. Anggraini, W.Y. Diew, S.D. Delai, Mechanistic performance of asphalt-concrete mixture incorporating coarse recycled concrete aggregate, *J. Mater. Civ. Eng.* 25 (2013) 1299–1305. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000668](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000668).
- [27] Main Roads Western Australia, Specification 501-Pavements, (2014).
- [28] Standards Australia, Aggregates and rock for engineering purposes. Part 2: Aggregate for sprayed bituminous surfacing, (2009). <https://doi.org/AS 2758.2>.
- [29] Standards Australia, Bitumen for pavements, (2013). <https://doi.org/AS 2008>.
- [30] Main Roads Western Australia, Specification 504 Asphalt wearing course, Perth, WA, 2017.
- [31] Standards Australia, Methods for sampling and testing aggregates – Los Angeles value, (2009). <https://doi.org/AS 1141.23>.

- [32] Austroads, Guide to pavement technology part 4B: Asphalt, (2014).  
<https://doi.org/AGPT04B-14>.
- [33] Standards Australia, Methods of sampling and testing asphalt Method 2.2: Sample preparation – Compaction of asphalt test specimens using a gyratory compactor, Sydney, NSW, 2014. <https://doi.org/AS 2891.2.2>.
- [34] Main Roads Western Australia, Test method – stability and flow of asphalt – Marshall Method, Perth, WA, 2010. <https://doi.org/WA 731.1>.
- [35] Standards Australia, Methods of sampling and testing asphalt – Sample preparation – Mixing, quartering, and conditioning of asphalt in the laboratory, (1995). <https://doi.org/AS 2891.2.1>.
- [36] Standards Australia, Methods of sampling and testing asphalt – Determination of stability and flow – Marshall Procedure, (2004). <https://doi.org/AS 2891.5>.
- [37] Standards Australia, Methods of sampling and testing asphalt – Determination of the MR of asphalt – Indirect tensile method, (1995). <https://doi.org/AS 2891.13.1>.
- [38] AASHTO, Standard method of test for determining the dynamic modulus and flow number for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT), (2011).
- [39] Austroads, Commentary to AG: PT/T232 – Stripping potential of asphalt – Tensile strength ratio, Melbourne, VIC., 2007. <https://doi.org/AG: PT/T232>.
- [40] Y.R. Kim, Modeling of asphalt concrete, ASCE Press, McGraw-Hill, NY, 2009.

- [41] S. Alam, Z. Hossain, Changes in fractional compositions of PPA and SBS modified asphalt binders, *Constr. Build. Mater.* 152 (2017) 386–393.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.07.021>.