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Development of a Double Coating Technique for Recycled Concrete Aggregates Used in Hot-mix Asphalt

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***Abstract*—**The use of recycled concrete aggregates (RCAs) in hot-mix asphalt (HMA) production could ease natural aggregate shortage and maintain sustainability in modern societies. However, it was the attached cement mortar and other impurities that make the RCAs behave differently than high-quality aggregates. Therefore, different upgrading treatments were suggested to enhance its properties before being used in HMA production. Disappointedly, some of these treatments had caused degradation to some RCA properties. In order to avoid degradation, a coating technique is developed. This technique is based on combining of two main treatments, so it is named as double coating technique (DCT). Dosages of 0%, 20%, 40% and 60% uncoated RCA, RCA coated with Cement Slag Paste (CSP), and Double Coated Recycled Concrete Aggregates (DCRCAs) in place of granite aggregates were evaluated. The results indicated that the DCT improves strength and reduces water absorption of the DCRCAs compared with uncoated RCAs and RCA coated with CSP. In addition, the DCRCA asphalt mixtures exhibit stability values higher than those obtained for mixes made with granite aggregates, uncoated RCAs and RCAs coated with CSP. Also, the DCRCA asphalt mixtures require less bitumen to achieve the optimum bitumen content (OBC) than those manufactured with uncoated RCA and RCA-coated with CSP. Although the results obtained were encouraging, more testing is required in order to examine the effect of the DCT on performance properties of DCRCA- asphalt mixtures such as rutting and fatigue.

***Keywords*—**Recycled concrete aggregates, hot mix asphalt, double coating technique, aggregate crashed value, Marshall parameters.

I. Introduction

THE uses of the RCAs in pavement infrastructures have been investigated in different countries. Vast quantities of RCAs come from man’s construction and demolition activities, and natural disasters had encouraged its usage in HMA. However, many researchers have mentioned that the RCAs had a lower unit weight [1]-[4], a lower abrasion resistance [1], [2], [4], [5] and higher water absorption [1]-[3], [5], [6] compared to natural aggregates. In such a situation, the RCA-asphalt mixtures were found to behave differently from those made with high-quality aggregates. Therefore, treatment is required to upgrade the performance of RCA to be used as aggregates in HMA industry [5].

As a result of discouraging performance obtained for RCA-asphalt mixtures and their high demand on bitumen compared with those made with natural aggregates, it is not recommended to use the RCAs in HMA [7]. During the last decade, different upgrading treatments were suggested to improve the performance of the HMA made with RCAs [2], [4], [5], [8]-[11]. Some treatments were required to coat the RCAs with another product, while the others need to heat the RCAs/asphalt mix for additional time in the oven to achieve their objectives. The aims of these treatments were to reinforce the weak particles of the RCA and/or reduce their permeability (decrease water/bitumen absorption). However, sometimes the treatment was found to cause degradation of the RCA properties. For instance, although treatments suggested by Lee, Du [9] and Hou, Ji [5] were reported to enhance the resistance of coated RCA against abrasion, however, such treatments increase the water/bitumen absorption of the final product simultaneously. This means that some of previously used treatments are not efficient enough to remedy all the RCAs’ defects and sometimes they degrade some properties of the final product. The level of confidence in the RCA is therefore still below the limits required by the road authorities worldwide to be widely accepted in HMA. Thus, development of a treatment to upgrade the engineering properties of RCAs is still needed.

II. Development of the Coating Technique

In this study, a coating technique is developed. The technique is based on combining two previously used treatments. Therefore, this coating technique will hereafter be called Double Coating Technique (DCT). The coarse RCA was firstly coated with CSP as suggested by Lee, Du [9] and then the product was coated with a second layer of bitumen emulsion as proposed by Pasandín and Pérez [4]. The DCT is expected to produce RCA-asphalt mixture with better performance. There are different reasons for this expectation. First, the RCA coated with CSP was reported to have better resistance to abrasion [9]. In addition, the results obtained for HMA made with RCA coated with CSP were affected by the percentage of RCA in the mix. For example, the OBC, indirect tensile strength and dynamic stability (DS) were found to increase as the RCA percentage increased in the mix, while the TSR decreased [9].

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In contrast, the RCA coated with asphalt emulsion was found to homogenize the performance of asphalt mixtures regardless the percentage of RCA or bitumen in the mix, and improve stripping resistance [4]. Therefore, coating the RCA particles with CSP and bitumen emulsion before mixing with bitumen is expected to produce asphalt mixtures with better performance. The first coat (CSP coat) is expected to reinforce the weak RCA particles while the second coat (Bitumen emulsion coat) is expected to mitigate water/bitumen absorption.

III. Materials Used

A. Aggregates and Bitumen

RCAs from Capital Recycling in Perth, Western Australia, were used as coarse HMA aggregates. Granite aggregates from a local quarry and C320 bitumen were also used. The bitumen had a penetration grade of 50 and a density of 1.03 t/m³. The fundamental properties of granite and RCAs are shown in Table I. Two types of treated RCA were also used. RCA coated with CSP and RCA coated with CSP and Sike Tite-BE. The coated RCAs with CSP and Sika Tite-BE hereafter will be named as Double Coated Recycled Concrete Aggregates (DCRCAs). The properties of the RCA coated with CSP and DCRCAs were discussed in a separate section in the paper.

TABLE I
BASIC PROPERTIES OF NATURAL AND RECYCLED AGGREGATES

Standard	Property	Granite	RCAs	Limi-
	(a) Course			
AS 1141.6.1	Qa^{a}, g/cm³	2.692	2.549	-
	Qd^{*}, g/cm³	2.663	2.230	-
	$Qs^{\times}$, g/cm³	2.674	2.355	-
AS 1141.23	LA, %	24.2	40.7	<35
	(b) Fine aggregates			
AS 1141.5	Qa, g/cm³	2.697	2.679	-
	Qd, g/cm³	2.633	2.256	-
	Qs, g/cm³	2.657	2.414	-
	$WA^{\times\times}$, %	0.6	7.0	≤2

^{a} = Apparent particle density, * = particle density on dry basis, $^{\times}$ = particle density on saturated dry basis, and $^{\times\times}$ = water absorption.

B. Materials Used in the DCT

The following materials were used for RCA coating: GP grey cement, and ground granulated blast furnace slag (GGBFS). The properties of these two products are shown in Table II. In addition, Sikament NN superplasticizer and Sika Tite-BE acrylic based bitumen emulsion were also used.

The CSP mix was prepared as follows: A total of 15% by weight of GP grey cement was replaced with GGBFS, and the Sikament NN superplasticizer was added to the mix in a fixed percentage, 0.8%. The water to binder ratio was set at 0.45.

Sika Tite-BE was used to coat the RCA coated with CSP in two coats as recommended by the supplier. The Sikament NN superplasticizer and Sika Tite-BE were supplied by Sika Australia Pty. Ltd. The physical and chemical properties of these products were shown in Table III.

IV. DCRCA Fabrication

The DCT is based on combining two previously used treatments. Therefore, it consists of two coating layers. The first coating layer is a thin coat of CSP, and the second coating layer is formed by two coats of Sika Tite-BE. A series of CSP mixes were fabricated to coat the coarse RCA particles with four different theoretical coating thicknesses; 0.05 mm 0.1 mm, 0.2 mm and 0.4 mm to determine the optimal CSP thickness. The coarse coated particles with CSP were allowed to be hydrated in water for seven days. The LA abrasion, water absorption, the apparent particle density (Qa), the particle density on a dry basis (Qd), the particle density on a saturated surface dry basis (Qs) and the visual inspection were evaluated to select the best CSP thickness.

TABLE II
THE CHEMICAL COMPOSITION/INFORMATION ON INGREDIENTS OF TYPE GP CEMENT, AND GGBFS

Ingredient	Content Conc.
(a) GP cement	
Portland Cement	< 97%
Blast Furnace Slag	0 – 5%
Gypsum	3 - 8%
Limestone	0 – 5%
Chromium (VI)	< 20 ppm
Crystalline Silica, Quartz	0- 25%
(b) GGBFS	
Quartz	<1%
Chromium trioxide	<0.1%
Ground blast furnace slag	>90%
Calcium sulfate dehydrate	2 to 5%

TABLE III
PHYSICAL AND CHEMICAL PROPERTIES OF ABE AND SIKAMENT NN

Property	ABE	Sikament NN
Physical state	Liquid	Liquid
Colour	Black	Brown
Boiling point	100°C	-
Volume of solids	40%	-
Density	~1.2 g/cm³ at 20°C	-
Specific gravity	-	1.19-1.23

(a) (b)

Fig. 1 (a) RCA-coated with CSP, and (b) DCRCAs

The second coating layer was applied in two successive stages. During the first stage, a mixture consisting of 1 part of Sika Tite-BE and 2 parts of water was added to the RCA coated with CSP. 5% of the mix by the weight of dry RCAs has been added to the coarse recycled particles and mixed thoroughly until a satisfactory coating achieved. The product was then left for about three hours to be somehow dried. Then, a mixture consisting of 2 parts of Sike Tite-BE and 1 part of water was added to the coated RCA. 3.5% of the mixture (2 parts of Sika Tite-BE/1 part of Water) by the weight of dry RCAs has been added to coarse recycled aggregates and mixed thoroughly for about 2 minutes. The DCRCAs was then kept in a good ventilated area in the laboratory to allow for the water to be evaporated. Fig. 1 shows the RCAs coated with CSP and the DCRCAs.

V. Testing Program

A. Aggregates Characterization

The natural and recycled aggregate properties were evaluated in accordance with Australian standards [12]-[14], and the results were reported in Table I. Based on the results, the RCAs had a lower abrasion resistance and higher water absorption compared to granite aggregates. According to Australian standard, RCAs did not achieve the minimum requirements to be used in asphalt mixture production when considering its LA value and water absorption. The old cement mortar and the impurities such as bricks and tiles might produce such results. Therefore, it was decided to only use the coarse fraction (>4.75 mm) of RCA as HMA-aggregates. This is to mitigate the bitumen absorption [15] and facilitate the removal of impurities during screening and washing processes.

B. HMA Mix Design

Marshall design procedure was carried out in accordance with AS 2891.5 [16]. AC14 mix with 0%, 20%, 40%, and 60% of RCAs, RCA coated with CSP, and DCRCAs were designed and evaluated. The AC14 asphalt mixture is suitable for use in wearing courses for heavy duty applications and for intermediate courses [17]. The selected gradation was chosen to comply with upper and lower limit requirements of the standard, and it was located close to the midpoint of the grading envelope [17]. Marshall parameters were determined at 5% air void contents for all mixes. 1.5% hydrated lime by the weight of dry aggregates in the mix was added to the HMA as recommended by the Main Roads Western Australia [18]. The substitution of granite aggregates by RCAs was done on a volumetric basis. Table IV shows the upper and lower limit and the selected gradation of asphalt mixtures in this study.

TABLE IV
Gradation of AC14 Mix in the Study

Sieve size (mm)	Lower limit	Selected Gradation	Upper limit
19	100	100	100
13.2	90	93	100
9.5	72	77	83
6.7	54	62.5	71
4.75	43	53.5	61
2.36	28	35.5	45
1.18	19	28.5	35
0.6	13	20.5	27
0.3	9	14	20
0.15	6	8.5	13
0.075	4	5	7

VI. Results and Discussion

A. DCRCAs Properties

The laboratory results obtained for the DCRCAs, alongside with those obtained for natural aggregates (NA), RCAs, and RCA coated with CSP were presented in Figs. 2-4. According to Fig. 2, the RCA coated with CSP absorbs more water than uncoated RCAs. This result was in accordance with those obtained by Lee, Du [9]. In addition, it can be seen that the DCT reduces the amount of the water absorbed by DCRCAs as compared to RCAs, and RCA coated with CSP. The DCRCAs had 12% and 36% lower water absorption than RCA and RCA coated with CSP respectively. By these results, the developed DCT is more effective than the CSP coating technique in controlling the absorptive nature of the RCAs. Furthermore, the developed DCT decreases the density of the final product, Fig. 3. The decrease in density could be related to the fact that the used coating materials (CSP and Sika Tite-BE) had a lower density compared to RCAs' particles. The results of the ACV of four types of aggregates used are presented in Fig. 4. It can be seen that the DCT leads to improving the ACV of the final product. The DCT, therefore, helped to remedy some durability and strength related problems associated with RCAs.

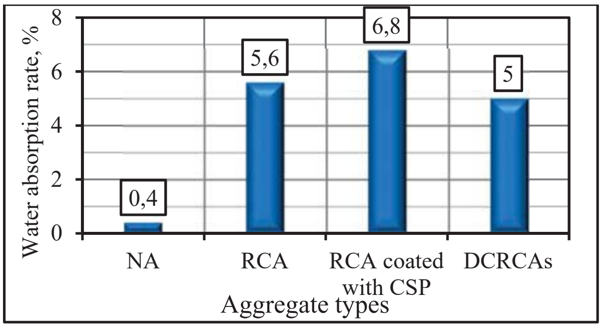

Fig. 2 Effect of DCT on water absorption

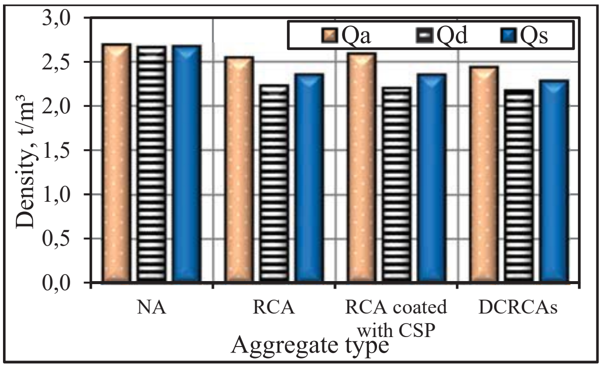

Fig. 3 Effect of DCT on aggregate density

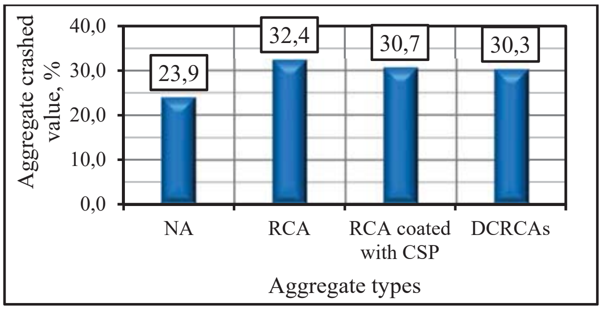

Fig. 4 Effect of DCT on ACV

B. HMA Properties

Marshall design parameters of HMA made with 0%, 20%, 40% and 60% uncoated RCA, RCA-coated with CSP, and DCRCAs are shown in Table V. According to the results obtained, the OBC was founded to increase as the dosage of RCA increased in the mix which proves the absorptive nature of the recycled aggregates used. It was also found that the DCT has helped to reduce the amount of bitumen required to achieve the OBC, Fig. 4. It should be noted that the developed DCT requires of the use of coating materials such as Sika Tite-BE and cement. However, the cost of coating materials used in the DCT could be offset by the lower price of RCA compared with NA, and the improvement achieved in case of DCRCA-asphalt mixtures. To test the effectiveness of the DCT, a comparison study to evaluate the environmental impacts resulting from the DCT and those produced by the RCA wastes needs to be conducted.

The bulk density of HMA mixtures were founded to have the following trend, the control mix, the mix made with untreated RCA, the mix made with RCA coated CSP, and those made with RCA coated with DCT, from highest to lowest. It can be seen that the stability was improved in case of mixes made with DCRCAs compared to those made with uncoated RCA and RCA coated with CSP respectively. It seems that the DCT enhances the bonding between bitumen and DCRCA and allows to mobilize high friction forces during loading simultaneously.

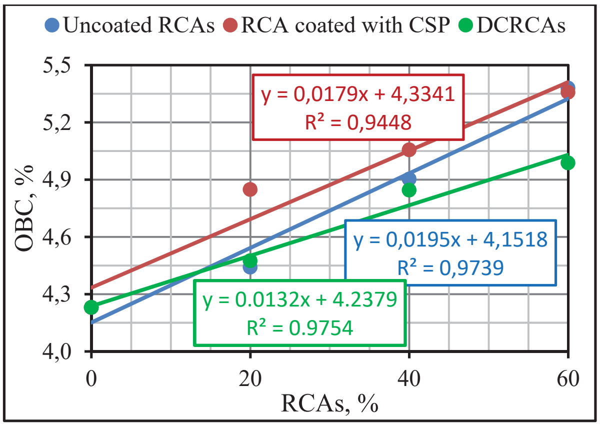

Fig. 5 Relationship between RCA percentage in different mixes and OBC

The inclusion of the RCA was found to produce, in general, a decrease in VMA and VFB regardless the type RCA used in HMA (uncoated RCA, coated with CSP, and Coated based on DCTs). It can be seen that the percentage of the absorbed bitumen was increased as the dosage of the RCAs in the mix increased. This leads to a higher percentage of the absorbed bitumen as shown in Table V, which explains the decrease in VMA and VFB respectively.

TABLE V
MARSHALL RESULTS OF HMA MADE WITH GRANITE AGGREGATE AND DIFFERENT RCAS

Aggregate type	RCAs, (%)	Density, (g/cm³)	S, (kN)	F, (mm)	VMA, (%)	VFB, (%)	VTM, (%)	OBC, (%)	b, (%)	Be, (%)
Granite	0	2.374	17.6	2.3	13.8	63.9	5	4.23	0.42	3.81
Uncoated RCAs	20	2.341	17.5	2.6	13.7	63.8	5	4.44	0.53	3.91
Uncoated RCAs	40	2.325	18.0	3.0	13.3	62.9	5	4.90	1.06	3.85
Uncoated RCAs	60	2.306	18.6	3.2	13.1	63.4	5	5.38	1.41	3.97
RCAs coated with CSP	20	2.319	17.0	2.83	14.6	66.6	5	4.85	0.13	4.72
RCAs coated with CSP	40	2.335	17.3	2.97	12.7	62.1	5	5.06	1.11	3.95
RCAs coated with CSP	60	2.310	17.4	3.02	12.5	61.2	5	5.36	1.45	3.91
DCRCAs	20	2.345	17.6	2.8	13.0	62.5	5	4.47	0.88	3.60
DCRCAs	40	2.316	17.5	2.9	13.1	63.0	5	4.84	1.08	3.76
DCRCAs	60	2.293	18.9	3.1	12.6	61.0	5	4.99	1.47	3.52
Standard limits AS 2150			≥8	2 to 4	≥ 15	60-80	3 to 7	4 to 6		

VII. CONCLUSION

In the present study, a DCT has been developed. AC14 asphalt mixes with 0%, 20%, 40%, and 60% of uncoated RCA, RCA coated with CSP, and DCRCAs were evaluated. Based on the results obtained, asphalt mixtures produced with RCAs exhibited a higher bitumen absorption rate than control mix. The results indicated that DCT decreases the water/bitumen absorption and improves the DCRCA strength compared with uncoated RCA and RCA coated with CSP. The RCA asphalt mixture is expected to have a thinner binder film around aggregates particles which stimulates them to mobilize high friction forces during loading. Coating the RCAs with CSP and Sika Tite-BE caused the stability of DCRCA mixes to be upgraded. This might be related to adhesion enhancement of such mixes in conjunction with high friction mobilized between DCRCA particles. It should be noted that both: cement and Sika Tite-BE are not cheap coating materials. However, the cost of coating materials could be offset by the lower price of RCAs compared with NA, and the behavior improvement of asphalt mixtures made with DCRCAs. The feasibility of the DCT needs therefore to be addressed by comparing its cost and ecological impacts with those produced by the RCA wastes.

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