

## Potential Use of Recycled Concrete Aggregates in Bituminous Concrete for Flexible Pavement

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**Abstract:** The need for recycling and reusing the waste materials has been arising due to disposal problems and other problems like excessive mining, depletion of natural resources. The present study focused on the utilization of demolition concrete waste in the form of aggregates in bituminous concrete (BC) mixes before and after thermal treatment. Experimental results showed that Marshall mix design parameters were satisfying the permissible requirements in case of bituminous concrete mixes prepared by using the recycled concrete aggregates (RCA) and thermally treated concrete aggregates (TRCA), though the optimum bitumen content was more as compared to mixes prepared with natural aggregates. Thermal treatment had positive impact on Retained stability value, but Marshall stability value in case of TRCA mixes was observed as lesser than that of RCA mixes. Material cost analysis suggested that the utilization of RCA is economical as compared to natural aggregates.

**Keywords:** demolition concrete waste; recycled concrete aggregates; thermal treatment; natural aggregates; bituminous concrete.

### 1. Introduction

With rise in construction activities, the depletion of natural resources due to their excessive usage is adversely affecting the environment. The increase in demand of construction material leads to excessive mining activities and other environmental concerns. Also, the amount of waste generated due to construction and demolition activities is very high and disposal of such a huge amount of waste presents another big problem. The generation of construction and demolition waste is increasing at a rapid rate in India. The amount of construction and demolition (C & D) waste generated in India was about 10 - 15 million tonnes in the year 2000 and it has been increased to 25-30 million tonnes annually till the year 2017. Out of total waste generated, only 5% is being processed for reuse (MoEFCC, 2017). The common method adopted for the disposal of C & D waste is landfilling. Lesser available space and shortage of landfills leads to the disposal problems and promotes the illegal dumping of waste in water bodies, on hill slopes etc. So, the present need of hour is to reduce the waste generation and to recycle and reuse the waste materials.

C & D waste contains mostly the materials like concrete, mortar, metal, plastics, bitumen etc. About 23 to 35% of total C & D waste consist of waste concrete (MoEFCC, 2017) and this component of the C & D waste can be effectively utilized due to its high strength. Crushed concrete of size similar to coarse sand is recommended to be utilized for providing capping and drainage layer in Sanitary Landfills, whereas, fine C & D waste is proposed to be utilized as landfill covers (MoEFCC, 2017). These waste materials are also utilized in making bricks, paver blocks, kerb stones and construction materials such as aggregates etc.

The Recycled concrete aggregates (RCA), obtained after crushing the segregated concrete waste, have different properties and composition as compared to the natural aggregates due to the attached cement mortar on the aggregate surfaces. A number of researches have been carried out for determining the viability of RCA in structural concrete (Yang et al., 2010; Wagih et al., 2012; Shaikh et al., 2013; Shahidan et al., 2017). RCA are recommended to be used in structural concrete as a replacement of natural aggregates upto 25% (IS 383:2016), whereas, even higher replacing percentage i.e., 30-50% is proposed in structural concrete for the construction of bank protection, base/fill of drainage structures, rigid pavements, sidewalks, kerbs and gutters etc. (NBC, 2005). Due to higher rate of waste generation as compared to their utilization, there is need for finding other alternatives for using the RCA in other construction activities. The use of RCA in flexible pavements is limited in India. Depending upon the properties of RCA, researches have been conducted for determining their feasibility in sub-base and base course for road construction (Leite et al., 2011; Esfahani, 2018; Arulrajah et al., 2013) and surface

course of flexible pavement (Giri et al., 2018a and 2018b; Wu et al., 2015; Tahmoorian and Samali, 2017). Very few studies had been conducted regarding use of RCA in the wearing course. Esfahani (2018) investigated the feasibility of RCA in sub-base and base course and concluded that use of RCA increased the required thickness of base course and suggested the use of RCA upto 10% of natural aggregates. In another study by Arulrajah et al. (2013), five types of construction and demolition waste materials viz. RCA, crushed bricks, waste rocks, reclaimed asphalt pavement and fine recycled glass were investigated for using in subbase course and superior results were observed in case of RCA and waste rocks, even better than natural aggregates. The study by Leite et al. (2011), concluded that the particle breakage during compaction should be controlled by adjusted compaction in order to maintain the grading requirement of the subbase or base materials and suggested the use of RCA in base and sub-base layer for low-volume roads.

Surface course, comprising of binder and wearing course, is prepared by bituminous mixes of specified gradation. Coarse aggregates form the basic structure of bituminous mixes and considerably influence the performance and behaviour of wearing course. Since the aggregates constitute to the major portion of the bituminous mixes, the use of RCA can be very effective in mass utilization of waste material. In a study conducted by Giri et al. (2018a), the performance of RCA in the Dense Bituminous Macadam (DBM) for binder course was investigated, in which RCA were used before and after treatment with bitumen emulsions and DBM mixes were modified with waste polythene. This study concluded that the performance of pre-treated RCA was better than other mixes. In another study by Giri et al. (2018b), the performance of DBM mixes prepared by two different types of fillers i.e., cement dust and stone dust, was evaluated after using RCA and pre-treated RCA with bitumen emulsion in place of natural aggregates and performance of DBM mixes with pre-treated RCA and cement dust as filler was observed as better. Arabani et al. (2012) investigated the performance of bituminous concrete mixes prepared by full and partial replacement of natural aggregates by RCA and experimental results observed better performance in mixes prepared by partial replacement with recycled fine concrete aggregates. In a study by Mahendra et al. (2018), the RCA properties were evaluated after treating them with acid and thermal treatment and experimental results observed better results in case of treated RCA. Thermal treatment is relatively easier method of treatment, but the large-scale application may be lesser effective due to high energy consumption and long processing duration. Even though the characterization of thermally treated RCA has been conducted in different studies, but the influence of using the thermally treated RCA in bituminous mixes has not been investigated. Various other studies have also been conducted for using RCA in bituminous mixes after pre-treating them with epoxy resins, acid treatment, polymer treatment etc. (Shahidan et al., 2017; Giri et al., 2018b). Although, pre-treatment of RCA has been done in most of the studies for using RCA in bituminous mixes and results with pre-treated RCA were satisfying the permissible requirements, but the practical feasibility as well as higher cost of pre-treatment process is another big problem. If RCA could provide satisfactory results with full replacement of mineral aggregate and without pre-treatment, then that will be very beneficial as per economic and environmental point of view. Therefore, no treatment/thermal treatment seems to be a potential method in terms of its application and it might be lesser expensive method than the other treatment methods. Therefore, these two methods have been included in the study.

In view of extensive literature review, it is now evident that most of the studies have been for use of RCA in sub-base, base course and binder course. Very few studies (Arabani et al., 2012) had investigated the use in wearing course. Therefore, the present study investigated the performance of recycled concrete aggregates (RCA) and thermally treated concrete aggregates (TRCA) in bituminous concrete mixes for wearing course of flexible pavement. Marshall mix design method was used for evaluating mix design parameters for the prepared mixes and retained stability tests were conducted to determine the moisture susceptibility of the bituminous mixes. Material cost analysis has also been carried out to determine impact of the use of RCA on the economics of the construction process.

## 2. Experiment Design

Experimental program was conceptualised as per the literature review and practical implications. The experimental program was divided into four phases.

- In first phase, aggregates of required sizes were obtained after crushing the waste concrete collected from a demolition site.

- In the second phase, characterization of natural aggregates, RCA and TRCA aggregates was done by determining Aggregate impact value, Los Angeles abrasion value, Aggregate crushing value, Water absorption, specific gravity, Flakiness and elongation index. Thermal treatment was done by heating the RCA in muffle furnace at 350 °C for 2 hours. Due to the difference between coefficient of thermal expansion of cement mortar and natural aggregate, the excess weak mortar gets separated from the aggregate surfaces, thus, improving the aggregate properties. Wet aggregate impact test was conducted whenever water absorption exceeds the permissible limit of 2% (MORTH, 2013).
- In the third phase, Marshall specimens were prepared by using natural aggregates, RCA and TRCA. RCA and TRCA were used in bituminous concrete mixes as a full replacement of natural aggregates. Marshall tests were conducted on specimens prepared by using natural aggregates, RCA and TRCA to evaluate the optimum bitumen content and other design parameters such as Marshall stability, Marshall flow value, Bulk density of mix etc.
- After determining the optimum binder content of bituminous mixes prepared with natural aggregates, RCA and TRCA, sets of two Marshall specimens were prepared at optimum binder content for each type of aggregates. Retained stability tests were conducted on prepared Marshall specimens for determining the moisture susceptibility of bituminous mixes.

The flowchart of experimental program is shown in Fig. 1.

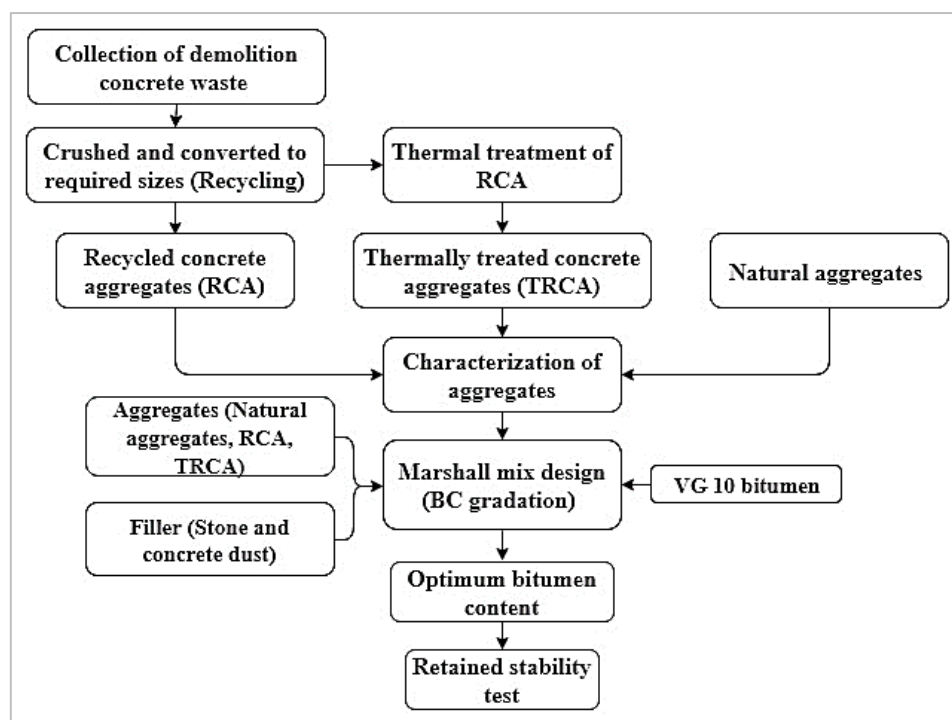


Fig. 1: Flowchart of experimental program

The experimental procedures adopted for conducting Marshall mix design and retained stability test are explained in sections 2.1 and 2.2.

## 2.1 Marshall Mix design

The commonly used method for mix design for dense graded bituminous mixes is Marshall method of mix design. In Marshall mix design, the optimum binder content for the mix design is evaluated by determining the engineering properties of bituminous mixes in terms of Marshall stability, density, flow value, air voids etc. In the present study, Marshall tests were performed in accordance with AASHTO T245 (AASHTO, 2001). Grading 1 was adopted for preparing bituminous concrete mixes for 50mm thick wearing course as per the MORTH specifications for roads and bridges, which is given in Table 1.

Asphalt Institute MS-2 Manual (AI, 2014) was adopted for the determination of optimum binder content. It recommends choosing the bitumen content at the median of the percent air voids limit, which is 4%. If all the calculated and measured mix properties at this bitumen content meet the mix design

criteria, then this is the optimum binder content for the mix design. If other mix design parameters do not satisfy the required specifications at bitumen content corresponding to 4% air voids, some adjustment can be made for the determination of optimum bitumen content. In the present study, optimum bitumen content was evaluated by taking the average of bitumen contents corresponding to maximum stability, maximum density and 4% air voids.

Table 1: Composition of Bituminous concrete pavement layer as per MORTH specifications, 2013

IS Sieve	Cumulative % passing (Specification limits)	Cumulative % passing adopted
26.5 mm	100	100
19 mm	90-100	95
13.2 mm	59-79	69
9.5 mm	52-72	62
4.75 mm	35-55	45
2.36 mm	28-44	36
1.18 mm	20-34	27
600 µm	15-27	21
300 µm	10-20	15
150 µm	5-13	9
75 µm	2-8	6
Pan	0	0

## 2.2 Retained stability test

Retained stability tests were conducted in accordance with ASTM D1075 (ASTM, 2011) specifications to examine the performance of bituminous mixes against the moisture-induced damage. Bituminous concrete specimens were prepared by using natural aggregates, recycled concrete aggregates and thermally treated concrete aggregates at their corresponding optimum bitumen contents. Marshall stability values of specimens prepared at optimum bitumen contents, were determined before and after the moisture conditioning process. Conditioning of Marshall specimens was done by immersing them in water at 60°C for 24 hours before testing. Those Marshall specimens were considered as unconditioned, which were immersed in water at 60°C for half an hour before testing. Retained stability was calculated by taking the ratio of Marshall stability of conditioned specimen to the Marshall stability of unconditioned specimen as given in equation 1.

$$\text{Retained stability (\%)} = \frac{\text{Marshall stability of Conditioned specimen}}{\text{Marshall stability of Unconditioned specimen}} \times 100 \quad \dots\dots (1)$$

## 3. Materials

### 3.1 Bitumen

Bitumen acts as a binder for aggregates in the bituminous mixes. In the present study, locally available binder corresponding to 80/100 penetration grade (viscosity grade 10) was used for preparing bituminous mixes. The characterization of binder was carried out by evaluating various properties such as penetration number, ductility value, viscosity etc. and the results are tabulated in Table 2.

Table 2: Characterization of Bitumen

Test	Result	IS 73:2013 Specifications
Penetration	87.23	80 (Min)
Softening Point (° C)	45.1	40 (Min)
Ductility (cm)	94	75 (Min)
Flash Point (° C)	261	220 (Min)
Fire Point (° C)	304	----
Specific Gravity	1.02	----

### 3.2 Aggregates and Filler material

Aggregate properties play an important role in the performance of bituminous mixes. The performance of bituminous mixes is primarily affected by the properties of aggregates. Characterization of

aggregates is required to determine their suitability for using them in particular course. In characterization process, various aggregate properties such as Aggregate impact value, Aggregate crushing value, Los Angeles abrasion value, Combined flakiness and elongation index, Water absorption etc. are evaluated. In this study, three types of aggregates viz. natural aggregates, recycled concrete aggregates (RCA) and thermally treated concrete aggregates (TRCA) were used to prepare bituminous concrete mixes. In case of mixes prepared by natural aggregates, locally available stone dust was used as a filler material, whereas in other two cases, concrete dust was used as a filler material, which was obtained during crushing of waste concrete. Characterization of aggregates and filler material is given in Table 3.

Table 3: Characterization of aggregates

Aggregate Property	Natural aggregates	RCA	TRCA	MORTH limits 2013	Test Procedure
Aggregate impact value (%)	13.00	16.25	15.67	< 24	IS 2386 (Part 4):1963
Aggregate crushing value (%)	19.08	25.35	25.87	----	IS 2386 (Part 4):1963
Los Angeles abrasion value (%)	21.87	24.32	22.93	< 30	IS 2386 (Part 4):1963
Combined flakiness and elongation index (%)	19.19	28.73	24.61	< 35	IS 2386 (Part 1):1963
Water absorption (%)	1.20	4.06	2.95	< 2	IS 2386 (Part 3):1963
Wet impact value (%)	----	18.25	17.37	----	IS 5640:1970
Bulk Specific gravity of coarse aggregates	2.64	2.38	2.44	----	IS 2386 (Part 3):1963
Apparent specific gravity of coarse aggregates	2.72	2.64	2.64	----	IS 2386 (Part 3):1963
Apparent Specific gravity of Fine Aggregate	2.71	2.49	2.45	----	IS 2386 (Part 3):1963
Apparent Specific gravity of Filler	2.58	2.16	2.15	----	IS 2386 (Part 3):1963

All other aggregate properties of RCA and TRCA except water absorption were satisfying the permissible limits specified by the MORTH for using them in bituminous concrete mixes. The water absorption of RCA and TRCA were observed as 4.06% and 2.95%, which was more than the maximum permissible value i.e., 2% (MORTH, 2013). In case it exceeds permissible limit, wet aggregate impact test is recommended as per MORTH specifications, 2013. As per the test results, wet aggregate impact value for RCA (18.25%) and TRCA (17.37%) were observed as lesser than the maximum permissible limit (max. 24% for BC).

The properties of natural aggregates, RCA and TRCA were compared and comparison results are given in Fig. 2.

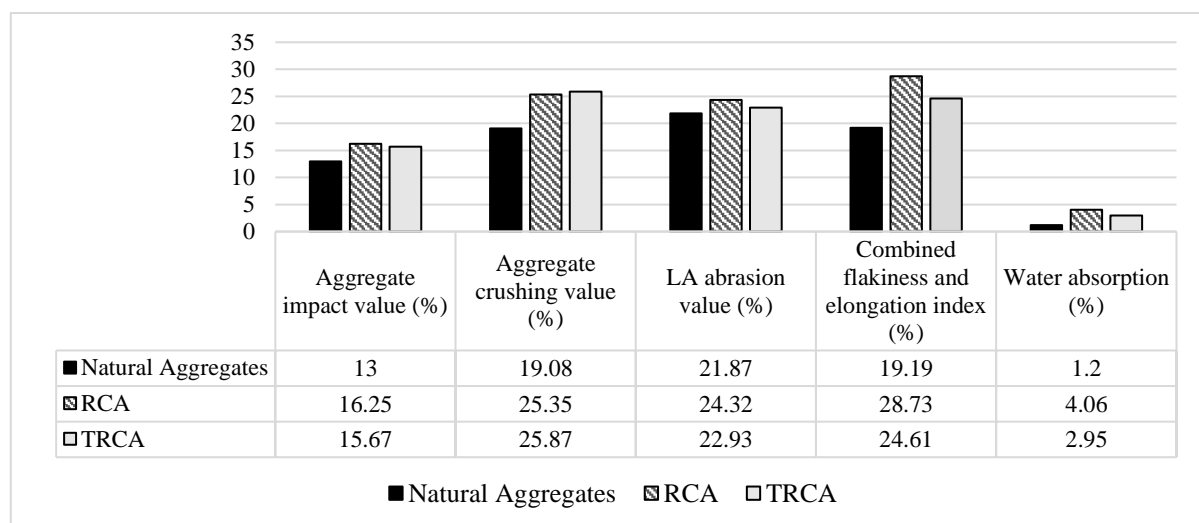


Fig. 2: Comparison of aggregate properties of Natural aggregates, RCA and TRCA



As it can be observed from Fig. 2, thermal treatment had lesser effect on properties like aggregate impact value, aggregate crushing value and LA abrasion value but the water absorption and combined elongation and flakiness index showed significant reduction in their value (1.11% decrease in water absorption and 4.12% decrease in combined flakiness and elongation index). The decrease in water absorption and combined flakiness and elongation index could be attributed to the separation of weak mortar from the aggregate surfaces during the thermal treatment. RCA and TRCA were satisfying the permissible limits for use in BC indicating that these could be tested for determining their suitability in wearing course.

## 4. Results and Discussion

### 4.1 Marshall test

The determination of mix design parameters is necessary in order to predict the performance of mix. Marshall stability is indicative to the resistance towards the permanent deformation. It is largely dependent upon the internal friction provided by the aggregate skeleton and meagrely upon the cohesion provided by bitumen. The bulk density ( $G_m$ ) of mix is important in calculation of air voids ( $V_v$ ) in the mix. Sufficient air voids are necessary to enable extra compaction of bituminous layer during traffic loading and expansion of binder during hot climate. Voids filled with bitumen (VFB) is an essential parameter in order to predict the assurance of adequate bitumen film thickness around the aggregates. Voids in mineral aggregates (VMA) is another design parameter influencing the durability of the bituminous mixes. In this study, two sets of Marshall specimens, for each type of aggregates, were prepared at different bitumen contents. The results of the tests are given in Table 4.

Table 4: Marshall test results

Aggregate s used		Bitumen content (%)	Marshall Stability (kN)	Marshall Flow (mm)	Air Voids (%)	VMA (%)	VFB (%)	Bulk Density (kN/m³)
Natural aggregates	Set 1	4	18.17	1.68	7.36	16.42	55.18	23.52
		5	19.58	2.19	4.04	15.76	74.36	24.02
		6	16.43	2.46	3.56	16.93	78.97	23.81
		7	14.81	3.07	3.20	18.68	82.87	23.59
	Set 2	4	17.39	1.78	7.95	16.92	53.01	23.37
		5	18.26	2.10	4.55	15.98	71.53	23.89
		6	17.64	2.51	3.69	17.15	78.48	23.78
		7	15.48	3.02	3.40	18.89	82.00	23.54
RCA	Set 1	4	15.32	1.52	10.52	19.10	44.92	21.60
		5.5	16.98	1.87	8.06	19.74	59.17	21.77
		7	17.98	2.45	4.86	19.89	75.56	22.12
		8.5	15.57	2.76	3.85	21.14	81.79	21.97
	Set 2	5	15.28	1.78	9.23	19.92	53.66	21.64
		6	16.51	2.06	7.56	20.23	62.63	21.76
		7	17.34	2.48	4.95	19.73	74.91	22.10
		8	15.26	2.70	4.14	20.81	80.11	21.98
TRCA	Set 1	5	14.01	1.65	8.83	19.22	54.06	21.59
		6	15.71	1.84	6.58	19.41	66.10	21.85
		7	14.74	2.16	4.50	19.45	76.86	22.07
		8	12.11	2.51	3.72	20.44	81.80	21.99
	Set 2	5	14.25	1.52	8.78	19.23	54.34	21.60
		6	15.45	1.75	6.97	19.53	64.31	21.76
		7	13.45	2.19	4.41	19.09	76.90	22.09
		8	11.90	2.41	3.59	20.12	82.16	22.02

In case of bituminous mixes prepared with natural aggregates, all other parameters corresponding to the bitumen content corresponding to the 4% air voids were meeting the permissible limits specified by the

MORTH, so bitumen content corresponding to 4% air voids was taken as optimum bitumen content. But in other two cases, optimum bitumen content was taken as the average of bitumen contents corresponding to 4% air voids, maximum stability and maximum bulk density, as some parameters were not satisfying the permissible limits at bitumen content corresponding to 4% air voids. The performance of bituminous mixes at the optimum binder content in terms of Marshall mix design parameters was evaluated by taking the average results of two sets prepared for each type of aggregates and comparison results are tabulated in Table 5.

Table 5: Comparison of mix design parameters at optimum bitumen content for each mix type

Aggregates used	Natural aggregates	RCA	TRCA	MORTH limits, 2013
Optimum binder content (%)	5.20	7.39	6.85	Min. 5.2
Marshall stability value (kN)	18.89	17.17	14.40	> 9
Marshall flow value (mm)	2.22	2.56	2.13	2-4
G <sub>m</sub> (kN/m <sup>3</sup> )	23.96	22.10	22.06	----
V <sub>v</sub> (%)	4	4.45	4.70	3-5
VMA (%)	16.11	20.11	19.32	Min. 11-13
VFB (%)	74.68	77.50	75.50	65-75

As observed in Table 5, use of RCA and TRCA results in increase in optimum bitumen content as compared to the natural aggregates. The increase in optimum bitumen contents in case of RCA and TRCA was mainly due to the higher bitumen contents corresponding to 4% air voids. Although, thermal treatment of the waste concrete aggregates observed the decrease in optimum bitumen content, but it had negative impact on the Marshall stability value and bulk density. The decrease in Marshall stability value could be attributed to the decrease in strength of aggregates as these were subjected to temperature of 350° c in thermal treatment more than 177° c, which is maximum allowable temperature for heating aggregates before preparing BC mixes (AI, 2014). Marshall flow value at optimum bitumen content was observed as minimum in case of thermally treated aggregates. VFB for mixes with RCA were slightly more than the permissible limits, but not that high. Whenever traffic is very high, a lower value of VFB is recommended because there is greater concern regarding mixture strength and stability, whereas higher value of VFB is recommended in normal traffic conditions to increase the durability of mix (AI, 2014). Higher value of VFB in case of RCA and TRCA mixes suggested their use in normal traffic conditions. Although, BC mixes containing natural aggregates showed better results as compared to other two cases, but satisfactory results were obtained in case of RCA and TRCA indicating their suitability for use in bituminous concrete for providing wearing course in flexible pavement. As for higher OBC in case of mixes containing RCA and TRCA, material cost analysis needs to be done in order to determine the impact of utilization of RCA on construction cost of pavement.

#### 4.2 Retained stability test

Resistance towards moisture damage is another factor which affects the durability characteristics of the mix. It is necessary to determine the moisture susceptibility of bituminous mixes prepared with RCA and TRCA due to their higher water absorption. Four Marshall specimens were prepared at optimum bitumen content for each type of aggregates, out of which two specimens were for conditioning and remaining two were unconditioned specimens. The results of retained stability tests are tabulated in Table 6. It showed that the retained stability for the mixes with natural aggregates had higher value as compared to other two mixes. Thermal treatment of aggregates increased the retained stability value. Retained stability value for RCA (73.09%) marginally falls below minimum required value of 75% (ASTM, 2011). Lower value of retained stability in case of RCA mixes could be due to more water absorption of RCA resulting in more permeable mixes. In heavy rainfall regions, utilization of RCA may have negative impact on durability of BC mixes. So, RCA mixes may be effectively used in normal rainfall conditions providing an adequate drainage system. In high rainfall regions, RCA mixes may be used with Anti-stripping compounds.

Table 6: Retained stability test results

Aggregates used		Marshall stability value of unconditioned specimen (kN)	Marshall stability value of conditioned specimen (kN)	Retained stability value (%)
Natural aggregates	Sample 1	18.64	16.28	
	Sample 2	18.99	16.57	
	Average value	18.82	16.43	87.30
RCA	Sample 1	17.54	12.41	
	Sample 2	17.09	12.91	
	Average value	17.32	12.66	73.09
TRCA	Sample 1	14.01	11.58	
	Sample 2	14.48	11.88	
	Average value	14.25	11.73	82.32

In case of BC mixes containing TRCA, the utilization of TRCA as 100% replacement of natural aggregates in bituminous concrete can be effective in all weather conditions (considering the higher retained stability in case of BC mixes containing TRCA).

#### 4.3 Results of the current study vis-à-vis other studies

The present study had been carried out on use of RCA obtained from demolished roof slab of a building to be used in BC layer of flexible pavement. The characteristics of RCA depends upon the source from which it is obtained. In the literature, there are various studies reported on the use of untreated and treated RCA in different layers of flexible pavement. A comparison of the results of present study with previous studies will give a better insight on the effect of characteristics of the source from which RCA is derived. The comparison of results is tabulated in Table 7. The general trend in some of the results of the past studies could be confirmed from the present study. Also, there are some contradictory behaviour which may be explained keeping in view the details of experimentation and characteristics of materials.

Similar trends for properties such as aggregate impact value, LA abrasion value, aggregate crushing value and water absorption had been observed for RCA when compared to natural aggregates (Arabani et al., 2012; Giri et al., 2018a; Mahendra et al. 2018; Daquan et al., 2018; Wu et al., 2015), however, the values were reported higher as compared to present study.



Table 7: Comparison of results of current study vis-à-vis previous studies

Research	Research objective	Characterization results					Marshall mix design parameters at OBC						Retained stability (%)
		Aggregate type	Aggregate impact value (%)	Aggregate crushing value (%)	LA abrasion value (%)	Water absorption (%)	Mix type	Optimum bitumen content (%)	Marshall stability value (kN)	Bulk density (kN/m <sup>3</sup> )	VFB (%)	VMA (%)	
Arabani et al. (2012)	Use of coarse RCA and fine RCA in BC mix	Dacite	-	-	22.60	-	Control mix:0% RCA	5.10	16.97	26.48	-	-	-
		RCA	-	-	35.50	-	FA: RCA, CA: dacite	5.60	19.46	25.27	-	-	-
							FA: dacite, CA: RCA	6.50	12.97	24.33	-	-	-
							RCA mix	7.00	12.05	23.26	-	-	-
Giri et al. (2018a)	Use of RCA and pre-treated RCA with bitumen emulsions in DBM with modification by waste polyethylene	NA	14.00	13.00	18.00	0.13	RCA mix	5.30	16.03	22.48	75.00	15.20	85.36
		RCA	25.00	23.00	29.00	5.60	PRCA mix	3.60	16.70	23.13	64.00	12.30	92.49
		PRCA	16.00	18.00	20.00	1.78	NA mix	5.13	11.96	23.65	73.00	16.10	91.92
							RCAP mix	4.33	20.25	21.82	79.00	12.20	91.72
							PRCAP mix	3.13	20.61	21.78	57.00	12.40	94.11
							NAP mix	3.70	18.80	23.27	66.00	12.70	93.76
Daquan et al. (2018)	Use of RCA as partial replacement of natural aggregates in asphalt concrete	Limestone (13.2-26.5 mm)	-	21.00	-	0.41	NA mix	4.00	10.24	25.04	67.34	13.68	81.00
		Limestone (4.75-13.2 mm)	-	21.50	-	0.43	C-60 mix	6.00	7.87	21.77	64.01	14.82	81.00
		Limestone (0-4.75 mm)	-	-	-	1.06	C-50 mix	5.70	7.98	22.33	65.34	14.17	80.00
		RCA (4.75-26.5 mm)	-	28.40	-	7.51	C-40 mix	5.50	11.33	22.95	68.75	13.53	85.00
		RCA (0-4.75 mm)	-	-	-	9.08	F-40 mix	6.50	11.61	22.55	72.84	15.29	92.00
							F-20 mix	5.30	11.90	23.80	69.99	13.75	90.00
Wu et al. (2015)	Use of fine and coarse RCA in bituminous mix	NA	-	19.00	19.80	0.26	NA mix	3.70	13.69	-	-	-	97.30
		RCA	-	25.30	33.60	6.91	Coarse RCA mix	5.60	13.34	-	-	-	91.08
							RFA mix	5.20	11.86	-	-	-	96.29
Mahendra et al. (2018)	Characterization of untreated and treated RCA	NA	23.07	23.16	21.94	1.64	-	-	-	-	-	-	-
		RCA	33.38	32.32	34.21	4.10	-	-	-	-	-	-	-
		RCA (thermally treated at 400 °C)	28.36	29.67	36.63	2.93	-	-	-	-	-	-	-
		RCA (after acid treatment: HCL 1 molar)	25.12	28.00	28.25	2.92	-	-	-	-	-	-	-
Current Study	Use of RCA and thermally treated RCA in BC mix	Natural aggregate	13.00	19.08	21.87	1.20	NA mix	5.20	18.89	23.96	74.68	16.11	87.30
		RCA	16.25	25.35	24.32	4.06	RCA mix	7.39	17.17	22.10	77.50	20.11	73.09
		TRCA	15.67	25.87	22.93	2.95	TRCA mix	6.85	14.40	22.06	75.50	19.32	82.32

Abbreviations in Table 7- NA: Natural aggregates, RCA: Recycled concrete aggregates, PRCA: Pre-treated RCA with Bitumen emulsions, TRCA: Thermally treated recycled concrete aggregates, FA: Fine aggregates, CA: Coarse aggregates, 100% RCA mix: Mix containing RCA as 100% replacement of NA, PRCA mix: Mix containing PRCA as 100% replacement of NA, NA mix: Mix containing 100% NA, RCAP mix: Waste polythene modified mix containing RCA as 100% replacement of NA, PRCAP mix: Waste polythene modified mix containing PRCA as 100% replacement of NA, NAP mix: Waste polythene modified mix containing 100% NA, C-60: Mix containing RCA as 60% replacement of coarse NA, C-50: Mix containing RCA as 50% replacement of coarse NA, C-40: Mix containing RCA as 40% replacement of coarse NA, F-40: Mix containing RCA as 40% replacement of fine NA, F-20: Mix containing RCA as 20% replacement of fine NA, Coarse RCA mix: Mix containing RCA as 100% replacement of coarse NA, RFA mix: Mix containing fine RCA as 100% replacement of fine NA, TRCA mix: Mix containing TRCA as 100% replacement of NA.

The water absorption of RCA had been reported in the range of 5-10% in some of the studies (Giri et al., 2018a; Wu et al., 2015; Daquan et al., 2018), but in the present study as well as a few studies (Mahendra et al., 2018), it had been reported in the range of 4-5%. Different treatment methods for RCA resulted in decrease in the water absorption of RCA and improvement of other properties (Giri et al., 2018a; Mahendra et al. 2018).

The use of RCA in bituminous mixes resulted in increase in the optimum bitumen content (OBC) as indicated in Table 7. The OBC for mixes containing untreated RCA as 100% replacement of natural aggregates in the present study was observed as 7.39% and almost similar results were observed by Arabani et al., (2012), whereas, a little lower value in the range of 5-6% for OBC had been observed in some of the studies (Giri et al., 2018a; Wu et al., 2015; Daquan et al., 2018). The pre-treatment of RCA with bitumen emulsions resulted in significant decrease in OBC value in comparison to untreated RCA (Giri et al., 2018a and 2018b). Thermal treatment carried out in the present study also resulted in decrease in OBC value, but to a lesser extent.

The utilization of RCA as 100% replacement of natural aggregate in bituminous mixes resulted in decrease in the Marshall stability value of mixes (Arabani et al., 2012; Daquan et al., 2018), whereas some of the studies observed opposite trend (Giri et al., 2018a and 2018b). In the present study, there was slight decrease observed in the Marshall stability value of mixes containing RCA (17.17 kN) in comparison to natural aggregates (18.89 kN), similar to the trend reported in the study conducted by Wu et al., (2015). As opposite to other treatment methods of RCA such as treatment with bitumen emulsions, thermal treatment of RCA resulted in decrease in the Marshall stability value of BC mixes as observed in present study. This may be due to extreme heating of aggregates at 350 °C which may be resulted in disintegration of aggregate due to which lower results were obtained. Similar to the results of present study, some of the studies observed the VFB for RCA mixes in the higher range of permissible limit of 65-75% (Giri et al., 2018a and 2018b), whereas some of the studies observed VFB in the lower range of permissible limit (Daquan et al., 2018).

Bituminous mixes containing RCA observed lesser retained stability value in comparison to natural aggregates (Giri et al., 2018a and 2018b; Daquan et al., 2018; Wu et al., 2015). Although, the similar trend had been reported in the present study, but the values for RCA mixes in other studies were higher (in the range of 80 to 90%) as compared to 73.09% reported in the present study. One reason for this could be the use of high viscosity bitumen (VG30) in comparison to the low viscosity bitumen (VG10) used in this study. Different treatment methods of RCA resulted in increasing the resistance of mixes towards moisture induced damage (Giri et al., 2018a and 2018b), same trend was reported for thermal treatment in the present study.

As indicated in Table 7, all the previous studies had been conducted under different conditions with full/partial replacement of natural aggregates. Hence, there is a little variation in trends for some of the parameters for different studies. This is largely due to the fact that properties and composition of RCA depend upon the collection and segregation process of waste, method of crushing, concrete composition and grade, life of demolished structure and the extent to which weathering of the building has been occurred. Therefore, the results of particular study for the use of RCA in bituminous mixes cannot be generalised, but can be indicative of the general trends to some extent. The overall observation which can be drawn from the present study and other studies is that RCA can be effectively utilized in bituminous mixes under recommended conditions and performance of RCA in bituminous mixes may vary depending upon the quality of demolition waste and its recycling process.

#### 4.4 Material cost analysis

A two-lane road stretch of 1 km is assumed for carrying out the material cost analysis for the construction of wearing course by using natural aggregates and RCA. The thickness of wearing course is taken as 50 mm considering the CBR of soil as 5% and traffic as 30 msa (IRC, 2012). The rates for the materials and various construction practices involved in construction of wearing course are taken as per the CPWD report on Analysis of rates for Delhi, 2016 (CPWD, 2016). The distance of the recycling plant from the construction site is assumed to be 100 km. The hauling distance of natural aggregates and bitumen is also assumed as 100 km. the rates for recycled material and their transportation charges are taken in accordance with the report on 'Market Study of Construction and Demolition Waste Utilisation in Ahmedabad, 2016' (Sekhar et al., 2016). The material cost analysis is shown in Tables 8 and 9 in which INR is used for Indian rupee.

Table 8: Material cost analysis for BC mix prepared by using natural aggregates

<b>Natural aggregates; Volume of mix = 375 m<sup>3</sup> (1 km road length)</b>				
		<b>Quantity</b>	<b>Rate (INR)</b>	<b>Cost (INR)</b>
<b>Material Cost</b>	Bitumen	44411.25 kg	29.60/kg	1314573
	Aggregates	301.87 m <sup>3</sup>	1300/m <sup>3</sup>	392431
	Stone dust	13.13 m <sup>3</sup>	865/m <sup>3</sup>	11357.45
	Seal coat (Bitumen)	5760 kg	29.6/kg	170496
	Seal coat (Coarse sand)	45 m <sup>3</sup>	1200/m <sup>3</sup>	54000
<b>Carriage cost</b>	Bitumen	44411.25 kg	2.08/kg	92375.40
	Aggregates + stone dust	315 m <sup>3</sup>	2075.40/m <sup>3</sup>	653751
	Seal coat (Bitumen)	5760 kg	2.08/kg	11980.80
	Seal coat (Coarse sand)	45 m <sup>3</sup>	2075.40/m <sup>3</sup>	93393
<b>Total cost</b>				2794357.65

Table 9: Material cost analysis for BC mix prepared by using RCA

<b>Recycled concrete aggregates; Volume of mix = 375 m<sup>3</sup> (1 km road length)</b>				
		<b>Quantity</b>	<b>Rate (INR)</b>	<b>Cost (INR)</b>
<b>Material Cost</b>	Bitumen	57030 kg	29.60/kg	1688088
	RCA (Coarse)	424447.50 kg	290/ton	123089.78
	RCA (fine)+Concrete dust	347276.25 kg	235/ton	81609.92
	Seal coat (Bitumen)	5760 kg	29.6/kg	170496
	Seal coat (Coarse sand)	45 m <sup>3</sup>	1200/m <sup>3</sup>	54000
<b>Carriage cost</b>	Bitumen	57030 kg	2.08/kg	118622.40
	RCA + Concrete dust	771723.75 kg	250/ton	192930.94
	Seal coat (Bitumen)	5760 kg	2.08/kg	11980.80
	Seal coat (Coarse sand)	45 m <sup>3</sup>	2075.40/m <sup>3</sup>	93393
<b>Total cost</b>				2534210.84

As it can be seen from Tables 8 and 9, total material cost in case of RCA mixes was lesser than that for mixes with natural aggregates considering the supposed assumptions. Again, the economics of construction process depends upon the local availability of natural aggregates and the distance of recycling plant from the construction site. Baring economic profits, there could be numerous other indirect benefits e.g. conservation of natural aggregates, reducing disposal problems, energy conservation etc., which are not accounted for in this cost analysis.

The use of untreated RCA results in increase in OBC for the construction of bituminous mixes, which is evident in this study and other studies also. But the impact of utilization of RCA on economics of the construction has not been analysed in most of the studies. Although, the case assumed in this study for carrying out the cost analysis is region specific, but it gives an indication that use of RCA might be economical in spite of higher OBC than mixes containing natural aggregates.

## 5. Conclusions

Based on the experimental results, following conclusions have been drawn regarding use of recycled concrete aggregates in BC layer in flexible pavement.

- The present study arrived at the point that RCA can be effectively utilized as 100% replacement of natural aggregates (in addition to the replacement of stone dust by concrete dust as filler) in bituminous concrete in normal rainfall conditions with adequate drainage system. Since the rate of generation of C & D waste is more as compared to its recycling and reuse, the present research opens up another alternative, as 100% replacement of natural aggregates in bituminous concrete by RCA results in mass utilization of C & D waste. However, TRCA can be effectively utilized as 100% replacement of natural aggregates in bituminous concrete in all weather conditions.

- The water absorption of recycled concrete aggregates (4.06%) and thermally treated concrete aggregates (2.95%) was more as compared to natural aggregates. All other properties of recycled concrete aggregates (RCA) and thermally treated concrete aggregates (TRCA) were satisfying the permissible limits specified by the MORTH for using in bituminous concrete mixes. As for higher water absorption, wet aggregate impact values for RCA (18.25%) and TRCA (17.37%) were satisfying the maximum permissible limit (max. 24% for BC).
- The optimum binder content for the bituminous mixes prepared with natural aggregates, RCA and TRCA was 5.2%, 7.39% and 6.85% respectively. The higher value of optimum bitumen content in case of RCA and TRCA was primarily due to the higher bitumen content corresponding to 4% air voids.
- Thermal treatment decreased the water absorption of RCA due to removal of weak mortar from the surface. Hence in case of mixes prepared with TRCA, optimum bitumen content was lesser as compared to RCA mixes.
- Although the thermal treatment of aggregates resulted in decrease in optimum bitumen content in comparison to RCA, but it affected the Marshall stability value which was lesser as compared to other two cases. Marshall stability value in case of RCA (17.17 kN) was slightly lower than that of natural aggregates (18.89 kN).
- Higher value of VFB in case of RCA (77.50%) and TRCA (75.50%) mixes indicated that their utilization might be effective in normal traffic conditions, as strength and stability are of greater concern in very high traffic conditions. VMA in case of RCA and TRCA were observed as satisfying the required specifications, same was the case in mixes prepared with natural aggregates.
- Retained stability value for RCA (73.09%) marginally falls below minimum required value of 75% as per ASTM. In view of above, it is recommended that use of RCA may be restricted to normal rainfall regions with effective drainage or it may be used with anti-stripping compounds in high rainfall regions. Retained stability value for mixes containing TRCA (82.32%) indicated that TRCA can be effectively utilized as 100% replacement of natural aggregates in bituminous concrete in all weather conditions.
- Material cost analysis indicated that RCA mixes were more economical considering the assumed parameters. However, no indirect benefit has been considered to arrive at cost-benefit analysis. Also, the conclusion arrived are only region specific and indicative, hence it could not be generalized. Although thermal treatment helped in improving the properties of RCA, but the practical feasibility of this process needs to be determined.
- RCA can be gainfully utilized in bulk as a replacement of natural aggregates in bituminous concrete. It also addresses the problems arising from excessive generation of demolition waste and depletion of natural resources.

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