***FINAL RESEARCH REPORT*:**

RESEARCH ON THE USE OF RECLAIMED CONSTRUCTION MATERIALS IN LGED'S ROAD

Release 2.0

LGED

Government of the Peoples' Republic of Bangladesh
Local Government Engineering Department

Department of Civil Engineering
Bureau of Research, Testing and Consultation (BRTC)
Bangladesh University of Engineering and Technology
Dhaka – 1000, Bangladesh

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1. INTRODUCTION

Local Government Engineering Department (LGED) has been constructing roads, bridges, culverts, buildings and other civil infrastructures for more than three decades. Each infrastructure is built with specified construction materials and has a design life span. At the end of its useful design life, materials used in these infrastructures get deteriorated, loses their original characteristics and eventually become wastes. Similar situation is experienced by flexible pavements after its useful design life. At the end of service life of flexible pavements, significant quantities of deteriorated asphalt concrete extracted from the rehabilitation process become hazardous waste and pollute roadside soils and agricultural field unless they are properly disposed-off or reused in a safe manner. On the other hand, there is a significant scarcity of sources of construction materials in Bangladesh. Most of the construction materials are imported from outside either in raw forms or in finished forms requiring significant foreign currency expenditure. Although the reclaimed flexible pavement materials lose their original properties (e.g., binding capacity of bitumen or gradation of aggregates) to a certain extent, their usability and usefulness is not totally lost. To address these environmental issues and incorporate sustainability in infrastructure development and management, many developed as well as developing countries are using reclaimed road materials for construction/rehabilitation of roads.

With a vision of sustainable development, LGED has come forward to ensure the optimum use of its pavement waste materials through development and efficient application of indigenous cost-effective technologies/ methods. The current practice of LGED with regards to the use of reclaimed flexible pavement materials is to use them as sub-base and base course materials in rehabilitation or maintenance projects.

However, the reclamation process followed is quite crude, where harrows are used to scrape of the existing flexible pavement materials, and in this process the top asphalt concrete gets mixed with bottom aggregate layers making it difficult to separate them. Moreover, strength (e.g. bearing capacity i.e., CBR) properties and suitability of this mixed aggregate as subbase and base course material has not been properly evaluated for practical application and is being practiced as a makeshift arrangement. To this end, LGED collaborated with the Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET) to utilize the fund received from the Government of Bangladesh for conducting the research on how to utilize the reclaimed asphalt concrete materials in the best possible way in the maintenance and rehabilitation work either in its crude form or in combination with virgin materials (aggregate and bitumen). The objective of the consultancy service is to conduct a study and research on the reclaimed construction materials of flexible pavement to develop working procedure for reusing the reclaimed materials in LGED roads.

To familiarize with the current practice of LGED in road maintenance and widening projects and the flexible pavement reclamation process, a site visit was organized on 2nd June 2022. BRTC, BUET consultant team visited an active site in Saturia Upazila of Manikgonj District. The BUET team was accompanied by local higher officials of LGED to give them a better perspective of the current practices and discussed various aspects of road maintenance issues. The LGED officials informed that, in rural road works specially in maintenance, and in widening projects, scarifying and loosening of existing top surface is done using harrows (up to the depth of 75mm using mechanical means) which brings base/sub-base course materials along with the reclaimed asphalt concrete. Due to continuous utilization of road and scarifying, base/sub-base course materials also lose their original shape which makes re-bonding with bitumen quite difficult. The consultant team then visited a part of Daragram GC-Bangladesh hat GC road which is part of "Widening and Strengthening of Important Upazila and Union Road under Dhaka Division Project" (DDIRWSP) under Saturia Upazilla, Manikganj District. The google map location of the site is shown in Figure 1 (a). Figure 1(b) shows a picture of the visiting team of consultants.

(a)

(b)

Figure 1: (a) Google Map Location of Sample Collection (b) Team of Consultants at Site

The Upazila Engineer, Saturia and the Sub Assistant Engineer, Saturia accompanied the consultants to the site. This was an upazilla road with existing road carriageway width of 12 ft, which is being widened to carriageway width of 18 ft.

It was observed that the wearing course and base course of existing road is removed manually where strengthening work is undertaken. The wearing course is of asphalt concrete (stone chips) and the base course is of brick chips. These two types of aggregate were then mixed together and put them back in preparation of sub-base of new road. There wasn't any data available on the performance of strengthened road's sub-base where reclaimed bituminous coated aggregate has been used.

Figures 2 shows the field condition, sample collection process and Figure 3 shows the typical condition of the reclaimed aggregates. Close up views of the reclaimed aggregate and reclaimed asphalt concrete (RAC) are shown in Figure 4 and Figure 5 below.

(a) (b)

Figure 2: (a) Sample aggregate collection from widened road sub-base. (b) Typical section of widened road (up to sub-base)

(a) (b)

Figure 3: Aggregate collected from sub-base of strengthened road

Figure 4: Close up View of Reclaimed Aggregates

Figure 5: Close up View of Reclaimed Aggregates

The scope of work under this research projects includes, but not limited to, as follows: -

- Collection of data and information from the site through field visit.
- Conducting necessary tests to find out various materialistic parameter of reclaimed road materials.
- Determination of physical properties of reclaimed road materials and their appropriateness.
- Determination of gradation of RAP materials (RBCA & Wearing Course).
- Assessing the applicability of RAP materials as base and sub-base of flexible pavement by determining California Bearing Ratio (CBR- Soaked) of RAP using different mixing composition with aggregates.
- Assessing the applicability of RAP materials in Wearing Course of flexible pavement.
- Performing job mix formula using RAP to meet requirement for flexible pavement.
- Conducting comparative study of using RAP materials as wearing course, base course, sub-base course of flexible pavement.
- Implementing simple techniques for removing coating from bituminous aggregates and examining their effectiveness for selecting the best performing one.
- Comparing the physical and mechanical properties of raw and surface modified reclaimed aggregates.

Some portion of the reclaimed aggregate from RAP is coated with bitumen around it and hence, will be termed as RBCA (Recycled Bituminous Coated Aggregate) from now on in this report. The full report has been arranged in parts, according to the major research objectives. In the first part, the potential of reclaimed material (RBCA) obtained from Reclaimed Asphalt Pavement (RAP) to be used as base and sub-base material has been comprehensively assessed and presented next. In the next part, the potential of reclaimed asphalt concrete (RAC) obtained from Reclaimed Asphalt Pavement (RAP) to be used in wearing course in new flexible pavement construction has been comprehensively assessed and presented. Job mix formula for using RAC in wearing course using different fractions and bitumen grades have been developed. Also, simple techniques for removing coating from bituminous aggregates were compared for effectiveness. In this report, the terms “bitumen” and “asphalt” are used interchangeably.

2. APPLICABILITY OF RAP IN BASE AND SUB BASE OF FLEXIBLE PAVEMENT

2.1 Review of Previous Studies

Use of Reclaimed Asphalt Pavement (RAP) in different components of flexible pavements such as base and sub base has been investigated by many researchers at home and as well as abroad.

In Bangladesh, some researches (Islam,2018; Islam, 2019) investigated the prospect of Reclaimed Asphalt Pavement (RAP) as aggregate base and sub-base by combining RAP at different dosages (100%, 70%, 60% and 50%) with virgin aggregate and determined the CBR values of each mix. Islam (2018) investigated the prospect of Reclaimed Asphalt Pavement (RAP) as Stabilized Base. The study suggests a method for creating asphalt mixes at various compaction temperatures. In this experiment, laboratory test samples of 100% RAP were compacted at various temperatures (130°C, 140°C,150°C and 160°C) and were evaluated for the mix's performance by various tests (Marshall stability, flow, and compressive strength). The RAP materials were collected from the wearing course of the road segment under the Banani overpass near Dhaka Cantonment during excavation process for utility shifting. Milling process was done manually with locally available cutting tools. Samples were collected in suitable pieces and then pulverized and sized manually. According to the findings, the optimum compaction temperature is 150°C which had a stability value of 9.5 KN. At this temperature, the compressive strength of the asphalt concrete specimen was 5.14 MPa. According to the study, asphalt mixes, including RAP, when utilized as a stabilized base with 20 or 30 mm of surface, can provide a service life more significant than that of 50 mm overlay.

Islam (2019) further examined the potentiality of RAP as aggregate base and sub-base by combining RAP at different dosages (100%, 70%, 60% and 50%) with virgin aggregate and determined the CBR values of each mix. According to the study, the CBR value is 15 when RAP aggregates are 100% which does not fulfill the minimum requirement of CBR value by LGED. When 50% of the RAP is replaced, a maximum CBR value of 20 is discovered. The CBR values do, however, noticeably increase when RAP and VA combinations are treated with cement, reaching a maximum of 47 for 50% replacement of RAP treated with 5% cement. According to the study, the CBR value of the compacted collected RAP at 155°C is 37. However, the CBR value increases to 52 when 1% virgin bitumen is added and mixed at the same temperature. According to the study, collected RAP alone can only be used as a sub-base or base if it is used with binders to increase its strength. However, in both cases, RAP means the bituminous concrete part (wearing course and binder course only i.e. only stone aggregate)

In other SAARC countries, similar studies on RAP material for use in base and sub-base have been studied. In India, Kasu (2020) investigated on design and durability characteristics of cement treated reclaimed asphalt (CTRA) for base and subbase layers. This paper presented the mechanical, durability and microstructure characteristics of CTRA bases and sub-bases material produced by varying the percentage of virgin aggregate (VA) and recycled asphalt aggregate (RA) (100/0, 80/20, 60/40, 40/60 of RA/VA), and cement content (2.5%, 5.0%, 7.5%, and 10.0% cement contents by wt. of aggregate). It was found that the optimum moisture content (OMC) was in the range of 6.5 to 7.5% for all mixtures. Maximum dry density (MDD) lies in the range 2.20–2.28 g/cc. The addition of cement had a more pronounced effect than the addition of RA in the mixtures. When the high RA proportion is used in base/subbase layers, the cost saving in the construction of flexible pavements was observed about 26–32%. CTRA is recommendable for use in bounded pavement layers (base and sub-base for flexible pavements.

In Pakistan, Arshad and Ahmed (2017) focused on the characterization of blended materials containing 50% and 75% of RAP with fresh granular materials to evaluate whether they are suitable for granular base/subbase layers of flexible pavements. A series of laboratory tests was performed to determine the resilient modulus (M_R) and the constrained modulus (M_c) for both fresh granular materials and their blends. Statistically, the notable increase was found in the M_R values of the blended samples containing 75% RAP material and 25% fresh granular, particularly at higher levels of bulk stresses. It was also found that the accumulative strains during cyclic loading generally increase with an increase in the percentage of RAP contents in the blended samples. M_c test results show an increasing trend with the increasing level of axial stress, however, M_c value decreases with increasing percentage of the RAP content.

In Oman, Taha (1999) performed an experimental investigation on well-graded RAP contents having uniformity coefficient (Cu) and curvature coefficient (Cc) equal to 6 and 1.5, respectively, while the fresh granular material was a mixture of well-graded sand and gravelly sand with little or no fines. The blends were obtained by adding 20, 40, 60, 80 and 100% of the granular material with RAP. On the basis of California Bearing Ratio (CBR) test results, they have suggested that up to *100% RAP* in subbase courses could be allowed but the amount of RAP in unbound granular base courses would have to be limited to *10%*.

In Egypt, Mousa (2021) also evaluated the feasibility of using RAP as base and subbase material through laboratory tests like particle size distribution, specific gravity, modified Proctor compaction, CBR, and hydraulic conductivity tests. Furthermore, resilient modulus test, static triaxial shear test, and X-Ray CT Scanning were conducted for the evaluation of material performance. In the laboratory, the RAP was blended with VA in percentage of 0%, 20%, 40%, 60%, 80%, and 100% by the total weight of the blend. It is important to control the gradation of the RAP/VA blends to cope with the gradation requirements as the RAP fractions tend to have lower fines content compared to the natural virgin aggregate. Based on the CBR, up to 60% RAP can be blended with crushed aggregates and used as a subbase material, however, RAP can only be used up to 20% in road base construction. Both CBR and hydraulic conductivity are lower for blends with higher amounts of RAP. Conversely, the increase in the RAP amount showed a significant increase in the resilient modulus. From the CT Scanning, it is found that the 0% RAP specimen had higher air voids content when compared to the 80% RAP specimen. This suggests that the lower air voids might lead to higher values of resilient modulus for samples consisting of a higher RAP amount.

In United Kingdom up to a maximum of 50% RAP by weight is permitted in Type 1 and Type 2 unbound subbase mixtures. Up to 100% RAP is allowed in Type 4 unbound aggregate mixture (Manual of Contract Documents for Highway Works 2014). In United States, the acceptable field compaction criterion is specified in terms of a wet density of not less than 95% of the maximum wet density when determined in accordance with one-point AASHTO T 180, Method D (American Association of State Highway and Transportation Officials. AASHTO T 180-10 2010) . Florida Department of Transportation (FDOT) specifications allow the use of up to 100% RAP only for nontraffic base applications, primarily at paved shoulders and bike paths, as described in Section 283 (Florida Department of Transportation. Standard Specifications for Road and Bridge Construction 2013).

The Idaho Transportation Department (2012) specifies that RAP can be mixed in approximately equal proportions with granular borrow for subbase applications and up to 50% RAP is allowed in the granular subbase (Idaho Transportation Department. Standard Specifications for Highway Construction 2012)

Another study in Montana (Mokwa , 2005) conducted laboratory tests on four different types of granular material blended with varying percentages of RAP (20, 50 and 75%). They found that blending of RAP with granular material resulted in only minor changes to the engineering properties of the fresh granular material. However, they suggested a limiting value of 50% RAP when used for the base course. Texas DOT and Washington State DOT specifications allow up to 20% RAP by weight in flexible bases.

2.2 Approach and Methodology

Reclaimed asphalt pavement (RAP) is the most available material with great potential to substitute natural resources. Use of RAP as a construction material can decrease the cost, provides a way to conserve landfill space, preserves natural resources, protects the environment, and improves sustainability. While several factors influence the use of RAP in asphalt pavement, the two primary factors are economic savings and environmental benefits. RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of HMA. The use of RAP also conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. Additionally, using RAP decreases the amount of construction debris placed into landfills and does not deplete nonrenewable natural resources such as virgin aggregate and asphalt binder. Ultimately, recycling asphalt creates a cycle that optimizes the use of natural resources and sustains the asphalt pavement industry.

2.2.1 Approach

The approach towards this task is more of a research oriented one, with the prime objective of developing a sustainable and cost-effective methodology for efficient reclamation of valuable resources and use of reclaimed asphalt pavement materials in an environmentally friendly way which are otherwise dumped as waste materials. The work-flow chart below shows the overall approach for this task.

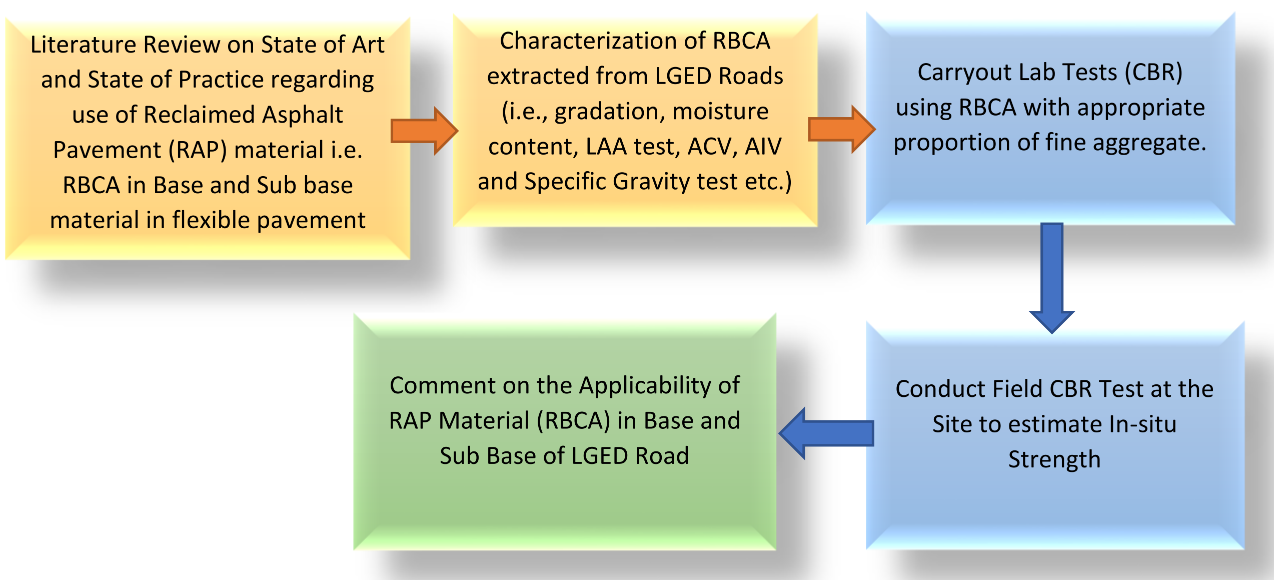


Figure 6: Work-flow chart of proposed RBCA usage as Base and Sub Base study

2.2.2 Methodology

The total work of this study can be divided into four parts- namely-

a) Literature review and LGED's flexible pavement construction practices, guidelines etc.
b) Characterization of Reclaimed Asphalt Pavement (RAP) materials i.e. RBCA through conducting standardized tests such as – Determination of specific Gravity, Gradation Test, Determination of Moisture Content, Aggregate Crushing Value Test, Aggregate Impact Value Test, Los Angeles Abrasion Test etc.).

c) Carry out base and subbase material related standard tests i.e. California Bearing Ratio (CBR) Test to ascertain suitability of RBCA in its original state or in combination with virgin aggregate in varying proportions (if necessary).

d) Carryout Field CBR Test on the site from where the materials have been collected to ascertain field performance.

The original proposed methodology proposed in the inception report has been slightly modified based of laboratory results and subsequent findings.

2.3 Analysis and Results of Tests Performed On Rap Material (RBCA) for Assessing Their Applicability as Base and Sub Base Material

In order to assess the applicability of RBCA as base and sub base various material characterization test has been performed and the results are shown below.

2.3.1 Characterization Tests of RBCA:

Particle size distribution: sieve analysis/gradation test was performed on the reclaimed bituminous coated aggregate (RBCA) according to ASTM C136. The results of the sieve analysis are shown below.

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
37.5	1581.0	11	11	90	**7.87 (Seven point eight seven)**
25.4	4510.0	30	41	59	
19.05	5816.0	39	79	21	
12.5	2820.0	19	98	2	
9.5	216.0	1	100	0	
6.3	0.0	0	100	0	
4.75	0.0	0	100	0	
2.36	0.0	0	100	0	
1.18	0.0	0	100	0	
0.6	0.0	0	100	0	
0.3	0.0	0	100	0	
0.15	0.0	0	100	0	
0.075	0.0	0	100	0	
Pan	57.0	0	100		
Total	15000				

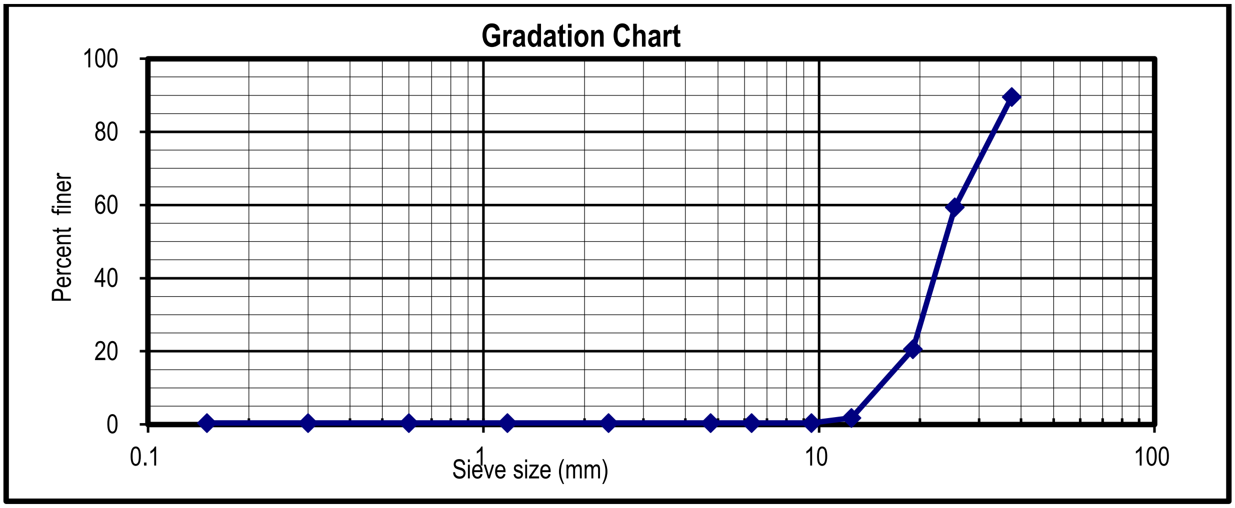


Figure 7: Gradation Curve of RBCA material (Whole Sample)

Close observation of the gradation of RBCA material revealed that, there are two kinds of coarse aggregate mixed together i.e. Stone aggregate from base course and binder course of reclaimed pavement and brick aggregate (Picked Jhama) from sub-base course of reclaimed pavement. Also, it was evident that for greater than 1” size fraction, only brick aggregates (Picked Jhama) were present as seen in Figure 7. For this reason, the aggregate sample was separated in greater than 1” size and less than 1” size for carrying out the characterization tests.

Figure 8: Greater than 1” Size RBCA (Picked Jhama Brick Aggregate)

The grain size distribution curves for the investigated materials compared with the gradation limits for the granular base, sub-base and asphaltic concrete materials with LGEDs specification were compared.

Table 1: Aggregate Grading for Sub-Base and Base Course (LGED)

Sieve Size (mm)	% Passing By Weight	
	Grading for Sub-Base Course	Grading for Base Course/WMM
50 mm	100	100
37.5 mm	100	95-100
19 mm	55-95	60-80
9.5 mm	35-75	40-60
4.75 mm	25-60	25-45
2.36 mm	15-50	15-30
0.600 mm	10-35	8-22
0.300 mm	10-25	-
0.075 mm	5-15	0-5

Bulk Specific Gravity (BSG): The bulk specific gravity as well as water absorption capacity test was carried out on the two fractions of RBCA (greater than 1" size and less than 1" size) according to ASTM C127 /AASHTO T85-91 standard test method. Test results are shown below.

Table 2: Bulk Specific Gravity and Absorption Capacity of different RBCA fraction

Sample ID	*Remarks*	*Bulk Specific Gravity*	*Absorption Capacity (%)*
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	1.94	8.50
RBCA (Less than 1")	Mix of Stone & Brick Chips	2.44	2.40
RBCA (Less than 3/4")	Mix of Stone & Brick Chips	2.45	2.30

Moisture Content: Moisture content of the two fractions of RBCA (greater than 1" size and less than 1" size) were also determined using ASTM C566 standard test method. Heating oven has been used to determine the moisture content of different fractions of the reclaimed bituminous coated aggregate. Test results are shown below.

Table 3: Moisture content of different RBCA fraction

Sample ID	*Remarks*	*Moisture Content (%)*
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	3.80
RBCA (Less than 1")	Mix of Stone & Brick Chips	1.20

<u>Bulk Density/ Unit Weight:</u> The bulk density of aggregate is evaluated using standard test methods- ASTM C 29/C29M-17a or BS 812-2:1995. The bulk density or unit weight is the weight per unit volume (mass per unit volume or density). Bulk density of the two fractions of RBCA (less than 1" size and less than 3/4" size) were also determined using ASTM C29 standard test method. Test results are shown below.

Table 4: Unit Weight of different RBCA fraction

Sample ID	***Remarks***	***Unit Weight (Kg/m^3)***
RBCA (Less than 1")	Mix of Stone & Brick Chips	1550
RBCA (Less than 3/4")	Mix of Stone & Brick Chips	1550

<u>Los Angeles Abrasion (LAA) Value Test:</u> Los Angeles abrasion test on aggregates is the measure of aggregate toughness and abrasion resistance such as crushing, degradation and disintegration. This test is carried out by AASHTO T 96 or ASTM C 131: Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. LAA value of RBCA for different fractions of were determined. Test results are shown below.

Table 5: Los Angeles Abrasion Value of different RBCA fraction

Sample ID	***Remarks***	***LAA Value (%)***
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	28
RBCA (Less than 1")	Mix of Stone & Brick Chips	19

<u>Aggregate Crushing Value (ACV) Test:</u> Aggregate crushing value test on coarse aggregates gives a relative measure of the resistance of an aggregate crushing under gradually applied compressive load. ACV for different fractions of RBCA were determined according to BS 812 (part3) test standard. Test results are shown below.

Table 6: Aggregate Cushing Value of different RBCA fraction

Sample ID	***Remarks***	***ACV Value (%)***
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	35*
RBCA (Less than 1")	Mix of Stone & Brick Chips	18

*The ACV test is not appropriate for this weak aggregate sample. It is recommended to perform 10% fine value (TFV) test to know the crushing properties of the sample. The TFV test result is shown next.

<u>Ten Percent Fines Value (TFV) Test:</u> The Ten Percent Fines Value Test is conducted to know the load (in KN) required to produce ten percent of fine material when subjected to a gradually applied compressive load. TFV for RBCA fraction greater than 1" size (Brick Chips) was determined according to BS 812 (part3) test standard. Test results are shown below.

Table 7: Ten Percent Fine Value of RBCA (greater than 1")

Sample ID	***Remarks***	***TFV Value (KN)***
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	120

<u>Aggregate Impact Value (AIV) Test:</u> The aggregate impact value gives a relative measure of the resistance of an aggregate to sudden shock or impact, which in some aggregates differs from its resistance to a slow compressive load. AIV for different fractions of RBCA were determined according to BS 812 (part3) test standard. Test results are shown below.

Table 8: Aggregate Impact Value of different RBCA fraction

Sample ID	***Remarks***	***AIV Value (%)***
RBCA (Greater than 1")	Brick Chips (Picked Jhama)	34
RBCA (Less than 1")	Mix of Stone & Brick Chips	15

2.3.2 California Bearing Ratio (CBR):

The CBR test ASTM D1883 (AASHTO T193) has been performed to assess the potential strength of the RBCA under uniaxial load. Figure 8 shows typical equipment for CBR test.

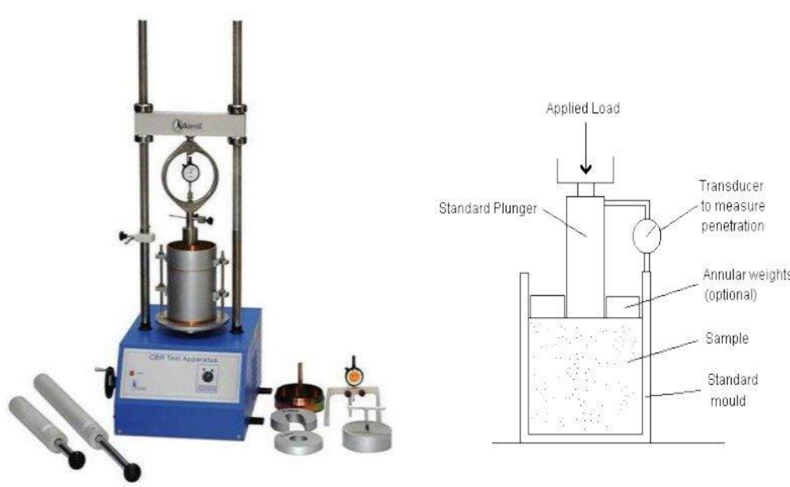


Figure 9: California Bearing Ration Test Equipment

The California Bearing Ratio (CBR) of base/ sub-base material is an indication of its bearing capacity under traffic loading and is determined as the ratio of the penetration resistance of the base material to that of a standard crushed stone.

According to ASTM D 1883, "the test method covers the determination of the CBR (California Bearing Ratio) of pavement subgrade, subbase, and base course materials from laboratory compacted specimens. The test method is primarily intended for (but not limited to) evaluating the strength of materials having maximum particle sizes less than 3⁄4 in. (19 mm)". So as a starting point to carryout Lab CBR test on RBCA sample, the sample was separated at the ¾" Size. Samples containing less than ¾" size aggregates were used for Lab CBR test. The test results of characterization tests performed on this sample (less than ¾" size) is shown below.

Table 9: Characterization of Aggregate used in CBR Test

Sample	***Parameter***	***Test Standard***	***Results***
RBCA (Less than ¾" Size)	Specific Gravity (OD)	ASTM C127	2.45
	Water Absorption	ASTM C127	2.30 (%)
	Unit Weight/ Bulk Density	ASTM C 29	1550 (kg/ m^3)
	Voids in Aggregate	ASTM C 29	37 (%)

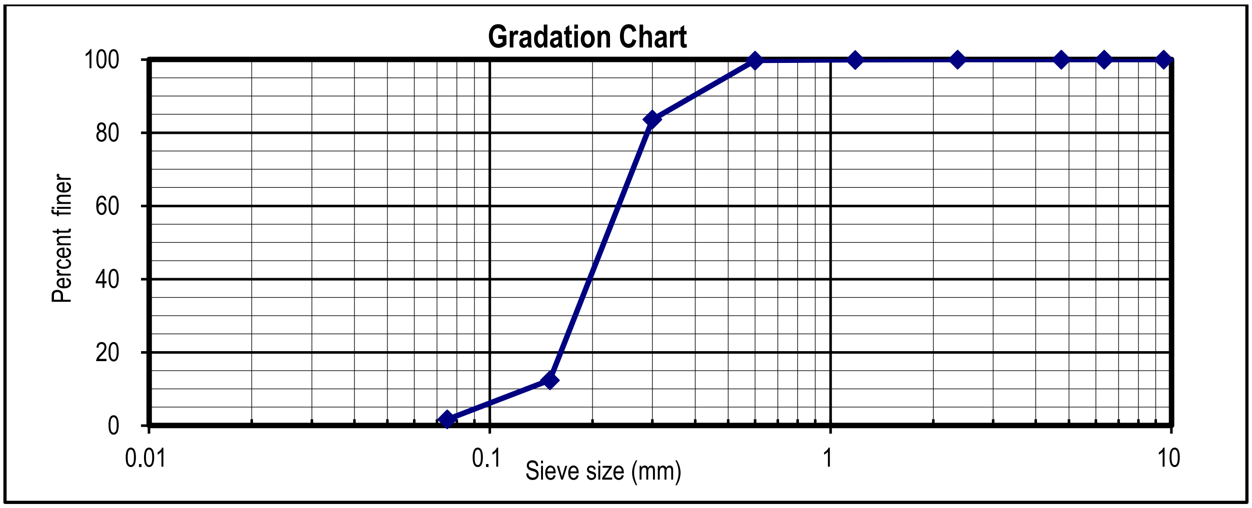
It was observed from the sieve analysis test of RBCA (shown above) that almost all fraction of the RBCA is larger than 9.5 mm size. As a result, molding of samples for CBR test using only the above reclaimed bituminous coated aggregate was not possible. Thus, for sample molding purposes, fine aggregate (local sand) was added to the RBCA in requirement amount based on voids percentage of RBCA. The properties of the sand used for molding purposes is shown below.

Table 10: Characterization of Local Sand used in CBR Test

Sample	***Parameter***	***Test Standard***	***Results***
Local Sand (used for CBR sample molding)	Specific Gravity (OD)	ASTM C127	2.61
	Water Absorption	ASTM C127	1.20 (%)
	Unit Weight/ Bulk Density	ASTM C 29	1540 (kg/ m^3)
	Fineness Modulus	ASTM C 136	1.04

Sieve analysis results along with gradation chart for local sand used in CBR sample preparation as per ASTM C 136 is shown below.

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
12.5	0.0	0	0	100	**1.04** **(One point zero four)**
9.5	0.0	0	0	100	
6.35	0.0	0	0	100	
4.75	0.0	0	0	100	
2.36	0.0	0	0	100	
1.18	0.2	0	0	100	
0.6	0.6	0	0	100	
0.3	48.2	16	16	84	
0.15	213.5	71	88	12	
0.075	32.0	11	98	2	
Pan	5.4	2			
Total	300				



Local sand of the above specification was mixed with RBCA at three different mix proportions to find the appropriate one that provides maximum unit weight and fills the target voids content in RBCA (3/4" down) which is 37 %. A volumetric mix proportion approach was used to make the process field ready. The mix proportions used along with the density achieved is shown below.

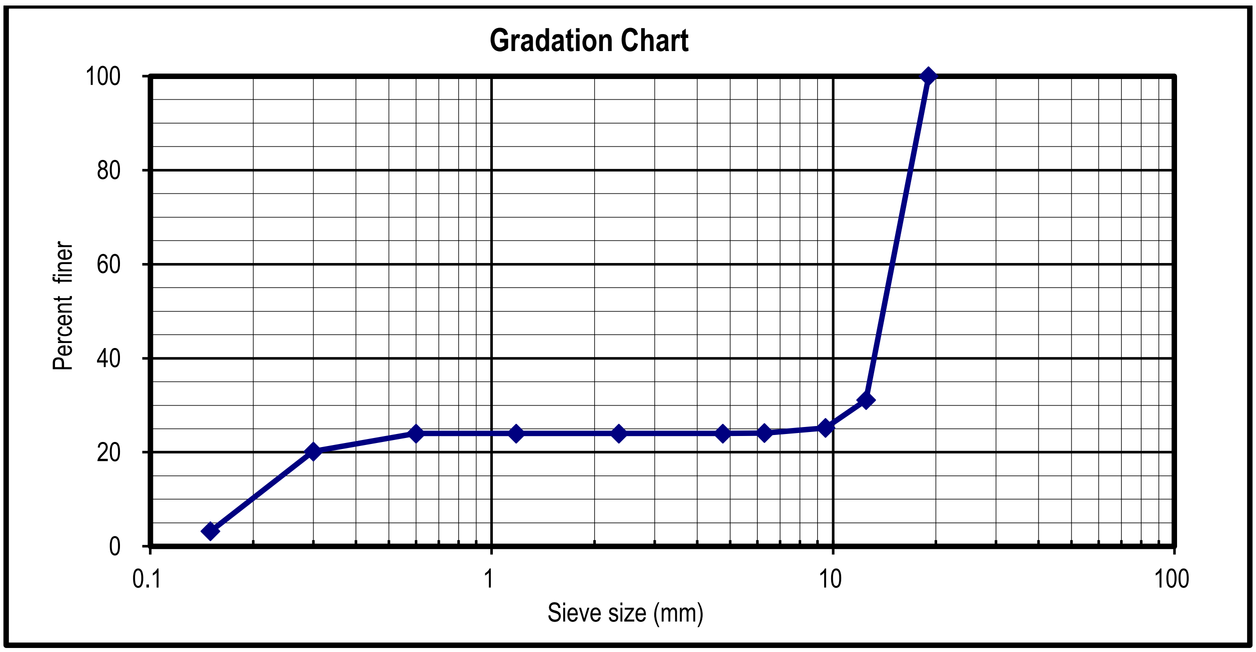
Table 11: Composition of various aggregate mixes considered for CBR Test

Mix Proportion RBCA (3/4" down) : Local Sand)	Mix Percentage RBCA (3/4" down) : Local Sand)	Unit Weight/ Bulk Density (kg/m^3)
3 : 1	75% : 25%	1990
5 : 2	71% : 29%	2010
2 : 1	67% : 33%	2010

The combined gradation of CBR samples for the different mix proportions of RBCA and local sand are shown next.

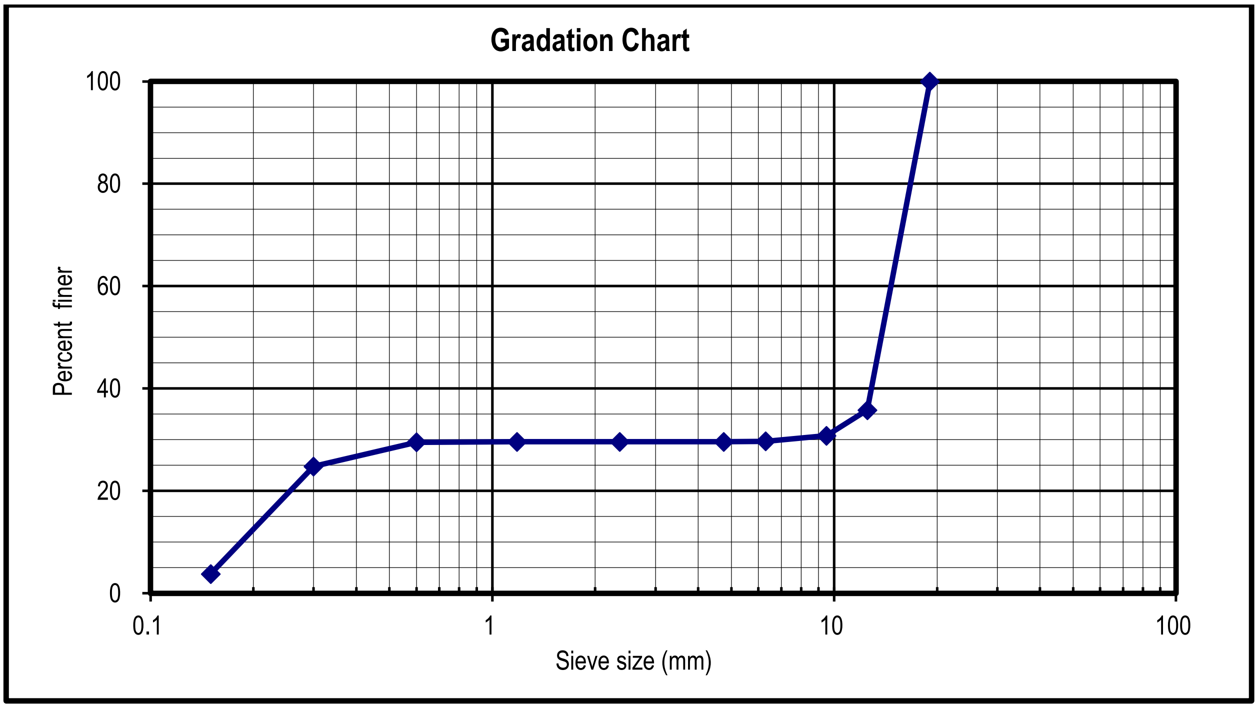
Combined gradation of CBR Sample for Mix Proportion- RBCA (3/4" down): Local Sand) = 3:1

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
19.05	0.0	0	0	100	**5.55 (Five point five five)**
12.5	4485.0	69	69	31	
9.5	387.0	6	75	25	
6.3	73.0	1	76	24	
4.75	6.0	0	76	24	
2.36	2.0	0	76	24	
1.18	1.0	0	76	24	
0.6	3.1	0	76	24	
0.3	249.6	4	80	20	
0.15	1110.0	17	97	3	
0.075	166.0	3	99	1	
Pan	28.1	0	100		
Total	6511				



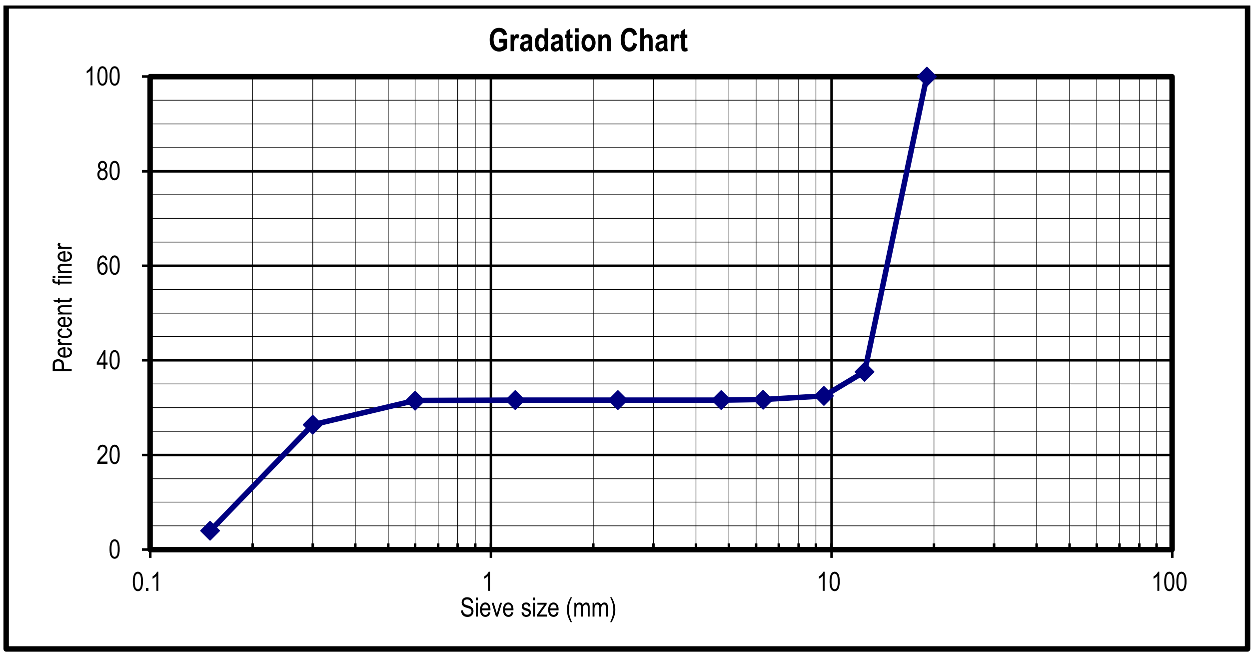
Combined gradation of CBR Sample for Mix Proportion- RBCA (3/4" down): Local Sand) = 5:2

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
19.05	0.0	0	0	100	**5.22 (Five point two two)**
12.5	4510.0	64	64	36	
9.5	354.0	5	69	31	
6.3	80.0	1	70	30	
4.75	6.0	0	70	30	
2.36	1.0	0	70	30	
1.18	1.4	0	70	30	
0.6	4.1	0	71	30	
0.3	331.9	5	75	25	
0.15	1473.0	21	96	4	
0.075	221.0	3	99	1	
Pan	37.3	1	100		
Total	7020				



Combined gradation of CBR Sample for Mix Proportion- RBCA (3/4" down): Local Sand) = 2:1

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
19.05	0.0	0	0	100	**5.11 (Five point one one)**
12.5	4515.0	62	62	38	
9.5	368.0	5	68	33	
6.3	60.0	1	68	32	
4.75	7.0	0	68	32	
2.36	1.0	0	68	32	
1.18	1.5	0	68	32	
0.6	4.6	0	69	32	
0.3	366.0	5	74	26	
0.15	1622.6	22	96	4	
0.075	243.2	3	99	1	
Pan	41.0	1	100		
Total	7230				



Although, the highest density was achieved for 5:2 ration, due to rounding both 5:2 and 2:1 ration appear to give same density. Based on this finding, CBR molds were prepared using 5:2 ration for test purposes. Two types of compaction were performed i.e. manual compaction and vibration (vibrating table) for sample preparation to find out the effects of compacting efforts on CBR. Figure 9 below shows the prepared samples for Laboratory CBR test.

(a) (b)

Figure 10: Prepared samples for CBR Test.

Next, Soaked CBR tests were performed on the prepared samples and results are shown below.

Soaked CBR test on samples prepared from vibrating for 10 minutes and 15 minutes on the vibrating table and 56 blows manually compacted sample are shown below. Figure 10 and Figure 11 Shows the corresponding graphs.

Table 12: Summary of CBR Test Results (Using Vibrating Table, and Manual Compaction)

SUMMARY OF RESULTS (SOAKED CBR)								
Specimen	Moisture	Dry Unit	Surcharge	Pen. Stress (psi)	Pen. Stress (psi)	Bearing Ratio	Bearing Ratio	CBR
	Content (%)	Wt. (pcf)	Weight, lbf	at 0.1” **	at 0.2“ ***	at 0.1” **	at 0.2” ***	Value (%)
10 min Vib.	10.79	120.93	10	735	1373	74	92	**74 / 92**
15 min Vib.	10.24	134.85	10	881	1901	88	127	**88 / 127**
56 blows	11.63	136.17	10	1120	2324	112	155	**112 / 155**

**Corrected, ***Corrected/ Uncorrected (for 0.2" or Maximum Penetration or Maximum Stress), Vib. Means Vibration on Vibrating Table.

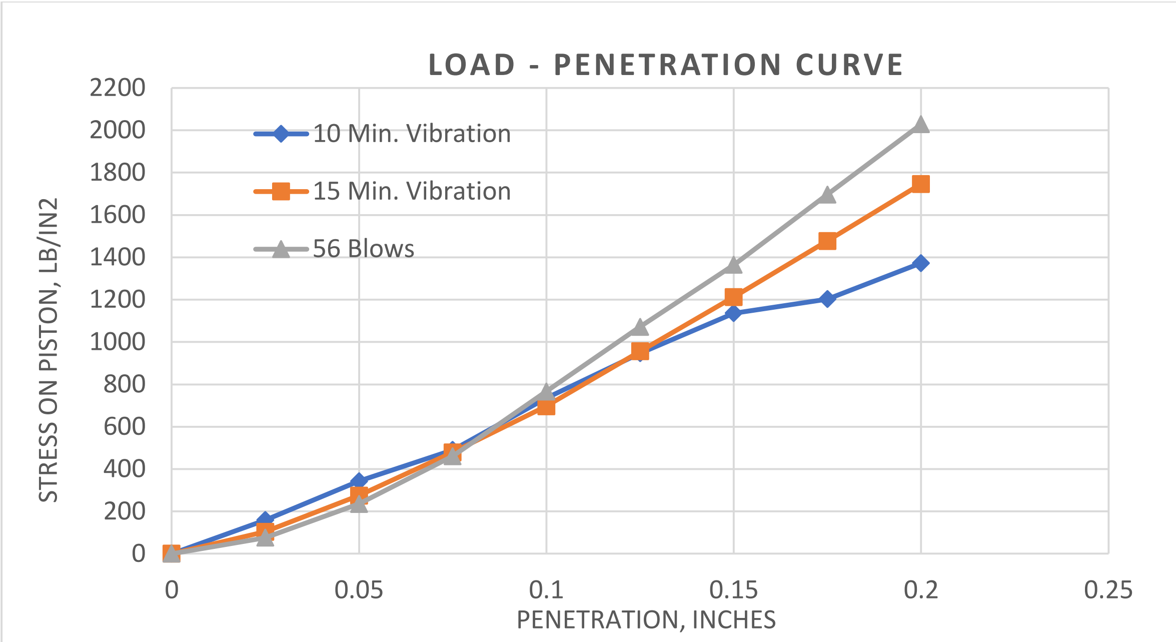


Figure 11: Stress-penetration Graph for soaked CBR test to identify effects of compacting force on density and CBR

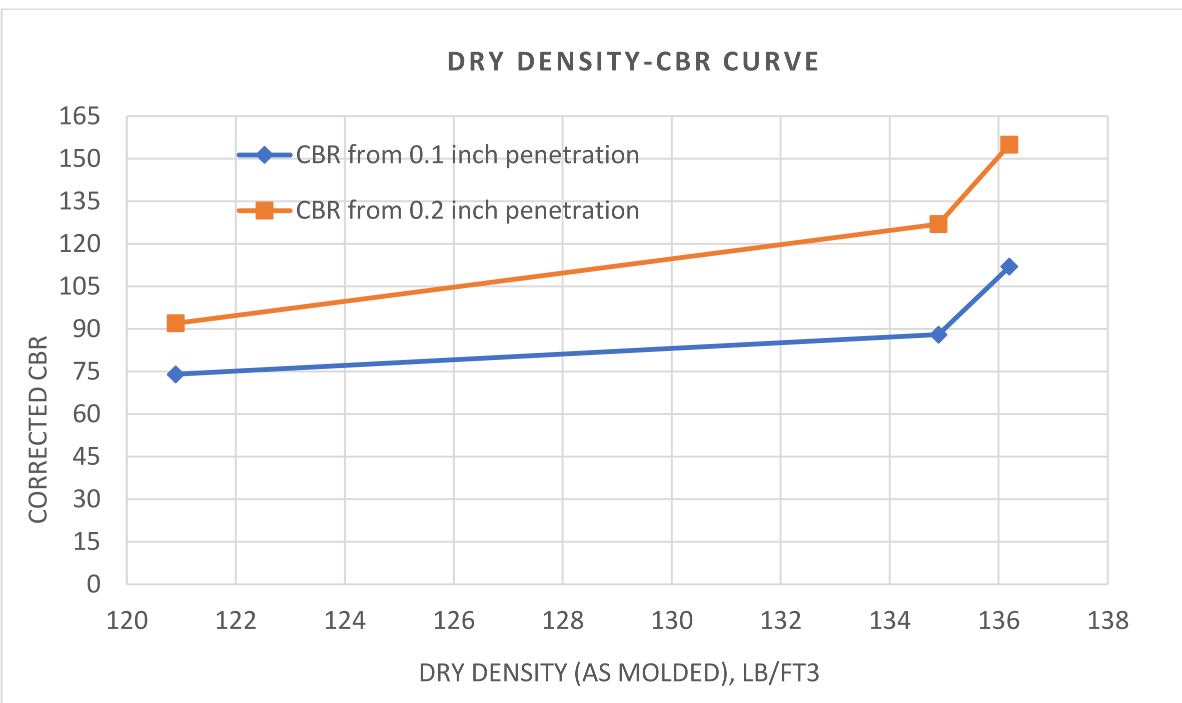


Figure 12: CBR- Density Graph for soaked CBR test to identify effects of compacting force on density and CBR

From the above results, it was evident that manual compaction produced denser sample compared to 10 minutes of vibration and slightly better compaction compared to 15 minutes of vibration. Based on this, samples were prepared using manual compacting effort at 10, 25 and 56 blows. Soaked CBR tests were performed on the prepared samples and the results are shown below. For 56 blows, a CBR value of 109% was found at 0.1" penetration and 147 % was found at 0.2" penetration. Figure 12 and Figure 13 Shows the corresponding graphs.

Table 13: Summary of CBR Test Results (Using Manual Compaction)

SUMMARY OF RESULTS (SOAKED CBR)								
Specimen	Moisture	Dry Unit	Surcharge	Pen. Stress (psi)	Pen. Stress (psi)	Bearing Ratio	Bearing Ratio	CBR
No. of Blows	Content (%)	Wt. (pcf)	Weight, lbf	at 0.1" **	at 0.2" ***	at 0.1" **	at 0.2" ***	Value (%)
10	9.80	128.59	10	482	1080	48	72	**48 / 72**
25	9.08	134.65	10	988	1841	99	123	**99 / 123**
56	9.19	137.82	10	1085	2212	109	147	**109 / 147**

**Corrected, ***Corrected/ Uncorrected (for 0.2" or Maximum Penetration or Maximum Stress)

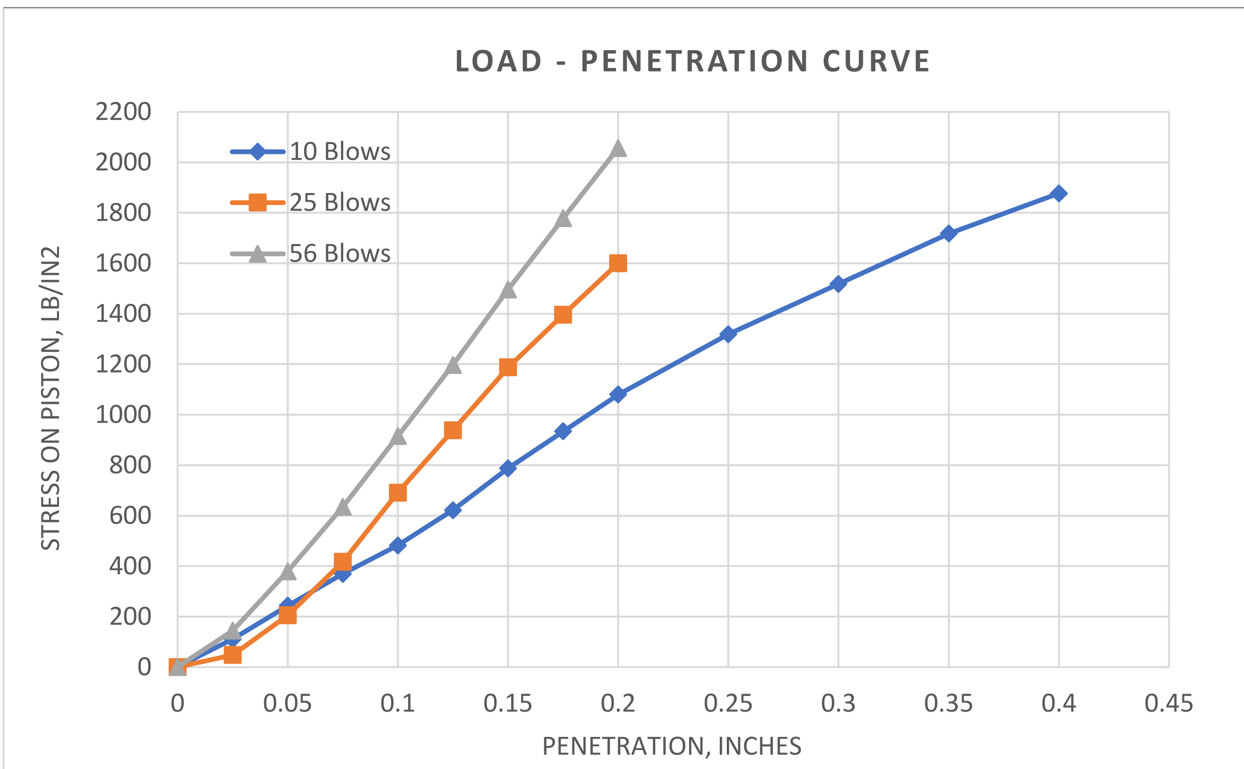


Figure 13: Stress-penetration Graph for soaked CBR test

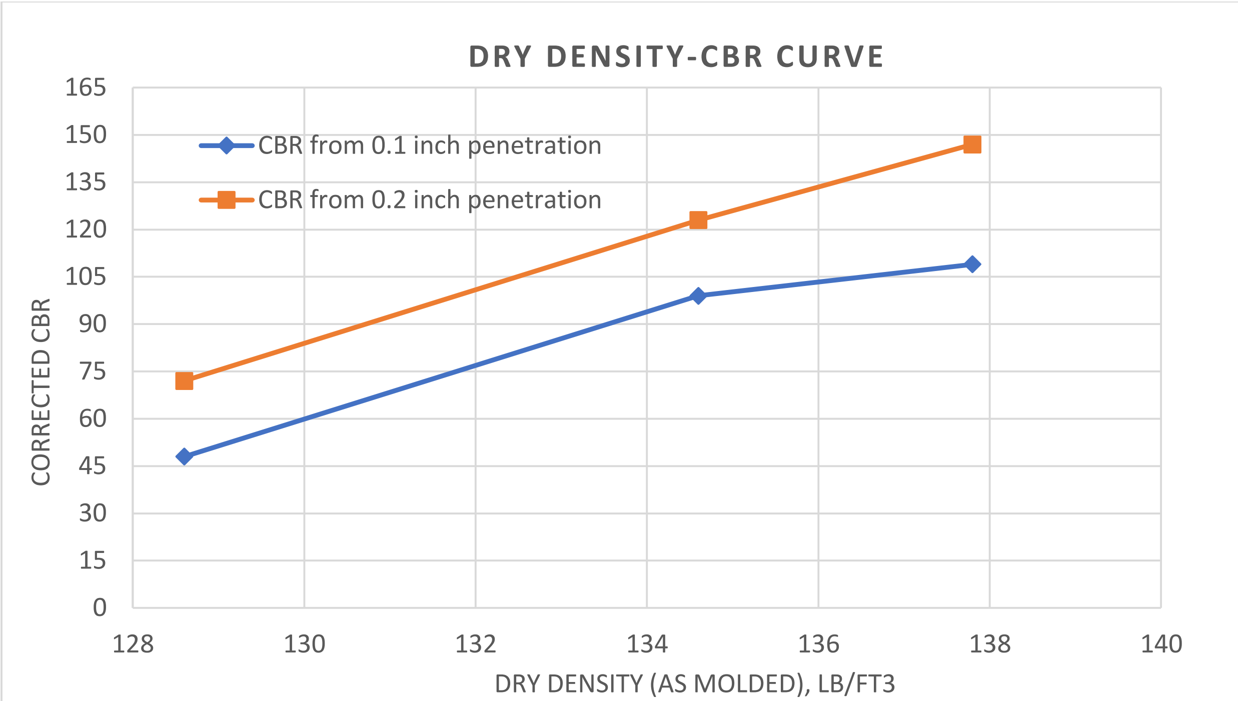


Figure 14: CBR- Density Graph for soaked CBR test

In order to correlate the laboratory CBR test results with field conditions, maximum density of RBCA was determined using ASTM D 4253 (Maximum Index Density/ Unit Weight of Soil). The modified proctor test (ASTM D 1557) is allowed for material having 30% or less by mass of their particle retained on the ¾" sieve, and in our case 79 % of the particles retained on ¾" sieve, thus ASTM D 4253 was used instead. In ASTM D4253, vibratory table is used to obtain maximum index density which is applicable to soils where 100 %, by dry mass, of soil particles pass a 3-in. (75-mm) sieve. Figure 14 shows the (a) vibrating table, (b) RBCA filled mold, (c) compaction in progress, and (d) the compacted RBCA sample.

(a)

(b)

(c)

(d)

Figure 15: Maximum Index Density test of RBCA- (a) vibrating table, (b) RBCA filled mold, (c) compaction in progress, and (d) the compacted RBCA sample.

The results of the Maximum Density test using only RBCA is shown below.

Table 14: Summary of Maximum Index Density of RBCA

Maximum Index Density/Unit Weight of Whole Rap aggregate (RBCA)		
Maximum Dry Density / Unit Weight	1.37	g/cm^3
	13.46	kN/m^3
	85.6	lb/ft^3

Also, in correlation with CBR test, maximum index density of RBCA mixed with local sand in the proportion of 5:2 was determined. The results are shown below.

Table 15: Summary of Maximum Index Density of RBCA and Sand Mix

Maximum Index Density/Unit Weight of (RBCA : Local Sand = **5 : 2**)		
Maximum Dry Density / Unit Weight	1.63	g/cm^3
	16.03	kN/m^3
	102	lb/ft^3

The maximum dry density achieved for only RBCA sample using ASTM D 4253 was 85.6 lb/ft^3 whereas the maximum dry density achieved for RBCA mixed with local sand in the ration (5:2) was 102 lb/ft^3. Both of them are quite below the density achieved in the laboratory CBR tests (136.17 ~137.82 lb/ft^3). The reason behind this is the mixture of two different aggregates i.e. stone chips and brick chips of two predominantly different sizes. Brick chips are lighter in weight compared to stone chips and comparatively larger sizes are brick chips in the mix. As a result, when CBR test sample is prepares using ¾" down size aggregates, larger proportion of stone chips are incorporated compared to when the whole RBCA sample is taken. For this reason, direct relationship between laboratory CBR and field density could not be established at this point. In order to overcome this difficulty, Field CBR tests were performed at the site of sample collection to get actual in-situ CBR values.

2.4 Field CBR Test

In order to evaluate the field CBR value where RAP (RBCA) material have been used to prepare sub-base/base, BUET Consultant Team visited LGED's road construction site at Manikganj on 19th February 2023. A field CBR test has been performed on that site. Figure 15 shows the pictures of BUET team performing filed CBR test at site.

Figure 16: Field CBR Test by BUET Team

However, due to limitation of testing arrangement at the site (unavailability of heavy truck to perform as support of CBR test equipment), the field CBR test could be performed up to 0.1 inch penetration only. Results of the field CBR test is shown below. The observed CBR value was 109 for 0.1 inch penetration as shown in Figure 16.

Table 16: Summary of Field CBR Test

SUMMARY OF TEST RESULTS								
Spot ID	Water Content (%)*	Dry Unit Wt.*	Surcharge	Pen. Stress (psi)	Pen. Stress (psi)	Bearing Ratio	Bearing Ratio	CBR
		pcf	kg	at 0.1 inch **	at 0.2 inch ***	at 0.1 inch **	at 0.2 inch ***	Value (%)
1	6.0	N/A	13.5	1087	--	109	--	**109 / --**
* Field Condition ** Corrected *** Corrected/Uncorrected (for 0.2" or Maximum Penetration or Maximum Stress)								

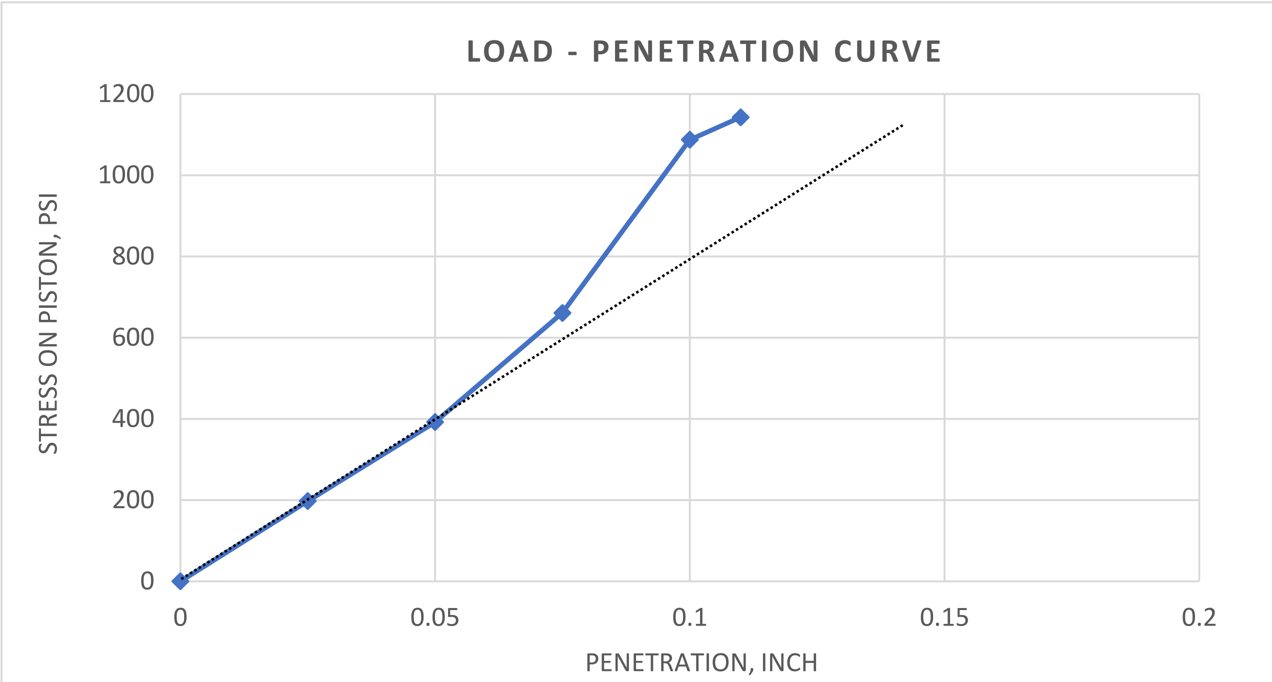


Figure 17: Stress-penetration Graph for Field CBR test.

2.5 Findings and Recommendation

The major findings of this research on the use of reclaimed bituminous coated aggregate (RBCA) obtained from reclaimed asphalt pavement are as follows-

- From laboratory CBR test, the soaked CBR value of RBCA (for 3/4" down portion) obtained was 109% at 0.1" penetration and 147 % at 0.2" penetration.
- Field CBR tests were performed for field verification of laboratory findings. Similar to lab results, a high CBR value of 109% was obtained for field compacted reclaimed bituminous coated aggregate at the test site in Manikganj. However, the field CBR test was performed in dry condition unlike the soaked condition used for laboratory CBR test.
- The field CBR test could not be performed beyond 0.1" penetration due to proper arrangement at the test site. In line with the findings from lab CBR test, it is expected that the CBR value corresponding to 0.2" penetration in field condition would also be higher than 0.1" penetration.
- Although it was intended to perform field density test along with field CBR tests, it wasn't possible to carry out due to the smaller thickness (less than 3 inch) of the compacted layer.

Limitation

Although high CBR values were obtained at laboratory soaked CBR tests (109% at 0.1” penetration & 147% at 0.2” penetration) as well as in field CBR test (109% at 0.1” penetration, which are quite higher than LGED’s required CBR value for base (80%) as well as sub-base (30%), there still remains some concern for their use in flexible pavement layers-

- RBCA is not virgin/fresh material, rather it is a reclaimed material that has been under actions of environmental and man-made forces during their service life. Durability i.e. long term performance of such reclaimed material will remain a concern and needs to be evaluated further. Hence, it is necessary to perform aggregate durability tests and other necessary tests to evaluate their long term performance.
- Another major issue is the hydraulic conductivity of such reclaimed materials which is important for sub-surface drainage of flexible pavement layers such as base and sub-base. Since certain portion of bitumen is mixed with the aggregate, it may hamper hydraulic conductivity of the compacted RBCA layer. During field conditions, it may not be possible to control uniform mixing of the bituminous portion throughout the layer, rather there is high probability of concentration of bituminous rich portion at certain parts of the compacted RBCA layer. This may lead to poor drainage at those locations. Hence Hydraulic Conductivity Test/Permeability Tests (As per relevant standard and practices) would give invaluable insight regarding their hydraulic performance.

Recommendation

Considering satisfactory CBR Test value from laboratory and from field test, it can be recommended that recycled material from LGED’s Road can be used as Sub-Base material as well as Base material. However, necessary durability tests and hydraulic conductivity tests are needed to be done to further assess the complete performance of these recycled materials.

3. APPLICABILITY OF RAP IN WEARING COURSE IN FLEXIBLE PAVEMENT

3.1 Review of Previous Studies

Reclaimed asphalt pavement is increasingly being used as a replacement for natural aggregates in order to conserve the natural aggregates. RAP substitution in bituminous concrete lowers the cost of flexible pavement construction while also gives satisfactory results. Use of Reclaimed Asphalt Concrete (RAC) in combination with virgin materials for use in flexible pavement binder and wearing course has been investigated by many researchers.

The degree to which new and aged asphalt are mixed is one of the main issues with the performance of hot mixed asphalt. There is a negligible difference in the change in binder grade when RAP content used is just at about 10%, at a higher percentage of about 40% or more, the RAP effect is much more pronounced in the mix. (Jie et al., 2011).

T. A. Pradyumna, et.al. (2013) investigated the mechanical characteristics of hot mix asphalt with incorporation of RAP (20%) to improve the performance of mix. Various tests were conducted such as Modulus test, moisture content, resilience rutting test, susceptibility test and it was found that mixes which was prepared with 20% RAP gave higher results than the conventional mixes under same conditions.

R Izaks, et.al. (2015) conducted study on mixtures with high RAP content to fulfil local volumetric properties with and without RAP (30% and 50% RAP) and fatigue and rutting characteristics were investigated. The results showed that there was a minor improvement in rutting and fatigue resistance when compared to standard mixes, but no visible changes in flow, hence it was suggested that up to 50% RAP may be used to meet the volumetric characteristics and performance requirements.

Z. Leng, et.al. (2018) evaluated the performance of asphalt mix prepared with PET and RAP at 15%, 30% and 50% and mixtures were undergone for Marshall Stability test and indirect tensile stiffness modulus test, it was discovered that mixtures containing 2% PET and RAP showed enhancement in Marshall Stability and Marshall Quotient as well as greater resilience to permanent deformation.

Umar Hayat, et.al. (2020) studied the use of PET in percentages (2%, 4%, and 6%) and recycled asphalt in percentages (20%, 30%, and 40%) in asphalt mix. Penetration and softening point tests were carried out to determine the optimum content of PET and Marshall Stability, and DSR tests were carried out on samples prepared with the above contents to determine their properties. It was concluded that 4% PET and 30% RAP improved rutting resistance and Marshall Stability.

Prabhakar Kumar, et.al. (2019) incorporated the RAP into asphalt mix, samples with 15% and 25% RAP were prepared and optimum binder content was determined. Test such as Marshall Stability was conducted and results showed the increment in Marshall Stability at 15% RAP.

P. Gireesh Kumar, et.al. (2020) studied the effect of RAP material over virgin material in asphalt mix. A Marshall test was performed on mixtures prepared with RAP at 0%, 30%, 40%, 50%, and 100%. Marshall Stability was found to be increased by 13.71% with 50% RAP as compared to a standard mix made without RAP. It was also discovered that using RAP 100% leads in weak and unstable pavement since the flow and total stability values are significantly lower than the limitation value.

Tuleshwar Choudhary, et.al. (2022) investigated the use of RAP mixed with plastic trash as a road pavement material. RAP was used as coarse aggregate, and plastic (6%, 8%, 10%, and 12% by weight of bitumen content) and 25% RAP content were used to make the mix. According to the requirements, the maximum Marshall Stability value was increased by 20% at 8% plastic content and at 25% RAP.

An evaluation of some projects based on binder properties, structural analysis, serviceability and mix by the Louisiana Department of Transportation and Development in the United States (Paul, 1996). The research indicates a satisfactory performance as compared to the use of conventional materials, about 20 to 50% of RAP was used on these projects.

A number of projects completed using RAP with percentages ranging between 8% and 79% were evaluated by the Washington State Department of Transportation (1985) and found that out of 16 projects, the first two initial projects performed well at the time of assessment. The remaining were completed at about 2.5 years before the study, the results indicated a promising result. However, the results indicated that pavement with RAP showed more longitudinal cracking distresses. A study by Jorisa et al (2019), using 30% RAP and evaluated after 6 years showed that pavement roughness was low, no rutting noticed and viscosity was higher than that of control asphalt mix. Kandhal & Kee, (1997) assessed the performance of RAP in five projects with service years of about 1.5 to 2.5 years using a varied RAP content of between 10-25%. The result showed no difference between RAP and virgin materials. A similar study also indicated the same result except that longitudinal and transverse cracks were observed the materials have the same properties. Fager, (1990) found similar results on the comparison of the performance of RAP with conventional aggregates however, 1% cracking was observed in the study.

3.2 Approach and Methodology

Reclaimed asphalt pavement (RAP) is the most available material with great potential to substitute natural resources. Use of RAP as a construction material can decrease the cost, provides a way to conserve landfill space, preserves natural resources, protects the environment, and improves sustainability. While several factors influence the use of RAP in asphalt pavement, the two primary factors are economic savings and environmental benefits. RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of HMA. The use of RAP also conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. Additionally, using RAP decreases the amount of construction debris placed into landfills and does not deplete nonrenewable natural resources such as virgin aggregate and asphalt binder. Ultimately, recycling asphalt creates a cycle that optimizes the use of natural resources and sustains the asphalt pavement industry.

3.2.1 Approach

The approach towards this task is more of a research oriented one, with the prime objective of developing a sustainable and cost-effective methodology for efficient reclamation of valuable resources and use of reclaimed asphalt pavement materials in an environmentally friendly way which are otherwise dumped as waste materials. The work-flow chart below shows the overall approach for this task.

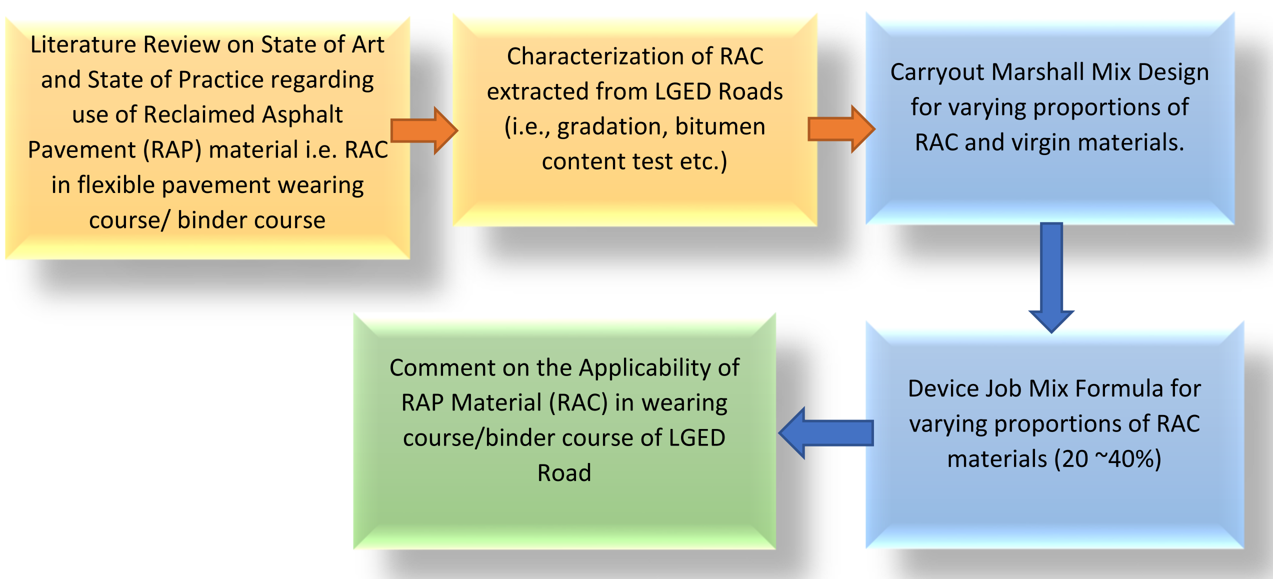


Figure 18: Work-flow chart of proposed RAC usage in wearing course/ binder course

3.2.2 Methodology

Reclaimed Asphalt Concrete (RAC) has been used as a valuable component of new asphalt mix for years. Since RAC consists of the same components as virgin HMA— aggregate and asphalt binder—it can readily be incorporated into a new mixture. Economically, there is a benefit to using RAP since these components can be reused, thereby lessening the need to purchase and use as much new (virgin) materials. In addition to the economic benefits, the use of RAP in asphalt mixtures also has an environmental benefit. Reuse of a resource such as RAP lessens the depletion of nonrenewable natural resources, such as virgin aggregate and asphalt binder (MS-2, Asphalt Institute).

The methodology for the purpose of evaluating RAC as a substitute of virgin materials in wearing course/ binder course involves carrying out Marshall Mix Design to determine appropriate binder content (content) for different virgin aggregate and RAC mix proportions. Assess the performance of RAC blended Hot Mix Asphalt (HMA) against Marshall Mix Design Criteria for practical applications.

The percentage of RAP used in the mix may be selected by determining the contribution of RAP in the total mix by weight or by determining the contribution of the RAP binder in the total binder in the mix by weight while maintaining volumetric properties requirements. Due to the stiffening effect of the aged binder in RAP, the specified binder grade may need to be adjusted. Penetration Grade bitumen of 60-70 or higher 80-100 will be used for Marshall Mix design. Based on the outcomes and scope of works, bitumen/ asphalt rejuvenators may be added for performance enhancement.

Figure 19: Marshall Stability Test Apparatus

Historically, the limits of RAC in HMA have been based on RAC percentage by weight of aggregate or by weight of the total mix. However, the primary issue with higher RAC content in asphalt mixes is the amount of binder replacement available since the use of RAC can reduce the need for virgin binder and impact the binder properties. Thus, RAC may also be specified according to percentage binder replacement. The percentage of RAC used in the mix can be selected by determining the contribution of the RAC binder toward the total binder in the mix by weight (i.e., a specified maximum percentage of the binder may come from RAC). In fact, several US State transportation departments have specified a minimum percentage of virgin binder content (e.g., 70 percent of the binder content must be virgin binder) (FHWA, 2011). The amount of total binder replaced by binder in RAC is computed as follows:

$$Binder\ Replacement, \% = \frac{(AxB)}{C}x100\%$$

Where: A = RAC percent binder content. B = RAC percent in mixture. C = Total percent binder content in mixture.

3.3 Material Characterization Test Results of RAC and Virgin Aggregate for Use in Flexible Pavement

In order to assess the applicability of RAC as a substitute for virgin material (aggregate and binder) in asphalt concrete mix to be used in wearing course/ binder course of flexible pavements various material characterization test has been performed on both RAC and virgin materials and the results are shown below.

3.3.1 Characterization Tests of RAC

Particle size distribution: sieve analysis/gradation test was performed on the residue aggregate obtained from asphalt content determination test from asphalt mix using Ignition Method (ASTM D 6307) according to ASTM C136. The results of the sieve analysis are shown below.

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
25.4	22.0	2	2	98	**5.33 (Five point three three)**
19.05	103.7	11	14	87	
12.5	129.4	14	27	73	
9.5	43.6	5	32	68	
6.3	112.7	12	44	56	
4.75	91.8	10	54	46	
2.36	183.7	20	74	26	
1.18	100.0	11	85	16	
0.6	40.4	4	89	11	
0.3	24.8	3	92	9	
0.15	26.3	3	94	6	
0.075	21.6	2	97	3	
Pan	31.2	3	100		
Total	931				

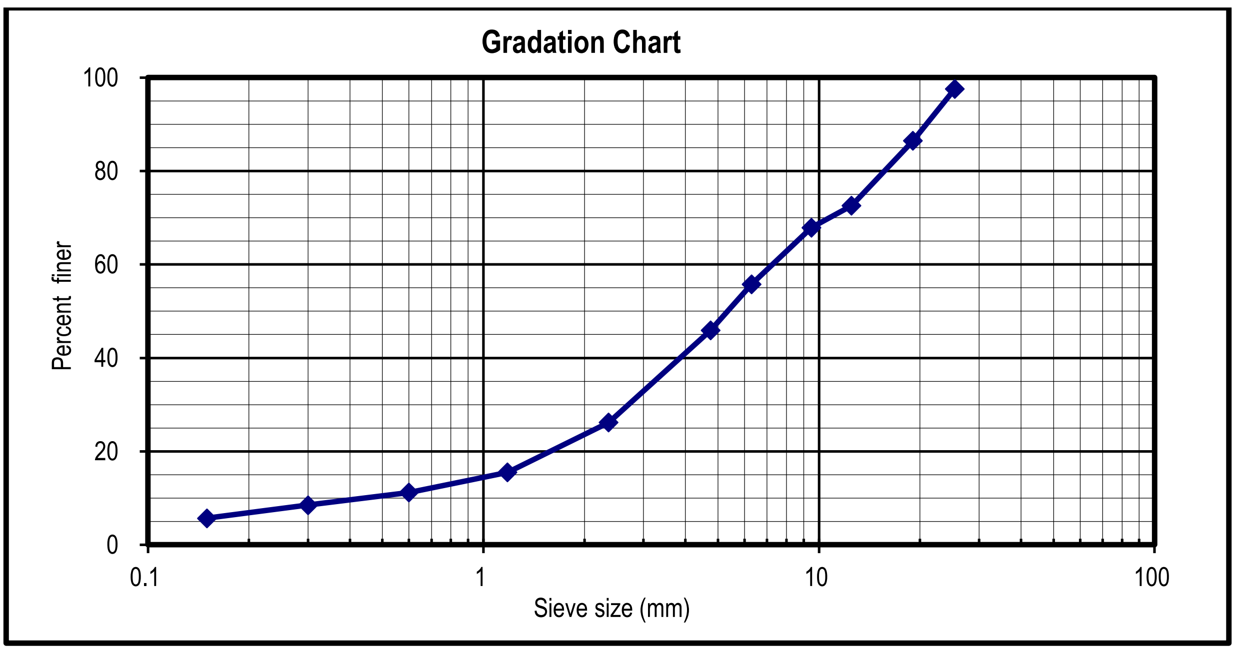


Figure 20: Gradation Curve of RAC aggregate obtained through Ignition Method (Wearing course)

The grain size distribution curves for the investigated materials were compared with the gradation limits for bituminous wearing course (40mm dense) for LGEDs specification.

Sieve Size (mm)	% Passing by Weight of Total Aggregate			
	For 25mm Dense	For 40mm Dense	For 50/40mm Normal BC	For 25mm Normal BC
25 mm	100	95-100	95-100	-
19.5 mm	100	85-95	85-95	100
16 mm	100	-	-	-
12.5 mm	75-90	60-80	58-77	75-90
9.5 mm	60-80	53-73	45-65	50-70
4.75 mm	35-55	35-52	25-40	25-40
2.36 mm	25-40	23-38	15-30	15-27
0.600 mm	15-25	13-24	8-18	8-18
0.075 mm	4-10	4-10	2-8	2-8

Figure 21: Aggregate Grading Requirements for Bituminous Wearing Course (LGED)

Bitumen Content/ Asphalt Content: The bitumen/ asphalt content of the RAC was determined using Asphalt Content of Asphalt Mixture by Ignition Method [ASTM D6307-98] and was found to be 4.38 %.

Test results are shown below.

3.3.2 Characterization of Virgin Materials for Marshall Mix Design

Two sources of virgin aggregates (Sample 1- supplied by LGED and Sample-2 collected from LGED field office premises) were used for the mix design. Also, two varieties of bitumen were used- one was 60-70 grade bitumen supplied by LGED and another was 80-100 grade bitumen collected by BUET team. The results of characterization tests performed on these virgin materials are shown below.

Virgin aggregate Sample-1:

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Fineness Modulus
mm	gm	%	%	%	
19.05	371.0	3	3	98	6.65 (Six point six five)
12.5	9291.0	62	65	36	
9.5	1354.0	9	74	27	
6.3	2858.0	19	93	7	
4.75	544.0	4	96	4	
2.36	235.0	2	98	2	
1.18	77.0	1	98	2	
0.6	46.3	0	99	1	
0.3	33.9	0	99	1	
0.15	50.2	0	99	1	
0.075	30.7	0	99	1	
Pan	99.7	1	100		
Total	14991				

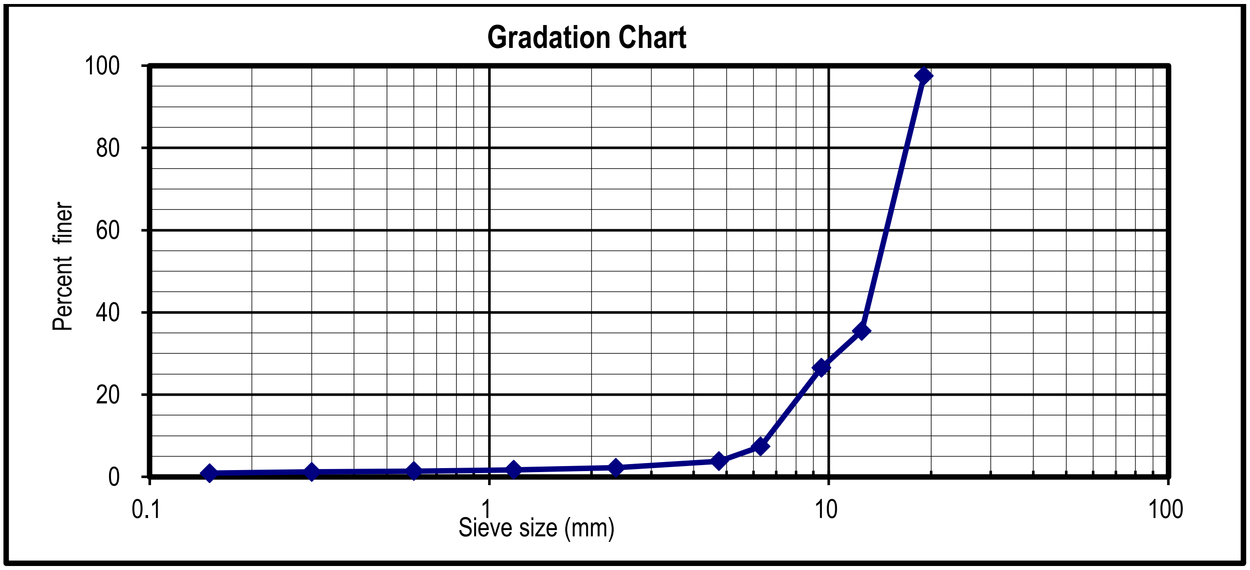


Figure 22: Gradation Curve of RAC aggregate obtained through Ignition Method (Wearing course)

The gradation of first batch of samples (sample-1) supplied to BUET by LGED is shown above. However, as can be seen from the gradation, the majority (about 62%) of the sample is of one particular size i.e. passing 19.5 mm and retained on 12.5 mm. For this reason, the supplied sample had to be crushed to smaller sizes, which was cumbersome, to carryout Marshall Mix Design meeting LGED specified gradation requirements. During the field visit to conduct Field CBR test at Manikganj on 19th February 2023, a second batch (Sample-2) of aggregates (different size fractions) were collected from the field office premises. Figure 23 below shows the pictures of samples 1 and 2 below.

(a) Sample -1 (b) Sample-2

Figure 23: Picture of Virgin Aggregate Samples Supplied by LGED for Marshall Mix Design

Only one mix design for heavy traffic condition using 80:20 ratio (Virgin Aggregate: RAC) and 60-70 penetration grade bitumen was carried out. Based on the feedback from LGED, the following four mix designs were carried out for medium traffic conditions using sample-2. Three ratio of virgin aggregate and RAC namely- 80:20, 70:30 and 60:40 were utilized to prepare Marshall Mix Design samples for medium traffic (50 blows). 60-70 grade bitumen was used for 80:20 and 70:30 ratio and 80-100 grade bitumen was used for 70:30 and 60:40 ratio. Various properties of virgin materials (aggregate and bitumen) useful for the Marshall Mix design are shown below in Table 17.

Table 17: Properties of virgin materials (aggregate sample-1 and bitumen) for the Marshall Mix design Purpose

Sample	***Parameter***	***Test Standard***	***Results***
Aggregate Sample -1	Specific Gravity – Coarse Fraction	ASTM C127	2.78
	Specific Gravity – Fine Fraction	ASTM C128	2.73
	Specific Gravity – Mineral Filler	ASTM D 854	2.76
Aggregate Sample -2	Specific Gravity – Coarse Fraction	ASTM C127	2.73
	Specific Gravity – Fine Fraction	ASTM C128	2.65
	Specific Gravity – Mineral Filler	ASTM D 854	2.7
Bitumen -60/70 Grade	Specific Gravity	AASHTO T 228	1.020
	Penetration Grade	AASHTO T 49	60
Bitumen -80/100 Grade	Specific Gravity (OD)	AASHTO T 228	1.023
	Penetration Grade	AASHTO T 49	81

3.4 Marshall Mix Design Using Different Proportion of RAC and Virgin Material for Use in Flexible Pavement Wearing Course/Binder Course

The Marshall method of mix design is for dense graded HMA mixes. It is used almost everywhere in the world. For a single selected aggregate gradation, five different asphalt contents are tested for various volumetric and strength criteria to select the optimum binder content. The selection of the optimum binder content requires engineering judgment, depending on traffic, climate and experience with the local materials used. In most cases, the optimum binder content should be selected for which the compacted specimens have 4 percent air voids. The Asphalt Institute recommends that the final selected mix design should be one whose aggregate structure and binder content, compacted to the design number of blows, results in 4 percent air voids and satisfactorily meets all of the other established criteria in Table 18 below.

Table 18: Marshall Mix Design Criteria

Marshall Method Criteria[1]	Light Traffic[3] Surface & Base		Medium Traffic[3] Surface & Base		Heavy Traffic[3] Surface & Base	
	Min	Max	Min	Max	Min	Max
Compaction, number of blows each end of specimen	35		50		75	
Stability[2], N (lb.)	3336 (750)	–	5338 (1200)	–	8006 (1800)	–
Flow[2,4,5], 0.25 mm (0.01 in.)	8	18	8	16	8	14
Percent Air Voids[7]	3	5	3	5	3	5
Percent Voids in Mineral Aggregate (VMA)[6]	See Table 7.3					
Percent Voids Filled With Asphalt (VFA)	70	80	65	78	65	75

Traffic classifications

Light Traffic conditions resulting in a 20-year Design ESAL < 10^4

Medium Traffic conditions resulting in a 20-year Design ESAL between 10^4 and 10^6

Heavy Traffic conditions resulting in a 20-year Design ESAL > 10^6

Source: Asphalt Mix Design Methods, MS-2, Seventh Edition, 2014. Asphalt Institute.

Figure 24 below shows the picture of Marshall Mix Design samples prepared for this study in BUET laboratory (after completion of tests).

Figure 24: Marshall Mix Design Samples in Laboratory.

Marshall Samples were prepared for a combination of three mix proportions of virgin aggregate and RAC, two grades of asphalt binder, two traffic categories and for two sources of virgin aggregates. The combination used for Marshall Mix Design for the current study are-

- For Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAC- RAP Wearing Course);
- For Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 RAC- (RAP Wearing Course);
- Marshall Mix Design Results: For Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAC- RAP Wearing Course);
- Marshall Mix Design Results: For Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAC- RAP Wearing Course);
- Marshall Mix Design Results: For Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAC- RAP Wearing Course)

Marshall Mix Design Results: For Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAC- RAP Wearing Course)

The resultant combined gradation obtained from mixing 80 % virgin aggregate with 20% RAC is shown in Table 19 below. Table 20 shows the Bitumen % used for preparation of Marshall Samples and Table 21 shows the test results of Marshall Samples.

Table 19: Gradation of Combined Aggregate

Sieve Opening (mm)	Wt. of Virgin Aggregate retained (gm)	% of Virgin Aggregate Retained	Wt. of RAP extracted Aggregate retained (gm)	% of RAP Extracted Aggregate Retained	% of Aggregate retained for Mixture (80: 20), (gm)	Cumulative % of Aggregate retained for Mixture (80: 20), (gm)	% Finer
25.4	0	0	22	2.4	0.5	0.5	99.5
19.05	0	0	103.7	11.1	2.1	2.6	97.4
16	0	0	-	-	-	-	-
12.5	240	20	129.4	13.9	18.8	21.4	78.6
9.5	144	12	43.6	4.7	10.6	32	68
4.75	300	25	204.5	22	24.4	56.4	43.6
2.36	150	12.5	183.7	19.7	13.9	70.3	29.7
0.6	150	12.5	140.4	15.1	13	83.3	16.7
0.075	156	13	72.7	7.8	12	95.3	4.7
Pan	60	5	31.2	3.4	4.7		
	1200	100	931.2	100.1	100		

Table 20: Bitumen % used for preparation of Marshall Sample

Virgin bitumen % (of Virgin Aggregate)	*Weight of Virgin Bitumen (gm)*	*Weight of RAP bitumen (gm)*	*Weight of Total Bitumen (gm)*	*Weight Bituminous Concrete mix (gm)*	*AC % of Total Mix*
4	38.4	10.512	48.912	1238.4	3.9
4.5	43.2	10.512	53.712	1243.2	4.3
5	48	10.512	58.512	1248	4.7
5.5	52.8	10.512	63.312	1252.8	5.1
6	57.6	10.512	68.112	1257.6	5.4

Table 21: Results of Tests on Marshall Specimens

Asphalt Content, % of Total Mix	*Marshall Stability, kN*	*Marshall Flow, mm*	*Unit wt. kg/cum*	*Percent Air Voids*	*Percent VFA*	*Percent VMA*
3.9	18.3	2.9	2466.1	4.1	69.9	13.8
4.3	15.1	3.5	2485.2	2.8	79.3	13.5
4.7	16.3	4.0	2510.1	1.2	90.8	13.0
5.1	14.0	3.9	2504.7	0.8	94.1	13.5
5.4	14.9	3.3	2491.1	0.9	93.9	14.3

Figure 25 below shows the zone satisfying Marshall Mix Design Criteria and Figure 26 shows the Marshall Mix Design Graphs.

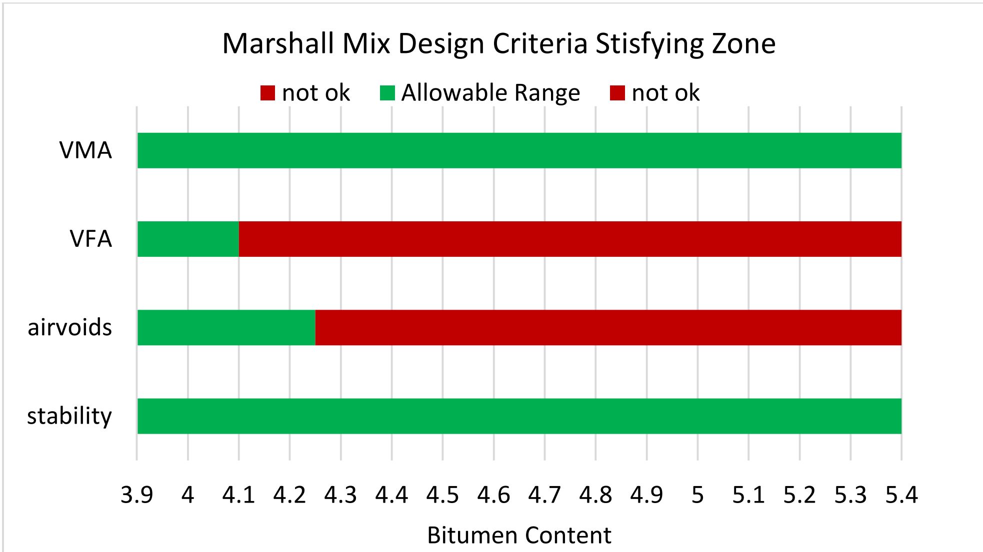


Figure 25: Marshall Mix Design Criteria Satisfying Zone for Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAP Wearing Course)

Optimum Virgin Binder Content:

Optimum Binder Content (at 4% air voids) = 3.9 % of Total Mix.

Optimum Virgin Binder Content to be added (at 4% air voids) = 3.1 % of Total Mix i.e. 4 % of Virgin Aggregate.

Important Marshall Parameters and Mix Properties for Optimum Binder Content (at 4% air voids) are-

Marshall Stability, kN = 18.3

Marshall Flow, mm = 2.9

Unit Weight, kg/m^3 = 2466.1

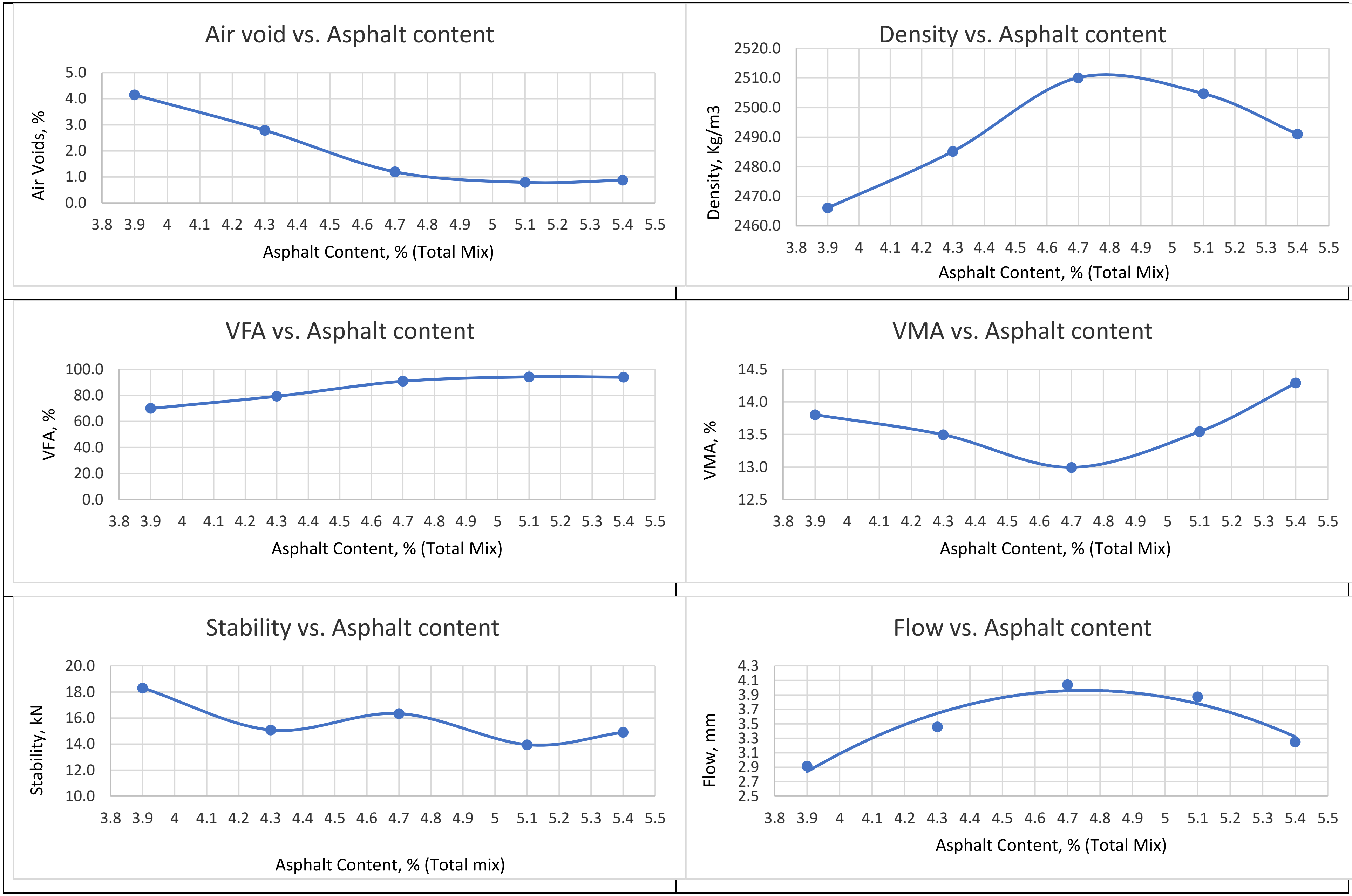


Figure 26: Marshall Mix Design Graphs for Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAP Wearing Course)

Marshall Mix Design Results: For Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 RAC- (RAP Wearing Course)

The resultant combined gradation obtained from mixing 80 % virgin aggregate with 20% RAC is shown in Table 22 below. Table 23 shows the Bitumen % used for preparation of Marshall Samples and Table 24 shows the test results of Marshall Samples.

Table 22: Gradation of Combined Aggregate

Sieve Opening (mm)	Wt. of Virgin Aggregate retained (gm)	% of Virgin Aggregate Retained	Wt. of RAP extracted Aggregate retained (gm)	% of RAP Extracted Aggregate Retained	% of Aggregate retained for Mixture (80: 20), (gm)	Cumulative % of Aggregate retained for Mixture (80: 20), (gm)	% Finer
25.4	0	0	22	2.4	0.5	0.5	100
19.05	0	0	103.7	11.1	2.1	2.6	97
16	0	0	-	-	-	-	-
12.5	201.2	25	129.4	13.9	22.9	25.5	75
9.5	80.5	10	156.3	16.8	11.3	36.8	63
4.75	161	20	91.8	9.9	18.1	54.9	45
2.36	120.8	15	183.7	19.7	15.9	70.8	29
0.6	104.6	13	140.4	15.1	13.4	84.2	16
0.075	104.6	13	72.7	7.8	12	96.2	4
Pan	32.2	4	31.2	3.4	3.9		
	804.9	100	931.2	100.1	100.1		

Table 23: Bitumen % used for preparation of Marshall Sample

Virgin bitumen % (of Virgin Aggregate)	*Weight of Virgin Bitumen (gm)*	*Weight of RAP bitumen (gm)*	*Weight of Total Bitumen (gm)*	*Weight Bituminous Concrete mix (gm)*	*AC % of Total Mix*
4	38.4	10.512	48.912	1238.4	3.9
4.5	43.2	10.512	53.712	1243.2	4.3
5	48	10.512	58.512	1248	4.7
5.5	52.8	10.512	63.312	1252.8	5.1
6	57.6	10.512	68.112	1257.6	5.4

Table 24: Results of Tests on Marshall Specimens

Asphalt Content, % of Total Mix	*Marshall Stability, kN*	*Marshall Flow, mm*	*Unit wt. kg/cum*	*Percent Air Voids*	*Percent VFA*	*Percent VMA*
3.9	11.7	3.5	2355.5	7.7	51.4	15.9
4.3	9.5	2.6	2380.4	6.2	59.8	15.4
4.7	9.6	2.4	2373.0	5.9	63.2	16.0
5.1	10.7	3.0	2420.4	3.4	76.7	14.7
5.4	10.1	3.3	2409.0	3.4	77.7	15.4

Figure 27 below shows the zone satisfying Marshall Mix Design Criteria and Figure 14 shows the Marshall Mix Design Graphs.

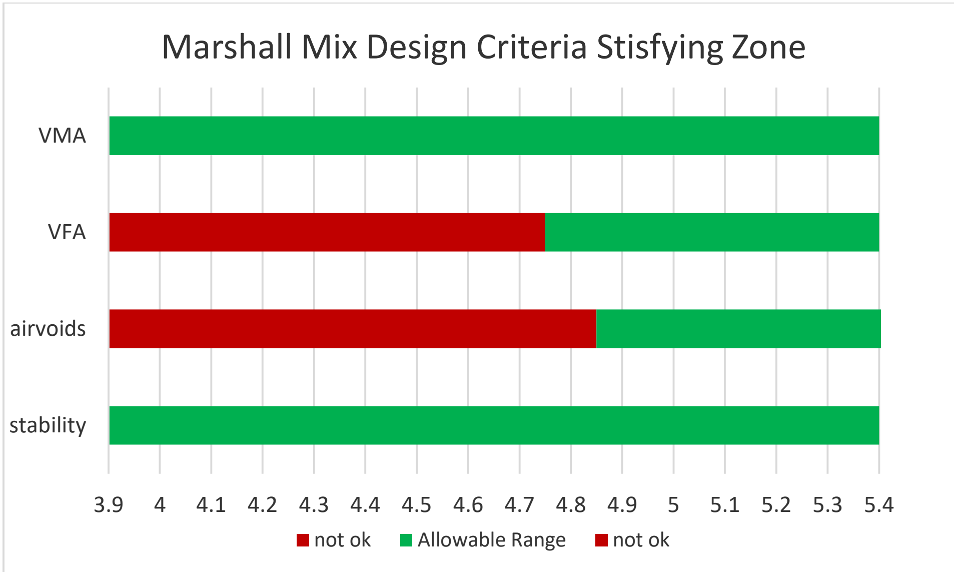


Figure 27: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 (RAP Wearing Course)

Optimum Virgin Binder Content:

Optimum Binder Content (at 4% air voids) = 5 % of Total Mix.

Optimum Virgin Binder Content to be added (at 4% air voids) = 4.1 % of Total Mix i.e. 5.4 % of Virgin Aggregate.

Important Marshall Parameters and Mix Properties for Optimum Binder Content (at 4% air voids) are-

Marshall Stability, kN	= 10.4
Marshall Flow, mm	= 2.9
Unit Weight, kg/m^3	= 2408.6

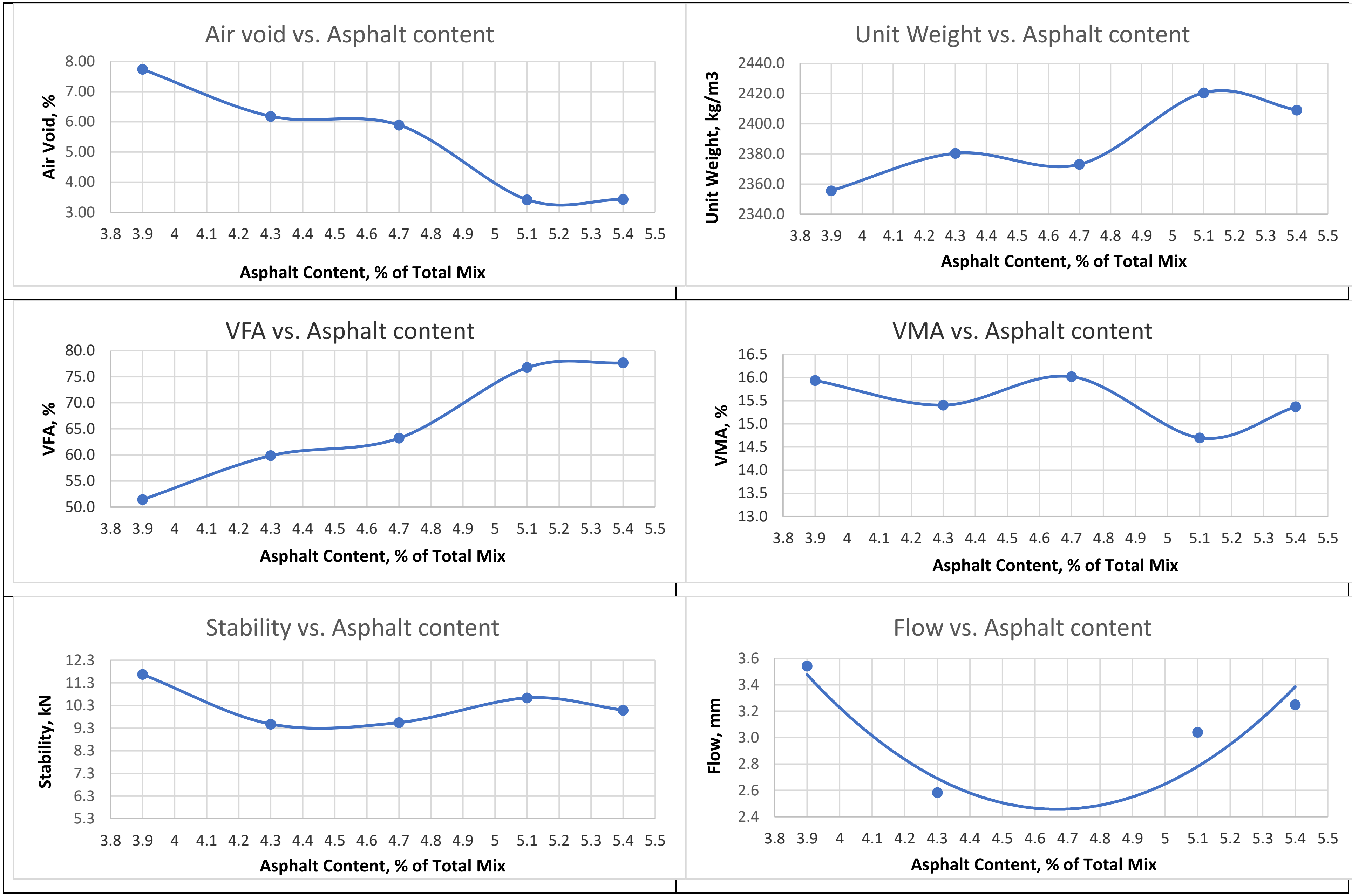


Figure 28: Marshall Mix Design Graphs for Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 (RAP Wearing Course)

Marshall Mix Design Results: For Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAC- RAP Wearing Course)

The resultant combined gradation obtained from mixing 70 % virgin aggregate with 30% RAC is shown in Table 25 below. Table 26 shows the Bitumen % used for preparation of Marshall Samples and Table 27 shows the test results of Marshall Samples.

Table 25: Gradation of Combined Aggregate

Sieve Opening (mm)	Wt. of Virgin Aggregate retained (gm)	% of Virgin Aggregate Retained	Wt. of RAP extracted Aggregate retained (gm)	% of RAP Extracted Aggregate Retained	% of Aggregate retained for Mixture (80: 20), (gm)	Cumulative % of Aggregate retained for Mixture (80: 20), (gm)	% Finer
25.4	0	0	22	2.4	0.7	0.7	99
19.05	0	0	103.7	11.1	3.2	3.9	96
16	0	0	-	-	-	-	-
12.5	201.2	25	129.4	13.9	21.8	25.7	74
9.5	80.5	10	43.6	4.7	8.5	34.2	66
4.75	161	20	204.5	22	20.6	54.8	45
2.36	120.8	15	183.7	19.7	16.4	71.2	29
0.6	104.6	13	140.4	15.1	13.6	84.8	15
0.075	104.6	13	72.7	7.8	11.5	96.3	4
Pan	32.2	4	31.2	3.4	3.8		
	804.9	100	931.2	100.1	100.1		

Table 26: Bitumen % used for preparation of Marshall Sample

Virgin bitumen % (of Virgin Aggregate)	*Weight of Virgin Bitumen (gm)*	*Weight of RAP bitumen (gm)*	*Weight of Total Bitumen (gm)*	*Weight Bituminous Concrete mix (gm)*	*AC % of Total Mix*
4.5	36.2	15.3	51.6	1191.2	4.3
5.0	40.3	15.3	55.6	1195.3	4.7
5.5	44.3	15.3	59.6	1199.3	5.0
6.0	48.3	15.3	63.6	1203.3	5.3
6.5	52.3	15.3	67.7	1207.3	5.6
7.0	56.4	15.3	71.7	1211.4	5.9
7.5	60.4	15.3	75.7	1215.4	6.2

Table 27: Results of Tests on Marshall Specimens

Asphalt Content, % of Total Mix	*Marshall Stability, kN*	*Marshall Flow, mm*	*Unit wt. kg/cum*	*Percent Air Voids*	*Percent VFA*	*Percent VMA*
4.3	12.9	3.2	2371.8	6.8	56.7	15.7
4.7	12.2	3.3	2370.3	6.4	60.1	16.0

5.0	12.4	3.3	2388.6	5.2	66.8	15.7
5.3	11.5	3.5	2379.1	5.1	68.6	16.3
5.6	10.3	3.4	2375.7	4.8	71.3	16.7
5.9	9.3	3.2	2384.5	4.0	76.2	16.7
6.2	9.6	4.0	2380.6	3.7	78.5	17.1

Figure 29 below shows the zone satisfying Marshall Mix Design Criteria and Figure 16 shows the Marshall Mix Design Graphs.

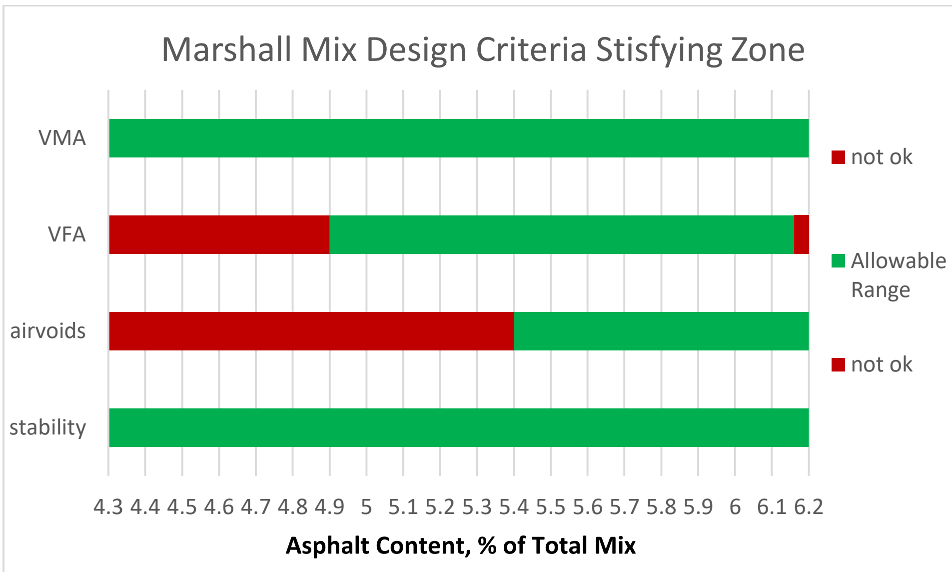


Figure 29: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

Optimum Virgin Binder Content:

Optimum Binder Content (at 4% air voids) = 5.9 % of Total Mix.

Optimum Virgin Binder Content to be added (at 4% air voids) = 4.7 % of Total Mix i.e. 7 % of Virgin Aggregate.

Important Marshall Parameters and Mix Properties for Optimum Binder Content (at 4% air voids) are-

Marshall Stability, kN = 9.3

Marshall Flow, mm = 3.2

Unit Weight, kg/m^3 = 2384.5

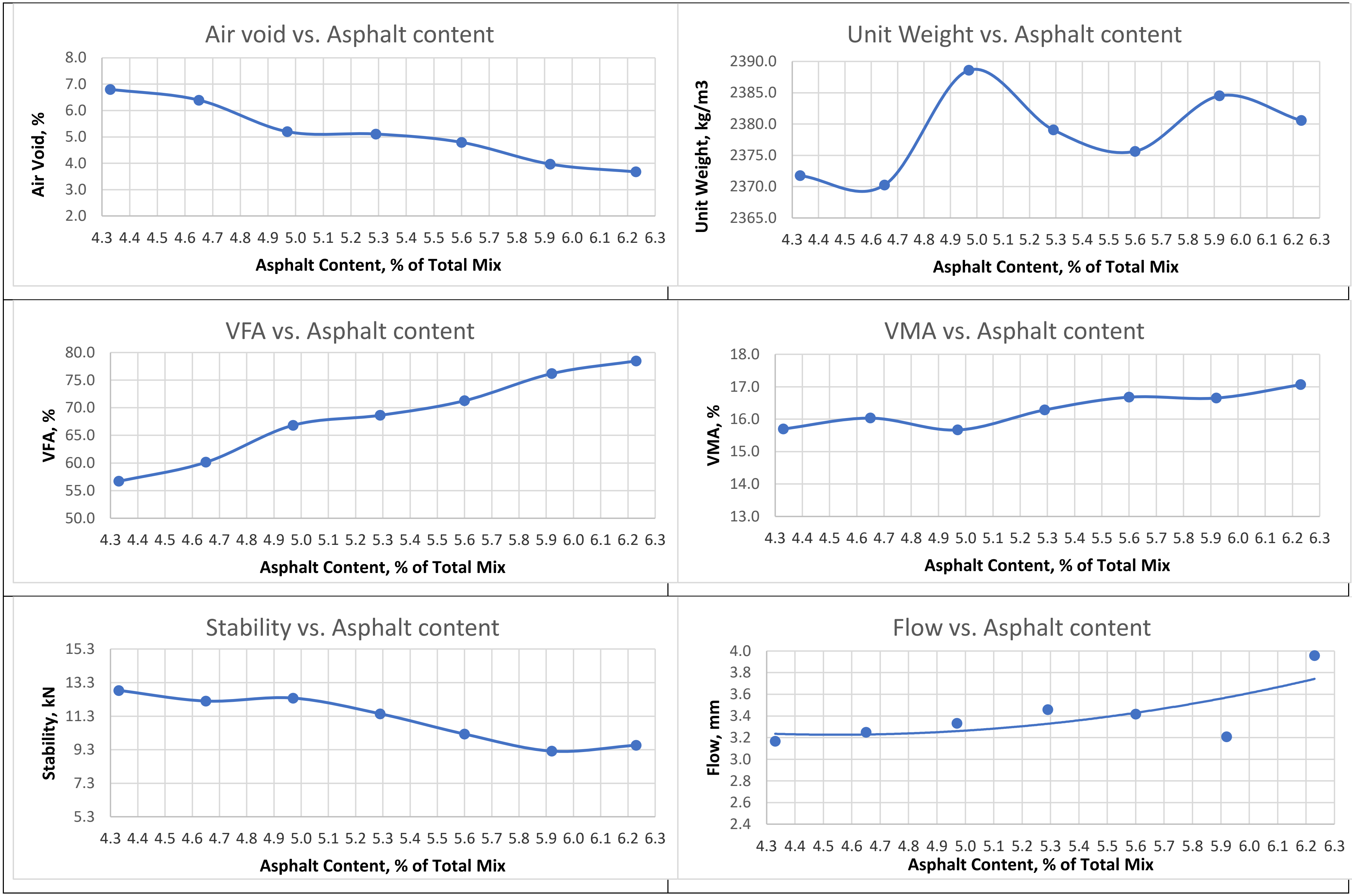


Figure 30: Marshall Mix Design Graphs for Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

Marshall Mix Design Results: For Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAC- RAP Wearing Course)

The resultant combined gradation obtained from mixing 70 % virgin aggregate with 30% RAC is shown in Table 28 below. Table 29 shows the Bitumen % used for preparation of Marshall Samples and Table 30 shows the test results of Marshall Samples.

Table 28: Gradation of Combined Aggregate

Sieve Opening (mm)	Wt. of Virgin Aggregate retained (gm)	% of Virgin Aggregate Retained	Wt. of RAP extracted Aggregate retained (gm)	% of RAP Extracted Aggregate Retained	% of Aggregate retained for Mixture (80: 20), (gm)	Cumulative % of Aggregate retained for Mixture (80: 20), (gm)	% Finer
25.4	0	0	22	2.4	0.7	0.7	99
19.05	0	0	103.7	11.1	3.2	3.9	96
16	0	0	-	-	-	-	-
12.5	201.2	25	129.4	13.9	21.8	25.7	74
9.5	80.5	10	43.6	4.7	8.5	34.2	66
4.75	161	20	204.5	22	20.6	54.8	45
2.36	120.8	15	183.7	19.7	16.4	71.2	29
0.6	104.6	13	140.4	15.1	13.6	84.8	15
0.075	104.6	13	72.7	7.8	11.5	96.3	4
Pan	32.2	4	31.2	3.4	3.8		
	804.9	100	931.2	100.1	100.1		

Table 29: Bitumen % used for preparation of Marshall Sample

Virgin bitumen % (of Virgin Aggregate)	*Weight of Virgin Bitumen (gm)*	*Weight of RAP bitumen (gm)*	*Weight of Total Bitumen (gm)*	*Weight Bituminous Concrete mix (gm)*	*AC % of Total Mix*
4.5	36.225	15.33	51.555	1191.225	4.33
5	40.25	15.33	55.58	1195.25	4.65
5.5	44.275	15.33	59.605	1199.275	4.97
6	48.3	15.33	63.63	1203.3	5.29
6.5	52.325	15.33	67.655	1207.325	5.6

Table 30: Results of Tests on Marshall Specimens

Asphalt Content, % of Total Mix	*Marshall Stability, kN*	*Marshall Flow, mm*	*Unit wt. kg/cum*	*Percent Air Voids*	*Percent VFA*	*Percent VMA*
4.3	11.3	4.3	2372.3	5.6	64.1	15.7
4.7	10.2	3.9	2372.9	5.1	67.7	15.9
5.0	10.4	3.6	2398.3	3.7	76.1	15.3
5.3	10.1	3.4	2412.7	2.6	82.6	15.1
5.6	10.3	4.1	2414.9	2.1	86.4	15.3

Figure 31 below shows the zone satisfying Marshall Mix Design Criteria and Figure 18 shows the Marshall Mix Design Graphs.

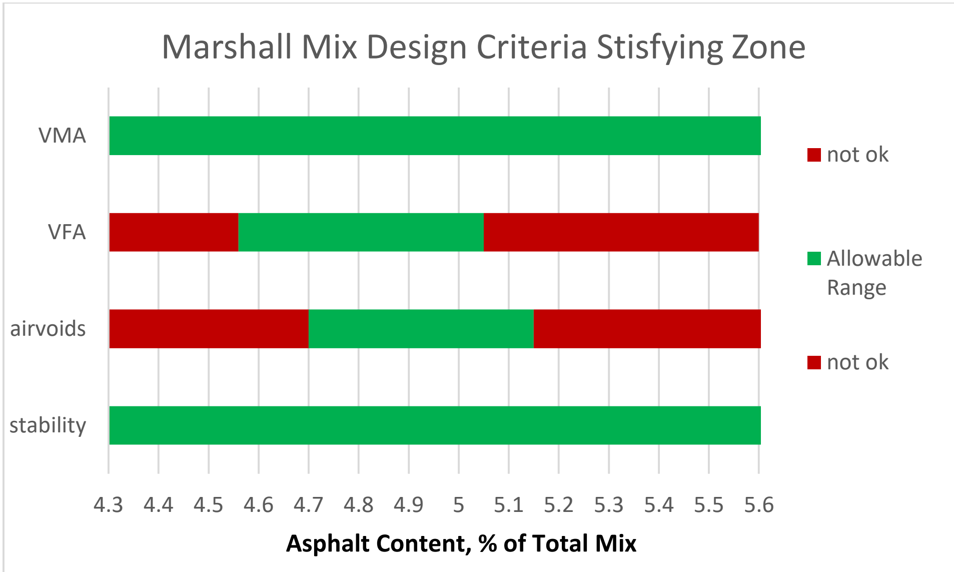


Figure 31: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

Optimum Virgin Binder Content:

Optimum Binder Content (at 4% air voids) = 4.9 % of Total Mix.

Optimum Virgin Binder Content to be added (at 4% air voids) = 3.6 % of Total Mix i.e. 5.4 % of Virgin Aggregate.

Important Marshall Parameters and Mix Properties for Optimum Binder Content (at 4% air voids) are-

Marshall Stability, kN = 10.4

Marshall Flow, mm = 3.7

Unit Weight, kg/m^3 = 2392.8

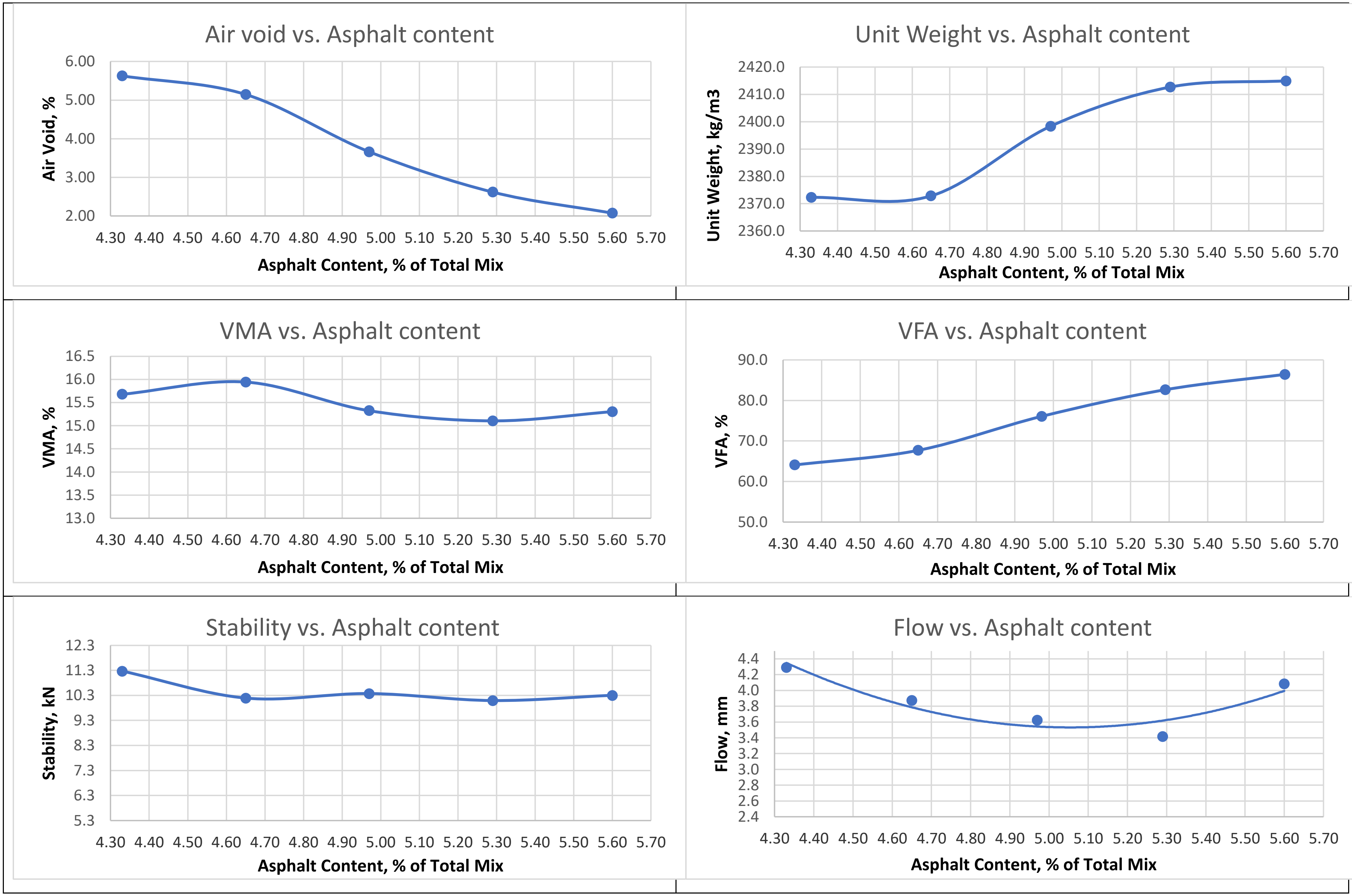


Figure 32: Marshall Mix Design Graphs for Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

Marshall Mix Design Results: For Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAC- RAP Wearing Course)

The resultant combined gradation obtained from mixing 60 % virgin aggregate with 40% RAC is shown in Table 31 below. Table 32 shows the Bitumen % used for preparation of Marshall Samples and Table 33 shows the test results of Marshall Samples.

Table 31: Gradation of Combined Aggregate

Sieve Opening (mm)	Wt. of Virgin Aggregate retained (gm)	% of Virgin Aggregate Retained	Wt. of RAP extracted Aggregate retained (gm)	% of RAP Extracted Aggregate Retained	% of Aggregate retained for Mixture (80: 20), (gm)	Cumulative % of Aggregate retained for Mixture (80: 20), (gm)	% Finer
25.4	0	0	22	2.4	0.9	0.9	99
19.05	0	0	103.7	11.1	4.3	5.2	95
16	0	0	-	-	-	-	-
12.5	173.3	25	129.4	13.9	20.7	25.9	74
9.5	69.3	10	156.3	16.8	12.6	38.5	62
4.75	138.6	20	91.8	9.9	16.1	54.6	45
2.36	104	15	183.7	19.7	16.8	71.4	29
0.6	90.06	13	140.4	15.1	13.8	85.2	15
0.075	90.06	13	72.7	7.8	11	96.2	4
Pan	27.7	4	31.2	3.4	3.8		
	693.02	100	931.2	100.1	100		

Table 32: Bitumen % used for preparation of Marshall Sample

Virgin bitumen % (of Virgin Aggregate)	*Weight of Virgin Bitumen (gm)*	*Weight of RAP bitumen (gm)*	*Weight of Total Bitumen (gm)*	*Weight Bituminous Concrete mix (gm)*	*AC % of Total Mix*
4	27.72	20.2356	47.9556	1182.72	4.1
4.5	31.185	20.2356	51.4206	1186.185	4.3
5	34.65	20.2356	54.8856	1189.65	4.6
5.5	38.115	20.2356	58.3506	1193.115	4.9
6	41.58	20.2356	61.8156	1196.58	5.2
6.5	45.045	20.2356	65.2806	1200.045	5.4
7	48.51	20.2356	68.7456	1203.51	5.7

Table 33: Results of Tests on Marshall Specimens

Asphalt Content, % of Total Mix	*Marshall Stability, kN*	*Marshall Flow, mm*	*Unit wt. kg/cum*	*Percent Air Voids*	*Percent VFA*	*Percent VMA*
4.1	11.6	3.5	2328.5	7.7	54.9	17.2
4.3	9.4	2.6	2341.3	6.9	58.8	16.9
4.6	9.5	2.4	2357.4	5.9	64.5	16.6
4.9	10.4	3.0	2352.0	5.7	66.7	17.0
5.2	9.9	3.3	2353.0	5.2	69.9	17.2
5.4	14.9	3.4	2403.5	2.9	81.7	15.6
5.7	14.9	3.9	2415.0	2.0	87.3	15.5

Figure 33 below shows the zone satisfying Marshall Mix Design Criteria and Figure 20 shows the Marshall Mix Design Graphs.

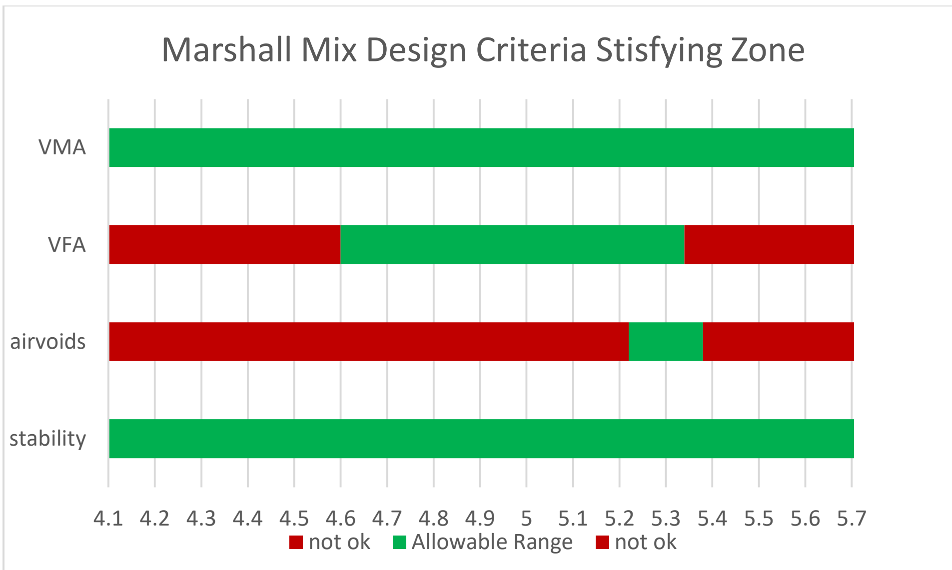


Figure 33: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAP Wearing Course)

Optimum Virgin Binder Content:

Optimum Binder Content (at 4% air voids) = 5.3 % of Total Mix.

Optimum Virgin Binder Content to be added (at 4% air voids) = 3.64 % of Total Mix i.e. 6.3 % of Virgin Aggregate.

Important Marshall Parameters and Mix Properties for Optimum Binder Content (at 4% air voids) are-

Marshall Stability, kN = 12.4

Marshall Flow, mm = 3.3

Unit Weight, kg/m^3 = 2378.3

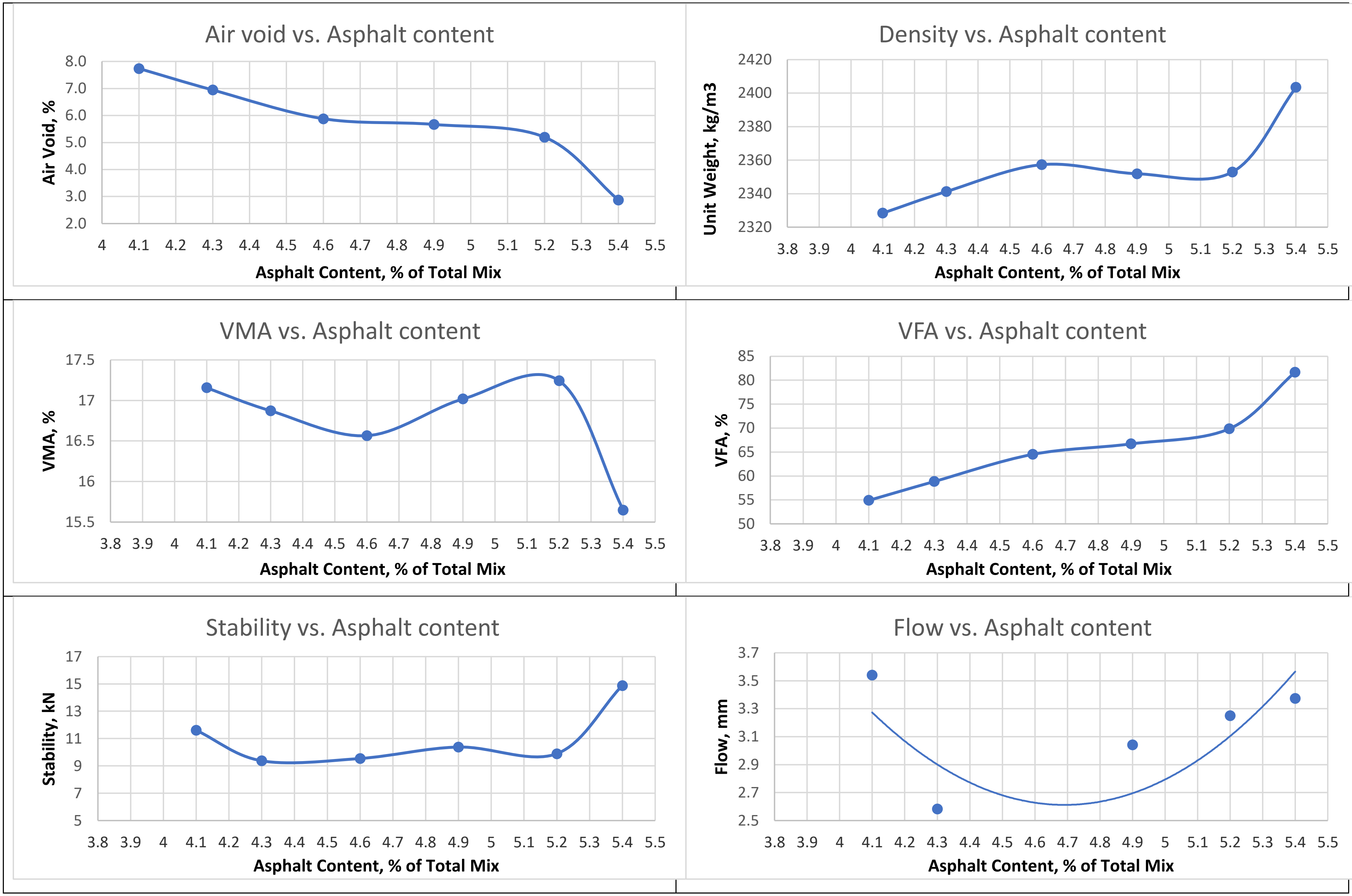


Figure 34: Marshall Mix Design Graphs for Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAP Wearing Course)

3.5 Findings and Recommendation

The major findings of this research on the use of reclaimed asphalt concrete (RAC) obtained from reclaimed asphalt pavement wearing course are as follows-

- For a 80 : 20 mixture of virgin aggregate (sample -1) and RAC and 60-70 grade asphalt, the optimum binder content i.e. optimum asphalt content for heavy traffic condition using Marshall Mix Design was obtained to be 3.9 % (as percentage of total mix) which is below the typical range of 5 to 7% usually recommend for flexible pavements to ensure durability.
- For a 80 : 20 mixture of virgin aggregate (sample-2) and RAC and 60-70 grade asphalt, the optimum binder content i.e. optimum asphalt content for medium traffic condition using Marshall Mix Design was obtained to be 5 % (as percentage of total mix) which falls within the acceptable range of asphalt content for flexible pavement construction.
- For a 70 : 30 mixture of virgin aggregate (sample-2) and RAC and 60-70 grade asphalt, the optimum binder content i.e. optimum asphalt content for medium traffic condition using Marshall Mix Design was obtained to be 5.9 % (as percentage of total mix) which falls within the acceptable range of asphalt content for flexible pavement construction.
- For a 70: 30 mixture of virgin aggregate (sample-2) and RAC and 80-100 grade asphalt, the optimum binder content i.e. optimum asphalt content for medium traffic condition using Marshall Mix Design was obtained to be 4.9 % (as percentage of total mix) which falls close to the acceptable range of asphalt content for flexible pavement construction and may be adjusted for practical application.
- For a 60: 40 mixture of virgin aggregate (sample-2) and RAC and 80-100 grade asphalt, the optimum binder content i.e. optimum asphalt content for medium traffic condition using Marshall Mix Design was obtained to be 5.3 % (as percentage of total mix) which falls within the acceptable range of asphalt content for flexible pavement construction.

Table 18 below shows the combined results obtained from Marshall Mix Designs using different proportions of virgin aggregate and RAC. Also, the binder replacement value for the corresponding mix designs are shown in table 18.

Table 34: Binder Replacement (%) for Different Mix Proportions used in the study.

Marshall Mix Design Using	RAC Binder Content, (%)	RAC % in Mixture	Total Binder Content in Mixture, (%)	Binder Replacement, %
60-70 grade Bitumen & 80 (Virgin Aggregate-Sample-1): 20 (RAC- RAP Wearing Course) for Heavy Traffic Condition	4.38	20%	3.9	22.5
60-70 grade Bitumen & 80 (Virgin Aggregate-Sample-2): 20 (RAC- RAP Wearing Course) for Medium Traffic Condition	4.38	20%	5	17.5
60-70 grade Bitumen & 70 (Virgin Aggregate-Sample-2): 30 (RAC- RAP Wearing Course) for Medium Traffic Condition	4.38	30%	5.9	22.3
80-100 grade Bitumen & 70 (Virgin Aggregate-Sample-2): 30 (RAC- RAP Wearing Course) for Medium Traffic Condition	4.38	30%	4.9	26.8
80-100 grade Bitumen & 60 (Virgin Aggregate-Sample-2): 40 (RAC- RAP Wearing Course) for Medium Traffic Condition	4.38	40%	5.3	33.1

In order to evaluate the bitumen stripping behavior and temperature susceptibility, relevant test such as Indirect Tensile Test (ITT) may be performed in later studies since such tests could not be performed due limited scope of the study.

Recommendations:

Based on the findings from literature review and Marshall Mix Design carried out for this study, the following recommendations can be drawn-

- Use of medium traffic condition may be considered instead of heavy traffic conditions, as the former results in very low design asphalt content which fall outside the usually recommended range of asphalt content for flexible pavement design. Also, according to design standards and codes, use of heavy traffic condition for mix design may result in excessive voids (i.e. more than 4%) remaining in the constructed pavements if actual traffic is quite less than the anticipated. This may lead to loss of durability and moisture susceptibility.
- For 20 % or less RAC usage in new flexible pavement wearing course, 60-70 penetration grade asphalt can be used following current LGED specifications.

- For 20% to 30% usage of RAC in new flexible pavement wearing course, 80-100 penetration grade asphalt is recommended. 80-100 grade requires approximately 1% less asphalt content compared to 60-70 grade asphalt. This will have cost implications on the overall project.
- Usage of more than 30 % RAC in new flexible pavement wearing course is not recommended at this stage. Although, an optimum binder content could be determined, the satisfying zone for optimum binder content was very narrow. Use of softer grade asphalt may allow use of higher percentage of RAC. However, due to unavailability of softer grade asphalt those tests could not be performed at this stage.

Table 35 below shows the optimum binder content (asphalt) as a percentage of total mix for Medium traffic. Also, the recommendations mentioned above are highlighted with asterisk (*) marks.

Table 35: Optimum Binder Content (Asphalt) as a Percentage of Total Mix for Medium Traffic

Mix Ratio / Penetration Grade	(Virgin Aggregate: RAC) 80:20	(Virgin Aggregate: RAC) 70:30	(Virgin Aggregate: RAC) 60:40
60-70 Grade	5*	5.9	---
80-100 Grade	---	4.9*	5.3

- Note: For Medium Traffic condition and using Aggregate Sample -2

Nevertheless, a few words are necessary here to keep in mind during handling RAC during the mix design process. Just as it is with virgin aggregates, the variability of a stockpile of RAC is important in both mix design and quality control during production. To effectively maximize the use of RAC in an asphalt mixture, the asphalt mixture producer should know the source of the RAC and, if practical, keep separate stockpiles of RAC from specific projects— or, at the least, keep RAC from one type of project separate from RAC of another type. A RAC obtained from a neighborhood street may have substantially different asphalt binder properties, asphalt binder content, aggregate physical properties and gradation than a RAC obtained from an urban highway.

4. REMOVAL TECHNIQUE OF BITUMINOUS LAYER FROM RAP AND ITS APPLICABILITY

In order to obtain the RAC aggregate properties, Asphalt fractions need to be separated using different extraction methods. In addition, to characterize the RAC binder properties, the aged binder has to be extracted and recovered using various asphalt binder extraction and recovery methods. There are different extraction methods, as introduced in ASTM and AASHTO standards. To maximize the benefit of using RAP, the properties of the recycled material, such as the aggregate and binder should be characterized and considered for the design of the mix, and this requires the use of extraction and recovery techniques.

4.1 Ignition Method

In this method, the RAP sample is heated in an ignition oven, which causes the bitumen binder to combust or burn off. The remaining material, which consists of the aggregate particles, is then weighed. The difference in weight before and after ignition provides an estimation of the bitumen binder content in the RAP. This method is primarily used to determine the binder content in RAP.

4.2 Solvent Extraction Method

The solvent extraction method is preferred when the goal is to separate the bitumen binder from the RAP aggregates and recover it for further testing or use. This method involves the use of a solvent, such as trichloroethylene (TCE), to dissolve the bitumen binder.

4.3 Extraction methods for Binder in RAP

The ASTM D2172 (2017) standard for “Quantitative Extraction of Bitumen from Bituminous Paving Mixtures” presents the following extraction methods:

a) Centrifuge method (Method A)
b) Reflux method (Methods B, C & D)
c) Vacuum method (Method E)

These differ in their use of heat, method of agitating of the mixture, and solvent types (Stacey 2014). Among the five methods mentioned in ASTM D2172, the centrifuge (method A) and reflux method (Method B) are the most popular with transportation agencies due to their practical simplicity. An improvement on these was attempted with the introduction of the US Strategic Highway Research Program ‘SHRP method’. It is also possible to use multiple extraction methods to achieve a more thorough extraction. Finally, some researchers have introduced automatic extraction methods with the goal of improving user safety and the consistency of results.

Centrifuge method (Method A)

Centrifuge extraction is a cold method for the extraction and determination of the binder content in mixtures. The removal of the asphalt binder is accomplished by submerging a loose HMA sample in the solvent to let the solvent disintegrate the asphalt. The centrifuge then separates the solvent and binder mixture from the aggregates. The solvent and binder mixture are collected in a separate container, while the aggregates stay in the bowl.

Reflux Extraction

Reflux extraction is a hot extraction method. The apparatus for Reflux Extraction consists of a glass jar, cylindrical metal frames, a condenser, filter paper, heat resistant-coated wire mesh, and electric hot plate. Solvent vapor generated by the hot plate passes around and through the asphalt mixture sample contained in two wire mesh cones lined with filter paper. The reflux solvent from the water-cooled condenser percolates through the sample repeatedly until the binder is extracted, with the solvent-binder solution condensing at the bottom.

Vacuum Extraction

Vacuum extraction is not as widespread use as Centrifuge or even Reflux Extraction. The procedure consists of mixing the solvent and asphalt mixture in the bowl, and then extracting the solvent-asphalt solution with a vacuum pump, with the fines the solvent solution being collected with a series of meshes. Vacuum extraction was found to give the most accurate results for the asphalt binder content when the mixture has highly variable and absorptive aggregates.

SHRP Extraction

The SHRP (Strategic Highway Research Program) in US, developed a solvent extraction method combined with the Rotovap recovery method to study the hardening of asphalt binder during extraction and recovery processes. This method was created to minimize binder hardening, reduce residual solvent in the binder, and improve the efficiency of binder removal from aggregates. In this method, a rotating cylinder with internal flights is used to mix the asphalt mixture and solvent during extraction. A vacuum line with a filter at the bottom of the cylinder removes the liquid, and centrifugation is performed to eliminate fines before recovery.

Automatic extraction

Several "automatic" extraction devices have been developed for analyzing asphalt mixtures. These devices aim to reduce labor, lower costs, and minimize exposure to hazardous materials. They may combine various extraction methods and comply with standards such as ASTM D2172 (2017b).

4.4 Solvent used in Asphalt Extraction and Recovery

The selection of an appropriate solvent for the extraction and recovery of asphalt binder needs to take into account the effectiveness of the solvent in dissolving the asphalt binder during extraction, and the ease of removing the solvent during recovery while not affecting the physical characteristics of the binder. The solvent performance will also depend heavily on the type of binder that is being extracted and recovered. Additionally, safety concerns for the operator and environmentally friendliness should be considered (Mikhailenko et al. 2019). This section describes the most widely used solvent for asphalt extraction and recovery.

Chlorinated Solvents

Chlorinated solvents have been widely used for asphalt extraction and recovery, notably trichloroethylene (CCl_2=CHCl), trichloroethane (CH_3-CCl_3) and dichloromethane (also methylene chloride, CH_2Cl_2) (Burr et al. 1990). These solvents are very effective at dissolving asphalt binder (Mikhailenko et al. 2021) and could be used multiple times, but have significant operator health and environmental concerns.

n-Propyl bromide

An alternative solvent called n-propyl bromide (nPB) was introduced as a substitute for chlorinated solvents in asphalt extraction and recovery in the 1990s (Stroup-Gardiner and Nelson 2000). It showed similar performance to trichloroethylene in modifying binder properties and could be used multiple times with a stabilizer (Collins-Garcia et al. 2000). However, there were concerns about acidity corroding equipment, so monitoring and using stabilizers were recommended (McGraw et al. 2001).

Toluene

Toluene (C_6H_5-CH_3) has been suggested as a solvent that can reduce negative environmental safety and health effects associated with extraction solvents. A study has found that it modifies the binder less than trichloroethylene when tested in the same conditions (Loh and Olek 1999). With a boiling point of around 110°C, Toluene is relatively less volatile compared to chlorinated solvents and nPB. The special standard for Rotovap recovery with toluene (ASTM D 7906 2012)) adds some provisions to the normal procedure, including slower flask rotation so that the exposure time is increased.

Bio-solvents

Bio-solvents provide an advantage as they are less toxic to humans and bio-degradable (Gu and Jérôme 2013), addressing the principal problems of currently used asphalt extraction and recovery solvents. There are disadvantages for using bio-solvents, as they are generally used with equipment that is calibrated to certain types of solvents and can be less accurate.

From the result of previous studies and based on available methods for asphalt extraction, it can be summarized that the available methods of extractions are used only to identify the quantity and quality of asphalt layer that surrounds the aggregate. Many solvents are also used during extraction process of asphalt, some of which may cause health hazard to the operator. Considering all the aspects, it can be concluded that removal technique to extract bituminous layers from RAP is limited to laboratory testing of bituminous layer only, large scale use of these methods to reproduce aggregate is not recommended.

5. WORKING METHODOLOGY

For use of RBCA in base and subbase course, the harrowed material should be properly broken down/separated to smaller size fractions, thoroughly mixed to ensure proper gradation and to avoid concentration of bituminous binder at a particular location of the pavement. Thorough mixing and compaction is necessary to avoid non-uniform strength and hydraulic conductivity parameters across the pavement layers.

The working methodology for use of RAC in new HMA concrete for wearing course is schematically shown in figure 35. Also, a sample calculation for selection of aggregate gradation following LGED's specification (40mm dense) and using 80 percent virgin aggregate with 20 percent RAC is shown in table 35.

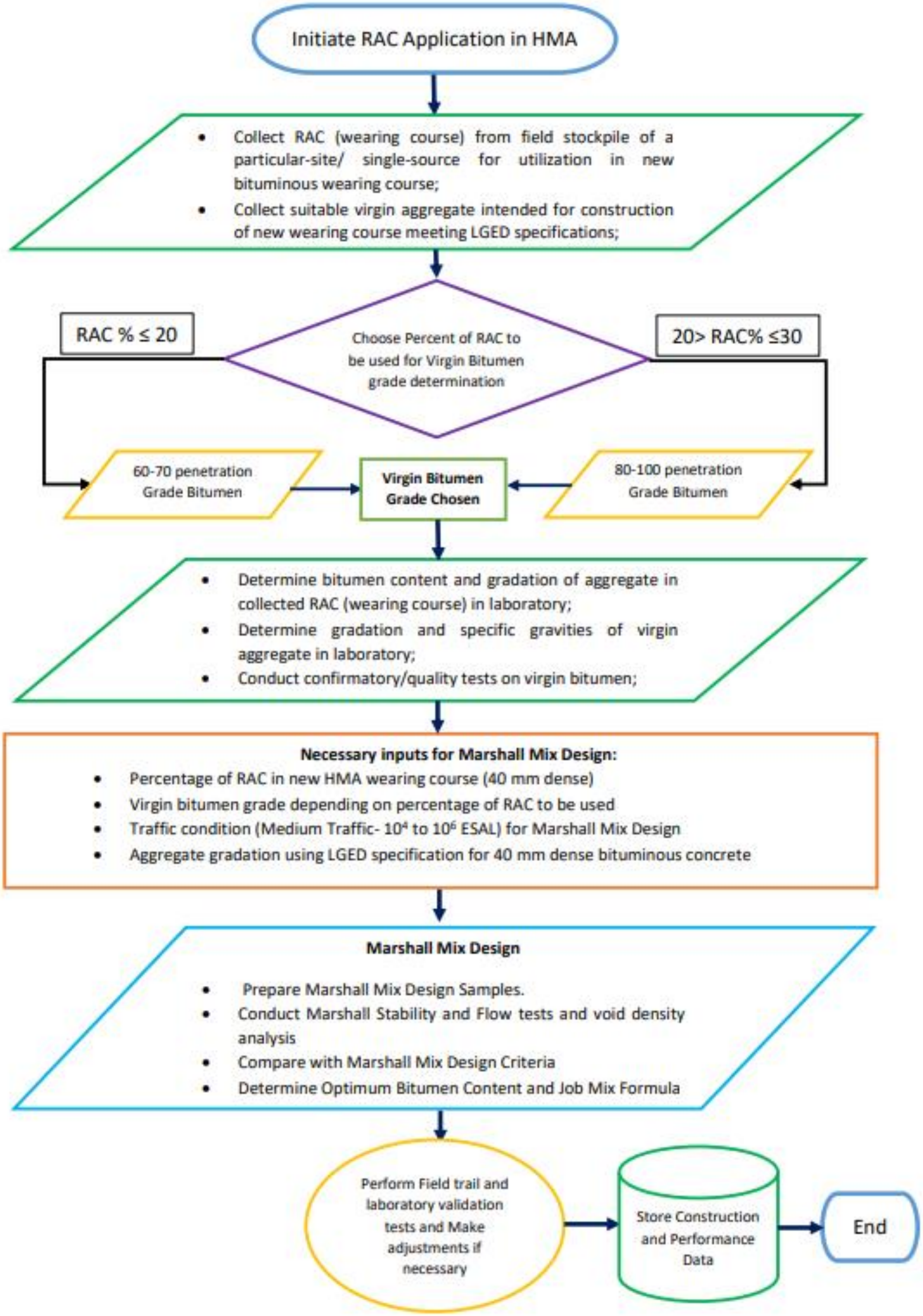


Figure 35: Working Methodology for RAC Use in New HMA Concrete Wearing Course

Table 35: Sample Calculation for- 80: 20 mixture of virgin aggregate and RAC

	Percentage, (%)	Weight for a Single Specimen, gm	RAC Bitumen Content, %	RAC Bitumen, gm	RAC Aggregate %
RAC	20	240	4.38	10.512	19.1
Virgin Aggregate	80	960	--	--	

Virgin Bitumen as % of virgin Aggregate	Weight (gm)	RAP Bitumen (gm)	Total Bitumen (gm)	Total weight of Mix (gm)	Bitumen Content (% of Total Mix)
4	38.4	10.512	48.912	1238.4	3.9
4.5	43.2	10.512	53.712	1243.2	4.3
5	48	10.512	58.512	1248	4.7
5.5	52.8	10.512	63.312	1252.8	5.1
6	57.6	10.512	68.112	1257.6	5.4

Sieve Size, mm	Virgin Aggregate Gradation		RAC Aggregate (Extracted from Ignition Method)		Gradation of Combination		
	Weight of Material Retained, (gm)	Percentage of Material Retained, (%)	Weight of Material Retained, (gm)	Percentage of Material Retained, (%)	Percentage of Material Retained, (%)	Cumulative % Retained	% Finer
25.4	0	0	22	2.4	0.5	0.5	100
19.05	0	0	103.7	11.1	2.1	2.6	97
16	0	0	-	-	-	-	-
12.5	201.2	25	129.4	13.9	22.9	25.5	75
9.5	80.5	10	156.3	16.8	11.3	36.8	63
4.75	161	20	91.8	9.9	18.1	54.9	45
2.36	120.8	15	183.7	19.7	15.9	70.8	29
0.6	104.6	13	140.4	15.1	13.4	84.2	16
0.075	104.6	13	72.7	7.8	12	96.2	4
mf/pan	32.2	4	31.2	3.4	3.9		
	804.9	100	931.2	100.1	100.1		

6. COMPARATIVE ADVANTAGES AND DISADVANTAGES OF USING RAP

6.1 Advantages

6.1.1 Economic Benefits

Using Reclaimed Asphalt Pavement (RAP) material in the roads has significant economic benefit. RAP contains coarse aggregate with asphalt binder coating on them. When RAP is mixed with virgin aggregate and virgin asphalt binder and used in flexible pavement works, the total amount of required raw materials (aggregate and asphalt binder) is reduced. Currently, Bangladesh needs to import coarse aggregate from India, Malaysia, and Middle East and from some other places at the expense of valuable foreign reserve. Using higher portion of RAP in pavement construction will save significant amount of foreign currency. According to a study (Babashamsi et al. 2016) on life cycle cost analysis, it was found that using RAP had shown to save $58,000/km in asphalt compounds that produce 30-50 percent RAP. This reduction comprises savings in material costs as a portion of virgin binders is replaced by RAP, which reduces delivery costs. Crushed stones that are not recycled are normally more expensive than crushed stones recycled. According to a study (Barzegar et al. 2023), up to 30 % of construction costs was saved by using RAP as a pavement base material. The most expensive component of asphalt construction is the asphalt binder. The use of RAP material in pavement construction requires a reduction in the amount of asphalt binding. The finding was that RAPs in asphalt mixtures were most cost-effective in the immediate and surface layers of flexible pavement (Rinkal et al. 2021).

6.1.2 Environmental Benefits

The use of RAP in pavement construction has many environmental benefits. Decreased demand for non-renewable energy, less scope for removing pavements, reduced use of fuel and contamination because of non-transport goods and reduced use of virgin materials are just some of the many environmental benefits of using RAP. A study has found that the incorporation of 15% RAP into warm-mix asphalt mixtures reduces combined total energy production, transition in atmosphere and fossil fuels by between 13 and 14%. According to (Barzegar et al. 2023) the incorporation of RAP as an alternative material in asphalt base and sub-base layer construction offers the potential for reducing global warming (20%), energy consumption (16%), water consumption (11%), life cycle costs (21%) and hazardous waste generation (11%).

6.1.3 Mechanical Properties

The primary technical advantage of asphalt mixes containing RAP is higher stiffness resulting from the combination of a virgin asphalt binder with an aged (hardened) asphalt binder. The resulting blended binder has a higher stiffness than the virgin binder because of higher activation energy. In other words, the aged asphalt binder increases the stiffness of the blended asphalt binder, which results in an increase in the dynamic modulus and indirect tensile strength of the asphalt mixture. The slope of indirect tensile strength (ITS) indicates that each additional percent of RAP increases the ITS of the mixture by 13 kPa. Moreover, the binder content in the RAP reduces the optimum new binder content (OBC). In Figure 36 Hajj et al. (2008) demonstrates the inverse relation between the OBC and RAP concentration.

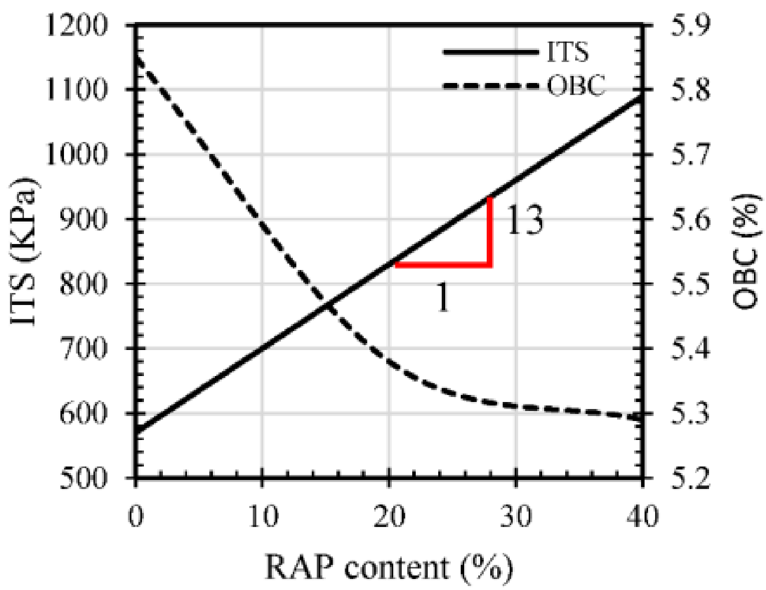


Figure 36: Correlation between ITS and OBC and RAP content

Therefore, incorporation of RAP not only increases the structural capacity of the asphalt mixture in terms of dynamic modulus and ITS, it also reduces the required volume of the new binder, resulting in greater sustainability benefits.

6.2 Disadvantages

i. If the recycled pavement is poorly designed, the expected service life of the pavement would be decreased, which might contribute to higher maintenance costs as well as higher energy consumption and emissions (Waymen 2012).

ii. In a study conducted by Lee et al. (2012), it was concluded that the service life of recycled pavement which included 30% RAP must not be lower than 80% of the conventional mixture.

iii. It was reported that using high amounts of RAP material in road pavement increases risk of premature pavement distresses, such as fatigue cracking, as result of RAP's stiff binder component (Baghaee Moghaddam and Baaj 2016).

iv. The stiff binder might also act as a deterrent factor for the field compaction which eventually might lead to premature field failure (Mogawer et al. 2012).

v. Using high percentages of RAP can also escalate premature pavement distresses such as fatigue and low temperature cracking, or increase the moisture susceptibility of asphalt mixture (He and Wong 2008).

vi. With higher RAP percentages the cracking tolerance becomes lower.

vii. Higher RAP content was found to increase permeability, thereby reducing the shear strength

viii. Strong RAP-WMA mixtures have greater fatigue resistance, regardless of the surface of pavement or WMA technology used, than low RAP-WMA mixtures.

ix. The construction temperature of mixes incorporating RAP is typically higher than that of traditional hot asphalt without RAP, which results in greater degrees of ageing, fatigue and susceptibility to low temperature cracking (Qiao et al. 2019).

7. OVERALL RESEARCH RECOMMENDATIONS

a) Considering satisfactory CBR Test value from laboratory and from field test, it can be recommended that recycled material from LGED's Road can be used as Sub-Base as well as Base material. However, necessary durability tests and hydraulic conductivity tests are needed to be done to further assess the complete performance of these recycled materials.

b) Based on the findings from literature review and Marshall Mix Design carried out for this study, the following recommendations can be drawn-

   - Use of medium traffic condition may be considered instead of heavy traffic conditions, as the former results in very low design asphalt content which fall outside the usually recommended range of asphalt content for flexible pavement design. Also, according to design standards and codes, use of heavy traffic condition for mix design may result in excessive voids (i.e. more than 4%) remaining in the constructed pavements if actual traffic is quite less than the anticipated. This may lead to loss of durability and moisture susceptibility.

- For 20 % or less RAC usage in new flexible pavement wearing course, 60-70 penetration grade asphalt can be used following current LGED specifications.
- For 20% to 30% usage of RAC in new flexible pavement wearing course, 80-100 penetration grade asphalt is recommended. 80-100 grade requires approximately 1% less asphalt content compared to 60-70 grade asphalt. This will have cost implications on the overall project.
- Usage of more than 30 % RAC in new flexible pavement wearing course is not recommended at this stage. Although, an optimum binder content could be determined, the satisfying zone for optimum binder content was very narrow. Use of softer grade asphalt may allow use of higher percentage of RAC. However, due to unavailability of softer grade asphalt those tests could not be performed at this stage.

Nevertheless, a few words are necessary here to keep in mind during handling RAC during the mix design process. Just as it is with virgin aggregates, the variability of a stockpile of RAC is important in both mix design and quality control during production. To effectively maximize the use of RAC in an asphalt mixture, the asphalt mixture producer should know the source of the RAC and, if practical, keep separate stockpiles of RAC from specific projects— or, at the least, keep RAC from one type of project separate from RAC of another type. A RAC obtained from a neighborhood street may have substantially different asphalt binder properties, asphalt binder content, aggregate physical properties, and gradation than a RAC obtained from an urban highway.

c) From the result of previous studies and based on available methods for asphalt extraction, it can be summarized that the available methods of extractions are used only to identify the quantity and quality of asphalt layer that surrounds the aggregate. Many solvents are also used during extraction process of asphalt, some of which may cause health hazard to the operator. Considering all the aspects, it can be concluded that removal technique to extract bituminous layers from RAP is limited to laboratory testing of bituminous layer only, large scale use of these methods to reproduce aggregate is not recommended.

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