***ASSESSMENT REPORT*:**

APPLICABILITY OF RAP IN WEARING COURSE IN FLEXIBLE PAVEMENT AND REMOVAL TECHNIQUE OF BITUMINOUS LAYER FROM RAP AND ITS APPLICABILITY

Release 2.0

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

June 2023

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1. INTRODUCTION

Local Government Engineering Department (LGED) has been constructing roads, bridges, culverts, buildings and other civil infrastructures for the last 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 basecourse 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 a close up view of the reclaimed asphalt concrete (RAC) from wearing course.

(a)

(b)

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

Figure 3: 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, subbase 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.

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 in this report. 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. 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. 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.

3.1 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.

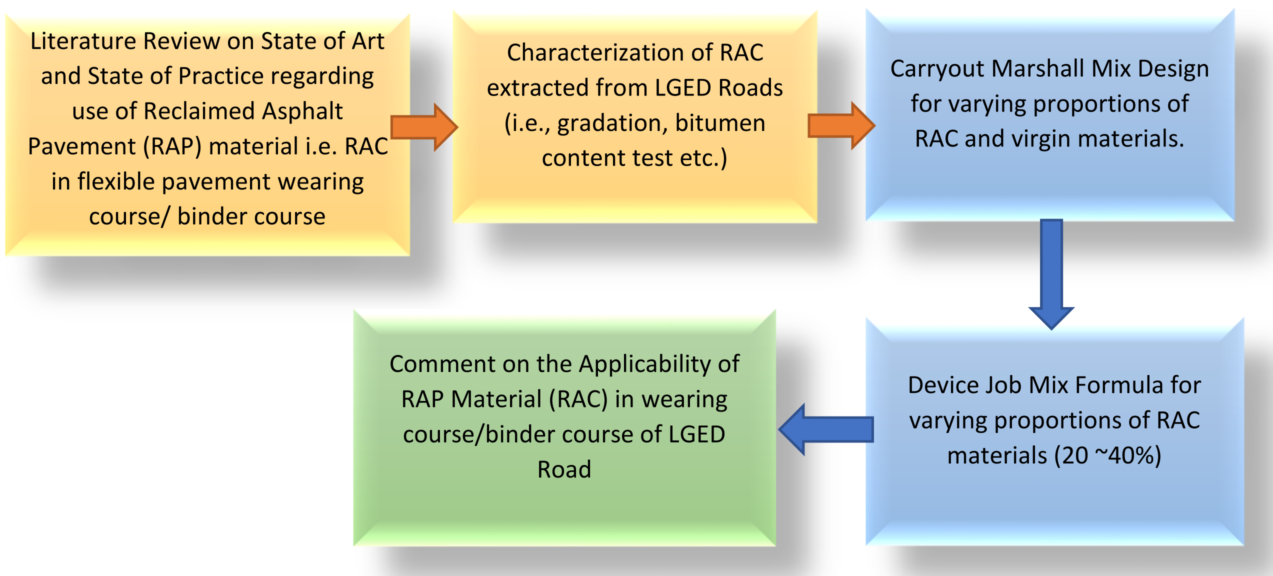

Figure 4: Work-flow chart of proposed RAC usage in wearing course/ binder course

3.2 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 5: 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.

4. MATERIAL CHARACTERISATION 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.

4.1 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				

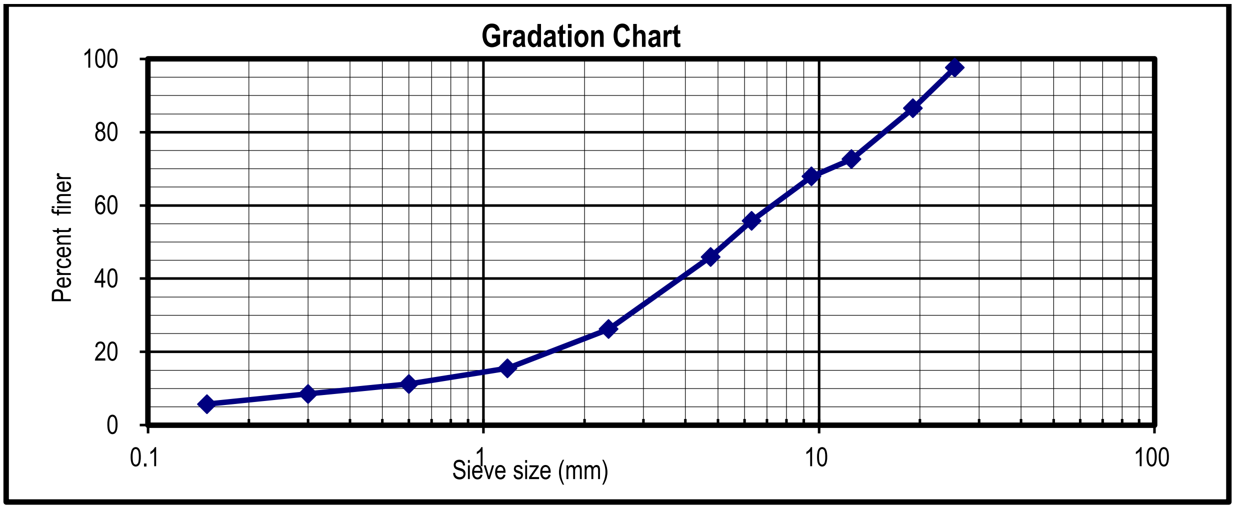

Figure 6: Gradation Curve of RAC aggregate obtained through Ignition Method (Wearing course)

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 7: 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.

4.2 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				

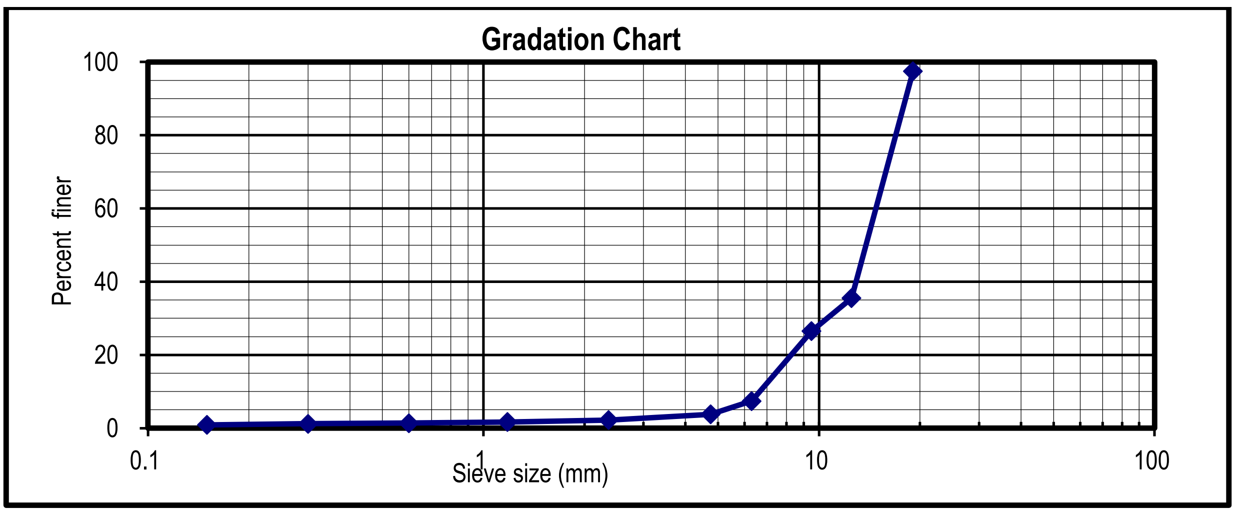

Figure 8: Gradation Curve of RAC aggregate obtained through Ignition Method (Wearing course)

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 10 below shows the pictures of samples 1 and 2 below.

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

Figure 9: 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 1.

Table 1: 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

5. 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 2 below.

Table 2: 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 10 below shows the picture of Marshall Mix Design samples prepared for this study in BUET laboratory (after completion of tests).

Figure 10: 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 3 below. Table 4 shows the Bitumen % used for preparation of Marshall Samples and Table 5 shows the test results of Marshall Samples.

Table 3: 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 4: 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 5: 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 11 below shows the zone satisfying Marshall Mix Design Criteria and Figure 12 shows the Marshall Mix Design Graphs.

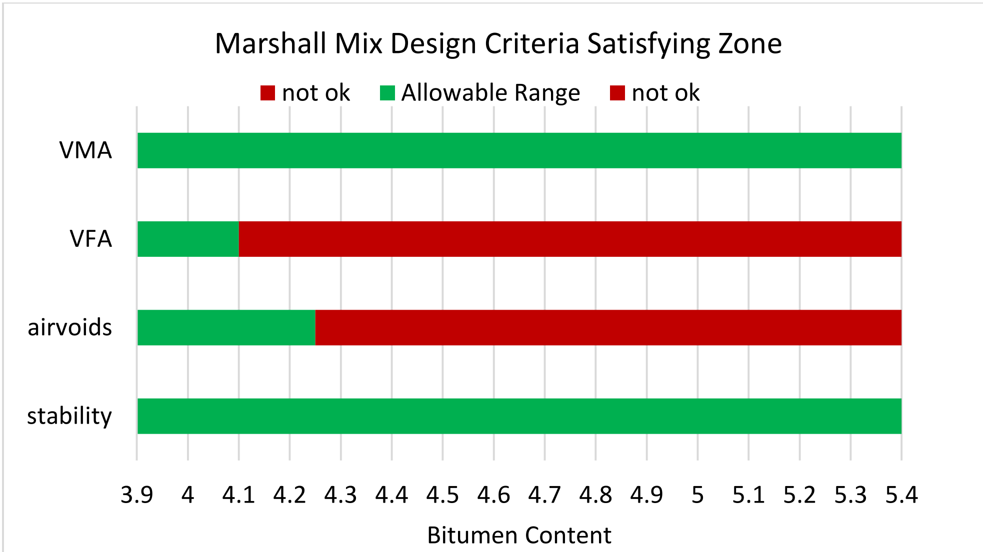

Figure 11: Marshall Mix Design Criteria Satisfying Zone for Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAP Wearing Course)

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

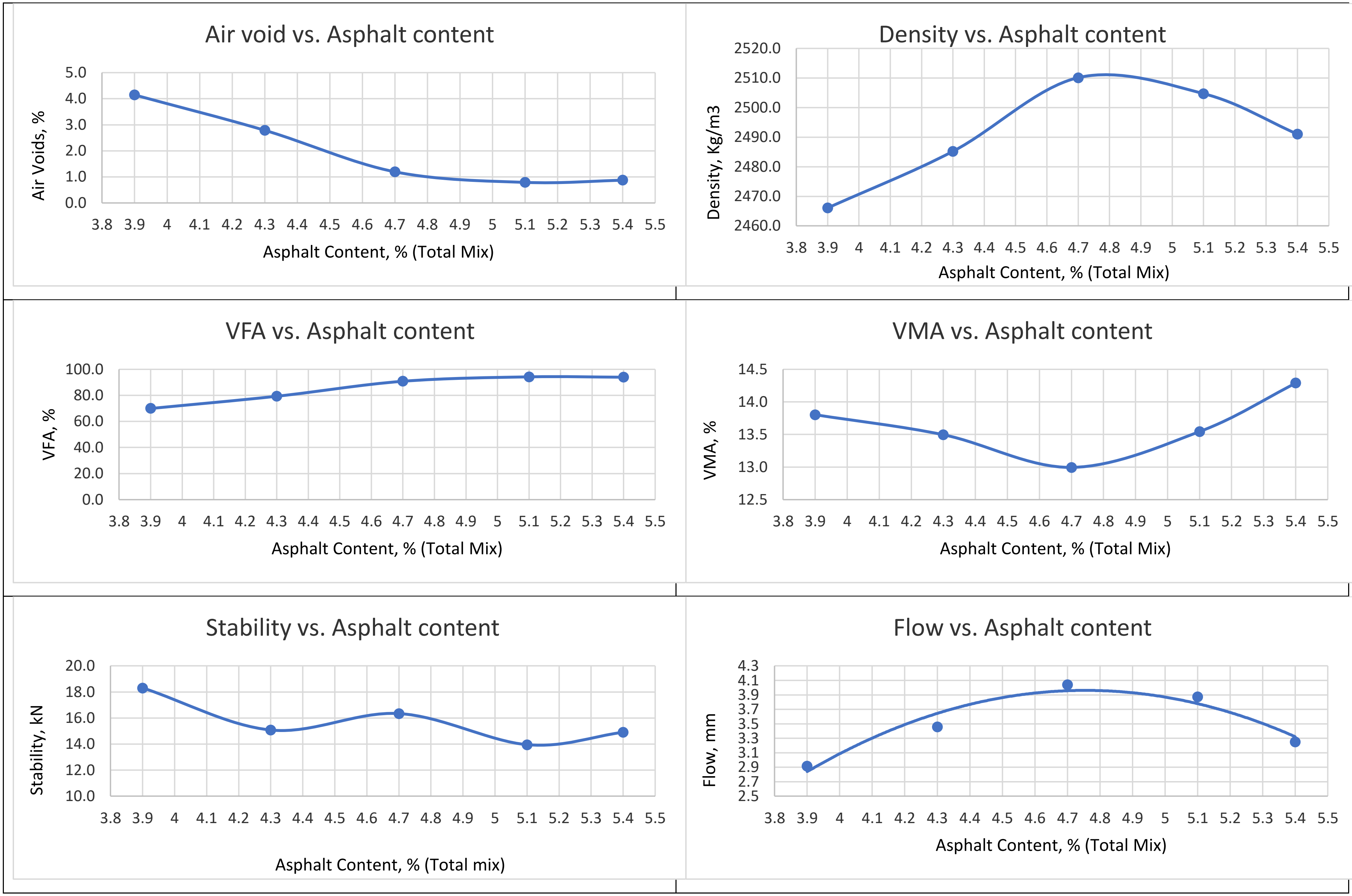

Figure 12: Marshall Mix Design Graphs for Heavy Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-1): 20 (RAP Wearing Course)

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 6 below. Table 7 shows the Bitumen % used for preparation of Marshall Samples and Table 8 shows the test results of Marshall Samples.

Table 6: 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 7: 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 8: 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 13 below shows the zone satisfying Marshall Mix Design Criteria and Figure 14 shows the Marshall Mix Design Graphs.

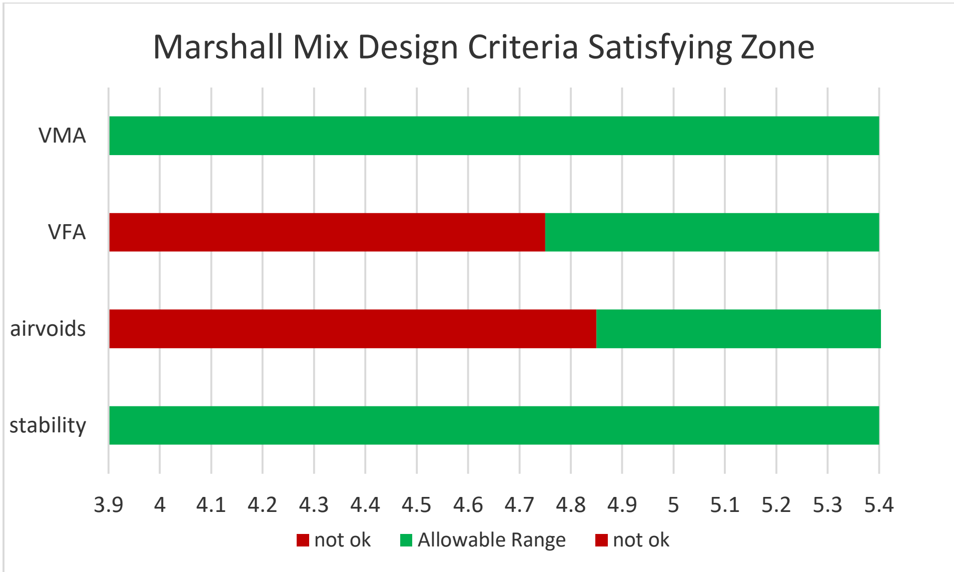

Figure 13: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 (RAP Wearing Course)

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

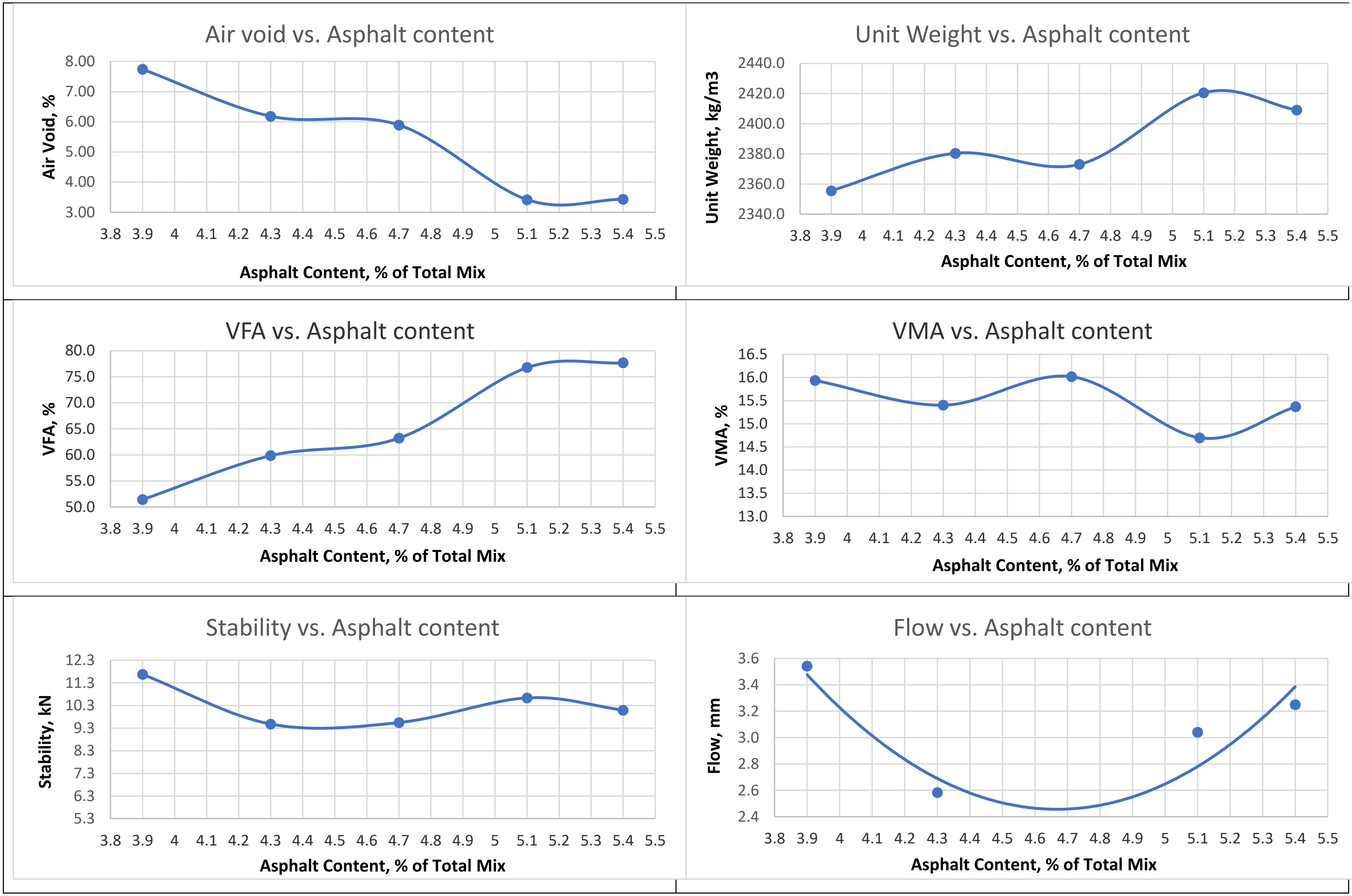

Figure 14: Marshall Mix Design Graphs for Medium Traffic Condition using 60-70 grade Bitumen & 80 (Virgin Aggregate- Sample-2): 20 (RAP Wearing Course)

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 9 below. Table 10 shows the Bitumen % used for preparation of Marshall Samples and Table 11 shows the test results of Marshall Samples.

Table 9: 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 10: 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 11: 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 15 below shows the zone satisfying Marshall Mix Design Criteria and Figure 16 shows the Marshall Mix Design Graphs.

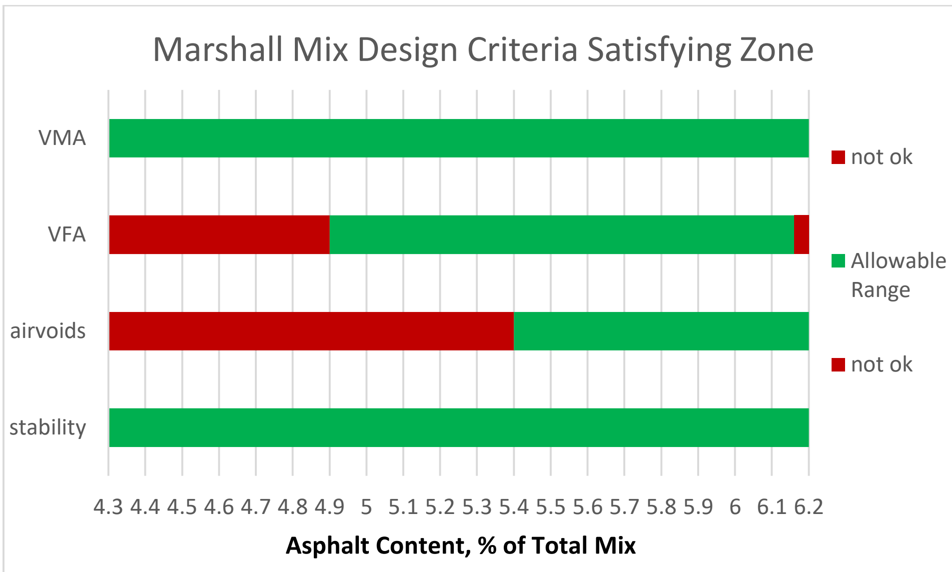

Figure 15: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

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

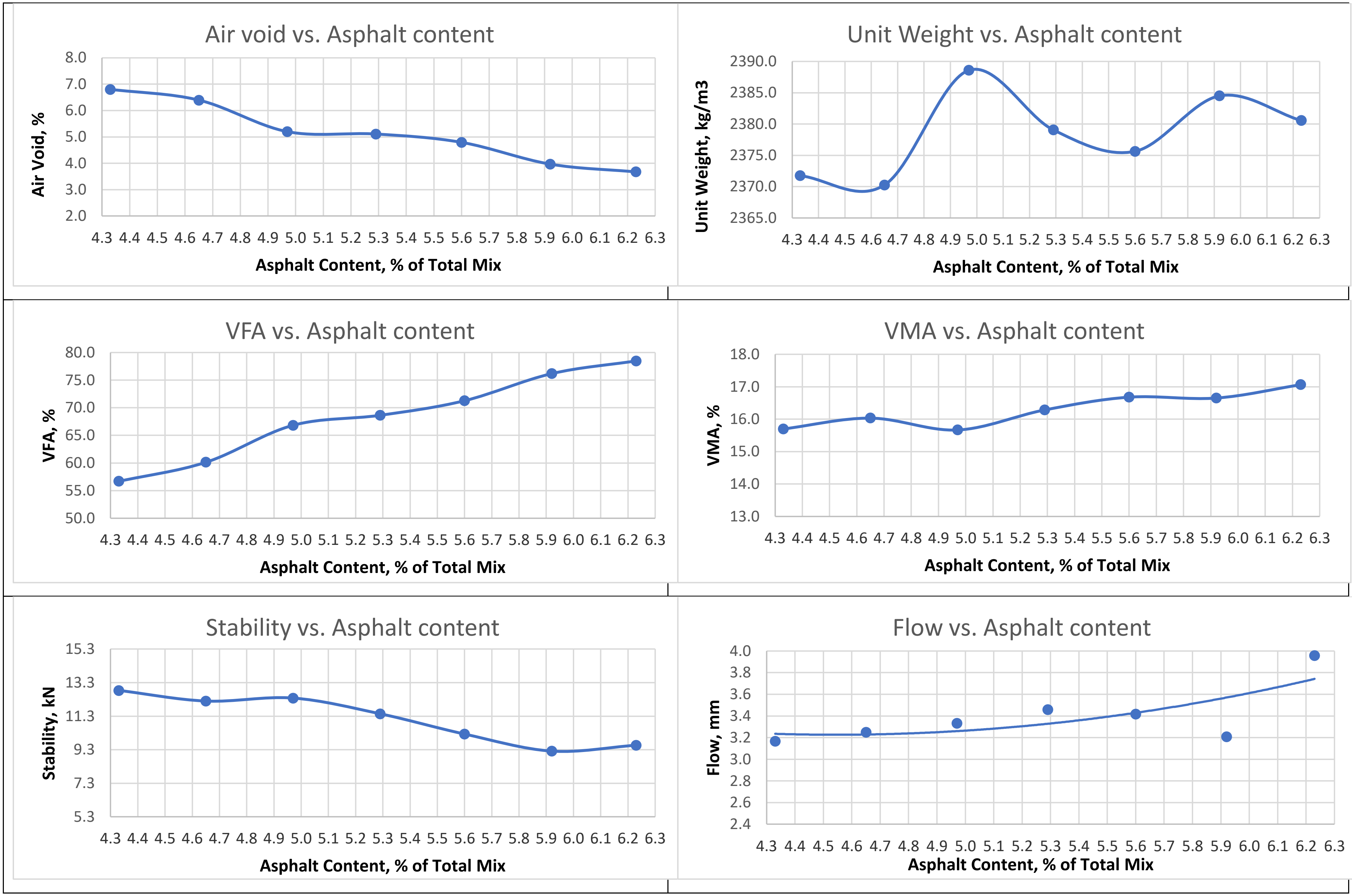

Figure 16: Marshall Mix Design Graphs for Medium Traffic Condition using 60-70 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

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 12 below. Table 13 shows the Bitumen % used for preparation of Marshall Samples and Table 14 shows the test results of Marshall Samples.

Table 12: 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 13: 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 14: 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 17 below shows the zone satisfying Marshall Mix Design Criteria and Figure 18 shows the Marshall Mix Design Graphs.

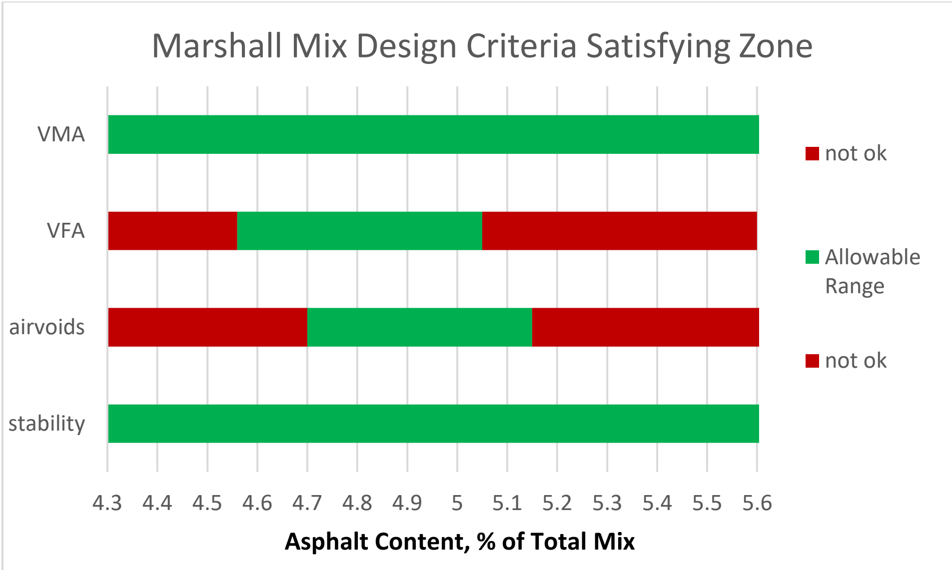

Figure 17: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

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

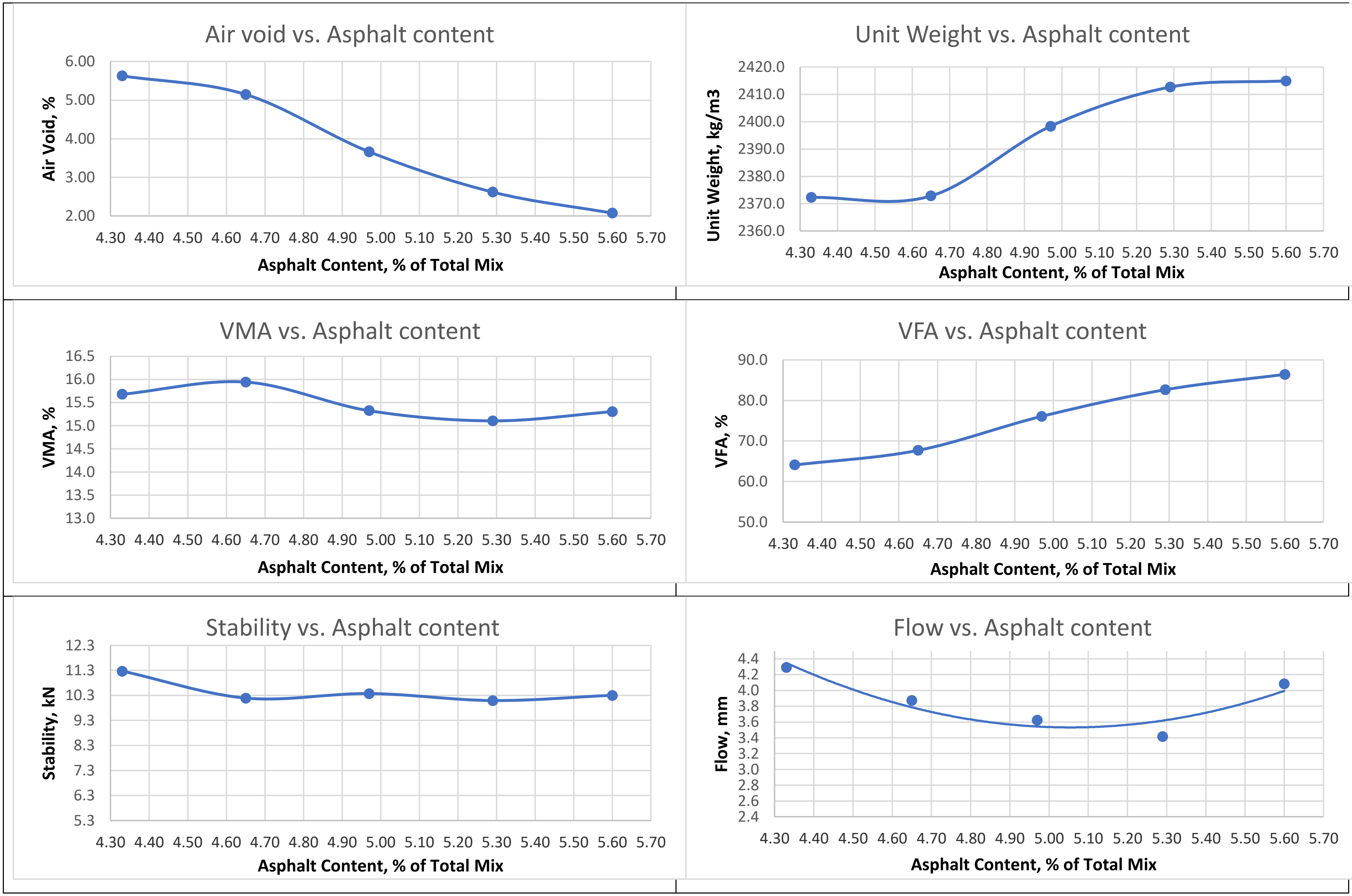

Figure 18: Marshall Mix Design Graphs for Medium Traffic Condition using 80-100 grade Bitumen & 70 (Virgin Aggregate- Sample-2): 30 (RAP Wearing Course)

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 15 below. Table 16 shows the Bitumen % used for preparation of Marshall Samples and Table 17 shows the test results of Marshall Samples.

Table 15: 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 16: 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 17: 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 19 below shows the zone satisfying Marshall Mix Design Criteria and Figure 20 shows the Marshall Mix Design Graphs.

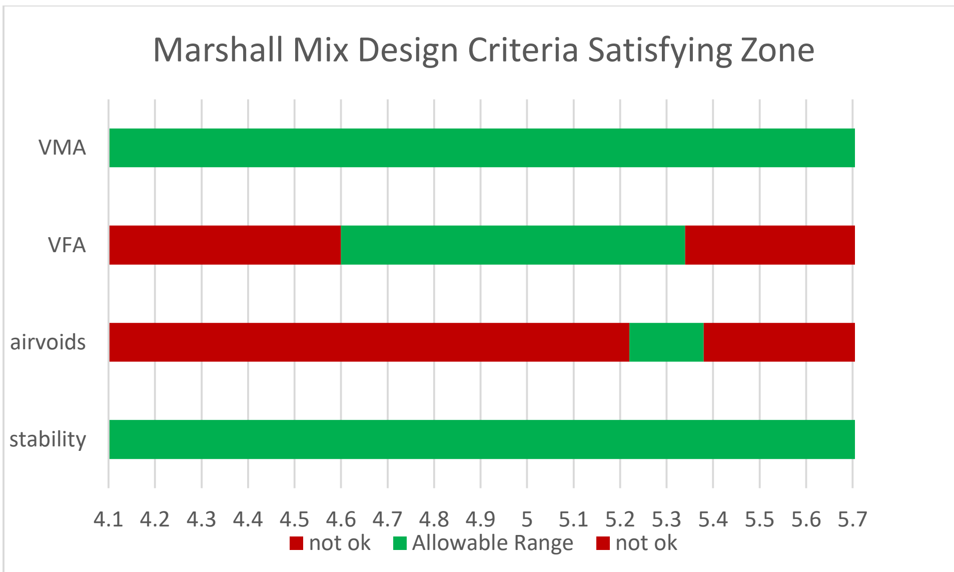

Figure 19: Marshall Mix Design Criteria Satisfying Zone for Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAP Wearing Course)

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

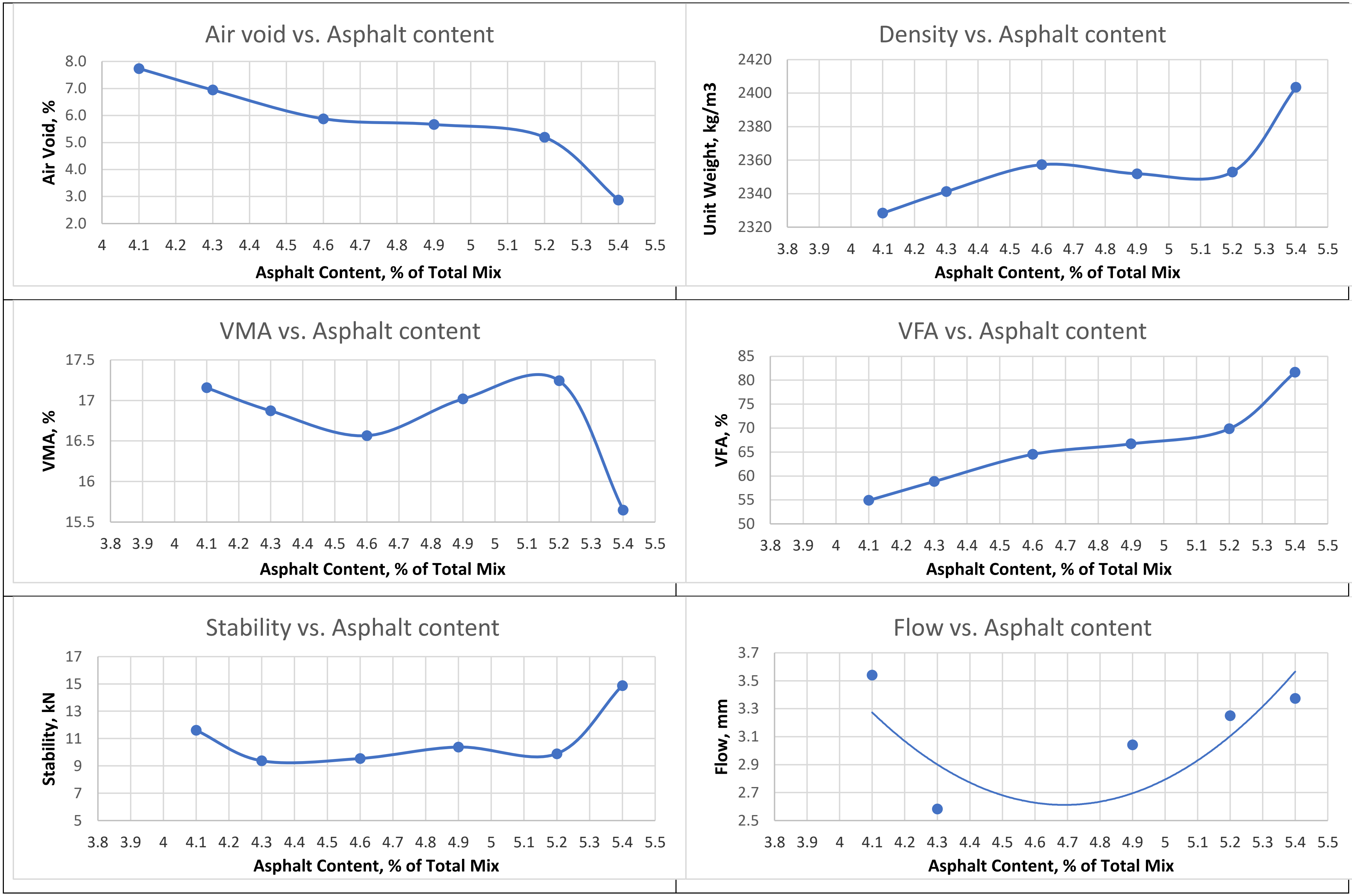

Figure 20: Marshall Mix Design Graphs for Medium Traffic Condition using 80-100 grade Bitumen & 60 (Virgin Aggregate- Sample-2): 40 (RAP Wearing Course)

6. 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.

6.1 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.

6.2 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.

6.3 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
b) Reflux method
c) Vacuum method

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 and reflux method 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

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).

6.4 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.

7. 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.

Table18: 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 19 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 19: 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.

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