Study on the Suitability of Reclaimed Asphalt Pavement Aggregate (RAPA) in Hot Mix Asphalt Production

Tiruwork Mulatu*, Biruk Yigezu** and Anteneh Geremew***

*, **, ***Jimma University, Faculty of Civil and Environmental Engineering, Jimma, Ethiopia

* Corresponding Author: tiruworkmule@gmail.com

Submitted : 27-07-2021

Revised : 21-09-2021

Accepted : 02-10-2021

ABSTRACT

The main objective of this study was to evaluate the suitability of recycled asphalt aggregate with crushed stone aggregate in hot mix asphalt production by using an experimental type of investigation. To attain this study, Non-probable sampling techniques were adopted to collect a sample. The engineering properties of the extracted Reclaimed asphalt pavement aggregate (RAPA) and the freshly crushed stone aggregate (CSA) were investigated based on standard specifications before further starting the Marshall Mix design processing. Then, the Marshall Stability test was conducted on CSA with three different aggregate gradation sizes 5.0%, 5.5%, and 6.0% by weight of aggregates and with five different bitumen content 4.0%, 4.5%, 5.0%, 5.5% and 6.0% by weight of the total mix. Depending on the selected aggregate gradation, the Marshall Stability test was conducted for reclaimed asphalt pavement aggregate with a replacement rate of 5.0%, 15%, 25%, 35%, 45%, 55%, and 65% by weight of CSA to determine its optimum bitumen content (OBC) according to National Asphalt Pavement Association method (NAPAM). In this, study a total of 64 mix designs and 190 specimens were prepared based on specifications. Based on this, the Marshall Stability and Moisture Susceptibility test with 3-trials, and additional 2-trials were conducted for the rutting test. From 190 specimens, 45 were for the control mix design, 105 were for partial replacement proportion, 36 were for Moisture Susceptibility and 4 were for the Rutting test conducted. Based on the Marshall test results and their performance tests such as Moisture Susceptibility and rutting test were considered up to the maximum allowable replacement percentage and their experimental results were compared with the standard specifications. The optimum bitumen content result obtained in percent was 5.1, 5.04, 4.98, 4.87, 4.81, 4.74, 4.67, and 4.53 for 0 % (control), 5.0%, 15%, 25%, 35%, 45%, 55%, and 65%, respectively. The experimental test result of the Tensile Strength Ratio, proportional rut depth and mean rut depth on 45% RAPA replacement percentage was 85.42%, 4.48 %, and 2.24 mm respectively. Finally, based on this investigation, the test result obtained from the marshal stability and the performance tests indicates that up to a maximum of 45% replacement of aggregate by a reclaimed asphalt pavement aggregate in hot mix asphalt production satisfies the required standard specifications.

Keywords: Reclaimed asphalt pavement; Marshall Test; Crushed aggregate; Proportional rut depth Tensile Strength Ratio; Percentage by weight.

INTRODUCTION

Roads are the broadest infrastructure to be constructed worldwide by providing door-to-door services to transport societies and the raw materials from one place to another at a reasonable cost when compared to the other modes of transportation. Based on the designing process, method of construction, and constituent materials used are classified into three major types: Rigid pavement, flexible pavement, and composite pavement. Rigid pavement is typically prepared by Portland cement concrete (PCC) and asphalt pavement is usually made of hot mix asphalt (HMA) whereas the composite pavement is composed of a combination of both flexible and rigid pavement types. The composite pavements type is rarely used in construction due to its high initial costs and the complex analysis involved during the design stage up to construction (Pranav et al., 2020).

The primary purpose of constructing a flexible pavement is to transmit load coming from the upper layer of the surface to the subbase and underlying subgrade soil. These materials contain sand and gravel or crushed stone aggregate when compacted with a binder of bituminous material to make more plasticity property absorb the developed stress, and a proper mix design is needed and adequately satisfies the required standard specification(Gonfa et al., 2020; Schaefer et al., 2008). There are different materials are required to prepare an appropriate mix design of an asphalt mixture, but these ingredient materials used are not easily available near the construction area due to limited accessible sources. Therefore to reduce this limitation, an alternative waste material to be substituted with virgin crushed stone aggregate to satisfy the required standard specification which is suitable to be an alternative construction material is Reclaimed Asphalt Pavement (RAP) (Geraldin & Makmur, 2020; Hrůza et al., 2020; Pourtahmasb & Karim, 2014).

The existing old asphalt pavement material may significantly value when the asphalt pavement even approaches its design life. Recognizing the importance of the existing aggregate and asphalt resources, agencies and contractors have prepared extensive use of RAP to produce new asphalt concrete pavements for a long time. RAP has been approved to be used in construction materials due to its economic advantage and environmental benefits. Also, the scarcity in the accessibility of virgin aggregates, and excavating operations restrictions make it a necessity to include RCA's use in concrete pavements (Alwetaishi et al., 2019; Swiertz et al., 2011).

These materials are produced while asphalt concrete pavements are removed during reconstruction, resurfacing, or access to buried utilities. Once properly crushed and screened, RAP comprises high-quality, well-graded aggregates coated by asphalt cement. Recycled asphalt aggregate materials adequately processed and blended with a conventional aggregate satisfy the performance of the granular road base longer than 20 years, and now it is considered a standard practice in many countries, including Ethiopia. Recycled asphalt aggregate is used as a capping layer and sub-base material in various construction projects.

Reclaimed Asphalt pavement is generally removed by either milling or full-depth removal. Milling entails the removal of the pavement surface using a milling machine, which can remove up to 50 mm (2 in.) thickness in a single pass. Full-depth removal involves ripping and breaking the pavement using a rhino horn on a bulldozer and/or pneumatic pavement breakers. In most instances, the broken material is picked up, loaded into haul trucks by a front-end loader, and transported to a central facility for processing. At this facility, the RAP is processed using a series of operations, including crushing, screening, conveying, and stacking (Pradhan & Sahoo, 2021; Roja et al., 2020).

The most difficult challenge in the development of a new road network is to implement projects in harmony with the concept of sustainable progress. Therefore, the road industry is looking forward to alternative materials and construction technology, an environment-friendly, energy-efficient, and cost-effective way to construct and maintain road projects. Most of the current road construction practices mainly depend on naturally occurring aggregates obtained from quarries site (Belay et al., 2021; Hidalgo et al., 2020; Tarsi et al., 2020; West, 2010). The extraction of these aggregates from their natural sources results in the loss of forest cover and pollution on a large scale leading to environmental degradation. This, in turn, has increased environmental concerns in many parts of the world (Seyfe & Geremew, 2019; Singh et al., 2020).

The application of RAP in pavement construction has grown rapidly in the last two decades to virgin aggregate usually used in constructing different pavement layers. Using RAP in pavement construction is considered a sustainable alternative due to its economic saving, reducing dumping of aggregate in landfills, and reducing the need for virgin aggregate and binder. Also, the use of RAP conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. For this purpose, transportation agencies, in different parts of the world, started using high percentages of RAP in asphalt concrete mixes. 20 to 50% of RAP is typically used in HMA mixes; however, up to 80% of RAP has been used in some HMA pavements (Abu Abdo, 2015). The rapid economic growth in Ethiopia from 2004 to 2015 is about 10.9%. In recent years, Ethiopia has dedicated to allocated three percent of its GDP to a road investment program focusing mainly on rehabilitation, upgrading, and widening of the road

(Shiferaw, 2017). Currently, large quantities of RAP aggregate remain unused in our country. The use of RAP in surface, base, and sub-base courses is not common, RAP will reduce the cost of highway construction and haul, and reduce improper use of local natural resources. One attractive option is to use RAP material in asphalt production. Therefore, this study investigates the Suitability of RAP in asphalt concrete production.

MATERIALS AND METHODS USED

Materials

Non-probable purposive sampling techniques were adopted to collect materials used for conducting this research method.

- Crushed stone Aggregate (Coarse, and Fine)
- Bitumen (60/70 Penetration Grade),
- Mineral Filler (Crushed Stone Dust),
- Reclaimed Asphalt Pavement Aggregate (Extracted coarse and fine).

Study design

For this research work, an experimental type design was performed as shown in Figure 1. To achieve the objective of the study, numerous laboratory tests were conducted to determine the Suitability of Reclaimed Asphalt Pavement Aggregate (RAPA) in Hot Mix Asphalt Production.

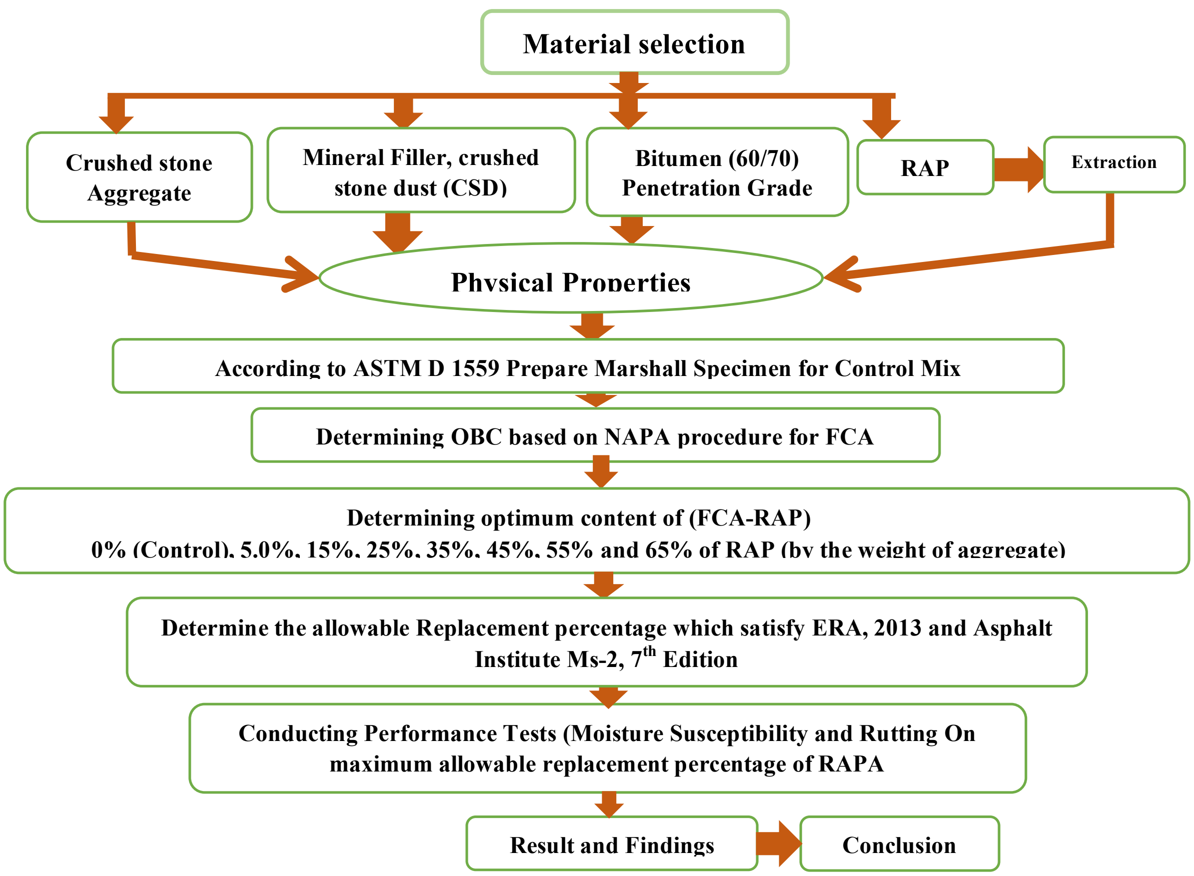

Figure 1. Research design method.

Standards and Specification for this Study

There are various tests were conducted based on standard specification procedures as listed in Table 1, Table 2, Table 3, and Table 4 to determine the engineering property of the materials used for this study.

Table 1. RAPA and crushed stone aggregate (CSA) engineering quality tests and methods.

Material	Test conducted	Test method
RAP	Extraction by centrifuge method	ASTMD 2172
Aggregate test for crushed aggregate and RAPA	Los Angles abrasion value	AASHTO T-96
	Aggregate crushing value	BS 812, Part 110
	Aggregate impact value	BS 812, Part 112
	Elongation index	BS 812, Part 105
	Flakiness index	BS 812, Part 105
	Specific gravity of coarse aggregate	AASHTO T 85
	Specific gravity of fine aggregate	AASHTO T 84
	Water absorption	BS 812, Part 2
	A sieve analysis (Gradation)	AASHTO T-27
	Blending	ASTMD 3515

Table 2. Performed bitumen test and test methods.

Material	Test conducted	Test method
Bitumen	Penetration test	AASHTO T- 49
	Specific gravity	ASTM D-70-97
	Ductility	AASHTO T- 51-94
	Softening point	AASHTO T- 53
	Flash point	ASTM D-92

Table 3. Test and test methods of mineral filler material.

Material	Test conducted	Test method
Filler	Specific gravity	ASTM D-854
	Plasticity Index (PI)	ASTM D-4318
	Gradation (sieve analysis)	ASTM D-242

Table 4. Performance tests for control and modified mix.

Test	TEST METHOD
TSR	AASHTO T 283
Rutting test	AASHTO TP 63

RESULT AND DISCUSSION

Aggregate quality and physical property test result

A huge quantity of reclaimed asphalt pavement is produced each year worldwide due to different reasons. These materials are produced while asphalt concrete pavements are removed during reconstruction, resurfacing, or access to buried utilities. However, there are some concerns and uncertainties about the actual environmental problem, the economic aspect, and the mechanical performance of the asphalt mixture containing recycled aggregates. To investigate the physical properties of aggregates and their suitability in road construction, There are various tests were conducted on the Physical properties of RAPA and crushed Stone aggregate (CSA), and the test result is presented in Table 5. The specific gravity of aggregate was determined for each percentage replacement of RAPA in crushed aggregate with each size proportion of aggregate 9- 25 mm, 2.36-9.5 mm, and 0-2.36 mm, which is very important for the determination of VMA and VFA of HMA.

Table 5. Physical properties of RAPA and crushed Stone aggregate (CSA) for the study.

Test	Test method	Test result [%]		Specification
		CSA	RAPA	
Los Angeles Abrasion (LAA), [%]	AASHTO T- 96	13.67	14.3	<35 %
Aggregate Crushing Value (ACV), [%]	BS:812, Part 110	13.86	16.67	<25 %
Aggregate Impact Value (AIV) [%]	BS:812, Part 112	10.45	14.61	<25 %
Elongation index	BS 812, Part 105	11.27	11.43	<15 %
Flakiness index	BS 812, Part 105	23.89	23.07	<45%
Specific gravity >4.75	AASHTO T-85	2.831	2.680	N/A
Specific gravity <4.75	AASHTO T-84	2.703	2.824	N/A
Water absorption of aggregate >4.75 mm	BS 812, Part 2	1.23	1.48	<2
Water absorption of aggregate <4.75 mm	BS 812, Part 2	1.55	1.42	<2

N/A - Not Applicable

Aggregate gradation for the study

Hot mix asphalt (HMA) is graded by the percentage of different-size aggregate particles it contains as shown in Table 6. Aggregate gradation should convince the control points specified by the specification guideline for Particle Size distributions HMA production. With 19 mm, maximum aggregate nominal size and three different percentages of fillers 5.0%, 5.5%, and 6% by weight of total mix added to the mix aggregate gradation for the study was performed in two different parts. The first part of aggregate gradation is for the control mix, and the second gradation is gradation blended with RAPA Figure 2, Figure 3, and Figure 4 respectively. Based on the standard specification of ASTM D3515 all aggregate gradation curves were drawn and upper limit, lower limit, maximum density (middle value), and gradation trials were indicated with a different color. Consequently, the gradation trials of control and RAPA convince the standard specification requirements.

Table 6. Suggested percentage combination of stockpile aggregate.

suggested percentage combination of stockpile aggregate						
Stockpile aggregate size	13.2-20 mm	6-13.2 mm	3-6 mm	0-3 mm	Filler	sum
Trial 1	15.00%	31.00%	26.00%	26.00%	2.00%	100.0%
Trial 2	14.50%	31.00%	26.00%	26.00%	2.50%	100.0%
Trial 3	16.00%	27.00%	24.00%	30.50%	2.50%	100.0%

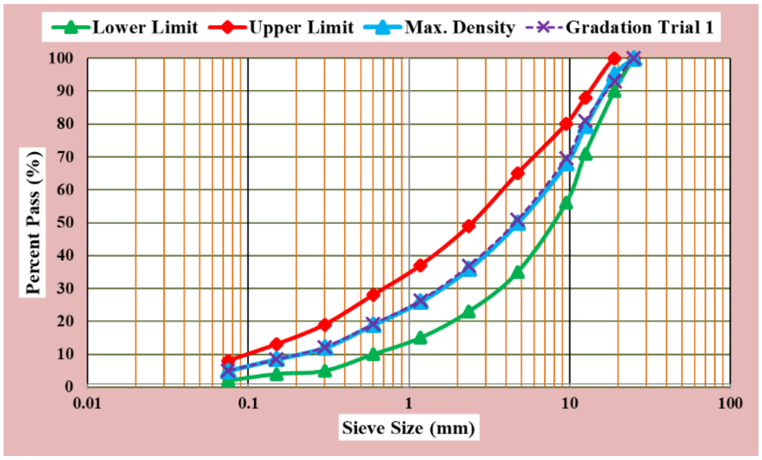

Figure 2. Aggregate gradation curve for 5.0% mineral filler gradation.

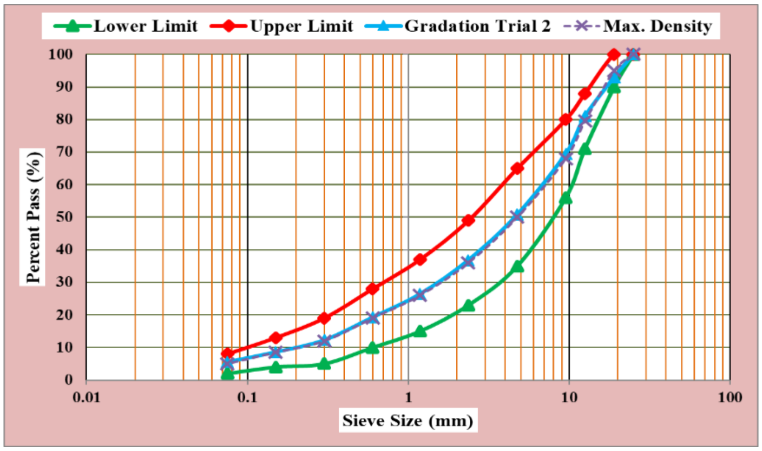

Figure 3. Aggregate gradation curve for 5.5% mineral filler gradation.

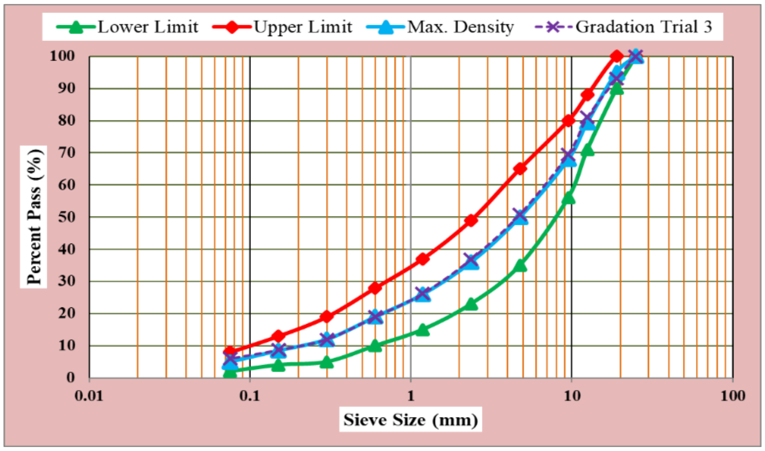

Figure 4. Aggregate gradation curve for 6.0% mineral filler gradation.

Bitumen Quality Test Result

For this study's performance, a series of bitumen quality tests were conducted as shown in Table 7 before the mix design was started.

Table 7. Physical properties of bitumen.

Test	Unit	Test method	Result	Recommended specification As ERA for bitumen 60/70
Penetration @ 25°C	1/10 mm	AASHTO T 49	65	60-70
Ductility @25 °C	cm	AASHTO T 51	108	min 50
Softening point	°C	AASHTO T 53	48	46-56
Specific gravity 25 °C	kg/cm^3	ASTM D-70-97	1022	---
Flashing point	°C	ASTM D-92	546	min 232

Crushed Stone Dust Mineral Filler Properties

The laboratory tests were conducted to evaluate the physical properties of crushed rock filler as shown in Table 8, which consists of the apparent specific gravity and plasticity index according to ASTMD-854, using the water Pycnometer method.

Table 8. Physical properties of filler material used.

S/N	Test description	Test method	Result	ERA Design standard specification 2002
1	Apparent specific gravity [kg/m^3]	ASTM D-854	2.848	N/A
2	Plasticity Index (PI)	ASTMD-423	NP	≤ 4
3	% passing 0.6 mm sieve	ASTM D-242	100	100
4	% passing 0.3 mm sieve	ASTM D-242	96.5	95-100
5	% passing 0.075 mm sieve	ASTM D-242	89.7	70-100

NP = Non-Plastic, N/A = Not Available

Analysis of Asphalt Mixture Properties

Marshall Test result of Control mix

The control mix design was prepared with three different aggregate gradations 5.0%, 5.5%, and 6.0% mineral filler content with five different bitumen content 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% to determine the optimum bitumen content and design gradation for the study. The control mix was used to govern the other RAPA replacement. For this study, all figures drawn to determine bitumen content were by 4th order degree because the data points those bitumen content values are five as shown in Table 9, Table 10, and Table 11.

Table 9. Marshall Properties of asphalt mixes with 5.0% mineral filler.

Marshall properties result from 5.0% Mineral filler by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/cm^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	8.05	2.371	16.64	50.27	8.7	2.19
4.5	6.37	2.389	16.44	60.34	9.7	2.54
5.0	3.96	2.403	16.38	69.69	10.6	2.96
5.5	2.55	2.413	16.48	83.34	10.2	3.48
6.0	1.71	2.421	16.65	90.84	9.2	3.84

The relationships between bitumen content and the mixture properties such as air voids, bulk specific gravity, VMA, VFA, stability, and flow by Marshall Method. As air void is decreasing with increased bitumen content, the value of stability and the unit weight of the total mix (bulk density) increases with increasing bitumen content up to pick a point and then gradually decreases although the increase in bitumen content. The value of voids filled with asphalt VFA and flow increases with an increase in bitumen content. In contrast, the percent of voids in mineral aggregate VMA decreases minimum value and increases as bitumen content increases. According to the NAPA mix design method criteria, the mix has 4.0% air voids at optimum bitumen content. Using this procedure, the optimum bitumen content was found to be 4.94% (by weight of the total mix). The laboratory test result of the mixture with an aggregate gradation of trial 2 was 5.5% mineral filler and the corresponding values of Marshall Properties for the control mix as shown in Table 10.

Table 10. Marshall Properties of asphalt mixes with 5.5% mineral filler.

Marshall properties result from 5.5% mineral filler by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/cm^3]	% VMA	% VFA	Stability [kN]	Flow [mm)
4.0	7.25	2.374	16.51	53.96	9.2	2.29
4.5	5.72	2.389	16.43	62.60	10.6	2.70
5.0	4.14	2.402	16.40	70.04	11.3	3.09
5.5	3.21	2.414	16.44	79.83	10.5	3.42
6.0	2.56	2.424	16.53	84.51	9.5	3.68

Its relationship between bitumen content and mixture properties with an aggregate gradation of 5.5% mineral filler is illustrated in Table 10. The mix's optimum bitumen content that resulted in 4.0% air voids of the specification is 5.10% from the graph drawn from air void vs bitumen content. The overall curve correlation between bitumen content and the Marshall properties for 5.5% mineral filler is similar to 5.0% mineral filler. Table 11 shows the obtained laboratory test result of the Marshall properties of the mix at different bitumen content with aggregate gradation with 6.0% mineral filler content.

Table 11. Marshall Properties of asphalt mixes with 6.0% mineral filler

Marshall properties result from 6.0% mineral filler by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/cm^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	7.10	2.373	16.57	57.15	9.7	2.39
4.5	5.89	2.388	16.45	64.17	10.8	2.90
5.0	4.70	2.402	16.40	71.32	11.2	3.32
5.5	3.41	2.413	16.48	78.68	10.6	3.69
6.0	2.54	2.423	16.57	84.69	9.4	3.85

The relationship between bitumen content and mixture properties with aggregate gradation 5.5% mineral filler. The optimum bitumen content of the mix that resulted in 4.0% air voids of the specification is 5.28%. The overall curve correlation between bitumen content and the Marshall properties for 6.0% mineral filler is similar to 5.0 and 5.5% mineral filler.

Determination of Optimum bitumen Content for Control mix (0% RAPA)

The optimum bitumen content for the control mix with three different aggregate gradations containing 5.0%, 5.5%, and 6.0% mineral filler was determined by using the Marshall test (ASTM D1559) and one of the methods called the National Asphalt Pavement Association (NAPA). According to the procedure that was suggested that the optimum bitumen content (OBC) was determined by finding the bitumen content, which corresponds to the median air void of 4.0% of the specification. This bitumen content Marshall Stability, Flow, VFA, VMA, and bulk specific gravity were determined. Depending on the result, the optimum bitumen content at 4.0% air voids is 4.94%, 5.1%, and 5.28 % by weight of total mix for the respective 5.0%, 5.5 %, and 6.0% crushed stone mineral filler. Table 12 summarizes the bitumen content corresponding to the standard specification criteria. The Marshall stability of a mixture of trial 1 (5.0% mineral filler content), trial 2 (5.5% mineral filler content), and trial 3 (6.0% mineral filler content) aggregate gradations were 10.3, 11.42, and 10.92 KN, respectively. It indicates that 5.5% mineral filler has maximum stability than the other two aggregate gradation trials. Therefore, 5.5% and 5.1% were selected as the optimum mineral filler content and optimum bitumen content, respectively.

Therefore these results, OBC and corresponding to other Marshall test properties of this mix gradation, were used as a control mix design, and RAP replacement, its moisture susceptibility, and rutting test were evaluated for further analysis of performance tests.

Table 12. Comparison of Marshall Properties of asphalt mixes with 5%, 5.5%, and 6% mineral filler with the specification.

Marshall properties	Marshall result of control mix			ERA 2002 specification limit		Asphalt institute limits		Status
	Trail 1 [5.0%]	Trail 2 [5.5%]	Trail 3 [6.0%]	Lower	Upper	Lower	Upper	
Optimum bitumen [%]	4.94	5.10	5.28	4	10	4	10	Ok
Stability [kN]	10.51	11.42	10.92	min 7	-	min 8.006	-	Ok
Flow value [mm]	2.86	3.10	3.49	2	4	2	3.5	Ok
VMA [%]	16.37	16.41	16.42	min 13	-	-	-	Ok
VFA [%]	67.54	71.6	74.98	65	75	65	75	Ok
Air Void [%]	4.00	4.00	4.00	3	5	3	5	Ok
Bulk specific gravity [g/cm^3]	2.400	2.404	2.406	-	-	-	-	-

Marshall Test Result of RAPA Replacement of Crushed Aggregate

The MarshallTest results of mixture properties mixed with 5.0% RAPA and 95% crushed aggregate are illustrated in Table 13. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content. The replacement RAPA in place of freshly crushed stone aggregate was performed based on selected design gradation of the control mix which is trial 2 presented in Table 6.

Table 13. Marshall Properties of asphalt mixes with 5.5% mineral filler and 5.0% RAPA replacement.

Marshall properties result from 5.5% CSD and 5% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/cm^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.69	2.372	16.59	53.97	8.5	2.33
4.5	5.26	2.388	16.45	62.61	9.9	2.75
5.0	4.01	2.404	16.36	70.08	11.0	3.12
5.5	2.98	2.413	16.47	79.85	9.8	3.48
6.0	2.00	2.423	16.58	84.52	8.2	3.71

The relationships between optimum bitumen content and mix properties contain 5% RAPA and 95% CSA. The relationships between bitumen content and the mixture properties such as air voids, bulk specific gravity, VMA, VFA stability, and flow curves are plotted. The optimum bitumen content was found equal to 5.04 by weight of the total mix. Table 14 presented the MarshallTest results of mixture properties mixed with 15% RAPA and 85% fresh Crushed Aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content was performed based on selected design gradation of the control mix which is trial 2 presented in Table 10.

Table 14. Marshall Properties of asphalt mixes with 5.5% mineral filler and 15% RAPA replacement.

Marshall properties result from 5.5% CSD and 15% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.70	2.360	16.20	58.63	8.3	2.36
4.5	5.23	2.383	15.94	66.73	9.4	2.85
5.0	3.79	2.400	15.73	73.67	10.2	3.26
5.5	2.70	2.406	15.88	82.77	9.8	3.56
6.0	1.72	2.412	16.13	89.32	8.6	3.78

The optimum bitumen content and mix properties contain 15% RAPA and 85% FCA. At 5.0%, the relationships between bitumen content and the mixture properties such as air voids, bulk specific gravity, VMA, VFA stability, and flow curves are plotted. The optimum bitumen content was found equal to 4.98 by weight of the total mix. Table 15 presented the MarshallTest results of mixture properties mixed with 25% RAPA and 75% freshly crushed stone aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content. As the RAPA replacement in 5.0% and 15% RAP aggregate in place of crushed aggregate was performed based on selected design gradation of the control mix which is trial 2 presented in Table 10.

Table 15. Marshall Properties of asphalt mixes with 5.5% mineral filler and 25% RAPA replacement.

Marshall properties result from 5.5% CSD and 25% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.53	2.362	16.11	59.46	8.1	2.40
4.5	5.01	2.382	15.83	67.29	9.2	2.83
5.0	3.63	2.399	15.70	74.93	9.8	3.28
5.5	2.48	2.408	15.82	83.71	9.7	3.56
6.0	1.48	2.415	16.03	90.77	8.4	3.79

The relationships between optimum bitumen content and mix properties contain 25% RAPA and 75% CSA and its optimum bitumen content were found equal to 4.87% by weight of the total mix. Table 16 presented the MarshallTest results of mixture properties mixed with 35% RAPA and 65% crushed aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content. All properties and gradation are performed as 5.0%, 15%, and 25%.

Table 16. Marshall Properties of asphalt mixes with 5.5% mineral filler and 35% RAPA replacement.

Marshall properties result from 5.5% CSD and 35% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.55	2.359	16.23	59.65	7.7	2.44
4.5	4.92	2.381	15.89	68.60	8.4	2.95
5.0	3.45	2.402	15.57	76.91	9.0	3.40
5.5	2.22	2.410	15.73	85.92	8.8	3.67
6.0	1.44	2.415	16.02	91.02	7.8	3.85

The relationships between optimum bitumen content and mix properties contain 35% RAPA and 75% CSA. The relationships between bitumen content and the mixture properties such as air voids, bulk specific gravity, VMA, VFA stability, and flow curves are also plotted as done before. The optimum bitumen content was found equal to 4.81% by weight of the total mix. Table 17 presented the Marshalltest results of mixture properties mixed with 45% RAPA and 55% freshly crushed stone aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content was performed.

Table 17. Marshall Properties of asphalt mixes with 5.5% mineral filler and 45% RAPA replacement.

Marshall properties result from 5.5% CSD and 45% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.18	2.364	16.03	61.46	7.0	2.49
4.5	4.72	2.381	15.76	69.65	7.9	3.13
5.0	3.19	2.396	15.55	78.43	8.1	3.60
5.5	2.02	2.410	15.73	87.20	7.5	3.89
6.0	1.38	2.415	16.01	91.40	6.7	4.07

The relationships between optimum bitumen content and mix properties contain 45% RAPA and 55% CSA. The optimum bitumen content was found equal to 4.74% by weight of the total mix. Table 18 presented the MarshallTest results of mixture properties mixed with 45% RAPA and 55% crushed aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content. All Marshall Properties and gradation used here were the same as used for bitumen content 5.0%, 15%, 25%, 35%, and 45%.

Table 18. Marshall Properties of asphalt mixes with 5.5% mineral filler and 55% RAPA replacement.

Marshall properties result from 5.5% CSD and 55% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	6.08	2.365	16.01	61.48	5.7	2.92
4.5	4.47	2.377	15.60	70.09	6.6	3.49
5.0	2.80	2.394	15.33	81.60	6.8	3.83
5.5	1.67	2.406	15.54	89.20	6.6	4.01
6.0	1.21	2.418	15.90	92.40	5.8	4.19

The relationships between optimum bitumen content and mix properties contain 55% RAPA and 45% FCA. The relationships between bitumen content and the mixture properties such as air voids, bulk specific gravity, VMA, VFA stability, and flow curves plotted the same as for bitumen content 5%, 15%, 25%, 35%, and 45%. The optimum bitumen content was found equal to 4.67 by weight of the total mix.

Table 19 presented the MarshallTest results of mixture properties mixed with 65% RAPA and 35% crushed aggregate. Marshall Properties of the mix at different bitumen content with aggregate gradation with 5.5% mineral filler content. All things here were also done as 5%, 15%, 25%, 35%, 45%, and 55%.

Table 19. Marshall Properties of asphalt mixes with 5.5% mineral filler and 65% RAPA replacement.

Marshall properties result from 5.5% CSD and 55% RAPA by wt. aggregate						
Bitumen content by wt. of total mix [%]	Air voids [%]	Bulk sg. [g/m^3]	% VMA	% VFA	Stability [kN]	Flow [mm]
4.0	5.84	2.369	15.86	63.17	5.7	2.92
4.5	4.85	2.376	15.66	69.06	6.6	3.49
5.0	3.10	2.400	15.26	79.71	6.8	3.83
5.5	1.59	2.416	15.54	89.78	6.6	4.01
6.0	1.23	2.416	15.98	92.34	5.8	4.19

The relationships between optimum bitumen content and mix properties contain 65% RAPA and 35% CSA and the optimum bitumen content was found equal to 4.53 by weight of the total mix. This trial was done to be sure that the next replacement was not recommended.

OBC determination for each RAP Aggregate Proportion with CA

The optimum bitumen content for each RAPA Proportion is determined according to NAPA (National Asphalt Pavement Association, The bitumen content corresponds to the specification's median air void content (4 percent typically) of the specification. This is the optimum bitumen content. The bitumen content is then used to determine the value for Marshall Stability, VMA, flow, bulk density, and percent voids filled from each of the plots. Compare each of these values against the specification values for that property, and if all are within the specification range, the bitumen content at 4 percent air voids is optimum bitumen content. If any of these properties are outside the specification range, the mixture should be redesigned. Table 20 presented the Marshall Test results of mixture properties with a 5.5% mineral filler and different RAPA contents. The comparison with the standard specification is also illustrated, except 55% and 65% of all replacements satisfied for ERA 2002 and Asphalt institute manuals.

Table 20. Summary of Marshall Properties for control and replacement

Marshall properties	Marshall result of control mix and replacement								ERA 2002 specification limit		Asphalt institute limits	
	0	5	15	25	35	45	55	65	Lower	Upper	Lower	Upper
Optimum bitumen [%]	5.10	5.04	4.98	4.87	4.81	4.74	4.67	4.53	4	10	4	10
Stability [kN]	11.42	10.98	10.45	9.74	8.98	8.11	6.70	6.10	min 7	--	min 8.006	
Flow [mm]	2.86	3.10	3.14	3.19	3.25	3.31	3.45	3.51	2	4	2	3.5
VMA [%]	16.41	16.37	15.80	15.69	15.61	15.54	15.48	15.40	min 13	--	--	
VFA [%]	71.60	71.90	72.60	73.25	74.00	74.68	74.87	75.36	65	75	65	75
Air Void [%]	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3	5	3	5
Bulk specific gravity [g/cm^3]	2.404	2.401	2.399	2.395	2.392	2.388	2.383	2.379	_	_	_	_
status	OK	OK	OK	OK	OK	OK	Not satisfied.	Not satisfied.				

Discussion and Analysis of Marshall Test results at optimum bitumen content

After the Marshall properties of asphalt mixture mixed with different percentages of RAP aggregate at each optimum bitumen content were determined, the next step was to evaluate RAP aggregate's potential effect on Marshall Properties. Since the objective of the study was to determine the effect of RAP aggregate on Marshall Properties, it is important to evaluate how the Marshall properties were changed by the addition of recycled percentage in the asphalt mix. The effect of RAP aggregate on Marshall Properties was evaluated based Control mix of the study and standard specification. Using the conventional mix's Marshall Properties, we can evaluate the other Marshall Properties results mixed with different RAP aggregate percentages. Furthermore, the value of Marshall Properties obtained at each OBC mixed with different RAPA percentages compared to the ERA design standard specification to evaluate the effects and determine the maximum RAP aggregate used in hot mix asphalt (HMA). Based on Marshall Properties' test result at each of the optimum bitumen content mixed with different percentages of RAP aggregate presented in Table 18.

Effect of RAPA on Bitumen content

The experimental results in Table 20 and Figure 5, the value of optimum bitumen content mixed with 0% RAPA aggregate (control mix) is greater than the other mixes 5%, 15%, 25%, 35%, 45%, 55%, and 65% RAP aggregate. From this, it can be noticed that the optimum bitumen content is decreased as Reclaimed Asphalt Pavement RAP aggregate is increased. This is due to the old bitumen, filled by the pore of the RAP aggregate. Moreover, increasing RAP from zero to 65% decreases the optimum bitumen content from 5.1 to 4.74%. This means that saving in optimum bitumen content by about 7.05% is achieved. But the bitumen might be old, so it is not considered as a high benefit.

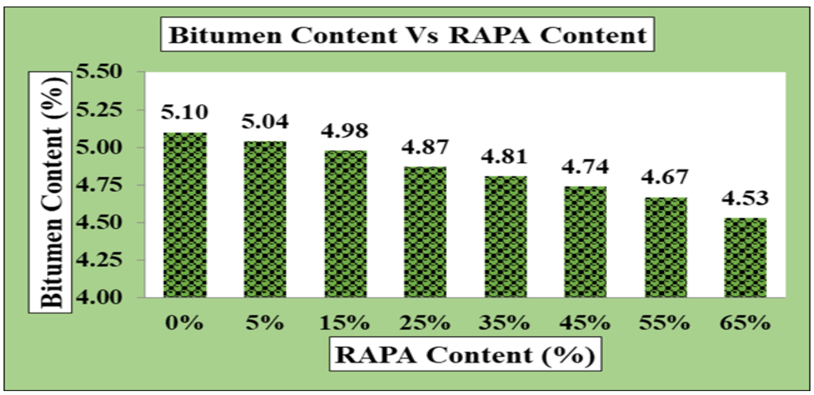

Figure 5. Comparison of Bitumen Content result at each RAPA percentage.

Effect of RAPA on Bulk specific gravity

RAPA has an unpronounced effect on the bulk density and its result with different RAPA percentages is presented in Table 11 and Figure 6; from this result, it was noticed that the value of Bulk density is decreased up to 65% RAPA replacement. This may be due to the Aggregate's bulk specific gravity, which means the bulk specific gravity of aggregate decreases.

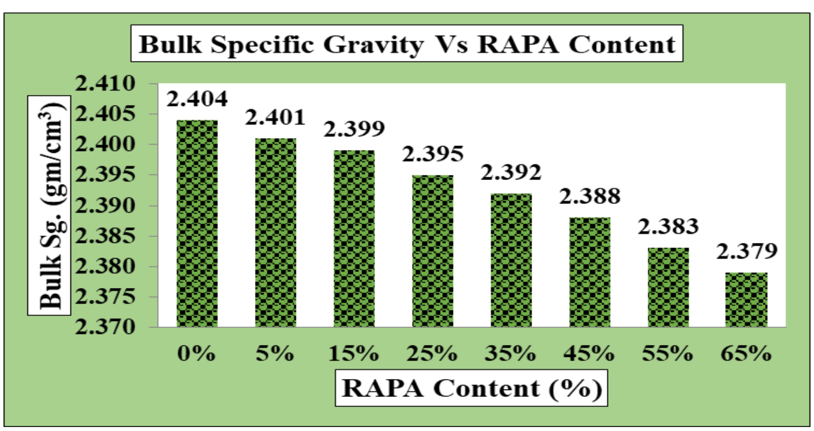

Figure 6. Comparison of bulk specific gravity result at each RAPA percentage.

Effect of RAPA on the void in mineral aggregate

Void in mineral Aggregate is the volume of intergranular void space between the aggregate particles of a compacted paving mixture, including air voids and bitumen volume not absorbed by aggregate. The mix's durability increases with thin layer thickness on the aggregate particles, and minimum requirements for VMA are recommending getting a more durable pavement structure. VMA value at OBC presented in Table 18 and Figure 7 was used to evaluate RAP aggregate effect on VMA. As we see in (Figure16) the VMA mix value is greater in 0% RAPA (control mix) and decreased to RAPA replacement of up to 65%. This shows that the Void in mineral aggregate is decreased with the increase in both bitumen content and RAP percentage in the mixture. This may be due to the Recycled aggregate and bitumen being perfectly blended with virgin materials and filling the space between compacted materials.

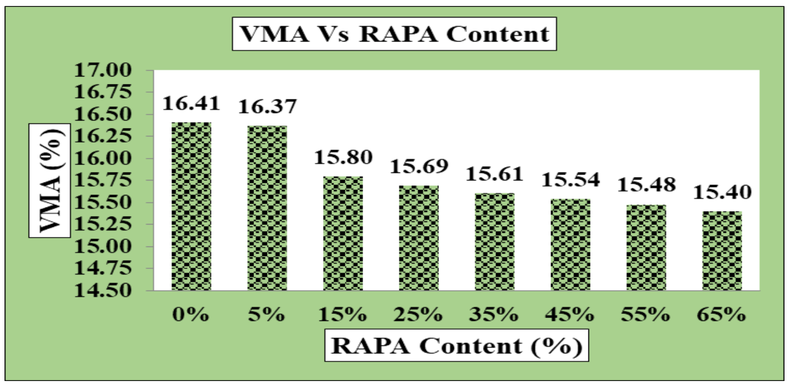

Figure 7. Comparison of VMA result at each RAPA percentage.

Effect of RAPA on void filled with asphalt

The VFA represents the volume of the effective bitumen content and ensures that the effective asphalt part of the VMA in a mix is not too little or too great and helps avoid those mixes subject to rutting in heavy traffic situations. The value of VFA at optimum bitumen content was present in Table 20 and Figure 8 identifies that the VFA the result of the conventional mix (0% RAP) was small rather than the VFA value mixed up to 65% RAPA replacement. Generally, this shows that VFA value increases as RAPA in the mix increased ease due to old bitumen in the replaced aggregate.

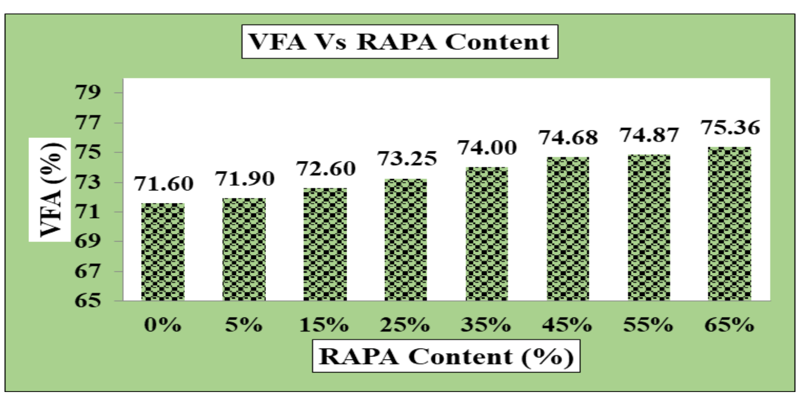

Figure 8. Comparison of VFA result at each RAPA percentage.

Effect of RAPA in stability

Marshall Stability is the most important parameter to know the maximum load resistance that the specimen will achieve at 60°C under specified conditions in the asphalt mix design. Stability is always related to an aggregate gradation; the coarse aggregate gradation in the mix has higher stability rather than fine aggregate gradation. The result of stability at Optimum bitumen content is presented in Table 20 and Figure 9 to determine the potential effect of RAPA on Marshall Stability. From Figure 9 we have obtained that the value of stability at 0% RAPA (control mix) is greater than the value of stability mixed with the different percentages of RAPA. The value of stability decreases gradually up to 45% RAPA replacement, and after that, it becomes out of the range. This may be due to the Recycled aggregate being used material and loaded before, so it becomes finer than virgin crushed stone aggregate, which has less stability than coarse aggregate.

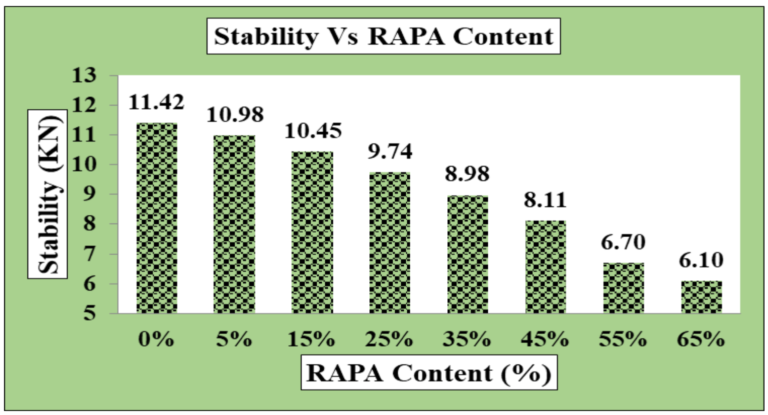

Figure 9. Comparison of stability result at each RAPA percentage.

Effect of RAPA on a flow

Flow in hot mix asphalt is an indicator of resistance to permanent vertical deformation. High flow values indicate that the mix contains a high amount of asphalt binder that fills all voids and affects the resistance to permanent deformation under traffic; in contrast, low flow values may indicate a mix has higher voids and insufficient asphalt binder, so it causes a crack mixture to become brittle. From Figure 10 we have seen that the value of Marshall Flow increases as the percentage of RAP aggregate increases. We see that the flow result mixed with 0% RAP aggregate has a minimum value rather than RAPA replacement up to 65% from the value presented. When the RAP aggregate increases from zero to 65%, the mix flow value is increased but in the range of specifications. Here we see that the RAP aggregate content in hot mix asphalt can affect the value of Marshall Flow.

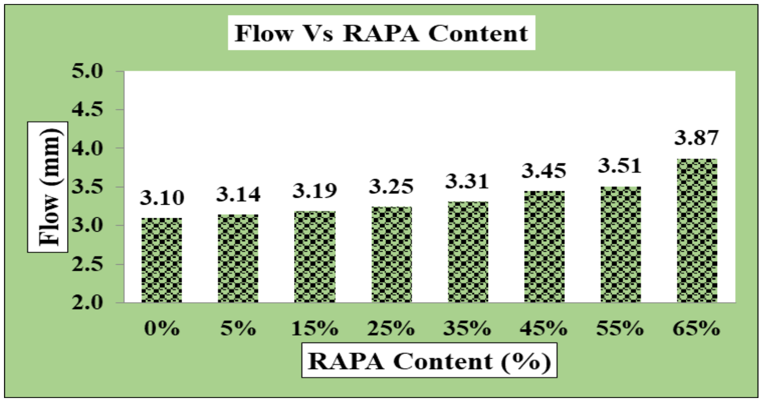

Figure 10. Comparison of flow results at each RAPA percentage.

Performance tests

Effects of RAP on Moisture Susceptibility of HMA

The Moisture damage of HMA is evaluated based on by comparing the mixes of several properties before moisture cases of conditioning and after it. The tensile strength ratio (TSR) is used to predict the moisture susceptibility of the mixtures. In this study, a total of 42 samples were prepared with a varying percentage of RAP 0% (Control mix) 5%, 15%, 25%, 35%, and 45% by weight of aggregate using optimum bitumen content of each replacement.

Indirect Tensile Strength

The dry and wet-conditioned specimens were subjected to indirect tensile strength, and the result obtained for both cases were averaged. Table 21 indicates the results obtained from the indirect tensile strength (ITS) test.

Table 21. Summary indirect tensile strength test results

RAPA content [%]	OBC [%]	Indirect tensile strength [kPa]		TSR [%]
		Unconditioned	Conditioned	
0%	5.10	760.0	699.6	92.05
5%	5.04	750.9	684.5	91.16
15%	4.98	717.8	646.2	90.03
25%	4.87	708.2	625.1	88.27
35%	4.81	695.7	604.1	86.83
45%	4.74	673.7	575.5	85.42

As shown in Figure 11, the indirect tensile strength (ITS) test result for the control mix and mixes containing RAP. The laboratory results of indirect tensile strength of conditioned samples have different values as compared to unconditioned specimens. As observed in Figure 11 below the values of indirect tensile strength of the two cases increase with an increase RAP until the optimum replacement proportion is up to 55%, and it has a higher value of the control mix. The obtained results of the control sample (0%RAP) and mix prepared with replacement proportion RAP, i.e. 5%, 15%, 25%, 35%, and 45 %, both for the un-conditioned, and conditioned or wet sample were 760 kPa, 750.9 kPa, 717.8 kPa, 708.2 kPa, 695.7 kPa, and 673.7 kPa, and 699.6 kPa, 684.5 kPa, 646.2 kPa 625.1 kPa, 604.1 kPa, and 575.5 kPa respectively.

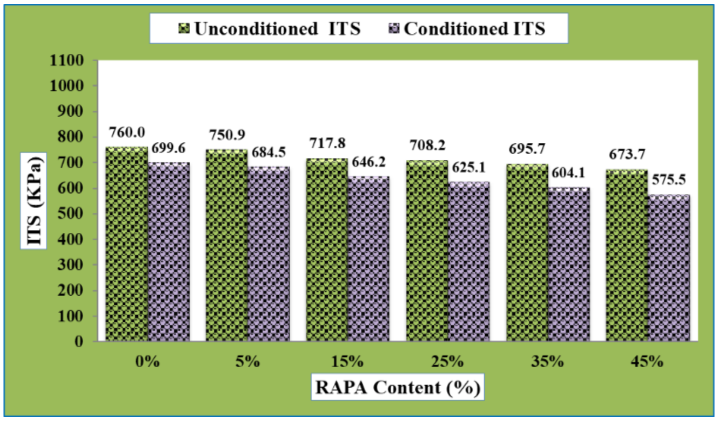

Figure 11. Unconditioned and conditioned ITS of HMA with varying percentages of RAPA.

Tensile Strength Ratios (TSR)

Figure 12 shows the tensile strength ratio for both control and RAP mixtures of HMA. As displayed in the graph below, the TSR values decrease with increasing RAPA content. The highest TSR value is 92.06 kPa at the control mix and the minimum TSR value is 85.42 KPa at 45% RAPA content in the mix. Therefore, it can be said that the RAPA mix is highly susceptible to moisture damage compared to mixes containing the control mix and the moisture damage rises with an increase in RAPA content. But, all the mixes have the potential to resist moisture damage since the TSR values obtained are greater than the recommended standard specification 80%.

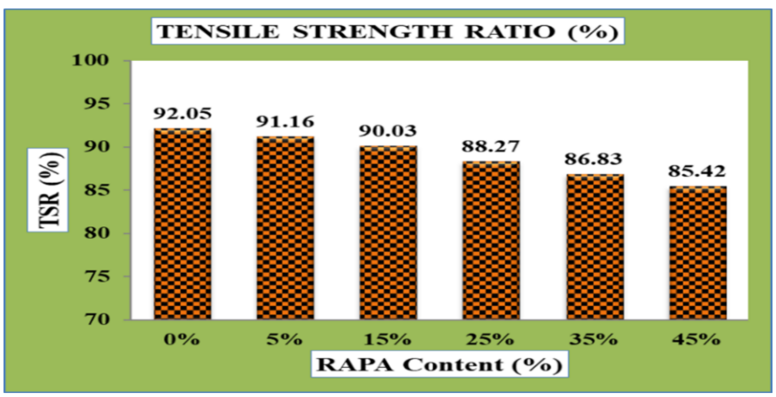

Figure 12. Tensile strength ratio (TSR) of HMA mixture containing RAPA.

Rutting test

The most basic element in the performance of asphalt is its resistance to rutting. It causes the loss of road surface regularity, which evidently has a negative impact on the quality of service to users. Resistance to rutting the wheel tracking test was performed for both control and the highest allowable RAPA replacement mixes. Figure 13 illustrated the laboratory test result for both control mixes. 100% FCR or control mix had a better rutting resistance in performance than mix blend with recycled asphalt pavement aggregate. Figure 13 illustrates rut depth with respect to the number of passes. The comparison showed that the rutting that occurred in the samples blended mix with recycled asphalt pavement aggregate at temperatures 60^{o}C is less than that of the control mix or freshly crushed stone aggregate. But the result was almost the same average rutting depth. Figure 13 also showed the rate of deformation decreased as the depth of rutting increased.

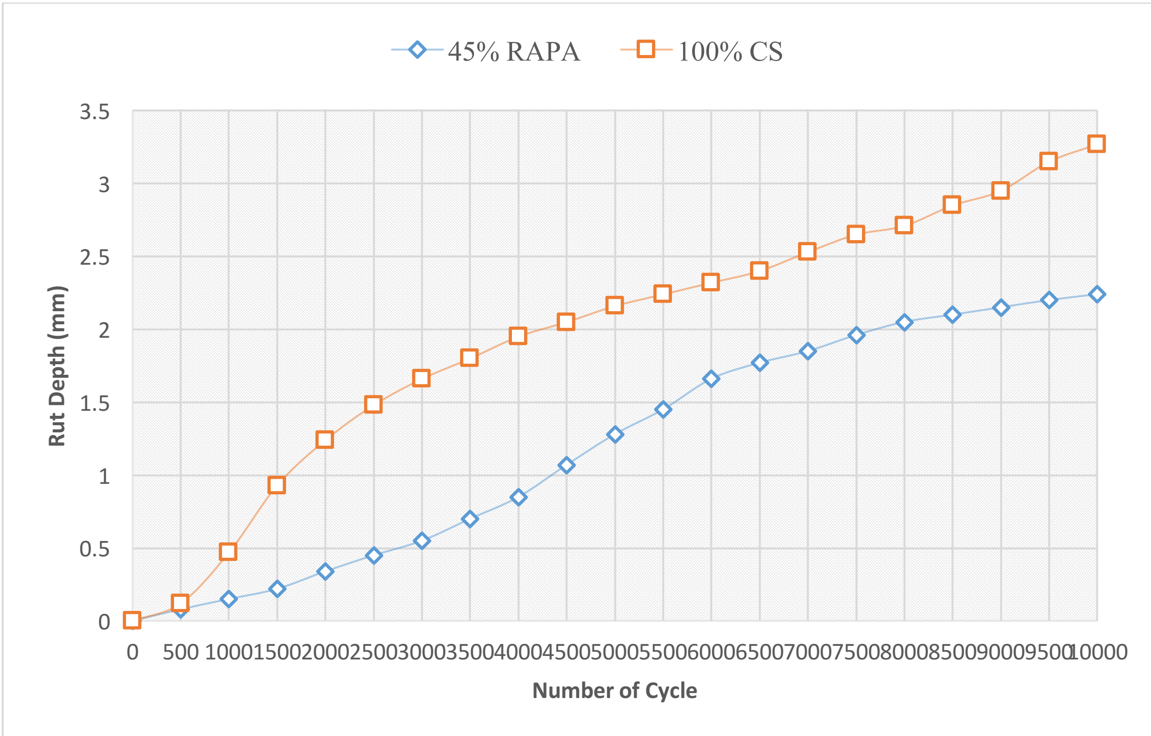

Figure 13. Wheel Tracking Test results for conventional and RAPA replacement.

Comparison of rutting result with specifications

Table 22 showed the result of the conventional or control mix and the modified mix satisfies the requirement. It showed that recycled asphalt pavement aggregate replaces up to 45% of freshly crushed stone aggregate by the weight of aggregate that is used in the control mix.

Table 22: Comparison of rutting performance of asphalt mix control and RAPA with standard specification.

Results of the UNE-EN 12697- 22 wheel-tracking test					
Mix name	WTS_{AIR} =(d10000−d5000)/5 (mm/10^3 load cycles)	PRD [%] =((RD)*100/h)/2))	Mean RD [mm]	Specification as per EN 13108	
				PRD [%]	RD [mm]
100%CA	0.222	6.540	3.270	< 9	< 6.5
55%CA&45%RAPA	0.192	4.480	2.240	< 9	< 6.5

Determination of Maximum percentage of using RAPA in HMA

Depending on the physical property of materials, Marshall Stability results and the performance tests moisture susceptibility and rutting compression of Marshall Properties with based on the standard specification were determined based on the maximum RAPA percentage. The maximum amount of RAPA in hot mix asphalt is replaced up to 45% only; i.e.; 45% RAPA mixed with Freshly crushed stone aggregate satisfies the required standard specification range, which is illustrated in ERA, Pavement Design Manual, 2013 and Asphalt institute Ms-2, Sixth Edition.

CONCLUSIONS

Based on this experimental study the following conclusion was made, the engineering properties of selected materials used in this study such as aggregates (extracted RAP and CSA), filler, and bitumen laboratory tests were conducted based on the standard test procedures of ASTM, AASHTO, and BS. This material satisfies the required standard specification of the quality test indicated in the Asphalt institute standard specification and Ethiopian road authority; consequently, RAPA can be used in HMA production based on the pretest that is conducted and satisfies the specification. In order to determine the optimum bitumen content three different aggregate gradation size which contains 5%, 5.5%, and 6% mineral filler with five different amounts of bitumen content 4%, 4.5%, 5.0%, 5.5%, and 6.0% by weight of the total mix was prepared. Therefore, aggregate gradation containing a 5.5% mineral filler has maximum stability, with 5.1% of optimum bitumen content of 5.0% among the three aggregate gradations. To determine RAPAs optimum bitumen content to each replacement percentage 5%, 15%, 25%, 35%, 45%, 55%, and 65% with five different bitumen content 4 %, 4.5%, 5%, 5.5%, and 6% by weight of total mix have done by using NAPA method and determine each Marshall and volumetric properties stability and flow. Consequently, except 55% and 65%, all replacements were under standard specifications. At 45% RAPA with 4.74% optimum bitumen content replacement of freshly crushed stone aggregate, the mixture properties such as Marshall Stability, flow values, and volumetric properties are satisfied with the ERA Pavement Design Manual and asphalt institute specification limits. The Tensile Strength Ratio value decreased as the RAPA content increased, but highly satisfied the standard specification, and the mix provides resistance to moisture-induced damage. Rutting depth is also permitted in EN standard specification, so that this mix design provides resistance to deformation. The obtained value of Tensile Strength Ratio, proportional rut depth and mean rut depth on 45% RAPA replacement was 85.42% and 4.48%, 2.24 mm respectively. As a whole, based on laboratory studies it was concluded that a maximum of 45% RAPA can be as crushed aggregate in the hot mix asphalt.

RECOMMENDATIONS

Pavement construction, maintenance, and rehabilitation are increasing in Ethiopia; about 95% of

Hot-mix asphalt is constructed from various types of aggregate sources. An endeavor to work on replacing construction materials is to be done by road authorities and any other concerned bodies. The Reclaimed Asphalt Pavement aggregate (RAPA) is recommended to use in hot mix asphalt mixes instead of pure crushed aggregate with minimum bitumen content to save the natural resource. RAP aggregate content is changing the value of volumetric parameters, so it is important to know the relationship between those two variables (RAPA and CA) during the Asphalt mix design. A percent of RAPA up to 45 is suitable to be used in flexible pavement construction during hot mix production for the study.

REFERENCES

Abu Abdo, A. M. 2015. Utilizing Reclaimed Asphalt Pavement (RAP) Materials in New Pavements—A Review. *International Journal of Thermal and Environmental Engineering*, *12*(1). https://doi.org/10.5383/ijtee.12.01.008

Alwetaishi, M., Kamel, M., & Al-Bustami, N. 2019. Sustainable applications of asphalt mixes with reclaimed asphalt pavement (RAP) materials: Innovative and new building brick. *International Journal of Low-Carbon Technologies*, *14*(3), 364–374. https://doi.org/10.1093/ijlct/ctz023

Belay, S., Quezon, E. T., & Geremew, A. 2021. Effect of Selected Conventional and Non-conventional Mineral Fillers with ‘Enset’ Fibers on Compaction Characteristics of Stone Mastic Asphalt Pavement (SMAP). *Jordan Journal of Civil Engineering*, *15*(1), 11.

Geraldin, J., & Makmur, A. 2020. Experimental Study on the Effects of Reclaimed Asphalt Pavement towards Marshall Parameters on Asphalt Course-Wearing Course. *IOP Conference Series: Earth and Environmental Science*, *498*, 012025. https://doi.org/10.1088/1755-1315/498/1/012025

Gonfa, L. G., Tucay Quezon, E. T. Q., & Geremew, A. 2020. EXPERIMENTAL STUDY ON APPLICATION OF MARBLE WASTE AS CONVENTIONAL AGGREGATE FOR BASE COURSE MATERIALS. *Journal of Civil Engineering, Science and Technology*, *11*(2), 144–163. https://doi.org/10.33736/jcest.2620.2020

Hidalgo, A. E., Moreno-Navarro, F., Tauste, R., & Rubio-Gámez, M. C. 2020. The Influence of Reclaimed Asphalt Pavement on the Mechanical Performance of Bituminous Mixtures. An Analysis at the Mortar Scale. *Sustainability*, *12*(20), 8343. https://doi.org/10.3390/su12208343

Hrůza, P., Blahuta, J., Pelikán, P., Olišarová, L., Nedorost, J., Mikita, T., & Patočka, Z. 2020. Recycled Asphalt as an Alternative to Natural Aggregates for Forest Road Reinforcement. *Croatian Journal of Forest Engineering*, *41*(1), 149–161. https://doi.org/10.5552/crojfe.2020.571

Pourtahmasb, M. S., & Karim, M. R. 2014. Utilization of Recycled Concrete Aggregates in Stone Mastic Asphalt Mixtures. *Advances in Materials Science and Engineering*, *2014*, 1–9. https://doi.org/10.1155/2014/902307

Pradhan, S. K., & Sahoo, U. C. 2021. Evaluation of recycled asphalt mixtures rejuvenated with Madhuca longifolia (Mahua) oil. *International Journal of Pavement Research and Technology*, *14*(1), 43–53. https://doi.org/10.1007/s42947-020-0279-6

Pranav, S., Aggarwal, S., Yang, E.-H., Sarkar, A. K., Singh, A. P., & Lahoti, M. 2020. Alternative materials for wearing course of concrete pavements: A critical review. *Construction and Building Materials*, *236*, 117609.

Roja, K. L., Masad, E., & Mogawer, W. 2020. Performance and blending evaluation of asphalt mixtures containing reclaimed asphalt pavement. *Road Materials and Pavement Design*, 1–17. https://doi.org/10.1080/14680629.2020.1764858

Schaefer, V. R., Stevens, L., White, D., & Ceylan, H. 2008. *Design Guide for Subgrades and Subbases* (p. 134) [Final Report]. Iowa Highway Research Board (IHRB Project TR-525).

Seyfe, M., & Geremew, A. 2019. POTENTIAL USE OF CINDER GRAVEL AS AN ALTERNATIVE BASE COURSE MATERIAL THROUGH BLENDING WITH CRUSHED STONE AGGREGATE AND CEMENT TREATMENT. *Journal of Civil Engineering, Science and Technology*, *10*(2), 101–112. https://doi.org/10.33736/jcest.1465.2019

Shiferaw, A. 2017. *Productive Capacity and Economic Growth in Ethiopia*. 1-24.

Singh, A. K., Kulshreshtha, A., Banerjee, A., & Singh, B. R., 2020. *Nanotechnology in road construction*. 050002. https://doi.org/10.1063/5.0000772

Swiertz, D., Mahmoud, E., & Bahia, H. U. 2011. Estimating the Effect of Recycled Asphalt Pavements and Asphalt Shingles on Fresh Binder, Low-Temperature Properties without Extraction and Recovery. *Transportation Research Record: Journal of the Transportation Research Board*, *2208*(1), 48–55. https://doi.org/10.3141/2208-07

Tarsi, G. Tataranni, P., & Sangiorgi, C., 2020. The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials*, *13*(18), 4052. https://doi.org/10.3390/ma13184052

West, R. C. 2010. *RECLAIMED ASPHALT PAVEMENT MANAGEMENT: BEST PRACTICES* (NCAT Report XX-XX; p. 34). National Center for Asphalt Technology at AUBURN UNIVERSITY.