PERFORMANCE EVALUATION OF LABORATORY PRODUCED POLYMER MODIFIED ASPHALT MIXTURE CONTAINING HIGH RAP CONTENT

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

I dedicate this effort to my parents for being a source of inspiration, affection, and guidance to me.

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I express my sincerest gratitude to everyone who stood by me and believed in me in order to make this possible. Words cannot suffice the appreciation and gratitude towards my advisor Dr. Arshad Hussain, whom with timely, holistic, and sincere counseling enabled me to complete my research work.

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I am thankful to PARCO for providing me bitumen of penetration grade 60/70.

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ABSTRACT

Now a day in Pakistan, many roads including Motorways and Highways are reconstructing and resurfacing. Hence, tons of asphalt have been wasted. By wasting the RAP, natural resources and major portion of our finances are depleting. The sustainability of our next generation depends upon the availability of natural resources. From the last two decades, it is a worldwide practice to use the already used materials i.e., RAP in pavement construction. Many research studies have suggested that, utilizing RAP not only reduces the wastes but also minimizes the need of natural aggregates and virgin binder. Likewise, when RAP is being used it improves the performance of pavement structure. RAP being aged material, possesses more stiffness due to various environmental effects hence making it more vulnerable to thermal and fatigue and moisture susceptible. Rejuvenators are used to decrease the viscosity of aged binder. In this study RAP is being used in percentages of 0, 30, 40 & 50 along with 1% Elvaloy Polymer and 40% RAP combinations. Marshall mix design was used to determine the OBC and volumetrics of control mix, and RAP binder content was found by ignition test method.

Fatigue, Rutting and Moisture parameters of RAP modified Asphalt mix were studied using Four-point beam fatigues test, Double wheel tracker test, Indirect tensile strength test approaches, respectively. Dissipated energy approach is used to determine the fatigue property of RAP modified Asphalt mix which is based on the internal damage produced in asphalt mixture used in this research. Dissipated energy allows to predict fatigue life of asphalt mix without performing millions of loading cycle unlike in traditional phenomenological approaches. Dissipated energy ratio (DER) was calculated at every 100 loading cycles and a graph was plotted. Plateau value (PV), which is constant value of DER, was calculated at loading cycles corresponding to 50% of initial stiffness for each mix. Fatigue life of RAP content and polymer modification on asphalt mixture was found in terms of PV. PV is considered as the sole parameter to measure the fatigue property of asphalt mixtures. Higher PV indicates more fatigue susceptibility of asphalt mixture and vice versa. Four-point bending test was performed on the asphalt mixture beams at 20^{o}C temperature and 10 Hz loading cycles. The test was performed at controlled strain mode at fixed strain level of 500ms. Indirect tensile strength (TSR) was performed to assess the moisture susceptibility in terms of TSR (tensile strength ratio) of polymer and RAP modified asphalt mixtures. From this study it is concluded that, 30% and 40% RAP modified asphalt mixtures showed increment in the fatigue life and 50% RAP modified asphalt mix shows almost similar fatigue strength as of unmodified asphalt mixture. However, Elvaloy modified binder along with 40% RAP mix has shown insignificant effect on the fatigue life asphalt mixture. Also, 40% RAP modified and 40% RAP & 1% Elvaloy modified asphalt mixtures showed an increase of 23% and 44% in the rut resistance, respectively. Moreover, 40% RAP modified mixtures have slightly increased the moisture susceptibility of asphalt mixture, while 40% RAP & 1% Elvaloy Polymer has also increased the TSR value.

Keywords: Reclaimed Asphalt Pavement (RAP), Elvaloy Polymer, Plateau Value (PV), Indirect Tensile Strength (ITS), Dissipated Energy Ratio (DER). Double Wheel Tracker (DWT).

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LIST OF ABBREVIATIONS

RAP - Reclaimed Asphalt Pavement

HMA - Hot Mix Asphalt

TSR - Tensile Strength Ratio

DWT - Double Wheel Tracker

OBC - Optimum Binder Content

ASTM - American Society for Testing and Materials

AASHTO - American Association of State Highway & Transportation Official

JMF - Job Mix Formula

NHA - National Highway Authority

SG - Specific Gravity

IDT - Indirect Tensile Strength Test

TSR - Tensile Strength Ratio

DER - Dissipated Energy Ratio

PV - Plateau Value

CHAPTER 1

INTRODUCTION

1.1 Background

The transportation of people and goods in Pakistan, being a developing country, majorly depends upon the road network in Pakistan. Reusing or recycling of asphalts in pavement construction is a profitable method for methodological, efficient, or cost-effective and natural reasons. RAP with unused or virgin content has been preferred due to the rising expense of bitumen, the scarcity of high-quality aggregates, and the pressing need to safeguard the environment. Many state offices have likewise detailed huge savings in funds when RAP is utilized. Considering material and development costs, it was evaluated that utilizing recovered HMA asphalt gives economical savings from 14 to 34% for a RAP content going from 20 to 50%. Throughout the year, transportation being the backbone of a country's economy, the bulk of our finances is spent on maintenance and rehabilitation of previously constructed roads and for new road projects. In Pakistan, every year billions of rupees are only allocated to serve this purpose. Pavements play a significant role in prosperity and development of a country. And with an increase in its meaning, its use is improving day by day.

The roads need to be sustainable and durable for the efficient movements of goods and people. Recycled materials and various modifiers are continuously being used, to enhance the sustainability and durability of the pavements. Using RAP materials with virgin asphalt binder, on the other hand, degrades the performance attributes of asphalt mix, especially when utilised in greater content levels. Several studies have been conducted to evaluate the effect of different polymers on performance of asphalt binder. In this study, asphalt mix consisting of elvaloy (polymer) modified binder incorporating various percentages of RAP will be evaluated in terms of rutting and fatigue performance. Moreover, the moisture susceptibility of the asphalt mix will also be studied in terms of tensile strength ratio (TSR).

1.2 Problem Statement

Since asphalt is mainly a mixture of various constituent materials i.e., aggregate and bitumen and recently many major roads in Pakistan were reconstructed and tons of asphalt is going to waste. By wasting the RAP, we are not only wasting our money but also minimizing the natural resources and, in this way, we may have to purchase the bitumen at higher prices from other countries. Pakistan being passing through financially weakened situation, trying hard to meet the demands of infrastructural development. Since it is yet a developing country whose economy needs to be strengthen by saving financial as well as natural sources from their depletion. Keeping the declining financial condition of country in our mind, this study aims to make the reuse of RAP (in various percentages) possible by modifying bitumen with elvaloy polymer. The reuse of RAP in our construction industry help save our county's economy to make it financially stable and also save the natural resources of our country for our future generation. It will also as save energy especially in the case of in place recycling technique used for the construction of the roads.

The problem under discussion signifies the need of a study to test mix designs with varying percentages of RAP along with the polymer modified bitumen under numerous performance conditions. Double Wheel Tracker (DWT) test for rutting at room temperature under dry condition is carried out along with tests to find Fatigue Performance by Four point beam fatigue test, and Moisture Susceptibility of the asphalt mix in terms of tensile strength ratio (TSR).

1.3 Research Objectives

- ✓ To investigate the impact of a high RAP concentration on asphalt mix rutting performance incorporating polymer modified binder.
- ✓ To investigate the impact of a high RAP concentration on asphalt mix fatigue performance incorporating polymer modified binder.
- ✓ To investigate the impact of a high RAP concentration on asphalt mix moisture susceptibility performance incorporating polymer modified binder.
- ✓ To optimize the RAP content for asphalt mix having polymer modified binder.

1.4 Scope of the Thesis

To achieve the desired objectives of this research, a plan was devised, and the research essential tasks were imprinted. A comprehensive literature review was carried out on Marshall Mix design, RAP incorporation in HMA, Rutting, Double Wheel Tracker (DWT), Fatigue Performance by four point beam fatigue test, Moisture Susceptibility, and Tensile Strength Ratio (TSR).

The matrix for various tests is formulated hereunder:

Table 1- 1 Test matrixes for Marshall Mix Design

S. No	Bitumen Content	No. of samples
1	3.5	3
2	4	3
3	4.5	3
4	5	3
5	5.5	3
	Total	15

Margalla crush was acquired and NHA-B gradation was followed with PARCO 60/70 binder. Marshall Mix Design Method was used to determine OBC (Optimum Binder Content).Samples were prepared for Double Wheel Tracker (DWT) test, four point beam fatigue test, Tensile Strength Test (TSR), and Moisture Susceptibility Test following the standard test procedures of ASTM/AASHTO. However, for DWT samples were sawed using Diamond Saw.

1.5 Thesis Organization

The research thesis has been organized into Five Chapters and summarized below.

Chapter One explained the overview and background of the RAP, it's importance from reuse perspectives, Marshal Mix Design, Problem Statement, Objectives of this research study and scope of the study.

Chapter Two contains a literature review and background analysis of the various features of RAP when employed in Pavements**.** This chapter explains the previous work done on RAP relevance to the field of pavement engineering.

Chapter Three The experimental programme is discussed in depth. It covers the fundamentals of experimental setup and sample preparation for RAP and polymer modified mixtures, as well as test methods, input and output restrictions, and their significance.

Chapter Four contains the discussion of results obtained through extensive and detailed experimental work. Results were compiled comprehensively in this chapter. Different graphs, charts, tables and all the necessary data related to the experimental program was described in detail in this chapter.

Chapter Five consists of the analysis and conclusions of conducted research and contains the recommendations made for forthcoming work based on research study and methodology adopted for this research work.

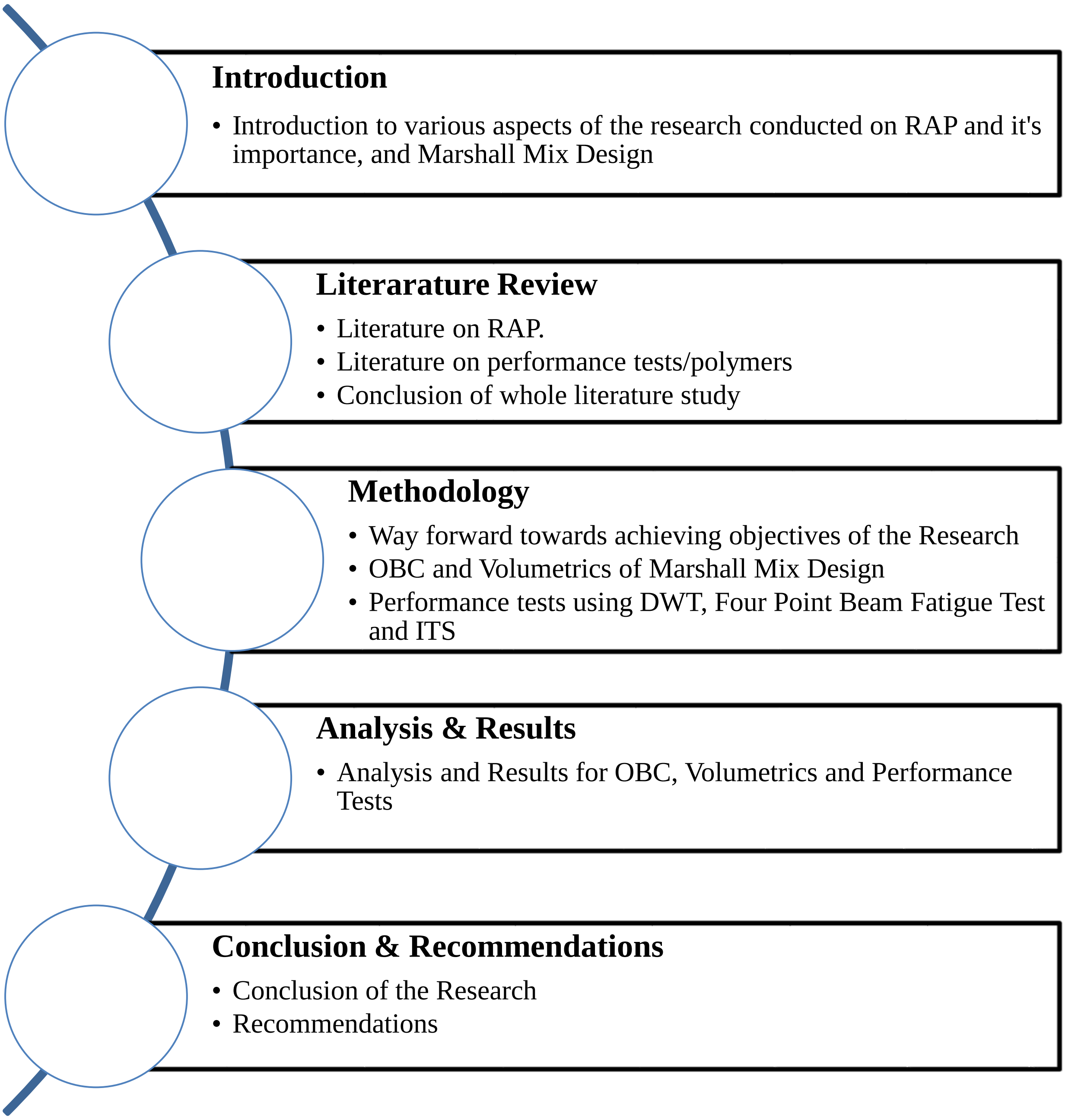


Figure 1- 1 Organization of Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 Background

A well-maintained road network is crucial to a country's social and economic prosperity. The number of kilometres of paved roads in a country is frequently cited as an indicator of its growth. (Aldagheiri, 2009). Hence it is important to invest into the extension & development of road transport infrastructure. Asphalt has been widely used for building pavement for a long time and bitumen is its main constituent. Bitumen being black in color dominates when mixed with aggregates. This black colored pavement is conventional and being used globally.

During summer, due to visco-elastic nature of asphalt, mix rutting is one of the major distress under vehicular loading as the temperature of (black colored) pavement surface rises significantly (Du & Wang, 2015). In this context, conventionally used black colored pavements are unable to meet the practical demands for current and future traffic loadings. Thus, higher quality, more safe, more reliable and more environment friendly (light colored and cool) pavement materials are urgently demanded (Li, Xiao, Amirkhanian, You, & Huang, 2017). Different types of polymers and modifiers have been employed in asphalt in recent years to increase the pavement's performance and life, however the idea towards cooler pavements was almost unexplored.

Bitumen/Asphalt binder is produced by petroleum refineries. It acts as a binding agent to stick aggregate particles together and make a dense mass. Three properties of the asphalt binder play a very important role in the performance of asphalt mixture: Aging effects, temperature susceptibility, and viscoelasticity.

Road networks are the foundation for any country's economic development. Overtime, damages like rutting, stripping and fatigue cracking render the pavement unusable. The application of RAP plays an important role in reaching the national goal of prosperity. This chapter will provide a brief literature review of the studies and research findings related to the RAP being incorporated in the asphalt pavements.

Reusing of waste has increased most extreme significance in late time. Throughout the Transportation Industry, RAP is becoming more popular due to its environmental and economic benefits over virgin aggregate and binder. Because resources are limited around the world, RAP is the most cost-effective option for contractors and government authorities. RAP also allows some of the binder that would otherwise be utilised in the mix to be replaced, reducing the amount of virgin binder required. The RAP becomes noticeably stiffer as it ages, which can lead to greater strength, rutting resistance, and moisture resistance.(Al-Qadi, Carpenter, Roberts, Ozer, & Aurangzeb, 2009) than the softer virgin binders. However, the stiffness may cause other issues, such as cracking, although there are a variety of additives that may be used in conjunction with the RAP to mitigate this issue. RAP usage will continue to rise, resulting in a significantly more long-term and sustainable transportation infrastructure across the country.

Some of the important topics of the studied literature are:

2.2 Reclaimed Asphalt Pavements

RAP is the terminology which defines recycled as well as reused asphalt/roadway materials involving aggregates and asphalt. When asphaltic pavements are grubbed for rehabilitation or reemerging, or to get admittance to covered or stifled facilities as a result RAP is produced. At the point when appropriately crushed and separated, RAP comprises of superb, aggregates which are good in gradation and covered by bitumen.

As RAP becomes better understood and studied, its use has progressively risen across the country. Over 80 million tonnes of asphalt are recycled each year, saving taxpayers $1.5 billion in new building costs. RAP is limited to roughly 20 to 25 percent of the overall mix by weight in many states. The amount of RAP employed will gradually increase as more research is undertaken, until 100% RAP pavements can be used entirely. RAP usage is much lower till then, as seen in Table 2-1, which illustrates the present use of RAP in each state across the country. (Hansen, Copeland, & Association, 2013).

RAP material was collected in chunks from Pakistan's Charsadda to Peshawar G.T Road. The RAP materials were not properly stored and were subjected to severe ageing and weathering, which had a negative impact on their rheological properties. The virgin binder 60/70 penetration grade was obtained from PARCO (second Largest Oil Marketing Company in Pakistan). In Pakistan, binders are still rated according to their penetration value, and there are no PG binders available for testing. The impact of the RAP material's characteristics on the final products is minor for low RAP levels (5 to 20%), hence the tests are not required. On the other hand, with high RAP levels, RAP features will have a considerable impact on the final product's performance, so they must be thoroughly examined. Reclaimed Asphalt Pavement (RAP) not only saves money on new asphalt mixtures, but it also helps the environment. It's critical to understand the amount and quality of residual binder before incorporating it into asphalt mix design.

Table 2- 1 RAP in HMA paving mixtures per state (Hansen et al., 2013)

State	Average RAP Content(%)				State	Average RAP Content(%)			
	2009	2010	2011	2012		2009	2010	2011	2012
Alabama	19	25	21	22	Montana	7	8	8	10
Alaska	5	3	13	8	Nebraska	NR	NR	30	22
Arizona	13	5	11	14	Nevada	6	7	10	11
Arkansas	10	11	10	10	New Hampshire	15	18	21	19
California	10	19	9	16	New Jersey	4	17	16	16
Colorado	19	19	24	29	New Mexico	NR	NR	18	NR
Connecticut	15	17	13	21	New York	10	11	16	13
Delaware	20	20	NR	28	North Carolina	20	22	24	15
Florida	24	24	30	27	Ohio	23	24	23	24
Georgia	19	22	23	23	Oklahoma	12	13	18	12
Hawaii	10	9	11	14	Oregon	26	25	24	24
Idaho	6	10	23	28	Pennsylvania	13	13	16	16
Illinois	18	20	16	30	Puerto Rico	0	0	2	20
Indiana	23	24	26	23	Rhode Island	11	11	8	2
Iowa	12	17	14	15	South Carolina	17	20	22	24
Kansas	18	20	20	20	South Dakota	12	6	18	20
Kentucky	9	9	9	10	Tennessee	20	17	14	20
Louisiana	18	18	18	19	Texas	11	10	13	16
Maine	13	14	15	15	Utah	19	21	25	19
Maryland	19	21	24	22	Vermont	21	20	17	23
Massachusetts	14	14	11	16	Virginia	21	28	26	26
Michigan	27	30	30	34	Washington	18	16	16	15
Minnesota	16	19	22	20	West Virginia	10	11	11	12
Mississippi	16	17	18	19	Wisconsin	15	15	16	14
Missouri	12	12	19	19	Wyoming	6	5	1	2

Reclaimed asphalt pavement (RAP) is a great alternative to virgin resources in the production of new asphalt mixtures. Reclaimed and reprocessed pavement material containing asphalt binder and aggregates is referred to as recycled asphalt pavement. Manufacturing of bitumen necessitates huge amounts of crude oil. As the natural resources like crude oil are non-renewable, it is compulsory to recycle and reuse the old asphalt. The foremost benefit of using

Reclaimed Asphalt Pavement is a direct cost saving due to the lessening of virgin resources. The utilisation of previously existing resources is one of the environmental and economic benefits of employing RAP as a sustainable construction material. The elimination of waste disposal issues, Natural Resource Conservation., Development that is long-term, Material, energy, and total job costs are all reduced.

2.3 Bitumen

Bitumen is defined as: “A non-crystalline solid of viscous mixture of complex hydrocarbons that possesses characteristic agglomerating properties, soften gradually when heated, is substantially soluble in trichloroethylene and is obtained from crude petroleum by refining processes.”

Bitumen has been used by mankind for nearly 5000 years in a variety of uses, including mummifying and waterproofing. The Shell Bitumen Handbook (2003) lists 250 different applications for bitumen. Bitumen is mostly used in the road construction and maintenance business nowadays. The bitumen binder is combined with mineral aggregates in a chip seal to generate waterproof layers in the various combinations indicated above. Bitumen is particularly helpful to engineers as a binder since it is a strong, easily sticky, highly waterproof, and long-lasting material. Bitumen also gives mineral aggregate mixtures, with which it is commonly blended, considerable flexibility. The strong adhesion between the bitumen and the mineral aggregates allows the bitumen to operate as a binder, while the mineral aggregate provides the road with mechanical strength. Bitumen is also highly resistant to the action of most acids, alkalis, and salts (Read & Whiteoak, 2003).

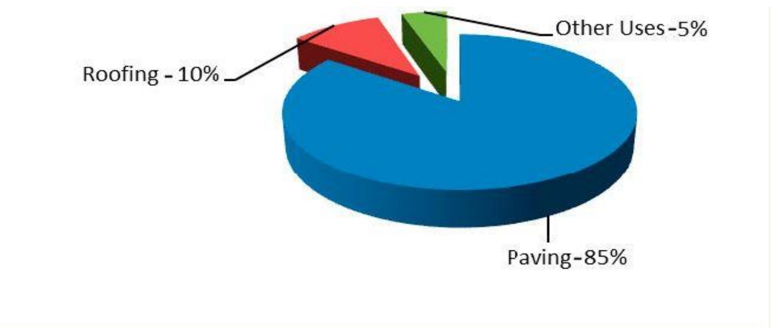


Figure 2- 1 applications of bitumen ("What Is Bitumen(Asphalt)?,")

2.4 Literature on performance tests/polymers

Literature on performance tests and was carefully observed and the crux of finding is presented hereunder.

2.4.1 Elvaloy polymer modified asphalt

Elvaloy RET is a Reactive Ethylene Terpolymer manufactured by DuPont (RET). It's sold as free-flowing pellets that melt into hot bitumen to create permanently changed bitumen that can't be separated. The most typical problems with pavements are rusting, peeling, heat cracking, and fatigue cracking. Elvaloy RET has the unique ability to address all of these features while not compromising any of them.Elvaloy RET 4170 Polymer is globally available and many countries are already using it pavement applications.Figure 2-2 shows free flowing pellets of elvaloy RET 4170.

Figure 2- 2 Free Flowing Pellets of Elvaloy RET 4170(Irfan, Saeed ,Ahmad &Ali,2017)

It is more effective when used in low dosage i.e., 1-2%, and less reactive when used in high dosage (Irfan, Saeed, Ahmed, & Ali, 2017). That's why 1% Elvaloy was used in this research as used by (Irfan et al., 2017). It has been rarely used more than 2.5%. (Babrock, 2009; Negulescu et al., 2006) studied the performance of various polymer modified asphalts and found that both SBS and Elvaloy increased the binder's resilience to rutting and fatigue damage.

2.4.2 Elvaloy polymer incorporation in Asphalt

Elvaloy polymer has also been used by Indian researchers to enhance the properties of bitumen. (Patel & Mishra, 2018) conducted a research, to enhance the stability of bitumen under Marshall mix criteria by the blending it with 1% Elvaloy polymer. Results have shown that, 1% Elvaloy polymer with 5.2% of optimum binder content has significantly increased the Marshall Stability values. The enhancement of the properties of bituminous mixes reveals the beneficial consequence of ELVALOY.

In the past, researchers have also used Elvaloy polymer to enhance the rutting resistance of Asphalt(Kamran Muzaffar Khan, 2013) compared the performance of Polyethylene modified, Lime modified, and Elvaloy modified asphalt mixes in enhancing the rutting resistance of asphaltic concrete to the performance of the traditional NHA (National Highway Authority Pakistan) Class-A mix. The resistance to rutting of compacted asphalt mixtures was tested in this study by subjecting all specimens to 10,000 cycles of a loaded wheel and using a wheel tracking machine to determine the rut depth for each specimen. Aggregates used in this study were obtained a quarry in Margalla and mixed according to NHA class–A. Two asphalt binders, one unmodified of 60/70 penetration grade and the other polymer modified, were used in this research. The binder content used for all the mixes was 4.3%. PMB (polymer modified bitumen) modified with 0.8% Elvaloy was supplied by the Attock Oil Refinery, Rawalpindi. Low Density Polyethylene (LDPE) was used in the proportion 19% by weight of bitumen. Hydrated lime was used in the amount of 1% by weight of total sample as recommended by National Lime Association. Following results were drawn from the respective test samples.

- Rutting occurred in the samples of modified mixes at different temperatures (30 and 60) is less than that of the conventional mix 60/70 penetration grade. The difference in rutting of the lime modified and polyethylene modified bitumen was almost same at lower temperature of 30° C but it was more pronounced at higher temperatures.
- At 30 °C, Polythene and lime modified mixes outperformed PMB and conventional (unmodified) mixes in terms of rutting resistance. The PMB-prepared mix performed better than the conventional mix.

• The polythene modified mixes beat all other mixes in terms of rutting resistance at 60 degrees Celsius, while the original NHA class-A mix performed the worst. The polythene modified mix outperformed the lime modified mix, elvaloy modified mix, and standard (unmodified) NHA class-A mix the best.

Elvaloy polymer has been used in the binder modification since very long. As conveyed by (Yildirim, 2007), SBS, SBR, **Elvaloy**, rubber, EVA, are polythene are the widely used polymers for the properties enhancement of bitumen.

2.4.3 Research Findings on Fatigue

Using reclaimed asphalt pavement (RAP) in asphalt mixture is an efficient technique to enhance sustainability of the pavement and also preserve natural resources. But using RAP especially in higher content, also induce various problems resulting in the degradation of durability of the asphalt pavements. Many studies have been conducted to find a solution to the problems caused by the RAP incorporation in the asphalt mix.

(Zhou, Gu, Jiang, Ni, & Jiang, 2019) conducted a study on polymer modified asphalt mix and concluded that higher RAP content has faster rate of fatigue damage and poor performance in mixture. (Shu, Huang et al. 2008) from his study concluded that inclusion of RAP into HMA mixture increased the tensile strength but decreased the fatigue life of HMA.

(Zhang et al., 2019) studied the effect of developed rejuvenator on RAP mixture and concluded that the inclusion of a rejuvenator extended the fatigue life of a recycled asphalt mixture, but not to the same extent as a conventional asphalt mixture.

(Vamegh, Ameri, & Naeni, 2019) studied the effect of SBR/PP polymer blend on fatigue resistance of asphalt mixture and concluded that polymer blend could significantly increase the fatigue life and also its tensile properties.

(Ameri, Yeganeh, & Valipour, 2019) used a four-point bending test to study the fatigue characteristics of an HMA mixture incorporating waste elastomeric polymers such as SBS and PBR, and found that 5 percent waste PBR has better fatigue resistance than 3 percent SBR.

Another study conducted by (Vamegh et al., 2019) with the same objective to enhance the fatigue performance of reclaimed asphalt pavements. SBR and PP polymers were used, for this purpose, in ratios of 70/30, 50/50 and 30/70, and the fatigue performance of asphalt mixes containing these polymer combinations was compared to asphalt mixtures containing 4% and 5% SBS polymer, respectively. The fatigue properties of asphalt mixtures could be improved using SBS modified polymer combinations, according to the results of fatigue experiments. This improvement is larger than 50% in mixtures with SBR polymer blends compared to mixes with this expensive polymer.

Efforts to improve the fatigue parameter of RAP modified mixtures has not been stopped yet. Another investigation was undertaken by (Elkashef & Williams, 2017) to see how a soybean-derived rejuvenator modified a PG58-28 binder at 6% and 12% by weight. To manufacture and test dynamic modulus specimens, RAP mixtures containing 100 percent RAP with the addition of both plain PG5 8-28 and soybean-modified PG 58-28 were utilised. The binder testing findings show that the soybean-derived rejuvenator has a significant impact on the RAP binder's low and high temperature characteristics. Using the tidy PG 58-28 alone would not have yielded such results. The rejuvenator generated from soybeans also has a long shelf life.

2.4.4 Research Findings on Permanent Deformation

Since the mid-1970s, RAP has been frequently employed in HMA. RAP has previously been shown to be cost-efficient, environmentally friendly, and beneficial in improving the rutting resistance of asphalt mixtures. Due to advancements in HMA plants and processing equipment, mixes containing 50% or more RAP can now be considered. HMA combinations using RAP have performed as well as mixtures made from all fresh components when correctly designed and manufactured, according to experience. So, besides focusing only at the fatigue performance, researchers have also worked on the enhancement of permanent deformation of RAP modified mixtures. Following studies summarizes those efforts.

Keeping the economic, environmental, and financial benefits in mind, researchers studied on numerous performance parameters of asphalt which includes cracking and rutting of mixtures with RAP. Studies reveal that pavement failure is caused not just by traffic, but also by the ageing of the asphalt binder. RAP components may age considerably more during stockpiling since they are exposed to air when the pavement is removed from the field. Furthermore, when RAP is mixed with HMA, the aged binder in RAP combines with the virgin binder to an unknown extent. As a result, an unknown composite effective binder system is generated, resulting in unexpected pavement performance. Adding RAP to HMA changes the physical behaviour of the mix, according to several RAP tests. The enhanced rigidity of the RAP binder is thought to be the reason of the HMA's elevated modulus. It also has an impact on the fatigue behaviour of the mixture and low-temperature cracking. Al-Qadi, Aurangzeb, Carpenter, Pine, and Trepanier (Al-Qadi, Aurangzeb, Carpenter, Pine, & Trepanier, 2012).

A research study conducted by (Zhou, Gu, Dong, Ni, & Jiang, 2019) shows that excess amount of RAP content usage in Chinese roads in quite challenging because of poor performance in permanent deformation. To cope with this issue, they used SBS modified RAP and the results were promising. SBS-RAP showed an increase in the rutting performance of RAP, however their recovery behavior was compromised at the same time.

(Yousaf, Hussain, Irfan, Khan, & Ahmed, 2014) did a study on NHA class-A and class-B gradations incorporating Bakelite in order to improve the rutting performance of asphalt. Bakelite is an old material that was employed as a modifier for penetration grade 60/70 binder. An Asphalt Mixture Performance Tester (AMPT) was utilised to examine rutting resistance using a Hamburg Wheel tracker at room temperature, as well as stiffness using a dynamic modulus test at various temperatures (25, 40, and 50 C) and frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz). Inside the NHA Class A and Class B gradation envelopes, the experiment was limited to two unique NMAS 19mm and 12.5mm wearing course combinations. Adjusting the amount of Bakelite in each gradation from 1.5 to 9% by weight of bitumen while keeping the Optimum bitumen percentage constant yielded the Optimum Bakelite content. The percentage reduction in rut depth at 6 percent ideal Bakelite content was discovered to be 29 percent and 38 percent for class-A and class-B combinations, respectively, when compared to controlled mixtures. The percentage increase in dynamic modulus values at 50 °C was found to be 36% for class-A combinations and 46% for class-B mixtures, respectively.

Researchers have also found that pavement is susceptible to premature rutting if volume of air voids remains lesser that 3%. Which means a minimum of 3% air voids should be ensured, to avoid this failure, during the construction. Using proper angular (fine & course) aggregates in asphalt mix also help minimize the rutting (Brown & Cross, 1992).

2.4.5 Research Findings on Moisture Damage

(Hunter & Ksaibati, 2002) in a research study clarified that from past numerous years impact of dampness on actual properties and mechanical conduct of asphalt paving combinations has been known. Numerous exact, semi experimental test strategies, for example, Boiling water Test and various test machines, for example, Wheel Tracking Device have been created to foresee moisture damage on asphalt mixes. The reason for these test techniques is to reproduce the damage done by dampness in field. Dampness damage in HMA combinations is reason for stripping.

(Roberts, Kandhal, Brown, Lee, & Kennedy, 1996) disclosed that to conquer this dampness susceptibility issue legitimate asphalt pavement design is required. However, appropriate compaction likewise assume part to battle moisture susceptibility if not done asphalt might be helpless to moisture damage. Subsequently, testing of HMA configuration ought to be done on those conditions where moisture penetrates in air voids of the combinations.

Hamburg Wheel Tacking machine was created in Germany to anticipate rutting capability of HMA, from that point forward this test machine is being in by U.S divisions to check the rutting capability of HMA. (Mogawer & Stuart, 1995) in research paper shared that Texas Department of Transportation (TxDOT) Construction Division demonstrated that this machine can be utilized to anticipate the moisture damage susceptibility of HMA. Testing and perceptions show that mixes containing delicate limestone goes through serious abrasion and total isolation (aggregate segregation) when tried in the Hamburg wheel tracking machine.

(Cooley, Kandhal, Buchanan, Fee, & Epps, 2000) explained the history of the wheel tracker, stating that it was invented in the 1970s in Hamburg, Germany, based on a similar British system using a rubber tyre. The test method and specifications for measuring rutting and stripping susceptibility were finalised and created by Helmut Wind incorporated of Hamburg. By driving a steel wheel across the surface of an asphalt concrete specimen soaked in hot water (40 oC to 50 oC, but can vary from 25 oC to 70 oC), HWTD examines the combined effect of rutting susceptibility and moisture damage in terms of stripping. This criterion is used to determine if rutting and moisture susceptibilities are pass or fail.

2.5 Summary

Most of the studied conducted in the past were focused only on the properties of asphalt binder without comprehensively studying the performance properties of asphalt mix containing polymer modified binder and RAP. According to the author’s best knowledge, limited number of studies have been conducted on the mix incorporating polymer modified binder along with various percentages of RAP. Therefore, in this study, the Asphalt mix consisting of polymer modified binder and high RAP content will be studied comprehensively in terms of rutting, fatigue performance, and moisture susceptibility.

After studying the existing literature on Fatigue parameter, Permanent deformation, and Moisture damage in asphalt pavements, a methodology was devised to cope with these distresses. The next chapter deals with methodology of the research.

CHAPTER 3

RESEARCH METHODOLODY

3.1 Introduction

This section focuses on methodology of planned research to capture all the mentioned objectives of study that are, acquisition of required material, sample preparation and testing. NHA Class-B gradation was followed and the performance tests like, Double Wheel Tracker Test (DWT) to find rutting, Indirect Tensile Strength test to find Tensile Strength Ratio (TSR), Four Point Beam Fatigue Test to assess fatigue performance, and moisture damage test were conducted. The virgin aggregates were acquired from a single source that is Margalla quarry situated in Islamabad Pakistan and grade 60/70 bitumen being used as binder, which was collected from PARCO Islamabad. Marshall mix design parameters were used to determine optimum binder content (OBC).

3.2 Research Methodology

The methodology of research is explained in the figure represented in Figure 3-1. It shows that in initial stages selection of material and aggregate gradation was selected. After the selection of materials, OBC is obtained using Marshall. After preparation, the specimens were cored and sawn according to the specifications. After conditioning the samples for required time period performance tests were performed and the results were obtained in the form of excel sheets that were used for further analysis and from analysis results were concluded which are explained in the later chapters.

3.3 Characterization of Materials

Characterization of materials used in this research is discussed in the sections hereunder:

3.3.1 Materials Procurement

For this research, the aggregates (fine and coarse aggregates) were acquired from Margalla quarry and the penetration grade 60/70 bitumen was collected from PARCO Islamabad. Grade 60/70 was chosen because it is widely used in Pakistan and is suitable for colder to moderate climates. The aggregate structure in the mix provides the majority of the resistance to permanent deformation (almost 95%), with the asphalt binder providing the remaining 5%. To withstand the repeated application of load.

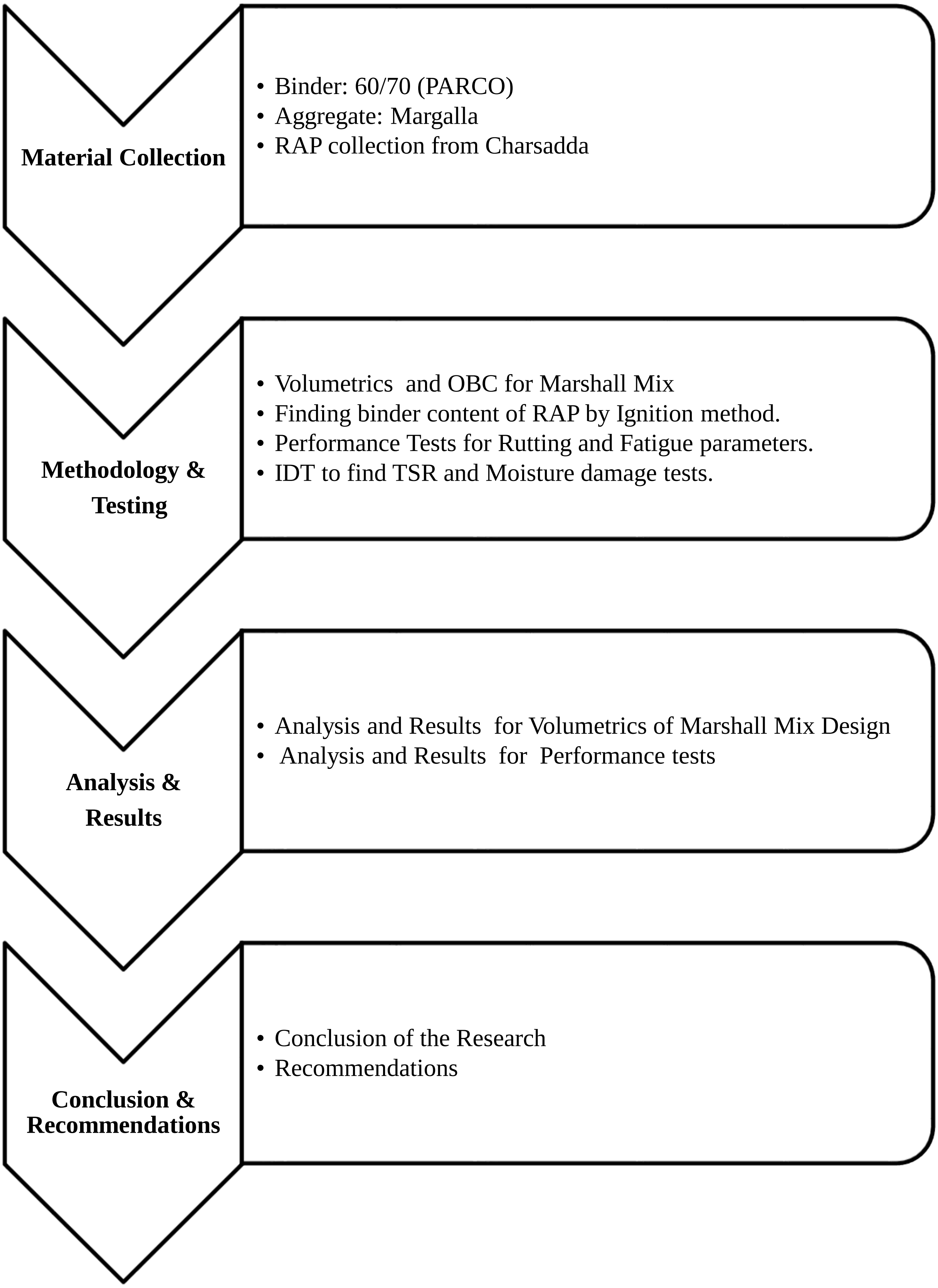


Figure 3- 1 Pictorial Representation of Research Methodology

aggregates provide a strong stone skeleton. The Gradation and surface texture etc. greatly affect the properties and volumetrics of Hot mix asphalt. Rough-textured aggregates provide more shear strength to the mix as compared to the smoothed surface aggregates. According to the standards and specifications all the necessary tests were performed on acquired aggregates and bitumen.

Figure 3- 2 Material Collection from Margalla Quarry

Figure 3- 3 Aggregates after gradation in LAB

The aggregates are of a basic nature, with limestone being a prominent component (Tufail, Ahmad, Mirza, Mirza, & Khan, 1992). For material selection and sampling, the National Highway Authority (a government entity responsible for the development of the country's highways) provided general standards. NHA class-B gradation for asphalt concrete wearing coarse was selected for the study as shown in Figure 3-4 (Badin, Ahmad, & Ali, 2020). Moreover, properties of the aggregates used in this study are given in Table 3-1 (Hussan et al., 2017a).

Table 3- 1 Mechanical properties of Margalla Quarry Aggregates

Material Properties	Percent (%)	Standard	NHA Recommendations (Hussan et al., 2017b)
Fractured Particles	100	ASTM D 5821	90% (min)
Flakiness	7	BS 812.108	10% (max)
Los angles abrasion	13	ASTM C 131	15% (max)
Elongation	10	BS 812.108	10% (max)
Water absorption	1.03	ASTM C 127	2 % (max)
Soundness (coarse)	6.7	ASTM C 88	8% (max)
Sand equivalent	75	ASTM D 2419	50 % (min)
Soundness (fine)	4.7	ASTM C 88	8% (max)
Uncompact Voids	38	ASTM C 1252	45% (min)

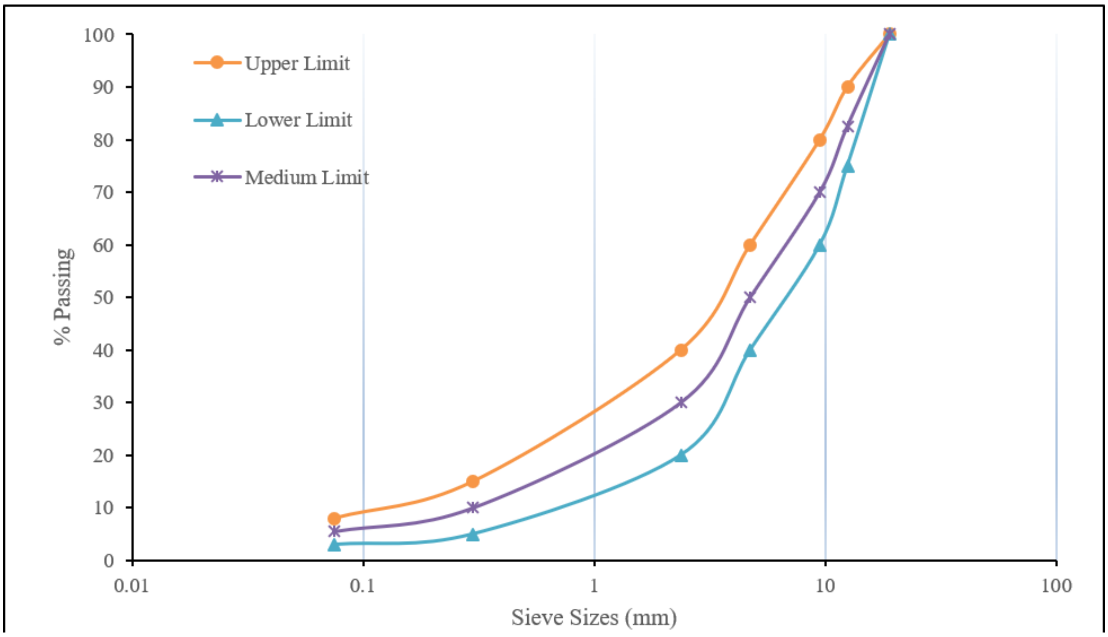


Figure 3- 4 NHA Class-B Gradation Curve

3.3.2 RAP Collection

For this study, RAP (reclaimed asphalt pavement) material was obtained in form of chunks from Charsadda to Peshawar G.T Road, Pakistan shown in Figure 3-5. The RAP materials were not properly stored and were subjected to severe ageing and weathering, which had a negative impact on their rheological properties.

It is also interesting to note that, collected RAP was regraded in laboratory to check its gradation and it comes out NHA-B gradation. RAP gradation is shown in Figure 3-5 below.

Figure 3- 5 RAP Collection from Charsadda Peshawar G.T Road

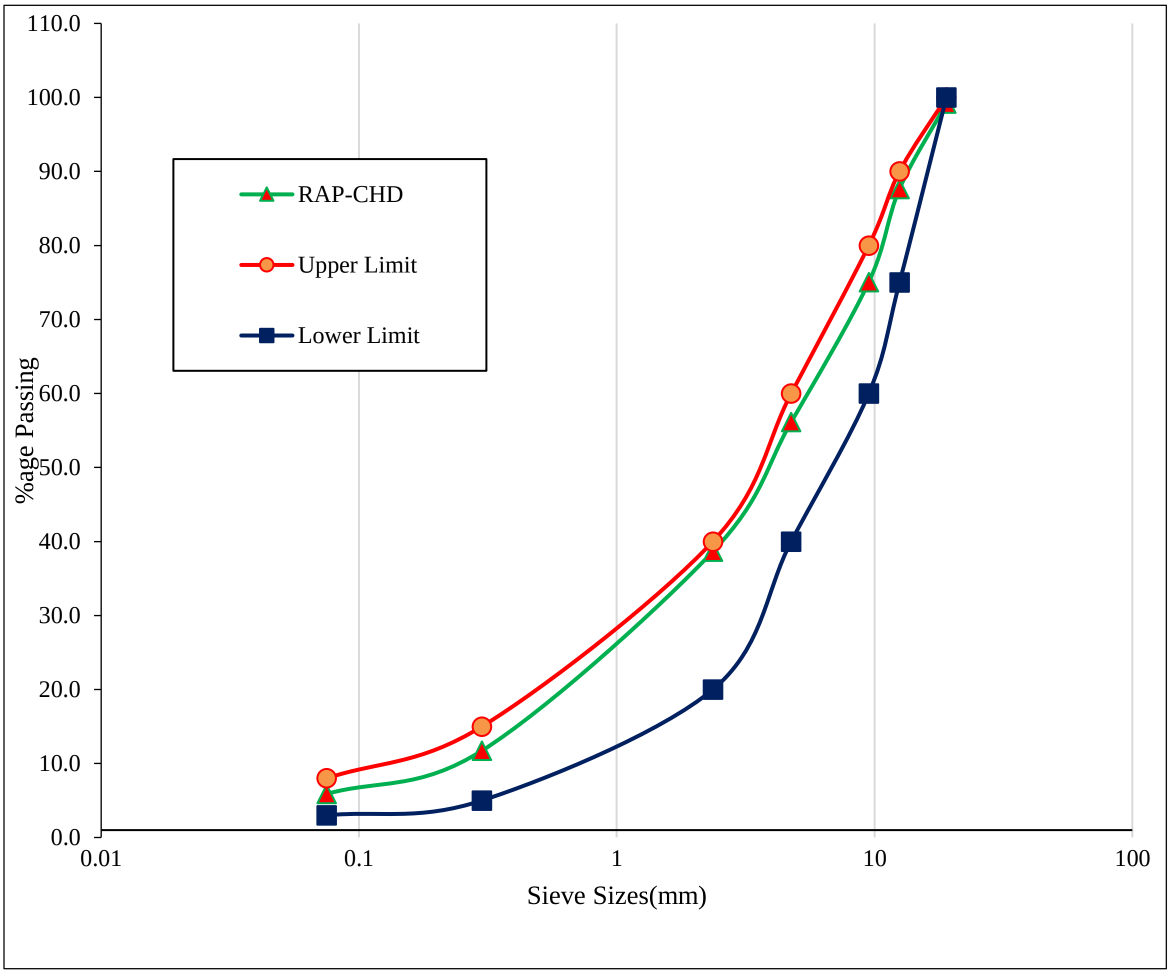


Figure 3- 6 RAP Gradation from Charsadda

Table 3- 2 Gradation of RAP Used

Sieve Size (mm)	RAP (% Passing)
19	99.20
12.5	87.64
9.5	75.06
4.75	56.14
2.36	38.65
0.3	11.73
0.075	5.90
Pan	0

3.3.3 Bitumen Content in RAP

Binder content of RAP was determined by ignition method through Asphalt Pavement Analyzer, which comes out 3.87% shown in Figure 3-7. Three samples of RAP were taken and regraded. Weight of each sample was 1500 grams. Procedure recommended in ASTM D 6307 – 98 for the asphalt content determination by ignition method was followed.

Figure 3- 7 RAP binder content findings by ignition method

3.3.4 Aggregate Testing

The aggregate skeleton of the mix is the central portion which resists permanent deformation and is expected to provide a strong skeleton for resisting repetitive loads. In order to determine the fundamental features of aggregate, such as gradation, each stockpile was subjected to a specific gravity laboratory test.

Tests conducted in the laboratory are:

- Specific Gravity and Water Absorption Test of aggregates
- Los Angeles Abrasion
- Aggregate Shape Test
- Impact Value Test
- Aggregate Crushing Value Test

All these tests mentioned above were conducted using three specimens and then average was considered for further process.

3.3.5 Aggregate Specific Gravity (S.G)

The weight volume characteristics of a substance are represented as S.G. Individually, the specific gravities of coarse aggregate, fine aggregate, and fillers were determined. By definition, the aggregate that are retained on No. 4 sieve is coarse aggregate while fine aggregates are those passing sieve No. 4.

3.3.6 Coarse Aggregate

The S.G. of coarse aggregate and water absorption were determined using ASTM C 127 techniques and equipment. The S.G test for coarse aggregate determine weight of coarse aggregate fewer than three different specimens conditions which are dried in oven, dipped in water and surface saturated. The test was accomplished for both of the course graded stockpiles and the findings are presented in Table 3-1.

Figure 3- 8 Specific Gravity of Coarse Aggregates

3.3.7 Fine Aggregate and Filler

S.G of fine aggregates were measured using the procedures and equipment stated in ASTM C 128. S.G test was carried out on fine aggregate to determine the values of bulk S.G, Saturated Surface Dry and apparent specific gravities with the result shown in Table 3-3.

Figure 3- 9 Specific Gravity of Fine Aggregate

3.3.8 Los Angeles Abrasion Test

This test determines hardness of road aggregate. Aggregate must be hard to the extent that they resist wear caused by heavy traffic loads. The apparatus for this test included Los Angeles Abrasion machine, balance, set of sieves and steel balls. Testing methodology or grading B was adopted for this procedure. 2500 g of aggregate retained on ½" and 3/8" sieves each, which is a total of 5000g (W1) of aggregate along with 11 steel balls or charges were placed in the equipment. It was rotated for 500 revolutions at a velocity of 30rpm to 33 rpm. After that, the material was sieved through 1.7mm sieve. Weight of sample passing through it (W2) was noted down. The abrasion value was found out by = W2/W1× 100. Table 3.3 shows the tests performed on the aggregates.

3.3.9 Shape Test of Aggregate

Strength and workability of asphalt mixture mostly depend on shape of particles. It also affects the effort required for compaction vital to achieve the necessary density. Therefore, through shape test the quantity of elongated and flat aggregate particles were determined. According to ASTM D4791, the aggregates will be called as flaky aggregate if its dimensions are less than 0.6 of their mean sieve sizes, while the aggregate will be called elongated if its length is more than 1.8 of their mean sieve sizes shown in Table 3-3.

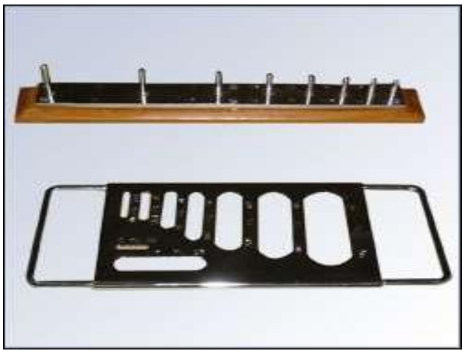


Figure 3- 10 Shape Test Apparatus of Aggregate

3.3.10 Impact Value Test

The impact value of aggregate is the resistance it offers to breaking. The apparatus required for measuring impact value included impact testing machine, tamping rod and sieves of sizes 1/2”, 3/8” and #8 (2.36mm.) Around 350g of aggregate passing through sieve size 1/2” and retaining on 3/8” sieve was taken and filled in the mould of Impact Testing Machine in 3 different layers, tamping 25 times (Each Layer). The sample was placed in the machine's larger mould, and 15 blows were delivered with a hammer weighing 13.5 to 14 kg at a height of 38 cm. The aggregate was then removed and filtered using sieve #8. The proportion of aggregates passing through a 2.36 mm sieve was used to calculate the impact value.

Figure 3- 11 Aggregate Impact Value Test

3.3.11 Crushing Value Test

To achieve a pavement with higher quality and strength, it is necessary for the aggregates to have enough strength to sustain traffic loads. The apparatus for this test consisted of a steel cylinder having open ends, plunger and a hole provided across it, so a rod could be inserted for lifting it, cylindrical measure, balance, tamping rod, and a compressive testing machine.

Figure 3- 12 Los Angeles Abrasion Test

Aggregates were passed through a set of sieves and that passing through sieve sized ½" and retaining on 3/8" were selected. Sample of aggregate was washed, oven dried and weighed (W1) and then added into a cylinder in layers of three and every layer is then being tamped twenty-five times. The specimen was shifted into the steel cylinder with base plate and the plunger was inserted; then placed in compressing testing machine and loads were applied. Crushed aggregate was then taken out and are allowed passing through sieve sized 2.36 mm. The sieved aggregate is W2 and Crushing value is the ratio of W2 and W1. In this way it was find out and its value is given in table 3-3.

Table 3- 3 Properties of Aggregates

Test Description		Specification Reference	Result	Limits
Elongation Index (EI)		ASTM D 4791	3.578 %	≤ 15
Flakiness Index (FI)		ASTM D4791	12.9 %	≤ 15
Aggregate Absorption	Fine	ASTM C 127	2.45 %	≤ 3
	Coarse		0.73 %	≤ 3
Impact Value		BS 812	17 %	≤ 30
Los Angles Abrasion		ASTM C131	22	≤ 45
Specific Gravity	Fine Agg	ASTM C 128	2.618	-
	Coarse Agg	ASTM C127	2.632	-

3.3.12 Tests on Asphalt Binder

For the construction and engineering purposes, consistency, safety, and purity are the three properties of binder which are essential to be considered. Consistency of bituminous binder changes with changes in temperature. As a result, a standard temperature is required for comparing asphalt binder consistency. Penetration or viscosity tests are commonly used to determine the consistency of asphalt binder. Other tests, such as binder ductility and softening point, provide additional information concerning consistency. Thus, for the purpose of characterizing the asphalt binder in laboratory, tests for the following characteristics were conducted.

- Ductility
- Viscosity
- Penetration
- Softening Point
- Flash and Fire Point

3.3.13 Ductility Test

Ductility is an important property of bitumen and a necessary feature to depict the performance of HMA mixture. Ductility shows the behavior of bitumen with the temperature changes. By definition it can be clarified as the "distance to which a specimen of binder lengthens without breaking when its two ends are pulled at a certain velocity and at a specified 25 °C temperature. Table 3-4 shows the standard conditions and results obtained for ductility tests for bitumen. All specimens had seen satisfying the minimum 100cm ductility criteria.

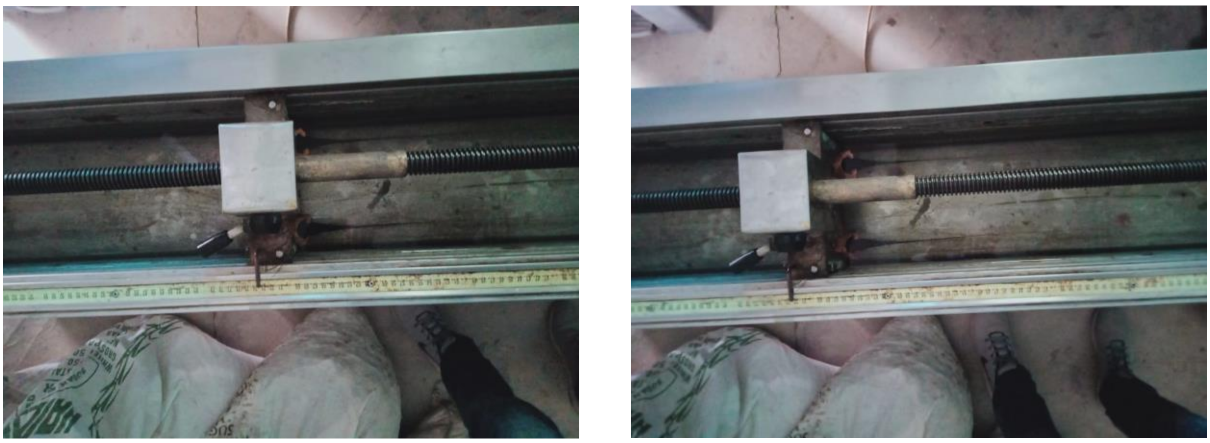


Figure 3- 13 Ductility Test

3.3.14 Rotational Viscosity Test of Bitumen

This test is used for asphalt binders' viscosity determination, at an increased temperature range. We can conduct RV at different temperatures, but since production temperatures are similar, irrespective of the environmental conditions, the test for Superpave performance grade asphalt binder description is always carried out at 135°Centigrade and 160°Centigrade.

To determine the viscosity of bituminous binder using RV apparatus as per AASHTO-T-316 and ASTM D 4402, Brookfield RV apparatus was used. First of all, heating of sample chamber, the spindle, and viscometer environmental chamber (Thermosel) to 135°C and 160°C then heat the bitumen to make it workable enough to get it pour. With taking great care for the entrapping bubbles, stir the sample steadily. Proper amount of binder shall be poured in sample chamber which varies with the equipment manufacturer and selected spindle. The sample should be brought to the chosen test temperature i.e. 135°C and 160°C and is allowed to equilibrate at the required temperature. The spindle rotates at a rate of 20 rotations per minute. Take three viscosity readings from the RV display once the sample has attained temperature and equilibrated, allowing one minute between each reading. The viscosity will be calculated as the average of the three values.

3.3.15 Penetration Test

A penetration test can be used to determine the penetration of asphaltic materials. Containers containing specimen and needles are used in the penetration test. Penetration values are higher when the binder is softer.

Figure 3- 14 Penetration Test being performed on Penetrometer Apparatus

According to AASHTO T 49-03, the temperature utilised was 25°C, the load was 100 grammes, and the test time was 5 seconds, unless otherwise specified.

Using two Parco 60/70 specimens, five values from each specimen were taken after performing penetration tests. All values obtained fulfilled the required limits. The results can be seen in Table 3-4.

3.3.16 Softening Point

Bitumen is a material with viscos-elastic property, but as the temperature goes higher it progressively becomes softer and its viscosity reduces. When bitumen specimen of specific standard size cannot bear the 3.5 gm steel ball weight at some specific temperature is termed softening point. Thus, once the 2 disks of bitumen soften enough at a temperature to permit the steel balls to drop a height of one inch, is the softening point.

For Softening Point determination as standard procedure ring and ball setup was used. The Table 3-4 represents the findings of softening point test.

Figure 3- 15 Softening Point Apparatus

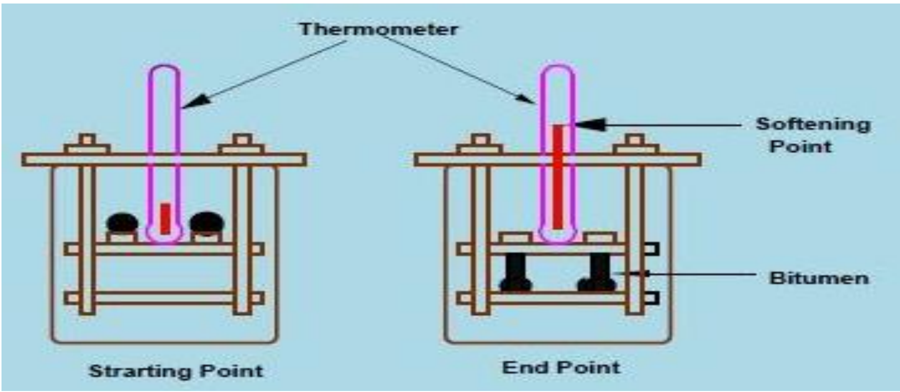


Figure 3- 16 Schematics of Ring & Ball Apparatus

3.3.17 Flash Point and Fire Point Test

This test was conducted as per D3143/D3143M-13 standards. Thus, for bituminous mixes preparation, it is also compulsory to check the bitumen for suitability as well, as per standard procedures and specification. The above-mentioned all tests conducted were carried out in laboratory to characterize the asphalt binder (PARCO 60/70).

Figure 3- 17 Flash Point and Fire Point Apparatus

Table 3- 4 Physical Properties of Parco 60/70 Binder

S No.	Test Description	Specification	Result
1	Penetration Test @ 25 (°C)	ASTM 5	64
2	Flash Point (°C)	ASTM D 92	268
3	Fire Point (°C)	ASTM D 92	293
4	Specific gravity	ASTM D 70	1.03
5	Softening Point (°C)	ASTM D36-06	48.2
6	Viscosity Test (Pa.sec)	ASTM D4402	0.2625
7	Ductility Test (cm)	ASTM D113-99	104

3.4 Asphalt Mixtures Preparation

Samples were prepared in laboratory for Marshall, Double Wheel Tracker, and IDT tests. These samples were tested upon and scrutinized for all the volumetrics and stability. The whole process for the preparation and experimentation is described in detail below:

3.4.1 Preparation of Mixes for Marshall Mix Design

Marshall Mixes are prepared for finding the OBC as per standard procedure using Marshal Apparatus. All the volumetric characteristics i.e., stability and flow were determined and verified by the criteria. Finally, OBC was found.

The aggregates were dried in an oven at 110 ^{0}C after sieve analysis. To make a compacted sample of four inches diameter using the Marshall Mix design method (ASTM D6926), 1200 grammes of aggregates are required. The amount of bitumen necessary for each sample was calculated as a percentage between 3.5%,5.0 %,4.5%, 5.0 %, and 5.5%.

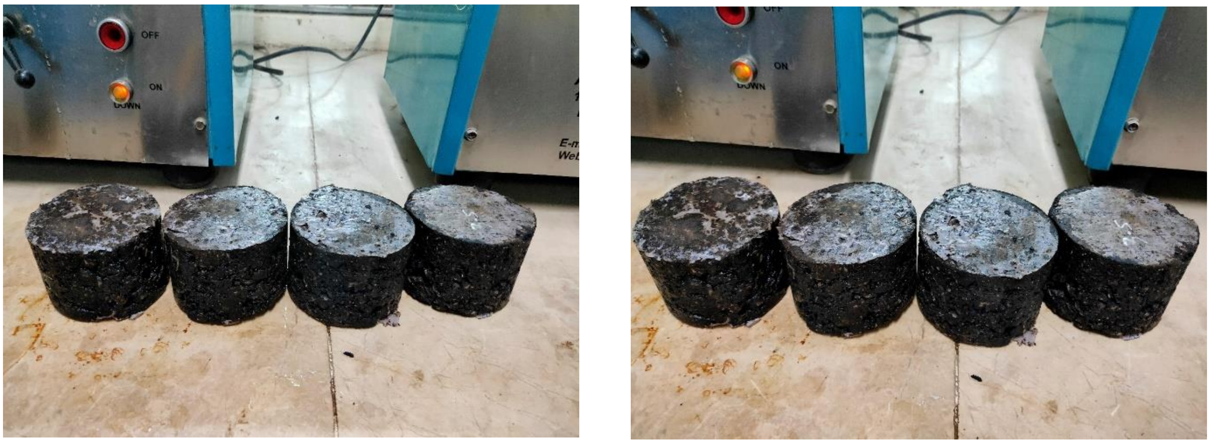


Figure 3- 18 Marshall Samples for OBC

Figure 3- 19 Gmb & Gmm tests & apparatuses

Standard protocols of ASTM D-6926 were followed for the mixing of bitumen and aggregates to ensure proper mixing. Aggregates and bitumen binder were immediately transferred into the mechanical mixer to be heated at 160°C—165°C as per NHA Specifications. The mixes were then compacted using Marshall Compactor. The mix was placed with spatula.

Both ends of the sample were covered with filter paper. For the heavy traffic criterion, the number of blows selected were seventy five (75) on each side. After cooling specimens were then ejected using the extraction jack. The specimens were then allowed to cool down at room temperature.

The volumetric properties, stability and flow correspond to the virgin mix in Table 3-5

Table 3- 5 volumetric properties, stability and flow correspond to the virgin mix

AC%	**G_{mb}**	**G_{mm}**	**Unit Wt (mg/cm^3)**	**Va**	**VMA**	**VFA**	**Stability (KN)**	**Flow (mm)**
3.5	2.32	2.49	2.32	6.83	14.2	50.9	10	2.5
4	2.35	2.47	2.35	4.86	13.5	63.3	11.9	2.7
4.5	2.37	2.46	2.37	3.66	12.95	71	12.7	3
5	2.38	2.45	2.38	2.86	13.2	78	11.9	3.4
5.5	2.39	2.42	2.39	2.59	13.6	82	9	4

For the determination of OBC of virgin mix, the graphs between asphalt contents and volumetric properties, stability and flow were plotted as shown in figure 3-20.

3.4.2 Optimum Binder Content (OBC) for Marshall Mix Design

The OBC should be determined to prepare samples for performance testing. For this purpose, all the samples were carefully tested to find their stability, flow, density, Gmb, Gmm, Air voids, VMA and VFA. The results of these tests were compiled to make a meaningful data. Graphical plots and curves were developed using this data. Following graphs were plotted to determine OBC.

- Binder Content Vs Percent Air Voids (Va)
- Binder Content Vs Percent VMA
- Binder Content Vs Percent VFA
- Binder Content Vs Stability
- Binder Content Vs Flow

They show the sensitivity of mix to the bitumen content. According to the graphs air voids and voids in mineral aggregate decreases with increasing bitumen content while VFA and flow increases with increase of bitumen in the mix. Stability first increases with increasing bitumen, reaches to a maximum value, and then starts decreasing. This research was carried

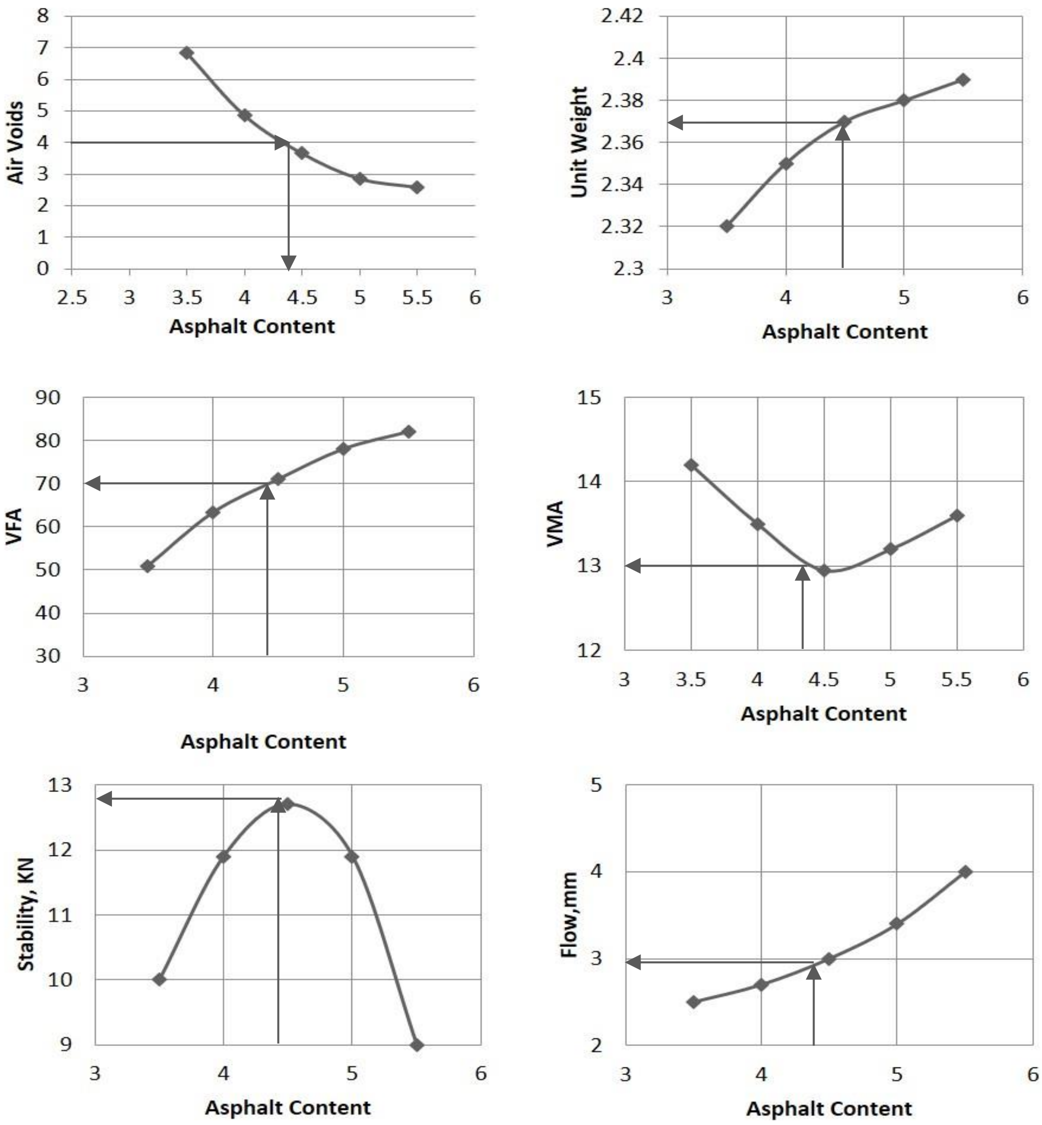


Figure 3- 20 Stability, Flow, Unit Weight, VMA, VFA, Va of Virgin Mix

out for wearing course gradation of heavy traffic road for which the Asphalt Institute recommends minimum stability of 816 kg, flow value between 8 and 14, air voids can vary from 3 to 5 percent and VFA 65 to 75. The OBC is determined as the bitumen content that produces 4 percent air voids. Other properties are then read from the graphs directly. OBC was found 4.4% from these graphs.

Figure 3- 21 Stability and Flow Apparatus

3.5 Performance Test on Asphalt

3.5.1 Preparation of Sample for Fatigue Test

For preparation of beams for the fatigue test aggregate, binder, and RAP was weighed and total sample weight was adjusted so that air voids of the compacted specimen would be 7%. All the material was heated in oven before mixing. Mixing was done in automatic mixer at the temperature of 165 ^{0}C for about 6 minutes. After mixing sample was conditioned for about two hours then poured into steel wheel roller laboratory compactor to produce larger beams having dimension of 14.8 in x 8.07 in x 2.95 in (376 mm × 205 mm × 75 mm). Compaction process was done at 160 ^{0}C temperature. Specimen was allowed to remain in the compactor for 24 hours then it was taken out and cutting process was started 48 hours after the compaction process was completed. Smaller beams with dimensions of 14.8 in × 2.48 in × 1.968 in (376 mm × 63 mm × 50 mm) were obtained after the cutting process.

Figure 3- 22 Slab cutting by diamond saw for beam preparation

Samples were prepared for 4 point beam fatigue test in the following order.

i. 0, 30, 40, & 50 % RAP
ii. 40% RAP with 1% Elvaloy Polymer

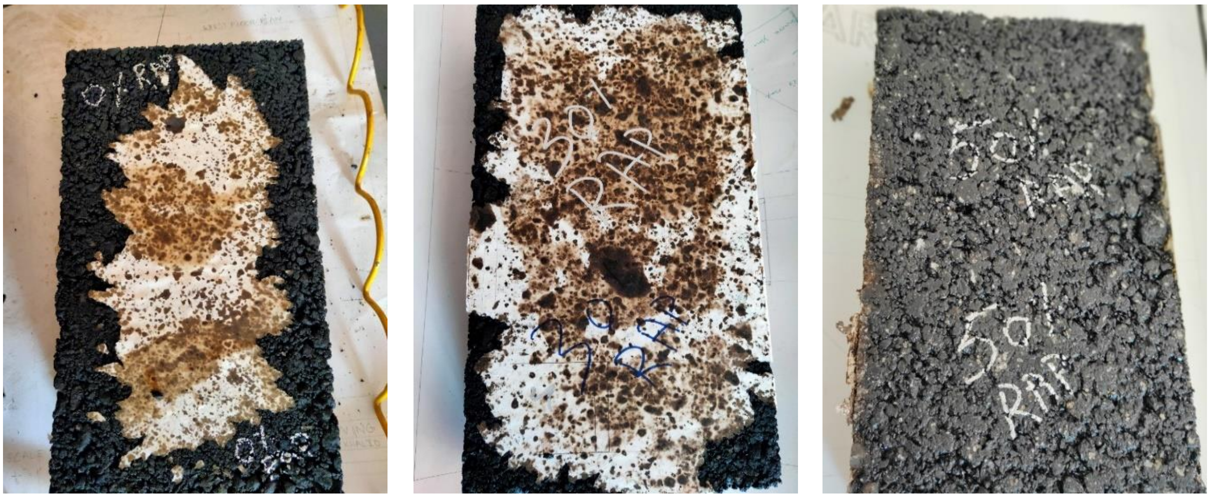


Figure 3- 23 0%, 30 % and 50 % RAP slab for Fatigue Test

Figure 3- 24 All prepared beams for 4 point test after cutting slabs

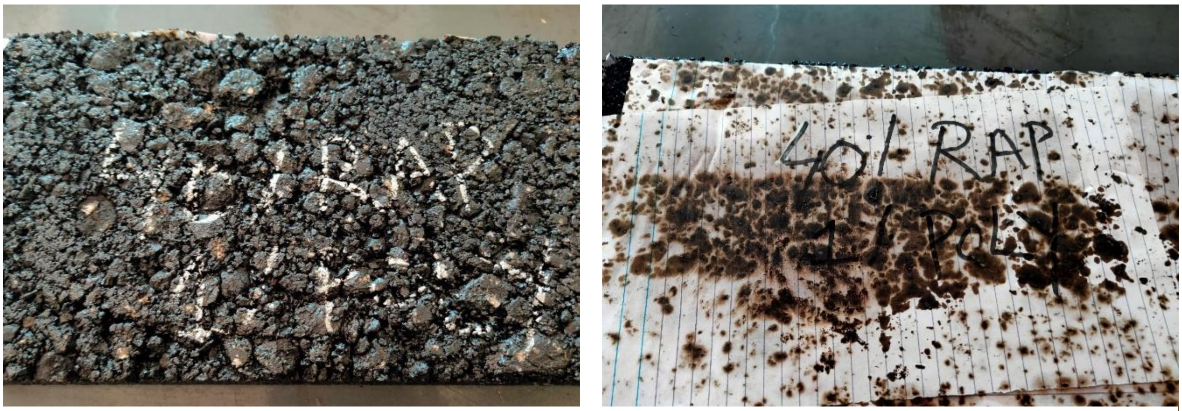


Figure 3- 25 40 % RAP and 40% RAP+1 % Elvaloy Polymer slab

3.5.2 Four-Point Bending Test

Beam fatigue test was carried using four-point bending test apparatus. Frequency was set at 10 Hz. Strain-controlled approach was adopted at the level of 500 micro strains. Failure criterion was set as 50% reduction in initial stiffness while initial stiffness was taken as stiffness corresponding to 50th load cycle. Dissipated energy for every 100 cycles of load was recorded and used for the determination of RDEC and PV (Ghuzlan & Carpenter, 2000). PV was used to analyze the fatigue behavior of asphalt mixture. Equation for the calculation of RDEC and PV are presented below (Carpenter & Shen, 2006). Sample preparation and test performance was done following AASHTO: T 321-07.

$$RDECa = \frac{1-\left(1+\frac{100}{a}\right)^{S}}{100} \quad \text{.......... 3.1}$$

$$PV = \frac{1-\left(1+\frac{100}{N_{f50}}\right)^{S}}{100} \quad \text{.......... 3.2}$$

a = Load cycle

N_{f50} = load cycle corresponding to 50% stiffness reduction

S = the exponential slope of power equation of regressed DE-LC curve.

A lower PV indicates higher fatigue life of asphalt pavement (Shen & Carpenter, 2005). Beam placed in 4 point bending machine for fatigue analysis is shown below.

Figure 3- 26 Beam placed in 4 point bending machine

3.5.3 Double Wheel Tracker Test

Double Wheel Tracker test (DWT) was performed in accordance with BS EN 12697-25, to determine the rutting of the asphalt mixes under number of cycles. Mixing and compaction was done at $158\pm5^{\circ}C$. Asphalt mix at required temperature was first poured into the gyratory mould and then compacted in gyratory compactor. After compaction, moulds were then cut by diamond cutter to match the specified dimensions of DWT. The wheel was operated at a speed of 25 cycles per minute. Samples were aged for 48 hours. The DWT was set to 5000 cycles under room temperature.

Samples were prepared for DWT test in the following order.

i. 0% (Virgin) and 40% RAP sample
ii. 40% RAP with 1% Elvaloy Polymer sample

Following figures shows the hierarchy from preparation of gyratory samples to the tests performed.

Figure 3- 27 Preparation and Compaction of Gyratory Molds for DWT

Figure 3- 28 Sample placed in DWT (double wheel tracker) for Rut test

3.5.4 Indirect Tensile Strength (ITS) and Moisture Susceptibility Using UTM

The moisture susceptibility test was conducted as per specified by ASTM D 6931-07. Three specimens per mix were tested unconditioned. These unconditioned specimens were placed in a water bath at 25±1°C (77±1.8°F) one hour prior to testing. Another set of three specimens per mix were tested conditioned. Conditioning of samples were carried out according to ALDOT-361 i.e., specimens were saturated and then positioned in a 60±1°C (140±1.8°F) water bath for 24 hours followed by one 50 hours in a water bath at 25±1°C (77±1.8°F). Both unconditioned and conditioned specimens were loaded on their diametric plane at a constant rate of 50 mm/minute.

For each specimen, the tensile strength was then calculated using specimen dimensions and failure load. The tensile strength ratios were then found as being the ratio of average conditioned tensile strength to the average unconditioned tensile strength. The acceptable value for tensile strength ratio employed was 80%.

Calculate the tensile strength as follows:

$$St = \frac{2000P}{\pi Dt} \quad \ldots\ldots \quad 3.3$$

Where:

- St = tensile strength (K Pa)
- P = maximum load (N)
- t = sample thickness (mm)
- D = sample diameter (mm)

The moisture resistance is then calculated as a ratio of the conditioned sample's tensile strength after conditioning to the unconditional tensile strength.

TSR is calculated as follows:

$TSR = \frac{S2}{S1}$ 3. 4

As:

- TSR: tensile strength ratio
- S1: average tensile strength of unconditioned samples
- S2: average tensile strength of conditioned samples

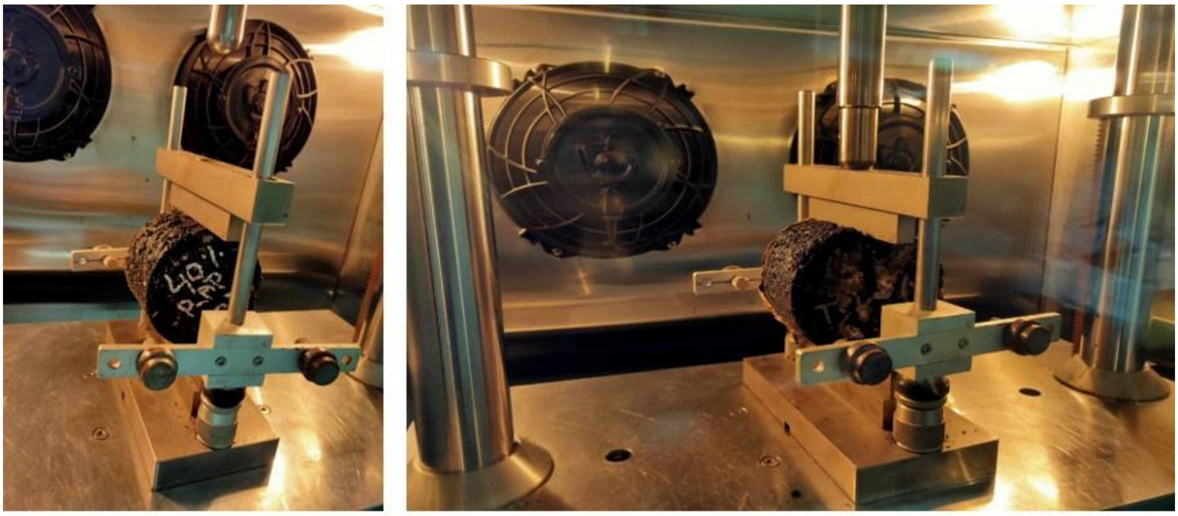
Samples were prepared for IDT test both for conditioned and unconditioned samples, in the following order.

i. 0% (Virgin) and 40% RAP sample
ii. 40% RAP with 1% Elvaloy Polymer sample

Also, below figures shows the hierarchy from preparation of IDT samples to the tests performed.

Figure 3- 29 IDT sample mixing and pouring in mould for compaction

Figure 3- 31 Prepared Gyratory samples (all combinations) and their cutting by diamond cutter



a)

b)

Figure 3- 30 a) Sample placed in UTM for IDT test, b) Sample after performing IDT test

Figure 3- 32 All (conditioned & unconditioned) samples of IDT test

Figure 3- 33 For conditioning samples of IDT in water bath

3.6 Summary

After establishing the procedural methodology, analysis is carried out to find the results which are then discussed. The next chapter deals with results and discussion.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

Data obtained from different binder and mixture tests of asphalts was subjected to a thorough analysis and is presented and discussed in this chapter in detail.

4.2 Basic Test Results

4.2.1 Aggregate Testing

Necessary/basic tests were performed (following standard protocols of ASTM/BS) on Margalla Quarry Aggregates to ensure their usage in wearing course of asphaltic pavements. Result column have shown that all the values are within the specified limits. Table 4-1 summarizes the aggregate tests performed.

Table 4- 1 Basic Aggregates Test Results

Test Description	Specification Reference		Results	Limits
Elongation Index (EI)	ASTM D 4791		3.58 %	≤ 15
Flakiness Index (FI)	ASTM D 4791		12.9 %	≤ 15
Aggregate Absorption	Fine	ASTM C 127	2.45 %	≤ 3
	Coarse	ASTM C 127	0.73 %	≤ 3
Impact Value	BS 812		17 %	≤ 30
Los Angeles Abrasion	ASTM C 131		22	≤ 45
Specific Gravity	Fine Aggregate	ASTM C 128	2.618	-
	Coarse Aggregate	ASTM C 127	2.632	-

4.2.2 Conventional Tests on Bitumen

Parco 60/70 pen grade bitumen was used in this study. Conventional tests were conducted to characterize the binder. Table 4-2 summarizes the conventional properties of binder. From result column, satisfactory results can be observed hence indicating its usage into asphalt pavements a viable option.

Table 4- 2 Conventional properties of bitumen used

Test Performed	Result	Standard
Penetration (0.1 mm, 25 ^{0}C)	64	ASTM D 05
Softening Point (^{0}C)	48.2	ASTM D 36
Ductility (cm)	104	ASTM D 113
Flash Point (^{0}C)	268	ASTM D 92
Fire Point (^{0}C)	293	ASTM D 92
Viscosity Test (Pa.sec)	0.2625	ASTM D 4402
Specific Gravity	1.03	ASTM D 70

4.3 Performance Testing

4.3.1 Four Point Bending Beam Fatigue Test

Fatigue life of asphalt mixtures, due to its brittle nature at lower temperatures is one of the most important performance prediction parameters. Effect of RAP content and Polymer

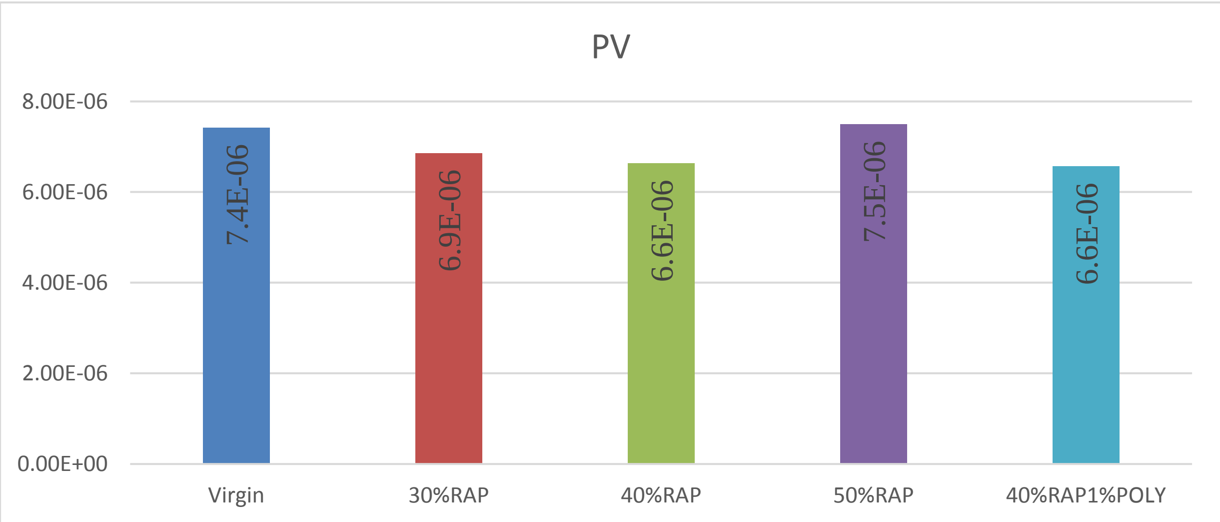


Figure 4- 1 PV values of RAP and Polymer modified Asphalt

modification on fatigue performance of asphalt mixtures was evaluated using flexural beam fatigue test as per AASHTO T-321 under strain controlled mode. Figure 4-1 shows the effect of RAP content and polymer modification on asphalt mixture fatigue life in terms of Plateau Value (PV). The effect of RAP content and polymer incorporation on asphalt mixture is also summarized in the table below.

Table 4- 3 Effect of RAP content and Polymer incorporation on Asphalt Mixture

Sample type	Temp (^{0}C)	Weight (Kg)	Frequency (Hz)	Strain	Cycles N_f	PV
Virgin	20	2.44	10	500	4800	**7.42019E-06**
30% RAP	20	2.51	10	500	5198	**6.85761E-06**
40% RAP	20	2.99	10	500	5378	**6.63027E-06**
50% RAP	20	3.2	10	500	4754	**7.49122E-06**
40%RAP 1% Polymer	20	3.1	10	500	5432	**6.56497E-06**

It is clear from the above figure that addition of RAP increases the fatigue life of asphalt mixture to a certain RAP content. Decrease in PV values was observed for 30% and 40% RAP content indicating improvement in fatigue life. However, for RAP content of 50% the PV value increased almost equal to the PV value of virgin asphalt mixture. On the other hand, Elvaloy modified binder mix has shown insignificant effect on the fatigue life of 40% RAP content based asphalt mixture. This improvement in fatigue life can be attributed to a higher affinity between the aged RAP binder and the unaged virgin asphalt binder in the Mix with the inclusion of RAP component. (Pasetto & Baldo, 2017). This could also be due to the formation of strong adhesive bond between asphalt binder and RAP grains (Pasetto & Baldo, 2017). Improvement in fatigue life has already been reported by some other researchers (Ma, Cui, Zhao, & Huang, 2017). The improvement in fatigue life assumed to be as result of the formation of a stiff layer of RAP binder between virgin binder and RAP grains reduce the stress concentration on the Asphalt mix. Moreover, the virgin asphalt binder plays the roles of covering the RAP grains and aggregates by further improving the fatigue life and striping resistance of asphalt mix. The reduction in fatigue life at 50% RAP content could be due to the presence of higher content of RAP binder failing to form a proper bond with the virgin asphalt binder, resulting in a relatively weaker asphalt mix and eventually reducing the fatigue life.

4.3.2 Double Wheel Tracker Test

The rutting performance of asphalt mixtures treated with Elvaloy and RAP concentration was evaluated using a DWT test. The effect of RAP and polymer modification on the rutting performance of an asphalt mixture is shown in Figure 4-2. The chart below shows how adding RAP material to asphalt mixtures enhances their rutting resistance, which can be attributed to increase in stiffness of asphalt mixture due to incorporation of RAP material. Moreover, further addition of Elvaloy modified asphalt binder in place of virgin asphalt binder further enhances the rutting resistance of asphalt mix. Previous studies also report the improvement of asphalt rutting performance with the addition of RAP and Elvaloy to the virgin asphalt binder (Irfan et al., 2017). The improvement in rutting resistance of Elvaloy modified asphalt mix could be due to chemical reaction between asphalt binder and Elvaloy, resulting in the formation of a strong polymer-linked asphalt (Domingos & Faxina, 2016). Another study regarding Elvaloy modified asphalt also report improvement in rutting resistance of asphalt due to formation of tough and rigid network in asphalt though a chemical reaction (Tarefder & Arifuzzaman, 2011).

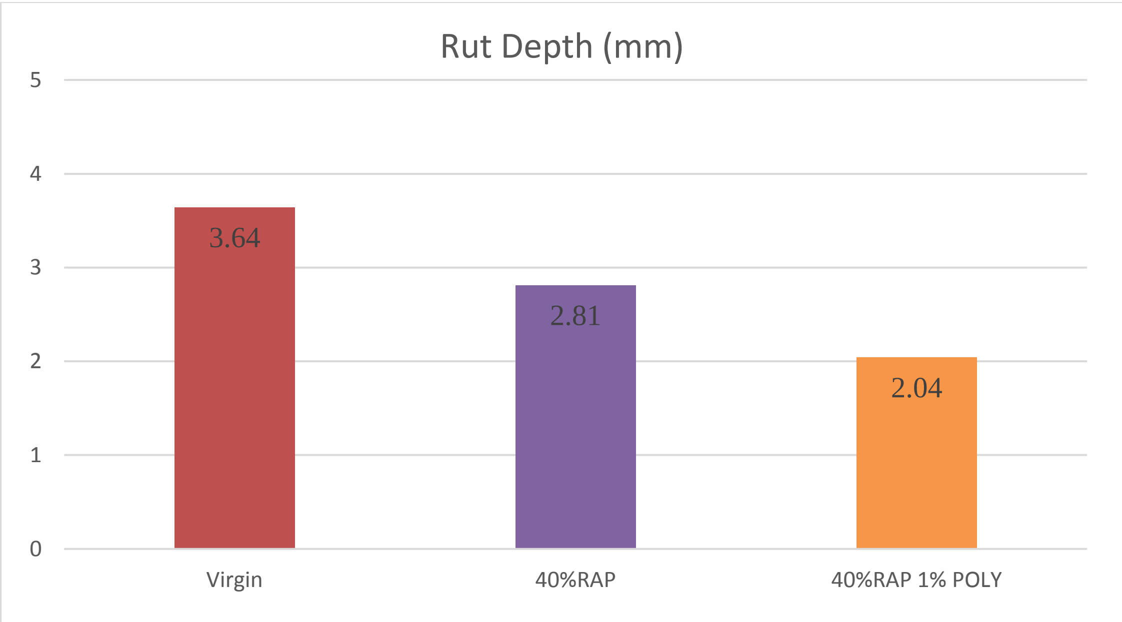


Figure 4- 2 Effect of RAP and Polymer on Rutting

Numerical details of DWT test are shown in Table 4-4.

Table 4- 4 DWT test details and results

Sample type	Wheel Type	No. of Passes	Temp (^{0}C)	Diameter (mm)	Thickness (mm)	Weight (Kg)	Rut Depth (mm)
Virgin	Rubber	10000	25	150	63.5	2.28	**3.64**
40% RAP	Rubber	10000	25	150	63.5	2.25	**2.81**
40%RAP 1% Polymer	Rubber	10000	25	150	63.5	2.26	**2.04**

4.3.3 Indirect Tensile Strength (ITS) and Moisture Susceptibility

Moisture susceptibility testing may be used to assess the risk of moisture damage to HMA mixtures. The results of the moisture susceptibility test can be used to predict the possibility of long-term stripping and evaluate anti-stripping additives, which are added to the asphalt binder, aggregate, or HMA mixture to prevent stripping.

Figure 4-3 shows the results of ITS conducted on various asphalt mixes along with the corresponding TSR values. TSR values for all the mixes were greater than 80% as per the requirement of AASHTO T283. TSR value for 40% RAP content based mixture was higher than the virgin asphalt mix which could be due to the formation of better bond between virgin asphalt binder and RAP Grains / Aggregates. Table 4-5 shows the numerical details of TSR test along with results.

Table 4- 5 TSR test details and results

Sample type	Temp (^{0}C)	Diameter (mm)	Thickness (mm)	Peak Force U (N)	Peak Force C (N)	Tensile Strength U (Kpa)	Tensile Strength C (Kpa)	TSR %
Virgin	25	97	65	5532	4631	558.85	467.83	**83.71**
40% RAP	25	97	65	5576	4712	563.29	476.01	**84.51**
40%RAP 1% Poly	25	97	65	5678	4831	573.60	488.01	**85.08**

Higher TSR value for Elvaloy modified asphalt mix with RAP content could be due to the chemical reaction between Elvaloy and asphalt binder (Irfan et al., 2017). This chemical reaction results in the formation of a strong bond between asphalt binder and aggregates eventually increasing adhesive properties of asphalt mix. Due to this behavior Elvaloy also reduces the moisture susceptibility of asphalt mix by acting as an anti-stripping agent (Tarefder & Arifuzzaman, 2011).-

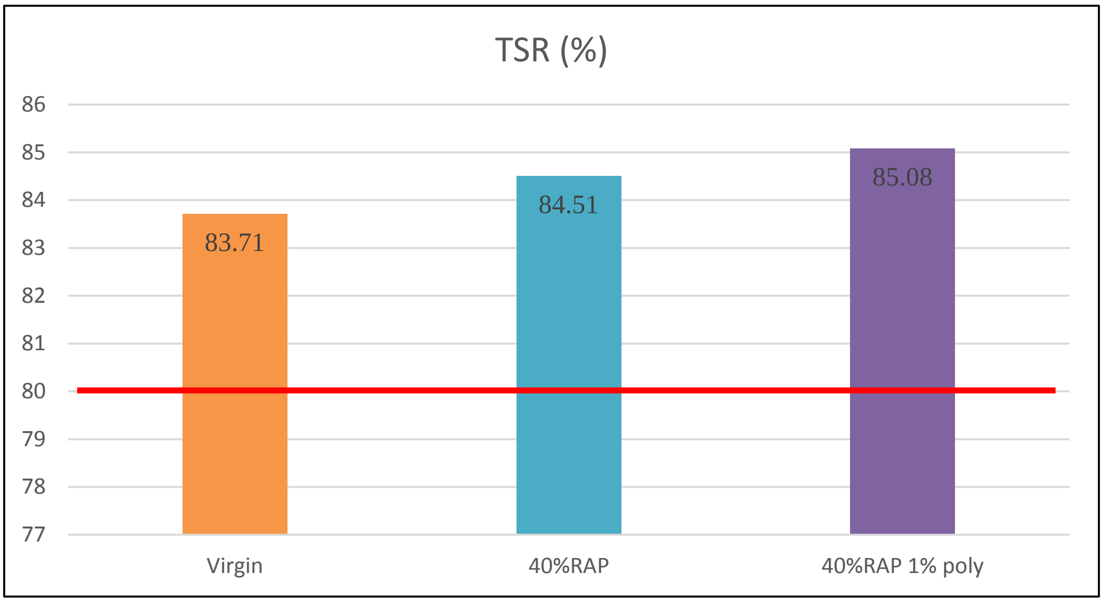


Figure 4- 3 Effect of RAP and Polymer on Tensile Strength Ratio (TSR)

4.4 Summary

In this chapter all the basic test results of aggregates and bitumen are presented in tabular form. And all the results of Rutting, Fatigue and Moisture Susceptibility analysis of asphalt using DWT, four-point beam test, TSR (UTM) apparatuses are presented, respectively. Dissipated energy analysis was used to predict fatigue life of asphalt mixtures. The PV against the load cycles to failure (N_f) for individual mixture was presented using graphs and elaborated. Rut depth was shown for each sample against specified no. of passes. At the end, tensile strength ratio is presented (in tabular and in graphical form) against each sample.

CHAPTER 5

CONCLUSIONS AND RECOMMEDATIONS

5.1 Summary

In this study RAP is being used in percentages of 0, 30, 40 & 50 along with 1% Elvaloy Polymer and 40% RAP combinations. Marshall mix design was used to determine the OBC and volumetrics of control mix, and RAP binder content was found by ignition test method. Fatigue, Rutting and Moisture parameters of RAP modified Asphalt mix were studied using Four-point beam fatigues test, Double wheel tracker test, Indirect tensile strength test approaches, respectively. The results were then analyzed and the following conclusion and recommendations are presented:

5.2 Conclusions

The experimental work conducted aimed at studying the effect of addition of varying percentages of RAP into the Asphalt mix along with the addition of 1% Elvaloy Polymer. Rutting, Fatigue, and Moisture parameters were thoroughly focused and elaborated. Based on detailed research and evaluations following points are concluded:

- Volumetric criteria passed when HMA was prepared with varying dosages of RAP.
- It is also observed that, most optimized HMA mix was with 40% RAP content.
- Both the aggregates and bitumen have passed the respective basic tests criterion.
- Addition of RAP content has increased the fatigue life of asphalt to a certain RAP content i.e., decrease in PV values was observed for 30% and 40% RAP content indicating improvement in fatigue life.
- Addition of 50% RAP content shows almost equal PV value to the PV value of unmodified asphalt mixture. However, Elvaloy modified binder mix has shown insignificant effect on the fatigue life of 40% RAP content based asphalt mixture.
- Addition of RAP content also improves the rutting resistance of asphalt mixtures i.e., 40% RAP modified asphalt mix showed up to 23% increase in rut resistance.
- Addition of 40% RAP along with 1% Elvaloy Polymer has further increased the rut resistance up to 44% in comparison with unmodified asphalt mix.
- Upon addition of 40% RAP into the asphalt mix resulted in slight improvement of TSR value.

- Addition of 40% RAP content along with 1% Elvaloy Polymer also showed improvement in the TSR value. Increase in the TSR value could be due to the chemical reaction between Elvaloy and asphalt binder. Hence, forming a strong bond between asphalt binder and aggregates eventually increasing adhesive properties of asphalt mix. Also, it acts as anti-stripping agent by reducing the moisture susceptibility of asphalt mix.

5.3 Recommendations

Based on the above conclusions, following recommendations are made.

- Highway authorities should endorse the maximum possible use of RAP in HMA wearing course as it is more rut resistant and cost effective. Also, it will reduce the use of natural aggregates along with overcoming wastes hence, leaving positive impact on the environment.
- Future researchers should study wide range of RAP percentages along with other polymers.
- Only 1% Elvaloy Polymer was incorporated in this research, higher and lower percentage of this polymer should be included in HMA to study it’s effects.
- Effect of Elvaloy polymer in combination with other polymers along with RAP content needs to be further explored.
- Different strain levels should be employed in future research because, in this research, four-point bending test was conducted at single strain level.
- The topic holds a great deal of potential in research and can be utilized by students in future studies.

When all is said and done, one can speculate about this research area being open for further research and holds promises of profound knowledge and newer findings.

REFERENCES

Al-Qadi, I. L., Aurangzeb, Q., Carpenter, S. H., Pine, W. J., & Trepanier, J. (2012). *Impact of high RAP contents on structural and performance properties of asphalt mixtures* (0197-9191). Retrieved from

Al-Qadi, I. L., Carpenter, S. H., Roberts, G. L., Ozer, H., & Aurangzeb, Q. (2009). *Investigation of working binder in hot-mix asphalt containing recycled asphalt pavements.* Paper presented at the Transportation Research Board 88th Annual Meeting, Transportation Research Board, Washington, DC.

Aldagheiri, M. (2009). The role of the transport road network in the economic development of Saudi Arabia. *WIT Transactions on the Built Environment*, 275-285.

Ameri, M., Yeganeh, S., & Valipour, P. E. (2019). Experimental evaluation of fatigue resistance of asphalt mixtures containing waste elastomeric polymers. *Construction and Building Materials*, *198*, 638-649.

Babrock, G. (2009). *DuPont asphalt modifier applications and examples.* Paper presented at the New Jersey APA Annual Conf., American Planning Association, NJ.

Badin, G., Ahmad, N., & Ali, H. M. (2020). Experimental investigation into the thermal augmentation of pigmented asphalt. *Physica A: Statistical Mechanics and its Applications*, *551*, 123974.

Brown, E. R., & Cross, S. A. (1992). *A national study of rutting in hot mix asphalt (HMA) pavements*. Retrieved from

Carpenter, S. H., & Shen, S. (2006). Dissipated energy approach to study hot-mix asphalt healing in fatigue. *Transportation Research Record*, *1970*(1), 178-185.

Cooley, L. A., Kandhal, P. S., Buchanan, M. S., Fee, F., & Epps, A. (2000). *Loaded wheel testers in the United States: State of the practice*: Transportation Research Board, National Research Council Washington, DC.

Domingos, M., & Faxina, A. (2016). Susceptibility of asphalt binders to rutting: literature review. *Journal of Materials in Civil Engineering*, *28*(2), 04015134.

Du, Y., & Wang, S. (2015). Oriented heat release in asphalt pavement induced by high-thermal-conductivity rods. *Applied Thermal Engineering, 90*, 424-431.

Elkashef, M., & Williams, R. C. (2017). Improving fatigue and low temperature performance of 100% RAP mixtures using a soybean-derived rejuvenator. *Construction and Building Materials, 151*, 345-352.

Ghuzlan, K. A., & Carpenter, S. H. (2000). Energy-derived, damage-based failure criterion for fatigue testing. *Transportation Research Record, 1723*(1), 141-149.

Hansen, K. R., Copeland, A., & Association, N. A. P. (2013). *Annual asphalt pavement industry survey on recycled materials and warm-mix asphalt usage: 2009-2012*. Retrieved from

Hunter, E. R., & Ksaibati, K. (2002). *Evaluating moisture susceptibility of asphalt mixes*: Mountain-Plains Consortium Fargo, ND, USA.

Hussan, S., Kamal, M. A., Hafeez, I., Farooq, D., Ahmad, N., & Khanzada, S. (2017a). Statistical evaluation of factors affecting the laboratory rutting susceptibility of asphalt mixtures. *International Journal of Pavement Engineering, 20*(4), 402-416. doi:https://doi.org/10.1080/10298436.2017.1299527

Hussan, S., Kamal, M. A., Hafeez, I., Farooq, D., Ahmad, N., & Khanzada, S. (2017b). Statistical evaluation of factors affecting the laboratory rutting susceptibility of asphalt mixtures. *International Journal of Pavement Engineering*, 1-15.

Irfan, M., Saeed, M., Ahmed, S., & Ali, Y. (2017). Performance evaluation of elvaloy as a fuel-resistant polymer in asphaltic concrete airfield pavements. *Journal of Materials in Civil Engineering, 29*(10), 04017163.

Kamran Muzaffar Khan, H., Mujaddad Afzal, Faizan Ali, Afaq Ahmed, Tahir Sultan. (2013). Rutting performance of Polyethylene, Lime and Elvaloy modified Asphalt Mixes. *Life Science Journal, 10 (7s)*.

Li, R., Xiao, F., Amirkhanian, S., You, Z., & Huang, J. (2017). Developments of nano materials and technologies on asphalt materials–A review. *Construction and Building Materials, 143*, 633-648.

Ma, T., Cui, K., Zhao, Y., & Huang, X. (2017). Fatigue evaluation of recycled asphalt mixture based on energy-controlled mode. *Advances in Materials Science and Engineering, 2017*.

Mogawer, W. S., & Stuart, K. D. (1995). Effect of coarse aggregate content on stone matrix asphalt rutting and draindown. *Transportation Research Record*(1492).

Negulescu, I., Mohammad, L., Daly, W., Abadie, C., Cueto, R., Daranga, C., & Glover, I. (2006). Chemical and rheological characterization of wet and dry aging of SBS copolymer modified asphalt cements: Laboratory and field evaluation (with discussion). *Journal of the Association of Asphalt Paving Technologists, 75*.

Pasetto, M., & Baldo, N. (2017). Fatigue performance of recycled hot mix asphalt: A laboratory study. *Advances in Materials Science and Engineering, 2017*.

Patel, R., & Mishra, C. (2018). Surveillance of Elvaloy-5170 as a modifier in BC Grade 1 mix design.

Read, J., & Whiteoak, D. (2003). *The shell bitumen handbook*: Thomas Telford.

Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D.-Y., & Kennedy, T. W. (1996). *HOT MIX ASPHALT MATERIALS, MIXTURE DESIGN AND CONSTRUCTION. SECOND EDITION* (2nd ed.).

Shen, S., & Carpenter, S. H. (2005). Application of the dissipated energy concept in fatigue endurance limit testing. *Transportation Research Record, 1929*(1), 165-173.

Tarefder, R., & Arifuzzaman, M. (2011). A study of moisture damage in plastomeric polymer modified asphalt binder using functionalized AFM tips. *Journal of Systemics, Cybernetics and Informatics, 9*(5), 1-12.

Tufail, M., Ahmad, N., Mirza, S. M., Mirza, N. M., & Khan, H. A. (1992). Natural radioactivity from the building materials used in Islamabad and Rawalpindi, Pakistan. *Science of the total environment, 121*, 283-291.

Vamegh, M., Ameri, M., & Naeni, S. F. C. (2019). Performance evaluation of fatigue resistance of asphalt mixtures modified by SBR/PP polymer blends and SBS. *Construction and Building Materials, 209*, 202-214.

What Is Bitumen(Asphalt)? Retrieved from http://www.bitumina.co.uk/whatisbitumen.html

Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials, 21*(1), 66-72.

Yousaf, A., Hussain, A., Irfan, M., Khan, M. B., & Ahmed, A. (2014). Performance evaluation of asphaltic mixtures using bakelite. *Life Science Journal*, *11*(7s).

Zhang, J., Sun, H., Jiang, H., Xu, X., Liang, M., Hou, Y., & Yao, Z. (2019). Experimental assessment of reclaimed bitumen and RAP asphalt mixtures incorporating a developed rejuvenator. *Construction and Building Materials, 215*, 660-669.

Zhou, Z., Gu, X., Dong, Q., Ni, F., & Jiang, Y. (2019). Rutting and fatigue cracking performance of SBS-RAP blended binders with a rejuvenator. *Construction and Building Materials*, *203*, 294-303.

Zhou, Z., Gu, X., Jiang, J., Ni, F., & Jiang, Y. (2019). Fatigue cracking performance evaluation of laboratory-produced polymer modified asphalt mixture containing reclaimed asphalt pavement material. *Construction and Building Materials, 216*, 379-389.