

INVESTIGATION OF IMPACTS OF CASTOR OIL AS A REJUVENATOR ON RECYCLED ASPHALT PAVEMENT

THESIS REPORT

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DECLARATION

I undersigned hereby declare that the project report “Investigation of Impacts of Castor oil as a Rejuvenator on Recycled Asphalt Pavement”, submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a genuine work done by me under supervision of Prof. Meenu Tomson and Dr. Kavitha Madhu. This submission represents my idea in my own words and where ideas or words of others have been included; I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by institute and/or University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

Certified that this report entitled '**INVESTIGATION OF IMPACTS OF CASTOR OIL AS A REJUVENATOR ON RECYCLED ASPHALT PAVEMENT**' is the report of thesis presented by **SANDRA R S, Reg No.: TKM21CETE16** during **2022-2023** in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Transportation Engineering of the A P J Abdul Kalam Technological University.

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ABSTRACT

The use of recycled asphalt pavement in road construction sector is limited due to its poor cracking performance. Application of rejuvenator is an emerging solution for regaining the lost properties of RAP. Prior research mainly deals with chemical rejuvenators which are unsustainable and sometimes carcinogenic. The usage of oil-based organic rejuvenators causes higher softening effects on pavement and thereby reduce the load carrying capacity. This study deals with this gap by evaluating the impacts of castor oil as a rejuvenator on the performance of binder and mixtures containing 30% and 60% RAP materials. The physical and rheological properties of binder were studied by conventional tests and dynamic shear rheometer test respectively. The volumetric properties of mixtures were evaluated by Marshall, Indirect tensile strength test and Self-healing capacity test. The findings revealed that, the physical properties could regain with the addition of 5% and 8% castor oil to the RAP binder. The rutting parameter of both rejuvenated RAP binder with optimum castor oil were higher than that of virgin binder while the fatigue parameter was reduced that of virgin binder. This ensure that the rheological parameters could enhances by the addition of castor oil. The mechanical properties and self-healing capacity of rejuvenated RAP mixtures were enhanced in comparison to the control mixture. In summary, the usage of RAP with optimum castor oil in mixtures show promising outcomes and there by ensure the sustainable development practices in the future.

Keyword: *RAP; rejuvenators; castor Oil; transesterification; stability; moisture susceptibility; healing index*

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ABBREVIATIONS

RAP	Recycled Asphalt Pavement
RTFO	Rolling Thin Film Oven
BC	Bituminous Concrete
MoRTH	Ministry of Road Transport and Highways
G_{mb}	Bulk Specific Gravity
G_t	Theoretical Maximum Specific Gravity
V_v	Volume of Voids
VMA	Voids In Mineral Aggregates
VFB	Voids Filled with Bitumen
P_b	Desired Bituminous Binder Content
ITS	Indirect Tensile Strength
TSR	Tensile Strength Ratio
HI	Healing Index

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Infrastructural development of a country is directly related to the transportation sector at that country. As the roadway network widens capacity of the traffic flow and accessibility to the remote areas are increasing and it result in high economic growth and social upcoming. But the construction and maintenance of roadways need huge amount of natural raw materials and may result high environmental depletion and pollution. Based on this, the focus should be on the sustainable road construction. That is without compromising the needs of future generation present day requirements are fulfilled. The main aspect of sustainable development is “3R concept; Reduce, Recycle and Reuse”.

Bituminous road construction is facing numerous challenges in terms of unavailability of good quality materials and distresses during the service life of pavement. Due to high temperature sensitivity and aging susceptibility, proper maintenance and rehabilitation is required to reduce the distresses like rutting, fatigue, low temperature cracking, and moisture sensitivity. This frequent maintenance operation results in the stockpiling of aged pavement materials. Despite the fact that the aged asphalt pavement materials cannot sustain the traffic loading, the binder and aggregates still have the potential for recycling and reuse. According to the concept of Waste into Wealth by Ministry of Road Transportation, India the incorporation of waste materials like plastic, construction and demolition waste, coir, recycled asphalt pavement (RAP) in new constructions is an emerging solution in the aspects of sustainable development. The major advantages of RAP are the reduction of landfill wastage and the excess need of fresh raw materials. The fact that America has 102.1 million tons of stock piled RAP and India owning 3.93 million km asphalt paved road highlights the significance of the study (Zhang et al., 2020). The asphalt pavement materials can be recycled and then reused effectively.

Recycled asphalt pavement is one of the most sustainable materials which can be used as a substitute for virgin binder in the road construction industry (Podosky et al. 2020). Even though

RAP usage has so many benefits, its usage is limited to less than or equal to 25%. In mix design due to its low fatigue resistance and low rutting resistance. During the aging process, the bitumen binder loses its visco-elastic nature due the conversion of maltenes to the asphaltene. These asphaltene undergo flocculation and resulted in a stiffer binder. The common solution for this is the addition of virgin binder. The carbon foot print of asphalt production is very high. Being a non-renewable natural energy resource asphalt production and handling is prime concern. Cost of production and life cycle cost of asphalt is also important. The huge requirement of virgin binder and aggregate can be fulfilled by recycled asphalt pavement materials. The recycling efficiency of RAP binders can be sustainably ensured by Rejuvenators. Rejuvenators are certain substance which can regain the lost properties of bitumen binder in RAP material. The addition of rejuvenator opens a new horizon to the asphalt industry by considering both environmental and economic aspects. Rejuvenators has high content of maltenes. Theses maltenes can separate the asphaltene floccules and regain its rheological properties. Among the various categories of rejuvenators like oil-based, chemical and organic, the organic rejuvenators are more efficient and noncarcinogenic. This mini-project aims to investigate the impacts of castor oil as a rejuvenator on recycled asphalt pavement. The Figure 1.1 shows the stockpiled RAP materials near the road side of Kazhakootam elevated highway works in Thiruvananthapuram district.



Figure 1.1 Stockpiled RAP Materials- Kazhakootam Elevated Highway Works

1.2 PROBLEM STATEMENT

In India around 3.93 million kilometers of road is made up of asphalt binder. Pavements are typically designed for a specific design period. IRC:37-2018 suggests a design period of 20 years for national highway, state highway and urban roads while for other category of roads, it's about 15 years. All these road's demand, regular maintenance and rehabilitation for comfort and robust transportation system. At the end of the design life, the entire structure is demolished and new pavement materials are laid on it. Also, the need of new road network is increasing day by day. Both rehabilitation and reconstruction demand a huge amount of fresh raw materials including aggregates and binder. One of the methods of reconstruction is the in-situ mixing of milled old pavements to the new materials. But complete recycling cannot be done here. During the road maintenance works, the used pavements are milled out & stockpiled. It leads to bulk landfill waste. The other method is the recycling of separated aggregate and binder from the milled pavement materials. Recycling of these materials will reduce huge requirements of natural resources. The major drawback of this method is the high stiffness of binder and wear and tear of aggregates. To resolve this high stiffness in recycled binder the common solution is the addition of virgin binder. But it is unsustainable and uneconomical. To overcome the low rutting and fatigue performance rejuvenators can be added. Rejuvenators are asphalt additives which can regain properties of aged binder in RAP. By adding rejuvenators, we can increase the percentage of addition of RAP in the new mix design. Selection of rejuvenators, method of its blending, optimum percentage of addition etc. will affect performance of the mix. Organic oil-based rejuvenators are highly efficient and non-carcinogenic. Studies were done on various oils like Sunflower oil, Date palm oil, Maize oil, Mahua oil, Polanga oil and Cotton seed oil resulted good performance binder. From the analysis of literatures, it is clear that petroleum byproducts have rejuvenating potential in RAP binder. The castor oil already proven that it has the ability in bio diesel production. In this work, the potential of castor oil as a rejuvenator on RAP binder is investigated.

1.3 OBJECTIVES OF THE STUDY

The objectives of the proposed study are as follows;

- 1 To evaluate physical and rheological properties of rejuvenated RAP binder.
- 2 To determine the volumetric properties of control and rejuvenated RAP mixes by Marshall Method.
- 3 To determine the optimum binder content, optimum castor oil for rejuvenated RAP mixtures.
- 4 To determine the moisture susceptibility and self-healing capacity of optimum mixes.

1.4 SCOPE

This thesis includes the study to evaluate the impacts of castor oil as a rejuvenator on recycled asphalt pavement by conducting physical and rheological property analysis on binder and performance of mixtures. Study is limited to the rejuvenating capacity of castor oil since it is under the category of oil-based rejuvenator which are more efficient, non-carcinogenic and sustainable. Aggregate gradations having nominal maximum aggregate size of 13.2 mm (BC Grade II) is selected. The samples with 30% and 60% RAP materials with optimum castor oil content were tested for marshall stability, flow value, volumetric properties, ITS, TSR and self-healing capacity and the results were compared with that of control mix using fresh binder (VG 30) and fresh aggregate. Rutting and fatigue characteristics of mixes can be investigated in future.

1.5 ORGANIZATION OF REPORT

The report consists of mainly 5 chapters. Chapter 1 discusses the relevance of current study in the present scenario, research significance, objectives and scope of the study. Chapter 2 contains a review of research papers as well as the research gap identification. Chapter 3 briefly describes the methodology of work. In addition, various test details used in the study have been explained. The experimental results are discussed and analyzed in the Chapter 4. The conclusions that arrived from the results and the future scope are included in the Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Several studies were done associated with RAP materials, its binder property, performance in mix design, incorporation of rejuvenators, chemical and rheological evaluation of the binder with rejuvenators etc. This section includes the impacts of rejuvenators on RAP, significance of castor oil and novelty of this study.

2.2 IMPACTS OF REJUVENATORS ON RECYCLED ASPHALT PAVEMENT

The analysis of the difference between field aging and the simulation of field aging conditions by laboratory aging tests like Rolling Thin Film Oven Test (RTFOT) followed by Pressure Aging Vessel (PAV) is one of the major steps in the feasibility study of RAP materials (Qian et al., 2020). In order to study this, the binder was extracted from the various RAP of four-year-old available on Hong Kong city using centrifugal extractor. Then using the rotary evaporator apparatus, the binder was extracted from the solution. The rheological properties of both the field and lab aged binder were tested by dynamic shear rheometer (DSR) and the chemical properties by Fourier transform Infrared Spectroscopy (FTIR). The conclusion reached was the lab aging conditions are underestimated the real field aging conditions in terms of rheological performance in the region of Hong Kong. Better methods are to be found out in future for increasing the accuracy in aging simulation.

Another important parameter in the field of rejuvenator is their types and its comparison which include organic and inorganic rejuvenators. Physical, rheological and chemical property analysis should be conducted in the same RAP to evaluate which one is more efficient. Zaumanis et al. (2014) studied five common rejuvenators (waste vegetable oil, waste vegetable grease, organic oil, distilled tall oil) and one unique rejuvenator (aromatic extract) which were added to lab samples of 100% recycled hot mix asphalt at a dose of 12% each, and the performance of the mix were

assessed. Rutting resistance of all rejuvenated samples were high compared to virgin mixtures which were tested by Hamburg wheel rut test. Waste vegetable oil and aromatic extract shows similar fatigue life that of virgin mixture while other mixtures show slightly higher cracking temperature. Workability of all rejuvenated RAP mixture was improved but not similar to that of virgin mixtures. Performance of the mixture were studied with only one percentage of rejuvenators (12%), so further studies are needed to optimize the percentages of addition of these rejuvenators. The comparison of Cyclogen, Rapiol and WCO were conducted by Ziari et al. (2019). Resilient modulus test, dynamic creep, indirect tensile fatigue and intermediate temperature fracture tests on short-term and long-term aged asphalt mixtures containing 50% RAP were conducted on this purpose. Among this Rapiol showed better rutting performance in long term aging and Cyclogen showed better fatigue resistance in long term aging. He reached the finding that these rejuvenators have the capacity to give aromatic and maltene contents back to the aged binder and thereby improving their performance and optimum characteristics. Similarly, Ahmed et al. (2020) studied the WCO & Hydolene as rejuvenators on PG 58-28 binder. He established transesterification on the WCO in order to reduce the Free Fatty Acid content on it, since FFA tends to reduce its workability by reducing its acid value. Chemical and morphological studies of the rejuvenated binder were conducted and reached the conclusion that transesterification can be used as modification technique on oil-based rejuvenators. Another study in this area was conducted by Saha et al. (2020). The effects of WCO and Soy oil as a rejuvenator on reclaimed asphalt pavement binder and HMA mixtures contain the various percentages of RAP materials were evaluated. Rheological properties of binder and rutting, fatigue cracking and low-temperature cracking performance of HMA mixes were evaluated. By analyzing the results, it was clear that, the HMA mixture containing 5%WCO_25%PG64-28_70%RAP & 5%SOY_25%PG64-28_70%RAP were comparable to that of virgin binder mixtures. Zhang et al. (2020) investigated the effect of waste engine oil, vegetable oil and composite rejuvenator (made up of aromatic oil, plasticizer, and anti-stripping agent) as a recycling agent on mixture containing 60% of RAP. The performance was evaluated by various including dynamic shear rheological test, zero shear viscosity test, wheel tracking test, three-point bending test, dynamic modulus test, four-point bending fatigue test etc. Composite rejuvenator showed better fatigue life and restoration of shear thinning behavior while all the rejuvenators could restore the visco-elastic behavior of RAP mixtures. WEO could not obtain the corresponding rejuvenating effect of composite rejuvenator due the presence of

lubrication component in it. Overall, it was clear that, compared to the virgin HMA mixtures, the rejuvenated RAP HMA mixtures proved better. Various rejuvenators like paraffinic oils, fatty acids and tall oils which includes five different oils like waste engine oil, commercial product derived from waste lubrication engine oil, tallow, waste vegetable oil and crude tall oil with 60% RAP were evaluated. Rutting and fatigue resistance of rejuvenated RAP binder and mixes were evaluated and compared with that of virgin binder and control mix. The test results imply that, if the desired dose of rejuvenator is chosen based on the softening point value or viscosity test results, rutting of asphalt mixes caused by excessive softening of the rejuvenated bitumen should not be a problem (Gunduru et al., 2021). The WEO of the paraffinic oil category proved to be the least successful at enhancing the fatigue resistance of asphalt mixes. It was discovered that the FA category regenerators, WVO and tallow were more successful at enhancing the fatigue damage resistance of asphalt mixes. Those made from crude tallow had low rutting resistance and fatigue resistance compared to that of virgin mix. Wróbel et al. (2021) proved Rapeseed and oleic imidazolines can be employed as rejuvenators to repair the characteristics of deteriorated asphalt found in RAP. Imidazoline was added to old asphalt, which increased penetration while lowering viscosity and softening temperature. Imidazoline also improves the asphalt's ability to resist ageing. According to the weight of the asphalt binder, 2% was the ideal addition rate for imidazoline. The penetration and softening temperature of the aged binder demonstrate that rapeseed imidazoline had a larger softening effect. When creating mineral-asphalt combinations, designers should consider the fact that imidazoline dosed to fresh asphalt also promotes its softening. However, injecting imidazoline straight into recovered asphalt pavement does not provide the desired effects. As a result, the imidazoline needs to be dosed into a new binder. A drop in air void content and a modest reduction in stiffness were observed in asphalt mixes when imidazoline was added. The combination containing polymer modified asphalt should have strong resistance to low-temperature cracks, according to the stiffness modulus' reduction at low temperatures. Polymer treated asphalt produced better rutting resistance outcomes. Rathore et al. (2022) studied the rheological and chemical properties of reclaimed asphalt mixtures containing four different rejuvenator crude tall oil-based rejuvenator, vegetable oil and polymer-based rejuvenator, bio-oil-based rejuvenator, and petroleum-based rejuvenator. In long-term aging, tall oil-based rejuvenator achieved lowest reduction in stiffness. Higher rutting susceptibility was shown by tall-oil and bio-oil based rejuvenator. Petroleum-based rejuvenator showed lowest

reduction in stiffness of binder in long-term aging and its FTIR showed increased carbonyl peak intensity after long-term aging.

In the aspect of sustainable development, organic rejuvenators are non-carcinogenic, easily available and user friendly. The establishment of bio-oil rejuvenators demand huge significance. Foroutan et al. (2020) looked on the usage of high RAP concentrations, up to 90% in WMA employing with bio-oil rejuvenator. In order to do this, various binder combinations were subjected to rheological testing, such as rotational viscosity (RV), multiple stress creep recovery (MSCR) and linear amplitude sweep (LAS). The asphalt blend containing 90% RAP and a bio-oil rejuvenator had a 37% higher fatigue life and a 4% improvement in moisture resistance, according to test data. Strategies for fixing the dosage of recycling agents based on the performance of recycled blend contain virgin binder, recycled binder and recycling agent with respect to its performance grade (PG) is a significant parameter (Arámbula et al., 2017). The best recycling agent can be determined based on the performance of the recycled blends and the way to restore high-temperature PG. The extracted binder with rejuvenators: Tall oil, aromatic extract, vegetable oil and bio-based oil were studied using DSR equipment by evaluating its stiffness and phase angle values. The optimum percentage of addition of rejuvenator were obtained as 2.0% or lower with addition method and for partial replacement method, it was more than 2.0% while the complete replacement method demands more than 5.0 % of recycling agent.

Rejuvenators has major impacts on retaining the homogeneity of binder. Mohammadafzali et al., (2018) studied the influence of parameters like diffusion of rejuvenators into RAP binder and the effect of blending procedure on homogeneity of modified binder by homogeneity index and stiffness gradient factor using Dynamic Shear Rheometer. The diffusion of the rejuvenator increases with increasing temperature and resulting a homogenize structure. In the rejuvenated binder both aging and rejuvenation occur from outside to inside which compliment to each other and form a good homogenous binder while the virgin mixtures show less homogeneity due to in consistent aging. Other than the homogeneity of binder, the rheological property requirement of RAP binder is the most important criteria for the selection of rejuvenators. Polanga oil with minimum dosage of 4% and maximum dosage of 18% could improve the rheological properties of RAP binder (Pradhan and Sahoo, 2018). The viscosity and complex shear modulus of stiff RAP binder could be reduced by the addition of Polanga oil. The 5 % rejuvenated aged binder was found

to be effective in obtaining the required rheological properties and lower creep compliance values compared to the virgin binder. Further studies needed for analyzing the impact of Polanga oil as a rejuvenator on mix design with RAP materials.

A comparative study on various addition methods like pre-blending of rejuvenators with virgin binder and mixing of rejuvenators on RAP binder using DSR and gel penetration chromatography tests were conducted by Ma et al. (2020). The rejuvenator with high compatibility with aging and retrieval of lost properties of RAP binder was selected for blending. Compared to conventional methods, better result was shown in the blend which was prepared by adding rejuvenators to RAP binder. Blend with rejuvenator and RAP binder shows low rutting parameter on short term aging and fatigue parameters was similar for both the blends in long-term aging. A subsequent mixture study is necessary in future since the incorporation method is expected to affect the performance of mixture.

Mullapudi et al. (2020) studied the fatigue and healing properties of RAP mixtures. Because of the chemical parameters of RAP binder blends differ from virgin binders (depending on the degree of ageing), bituminous mixes made from reclaimed asphalt pavement (RAP) material have distinct healing qualities from those of virgin mixes. Several mixtures of RAP and virgin binders (VG30) were created at various RAP material proportions (0%, 15%, 25%, 35%, and 45%). In order to assess the fatigue lives of various RAP mixtures, the rest intervals (400, 650, 900, and 1,400 ms). As the percentage of RAP in a mixture increased, so did its fatigue life. It was discovered that RAP content and rest period had an impact on the degree of healing reflected by the slope of the log (fatigue life) against log (rest period) line. The fatigue lifetimes and healing indices of the mixes related to various rheological and chemical properties of the binder blends as well as the time lag values of the mixes. The healing index and flow metrics like the softening point and viscosity at 60°C had a strong correlation. The effects of confinement pressure and rest periods on measurement of dynamic modulus of mixtures should give more priority (Janmejaya et al., 2021). Repeated haversine compression loading is applied to two dense graded bituminous mixtures (polymer-modified and unmodified) at ten test frequencies and six distinct test temperatures (5°C-55°C). The tests are run both with and without a rest time and confinement pressure. According to a study of the data, confinement pressure had a significant impact on the dynamic modulus and

phase angle in the temperature range of 35°C-55°C and the frequency range of 0.01-2 Hz. Dynamic modulus and phase angle appear to be barely impacted by the rest period.

Valente et al (2010) studied both the physical and chemical characteristics of fuels made from castor oil biodiesel with diesel oil and waste cooking oil biodiesel. According to accepted test procedures, the following characteristics were measured: fuel density, kinematic viscosity, cetane index, distillation temperatures and Sulphur content. As biodiesel concentration increased, Sulphur content of the fuel decreased and density and viscosity increased. Diesel oil with a high biodiesel percentage has a lower cetane index. 20% waste cooking oil biodiesel or 35% castor oil biodiesel showed optimum results. It showed that both waste cooking oil and castor oil has certain potential to reach the required fuel specifications similar chemical functional groups within it. Also, Liu et al. (2021) studied the impacts of castor oil-based polyurethane as a rejuvenator to modify the performance of bio-asphalt. Castor oil with kinetic viscosity (137m²/s), density(0.98g/ml) and moisture content (<0.2%) were studied. The major findings after the chemical, physical and rheological studies portrayed that, castor oil has high sensitivity towards the high temperature performance of bio-asphalt. The gap in this paper was it only aimed in binder characteristics not the mix performance.

2.3 SUMMARY

Significant number of studies on RAP materials were from American countries where as in India the studies based on RAP materials are limited. Regional differences exist in the practices and composition of RAP materials as well as the rejuvenators. Thus, local studies on the identification of potential of various organic rejuvenators on RAP binder modification could be necessary for efficient and sustainable pavement construction and rehabilitation. The efficiency of various rejuvenator including organic and inorganic types were studied in previous literatures. Comparing with inorganic rejuvenators, organic rejuvenators are easily available and non-carcinogenic. The present study investigates the potential of castor oil as a rejuvenator on RAP materials. Such studies should further improve the market for RAP materials with high percentage of addition on new mix designs and thereby ensure the sustainable development and low-cost construction practices. This study mainly aims to the incorporation of 30% and 60% RAP materials in to mix design along with castor oil as a rejuvenator.

CHAPTER 3

METHODOLOGY

3.1 GENERAL

This chapter provides a description of the methodology, materials used in the study, testing procedure for determining the physical properties of fresh and rejuvenated RAP binder, volumetric tests and performance test procedures for control and rejuvenated mixes. The methodology adopted in this study is shown in the Figure 3.1.

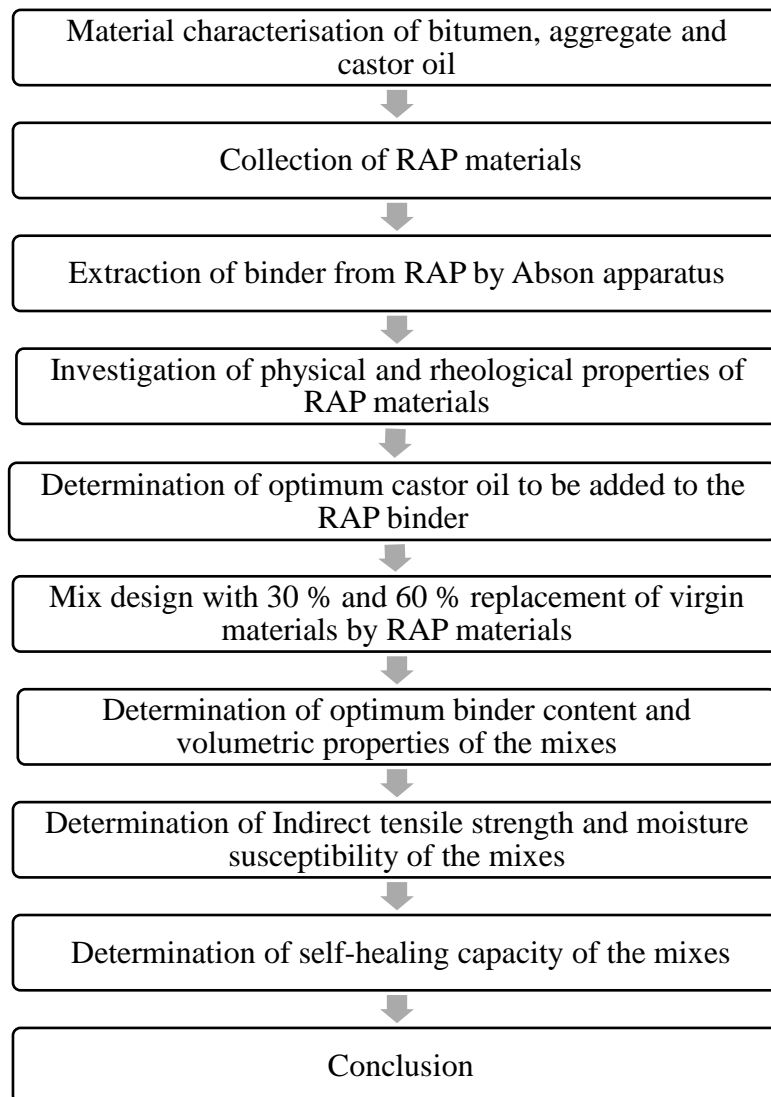


Figure 3.1 Flow Chart of Methodology

3.2 CASTOR OIL

Rejuvenators can be classified as Organic oils and Inorganic oils. Inorganic rejuvenators are asphalt additive which contains mainly aromatic extracts, naphthenic oils and paraffinic oils. Most of these are the byproducts of petroleum refinery and contains high percentage of free carbon in it. This free carbon will be emitted to the atmosphere under high temperature and traffic load condition. The chemical composition of these inorganic rejuvenators is similar to carcinogenic substances. So, its handling is very dangerous. The organic rejuvenators are oil-based rejuvenators obtained from natural products. A significant number of studies were conducted on organic rejuvenators like Sunflower oil, Polanga oil, Mahua oil, Date palm oil, Maize oil and Cotton seed oils. *Ricinus communis* oil (commonly known as castor oil) is found mostly in southern states of India such as Kerala, Tamil Nadu, Karnataka and Andhra Pradesh (Liu et al., 2021). Castor oil contains higher percentages of saturates which are enriched with maltenes. Previous studies showed that castor oil can be used in the bio-diesel production (Liu et al., 2021). The castor bean, from which the castor oil in this study was extracted, is refined by distillation, oxidation and other physical and chemical process. Castor oil is naturally regenerative, affordable and has three hydroxyl groups on its surface molecule chain and is quite useful. It is expected that castor oil will effectively rejuvenate the properties of the aged binder. Castor plant and castor oil is shown in the Figure 3.2 and Figure 3.3.



Figure 3.2 Castor Plant



Figure 3.3 Castor oil

The physical properties and chemical properties of castor oil used in this study are given in the Table 3.1 and Table 3.2 respectively.

Table 3.1 Physical Properties of Castor Oil

Property	Castor oil
Physical state at room temperature	Liquid
Color	Pale yellow
Water solubility	No
Density(g/cm^3)	0.96
Specific gravity	0.826
Viscosity at 135°C (cp)	403
Boiling point ($^\circ\text{C}$)	313

Table 3.2 Chemical Composition of Castor Oil

Rejuvenator Composition	Castor Oil (%)
Palmitic acid	12.01
Stearic acid	12.95
Oleic acid	34.09
Linoleic acid	38.26
Linolenic acid	0.30

3.3 INTRODUCTION OF TRANSESTERIFICATION ON CASTOR OIL

3.3.1 General

The process of allowing non-edible oil to chemically react with alcohol, is known as transesterification. Because the test procedures are easy and inexpensive methanol and ethanol are the most often employed as alcohols in this process. This process has been widely used to turn triglycerides into ester and to lessen the viscosity of non-edible oil. There are two ways to perform transesterification: catalytic transesterification and non-catalytic transesterification. Among this catalytic transesterification is more accurate and its result interpretation is easy. Here the reactions are catalyzed by the addition of certain acids or bases. While bases catalyze the reaction by removing positive ions from alcohol, making it more nucleophilic, the strong acids donate cations to carbonyl group and act as an electrophile. By the application of heat esters, acids, bases and alcohol groups vaporizes and reach at the equilibrium state. Esters with large alkoxy groups can be created from methyl or ethyl esters with high range of purity. The carbonyl groups of the initial esters react in the transesterification process to produce intermediate product which may returns to the starting material or continues to the trans-esterified product. The distribution of the products is highly correlated to the relative energy of the product and the many other species coexist in equilibrium.

3.3.2 Significance of transesterification

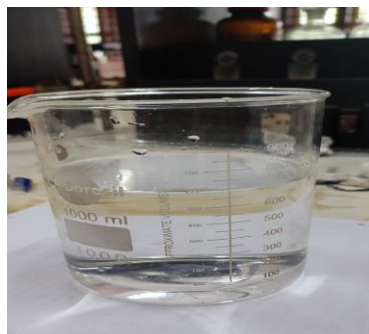
At high temperature, hydrolysis of the bio-oils causes the generation of Free Fatty Acid (FFA). The efficiency of bio-oils is highly dependent with the quantity of FFA (Ahmed et al., 2021). The presence of FFA has a negative impact on pavement design because it weakens the bond between oil and bitumen. The transesterification result can be correlated with acid value test; that is the FFA content before and after transesterification can be measured. Generally, the acid values of bio-oil rejuvenators are in the range of 2-7%. The rheological properties can be boosted with low acid value of rejuvenators. Since the castor oil is under the category oil bio-oils and it shows high oleic acid and linoleic acid which are the derivatives of fatty acids, transesterification should be conducted on it to reduce the expected FFA production while heating. So, the main significance of this transesterification is the reduction of FFA of castor oil and thereby reducing its acid value.

3.3.3 Procedure of transesterification

The castor oil and methanol undergo a chemical reaction in this procedure, with NaOH serving as a catalyst. Several steps must be taken before the transesterification process which include the fixing of various attributes like volume of components, total reaction time and the ratio of castor oil to methanol and the normality and volume of catalyst. For proper modification in the castor oil these parameters should be properly identified. According to Ahmed et al. (2020) the ideal ratio for methanol and castor oil is 7:1 and 0.1N NaOH was estimated to be 1.1% of volume of castor oil as catalyst. The NaOH and 700ml of methanol were taken to the beaker in pre-fixed proportion. Then using a magnetic stirrer, the solution was mixed for 15 minutes. Then 100ml of castor oil were added to the round bottom flask. Then it was transferred to the distillation column for 1 hour. After the entire solution were kept undisturbed for 24 hours at 60°C. This will allow the separation of the products. The changed oil will form the upper phase and the bottom layer was the glycerol. The upper layer of ester can be separate out and acid value test can be conducted. The Figure 3.4 given below shows the entire transesterification process.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 3.4 Transesterification Process (a) Methanol, (b) Mixing of Methanol & NaOH with Magnetic Stirrer, (c) Addition of Castor Oil, (d) Distillation, (e) Separation of Ester and Glycerol and (f) Modified Castor Oil.

After the transesterification process, the obtained modified castor oil was tested for acid value. Acid value test is a titrimetric process in which the 10 mg of oil before and after modification is

added to a conical flask. 100ml of benzene and ethanol (1:1) mixture is titrated with 0.1N KOH. Indicator used was phenolphthalein and end point are no color to pink color. The volume of KOH required for the titration were measured. Acid value of castor oil before and after transesterification were obtained as 6.45mg/L and 2.95 mg/L. Lower acid value indicates loss of free fatty acid and which will lead to better performance in physical property analysis.

3.4 TESTS ON BITUMEN

3.4.1 General

Physical properties of binder are the fundamental properties which ensures the basic characteristics of that material. The tests performed on fresh VG 30, RAP binder and rejuvenated RAP binder includes softening point, ductility test, penetration test, viscosity test and specific gravity test according to IS:73-2013, loss on heating test according to ASTM D-1754.

3.4.2 Softening Point of Bitumen

The softening point of bitumen enables us to determine whether a given bitumen may be used at a specific location; specifically, the softening point value must be higher than the pavement temperature in order to attain good strength and stability. Softening point is determined by ring and ball apparatus. The binder was heated to a temperature between 75°C to 100°C and then poured to the ring which was thoroughly greased before. After 30 minutes of air cooling the ring were assembled along the ball guides with thermometer and suspended in water. The liquid medium is heated at a rate of 5°C per minute while a steel ball is placed on the top of the sample. The softening point of bitumen is defined as the temperature at which the bitumen contacts a metal plate positioned a certain distance below the ring. The softening point test is shown in the Figure 3.5 given below.



(a)

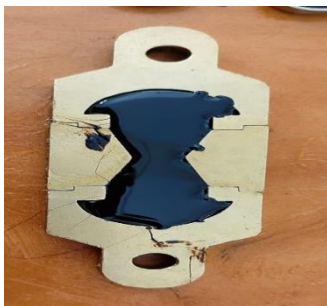


(b)

Figure 3.5 Softening Point Test (a) Air Cooling of Ring Apparatus, (b) Ring and Ball Assembly on Instrument

3.4.3 Ductility of Bitumen

Ductility is the ability to stretch as thin wires. In order to ensure proper, inter bonding between aggregate ductility of binder should be found out. Ductility of bituminous material was measured by the distance in centimeters to which it will elongate before breaking when two ends of standard briquette specimen of the material are pulled apart at a specified speed and at room temperature. Bituminous was heated to a temperature between 75 to 100°C and poured into the Briquette mold. Provided 30 minutes of air cooling followed by 90 minutes of water bath. The entire assembly was transferred to the machine and pulled two ends horizontally with a speed of 50mm per minute. The ductility test of bitumen is shown in the Figure 3.6.



(a)



(b)

Figure 3.6 Ductility Test (a) Air Cooling of Briquette Apparatus, (b) Briquette Assembly on Instrument,

3.4.4 Penetration Value of Bitumen

Penetration is a measure of hardness or consistency of bituminous material. The penetration value is expressed in one tenth of a millimeter. The material was softened and poured to the container to a depth at least 10mm in excess of expected penetration. The container was allowed for an air cooling for 1.5 hour and a water bath of 30 minutes at room temperature. Placed the container on the penetration apparatus, including the needle. Adjusted the needle to contact the surface of the sample. Released the needle for exactly 5 seconds and measured the distance penetrated. A minimum of three readings were measured in each sample. The penetration test is shown in the Figure 3.7.



Figure 3.7 Penetration Test

3.4.5 Viscosity Test

Viscosity of a liquid is the property that retards its flow due to internal friction and it is a measure of resistance to flow of the liquid. The Brookfield viscometer is used for measuring viscosity. Viscosity is the temperature depended property and viscosity grade is one of the major criteria for classification of binder. The principal of operation of the viscometer is to drive a spindle through a calibrated spring. For testing binders, generally spindle number 21 of the viscometer is used. An angular velocity of 20 rpm was selected and based on the torque experienced by the spindle against the angular velocity, viscosity values were calculated and displayed digitally on the machine. All units of measurement are displayed according to either CGS or SI system.

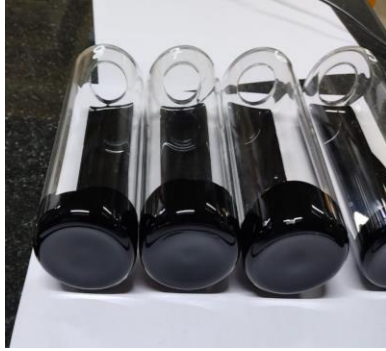
3.4.6 Specific Gravity Test

The specific gravity of bitumen is a fundamental property frequently used as an aid to classify the binders for use in paving jobs, it is defined as the ratio of mass of a given volume of the binder to the mass of an equal volume of water, the temperature of both being at 27 °C. The apparatus used to determine the specific gravity of bitumen includes specific gravity bottle of 50 ml capacity, weighing balance having least count of 1 g and water bath. The bottle is cleaned, dried and weighed along with the stopper (W_1). It is then filled with fresh distilled water along with stopper and it is then kept in water container for at least half an hour at a temperature of 27°C. The bottle is then removed and cleaned from outside and the specific gravity bottle containing distilled water is weighed (W_2). The bituminous material is heated to a pouring temperature and is poured in the empty bottle. The material is filled up to the half taking care to prevent entry of air bubbles. To prevent the escape of air bubbles, the sample bottle is allowed to stand for half an hour at suitable temperature and then weighed (W_3). The remaining space is filled with distilled water at 27°C and is kept in a water container and it is weighed (W_4), after being removed from water container. Specific gravity can be calculated using the equation 3.1.

$$\text{Specific gravity} = \frac{(W_2 - W_1)}{(W_3 - W_1) - (W_4 - W_2)} \dots \dots \dots (3.1)$$

3.4.7 Loss on Heating Test

When the bituminous binder is heated, it loses the volatiles and gets hardened. To study the effect of heating, an accelerated heating procedure is adopted. One of the most popular standardized tests to model the short-term aging of binder is the Rolling Thin Film Oven Test (RTFOT). About 50g of the sample is weighed and heated to a temperature of 163°C for 5 hours. After the heating period, the sample is cooled and weighed. The loss in weight is expressed as the percentage by weight of original sample. The Figure 3.8 shows the samples under various RTFO test procedures.



(a)



(b)

Figure 3.8 RTFO Test (a) Before Aging, (b) During Aging

3.4.8 Dynamic Shear Rheometer Test

Rheology is used to assess the deformation and flow behavior of materials. Dynamic Shear Rheometer (DSR) is capable of quantifying both elastic and viscous properties. DSR was used to determine complex shear modulus and phase angle under oscillating stress at different temperature and frequencies. It can characterize the viscous and elastic behavior of asphalt binder at high and medium temperatures. Frequency sweep test and linear amplitude sweep test were conducted at the Transportation engineering laboratory of NIT Calicut. The test frequency range was 0.2 to 30 Hz and test temperature range was 40 °C to 60 °C. DSR equipment is shown in the Figure 3.9.



Figure 3.9 Dynamic Shear Rheometer Apparatus

Complex shear modulus can be defined as the quotient of maximum stress and deformation at sinusoidal oscillation loading and phase angle is the phase difference between stress and strain

while testing. Complex shear modulus (G^*) and phase angle (δ) is obtained as results which can interpret the aging behavior of binder. Rutting parameter and fatigue parameter of binder can be found out by the equation 3.2 and 3.3 given below.

$$\text{Rutting Parameter} = \frac{G^*}{\sin \delta} \dots\dots\dots(3.2)$$

$$\text{Fatigue Parameter} = G^* \sin \delta \dots\dots\dots(3.3)$$

3.5 TESTS ON AGGREGATES

Aggregate impact test, crushing test, shape test, Los Angeles Abrasion Test, Specific gravity and water absorption test of aggregates were conducted.

3.5.1 Aggregate Crushing Value Test

This test is used to assess the strength of the coarse aggregates used in the pavement under gradually applied load. Aggregates measured to weight of about 3500 g is taken and transferred to set of sieves arranged in the order of 1.25 mm, 10 mm and pan. After that the sieves are placed in the mechanical shaker for 10 minutes. Sample retained on the 10mm sieve was collected. Then a cylinder was taken and empty weight of the cylinder (W_1) was noted. Aggregates were then added to the cylinder in three layers for each layer tamping was done at 25 times. Then weight of the cylinder with aggregates (W_2) was noted. Cylinder was paced on position along with plunger on the compression testing machine. After switching on the machine, 40 tons of load was applied and release the load after switching off the machine. Transfer the aggregates into 2.36 mm sieve and allow it to shaker for 10 minutes on the mechanical shaker. Weight of aggregates retained on pan was noted (W_3). Aggregate crushing value was calculated using the equation 3.4 and aggregate crushing strength test mold and instrument is shown in the Figure 3.10.

$$\text{Aggregate crushing value} = \frac{W_3}{W_2 - W_1} * 100 \dots\dots\dots(3.4)$$



Figure 3.10 Aggregate Crushing Strength Test (a) Mould with Aggregates, (b) Crushing Strngth Testing Machine

3.5.2 Impact strength

This test is used to evaluate the toughness of aggregate to break down under application of impact. Aggregates measured to weight about 350g is taken and transferred to the set of sieves arranged in the order of 12.5mm, 10mm and pan and it is then placed in the mechanical shaker for 10 minutes. Coarse aggregates retained on 10 mm sieve was collected. Empty weight of cylinder is taken (W_1) and then the aggregates retained on 10mm sieve is transferred into the cylinder in 3 layers. Each layer was given a tamping of 25 times. Weight of the cylinder along with the aggregates was noted (W_2). Cylinder was then placed in the impact testing machine and 15 blows were given at an interval of not less than 1 seconds. Before applying blows, release the hammer in order to apply the impact load. The aggregate is then transferred to the 2.36 mm sieve and placed in the mechanical shaker. Weight of the aggregates passing through 2.36 mm sieve was noted (W_3). Aggregate impact value was calculated using the equation 3.5.

$$\text{Aggregate impact value} = \frac{W_3}{W_2 - W_1} * 100 \dots \dots \dots (3.5)$$

3.5.3 Los Angeles Abrasion Test

This test is used to determine the resistance to wear and tear of aggregate by using an abrasive charge. Choose the grading to be set in the test so that it complies as closely as feasible with the grading to be used in construction.. Sieve the sample in a 20mm, 12.5mm and 10mm IS sieve using sieve shaker. Collect the sample retained on 10 mm and 12.5 mm sieve in a separate container and weigh it to 5000g (W_1). Then the weighed aggregates and abrasive charges are then

transferred to the circular drum of Los Angeles machine and fix the cove. The machine should be rotated at a rate of 30 to 33 revolutions per minute. The entire stone dust was sieved on 1.75 mm IS sieve and was placed in mechanical shaker. The material coarser than 1.70 mm size was weighed (W_2). Abrasion value is calculated using the equation 3.6.

$$\% \text{ wear} = \frac{W_1 - W_2}{W_1} * 100 \dots \dots \dots (3.6)$$

3.5.4 Specific Gravity and Water Absorption Test of Aggregates

Specific gravity of stone aggregate is a measure of strength or quality of material. In general, stones with a low specific gravity are weaker than those with a high specific gravity. On the other hand, stones having high water absorption are more porous in nature and are generally considered unsuitable. In this test, about 2 kg of aggregate sample was taken and washed thoroughly to remove fines and then drained and placed in a wire basket and immersed in distilled water at a temperature between 22°C and 32°C and a cover of at least 5 cm of water above the top of basket. After removing entrapped air bubbles, the basket and the aggregate remained completely immersed in water for a period of 24 hours afterwards and then weight was noted (W_1). The basket and the aggregate were removed from water and allowed to drain for a few minutes. After that the aggregates were transferred to one of the dry absorbent clothes. Then the empty basket was then returned to water and the weight was noted (W_2). When the aggregates placed on the dry cloth is completely surface dried, weight of the dried aggregates is noted (W_3). The aggregates were placed in a shallow tray and kept in an oven maintained at temperature of 110°C for 24 hours. It was then removed from the oven, cooled and weight was noted (W_4). Specific gravity and water absorption of aggregates is calculated using the equation 3.7 and 3.8.

$$\text{Specific gravity} = \frac{W_4}{W_3 - (W_1 - W_2)} * 100 \dots \dots \dots (3.7)$$

$$\text{Water absorption} = \frac{W_3 - W_4}{W_4} * 100 \dots \dots \dots (3.8)$$

3.5.5 Shape Test

The shape of aggregate particle is determined by the percentage of flaky and elongated particles contained in it. The fraction of aggregate particles by weight whose smallest dimension or thickness is less than three fifths or 0.6 of their mean dimensions, is known as the flakiness index

of aggregate. The fraction of particles in an aggregate whose largest size is more than one and a quarter or 1.8 times their mean dimension, is known as the elongation index. This test is not applicable for sizes smaller than 6.3mm. standard length gauge is used to gauge the greatest dimension or length of the aggregate samples. Samples were sieved through the IS Sieves of size 63, 50, 40, 31.5, 25, 20, 16, 12.5, 10 and 6.3mm. Flaky materials were separated through thickness gauge and the weight of material was taken. The non-flaky materials were separated and weighed to find out the elongation index of these aggregates. Each fraction was gauged on the length gauge in order to separate the elongated materials. weight of materials retained on length gauge were also taken. Flakiness index and elongation index is calculated using the equation 3.9 and 3.10.

$$\text{Flakiness index} = \frac{\text{Total weight of material passing through thickness gauge}}{\text{Total weight of sample gauged}} * 100 \dots \dots \dots (3.9)$$

$$\text{Elongation index} = \frac{\text{Total weight of non flaky material retained on length gauge}}{\text{Total weight of sample gauged}} * 100 \dots \dots (3.10)$$

3.6 TEST ON RAP MATERIALS

The collected RAP materials were processed and then conducted the basic tests like binder content determination, grade size analysis, impact strength and crushing strength.

3.6.1 Collection of RAP materials

RAP materials were milled from the old existing pavement of 9-year-old on the location of Anayadi using a bulldozer. The materials were obtained as large chunks which has collected in plastic sacks with proper zipping to avoid air inflow which may cause further oxidation. The collected materials were transported to transportation laboratory of TKMCE Kollam and stored under a shed. In order to prevent further aging due to direct contact of environment, the materials were properly covered. The Figure 3.11 shows the milling of pavement associated with Anayadi highway work.



Figure 3.11 Collection of RAP Materials from Anayadi Highway Work

3.6.2 Processing of RAP

The collected RAP materials were heated in the Hot Air Oven with a temperature of 60°C for 2.5 hours. The softened materials were spread on a metallic sheet and allowed air cooling until it became dry. Then the agglomerated particles were segregated with the help of a rammer. The processed RAP materials were stored in air tight plastic bags to prevent further oxidation. Processing of RAP is shown in the Figure 3.12.



(a)



(b)

Figure 3.12 Processing of RAP Materials a) Hot Air Oven (b) Processed RAP Materials

3.6.3 Binder Content Estimation

The test conducted to find the binder content within the RAP material was bitumen extraction test. The processed RAP materials was placed in the cup of centrifuge extractor. The solvent trichloro ethylene was then poured into the cup and then covered by a filter paper. After fixing the lid of the centrifuge in place, the entire system was left up for 1 hour for the solvent to dissolve the bitumen

of RAP materials. Then the centrifuge was allowed for extraction by applying 3600 revolutions per minute. The solution containing both solvent and bitumen drained out through the out let and stored in a container. Repeated the process until the entire binder is removed from the aggregate. Weight of the samples before and after the extraction and weight of filter paper was taken. The test was conducted for 3 samples and average of the value were taken as the binder content. Extraction of binder is shown in the Figure 3.13.



(a)



(b)

Figure 3.13 Extraction of Binder a) Centrifugal extractor, (b) Extractor cup with RAP materials and solution

3.7 GRADATION OF AGGREGATES

Bituminous concrete (BC) grade 2 has been selected in this present study for bituminous mix. Gradation of aggregate is selected according to the requirements specified by Ministry of Road Transport and Highways (MoRTH, 2013) and shown in Table 3.3. total weight of aggregates taken in this study is 1200 g. individual weight of aggregates according to MoRTH gradation is shown in Table 3.4

Table 3.3 BC MoRTH Requirements Grade 2

IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Mid-range of aggregate value selected
19	100	
13.2	90-100	95
9.5	70-88	79
4.75	53-71	62
2.36	42-58	50
1.18	34-48	41
0.6	26-38	32
0.3	18-28	23
0.15	12-20	16
0.075	4-10	7

Table 3.4 Individual Weight Calculations as per MoRTH Specification

IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Mid-range of aggregate value selected	Individual % by weight of aggregate retained	Individual weights (g)
19	100			
13.2	90-100	95	5	60
9.5	70-88	79	16	192
4.75	53-71	62	17	204
2.36	42-58	50	12	144
1.18	34-48	41	9	108
0.6	26-38	32	9	108
0.3	18-28	23	9	108
0.15	12-20	16	7	84
0.075	4-10	7	9	108
Pan			7	84

3.8 MARSHALL MIX DESIGN

Marshall samples for control mixes were prepared using above gradation at 5.2%, 5.4%, 5.6% and 5.8% of bitumen. Total weight of sample is about 1250g. Three samples were prepared at each bitumen content and Optimum Bitumen Content (OBC) is found out for bituminous mix. For the mix design, the aggregates are taken and heated to a temperature of 165°C to 180°C. The bitumen is also heated to a temperature of 160°C. The binder and aggregates are then mixed together and temperature is maintained at 145°C. The mix is then poured on to the mould assembly and is compacted with 75 blows on each side using Marshall compactor. After compaction the specimen with the mould is allowed to cool down to the room temperature for 24 hours. After that, Marshall specimens is then extracted from the mould and it is then immersed in water bath for 30-40 minutes

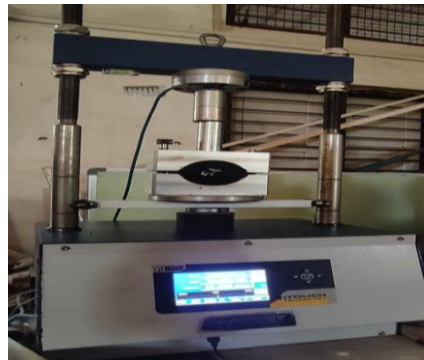
at 60°C. Then the specimen was tested in automatic Marshall stability testing machine. The Marshall stability test procedure is shown in the Figure 3.14.



(a)



(b)



(c)

Figure 3.14 Marshall mix design procedure a) Marshall compactor, (b) Specimen in Water Bath 30 minutes - 60 °C, (c) Automatic Marshall Stability Testing Machine

3.8.1 Density and Voids Analysis

The compacted specimen of bituminous mix consists of mineral aggregates, bituminous binder, and some air voids. Volumetric properties of the bituminous mix include bulk specific gravity, theoretical specific gravity, air voids, voids filled with bitumen, voids filled with bitumen, voids in the mineral aggregates, stability and flow values.

3.8.1.1 Bulk specific gravity (G_{mb})

It is the specific gravity containing air voids and is found out by equation 3.11.

$$G_{mb} = \frac{A}{B-C} \dots\dots\dots(3.11)$$

Where, A= dry mass of specimen in air

B= saturated surface dry mass of specimen in air

C= mass of specimen in water

3.8.1.2 Theoretical maximum specific gravity (G_t)

It is determined based on the known values of specific gravity of aggregate and bitumen and is found out by equation 3.12.

$$G_t = \frac{100}{\left(\frac{W_1}{G_1}\right) + \left(\frac{W_2}{G_2}\right) + \left(\frac{W_3}{G_3}\right)} \dots\dots\dots(3.12)$$

Where, W_1 = percentage by weight of coarse aggregate in total mix

W_2 = percentage by weight of fine aggregate

W_3 = percentage by weight of bituminous binder

G_1 = apparent specific gravity of coarse aggregates

G_2 = apparent specific gravity of fine aggregates

G_3 = apparent specific gravity of bituminous binder

3.8.1.3 Volume of voids or percentage air voids (V_v)

The volume of air voids in the compacted mix is expressed as percentage of volume of the test specimen and is calculated using the equation 3.13.

$$V_v = \frac{100 (G_t - G_b)}{G_t} \dots\dots\dots(3.13)$$

Where, G_t = theoretical maximum specific gravity

G_b = specific gravity of bitumen

3.8.1.4 Volume of bitumen (V_b)

The volume of bitumen in the compacted specimen is also expressed as a percentage of volume of the compacted specimen and is calculated using the equation 3.14.

$$V_b = G_b * \frac{W_3}{G_3} \dots \dots \dots (3.14)$$

3.8.1.5 Voids in mineral aggregates (VMA)

It is the total volume of air voids and the volume of bitumen in the compacted mix and it is found out by equation 3.15.

$$VMA = V_v + V_b \dots \dots \dots (3.15)$$

3.8.1.6 Voids filled with bitumen (VFB)

It is expressed as a percentage of volume of bitumen to the total voids in the mineral aggregates of the compacted mix and is found out by equation 3.16.

$$VFB = \frac{100 V_b}{VMA} \dots \dots \dots (3.16)$$

3.8.1.7 Marshall Stability and flow Value

To determine the Marshall Stability and flow value, load is applied at a rate of 51 mm/ minute and the maximum load value expressed in KN is noted as ‘Marshall Stability’ value of the specimen. The vertical deformation of the test specimen corresponding to the maximum load expressed in mm units is noted as the ‘Flow Value’. The measured value of maximum load is to be multiplied by the appropriate correction factor to obtain the corrected value of Marshall stability.

3.8.2 Marshall Mix Design With 30% and 60% Rap

Marshall mix design with 30% and 60% RAP materials were done based on the Asphalt Institute MS-2 (AI 2014). In addition to the normal mix design procedure, some blending calculations and batching adjustments were done for incorporating RAP materials to the mixes.

3.8.2.1 Aggregate blending

In this study mainly three types of aggregates were used; 20 mm down stockpile, stone dust stockpile and RAP aggregates. After conducting the sieve analysis of each of the stockpiles, optimum blending chart of aggregates were found out by trial-and-error method based on MoRTH bituminous concrete gradation 2.

3.8.2.2 Batching of Aggregates

RAP materials contains both aggregates and binder. During the batching of aggregates, the binder coated on the aggregates should be considered based on the equation 3.17 and 3.18 given below,

$$\text{RAP Stockpile} = \text{RAP blend} * \left(1 - \frac{P_b \text{ RAP}}{100}\right) \dots\dots\dots(3.17)$$

$$\text{Fresh Aggregate Stockpile} = \text{FA blend} + \frac{\text{FA blend}}{\Sigma \text{FA blend}} \dots\dots\dots(3.18)$$

Where, RAP blend = total percentage of RAP used in the mix

FA blend = percentage of fresh aggregate used in the mix

P_b RAP = binder content present in RAP

3.8.2.3 Fresh Binder Requirement

In order to find the optimum binder content, Marshall samples were prepared at 5.0%, 5.2%, 5.4%, 5.6% and 5.8% of bitumen based on the specific gravity of RAP materials. The fresh binder requirement of the corresponding RAP mixes was calculated based on the equation 3.19 and 3.20 given below.

$$\text{RAP Binder weight} = \frac{\text{RAP weight in mix} * \text{Binder Content of RAP}}{100 * 100} \dots\dots\dots(3.19)$$

$$\text{Fresh Binder weight} = \text{Total aggregate weight} * \frac{P_b}{P_s} - (\text{RAP batch weight} - \text{RAP aggregate weight})$$

(3.20)

Where, P_b = Desired bituminous binder content

$$P_s = \text{Aggregate content} (100 - P_b)$$

Three samples were prepared at each bitumen content. For the mix design, the fresh aggregates were pre-heated to a temperature of 178°C and 193°C to compensate for the lower temperature prevalent in 30% and 60% RAP mixes respectively. The bitumen is also heated to a temperature of 163°C. The binder and aggregates are then mixed and temperature is maintained at 145°C. The mix is then poured on to the mould assembly and is compacted with 75 blows on each side using Marshall compactor. The volumetric property analysis was conducted similar as control mix.

3.9 INDIRECT TENSILE STRENGTH TEST

This test was performed according to AASHTO T- 283 with air voids content of 7%. This test method is used to determine if the materials may be subjected to stripping and to measure the effect of additives. The mixes were prepared with a mixing temperature of 150°C to 160°C and the specimens were compacted at a temperature of 140°C to 150°C. The specimens were kept at room temperature for 24 hours after being taken from the moulds.

3.9.1 Indirect Tensile Dry Test

At the end of curing period, the specimens were placed in a leak proof plastic bag. The specimens were then submerged in a water bath at 25°C for 2 hours with a minimum of 25 mm of water above the surface. Specimens were then removed from the water bath and placed on the testing machine. A load was applied at a constant rate of 51 mm/minute and the load at which the specimen fails were noted.

3.9.2 Indirect Tensile Wet Test

At the end of curing period, the specimens were put in a vacuum container for 5 to 10 minutes. A vacuum of 13-67 KPa absolute pressure is applied for approximately 5 to 10 minutes. After that

vacuum is removed and the specimen is left submerged for this duration. The conditioning by freezing may go on if the saturation level is between 70% and 80%. If the saturation level is then 70%, the vacuum technique is repeated with increased vacuum and/or duration. The specimen is considered damaged and rejected if the saturation level is greater than 80%. After that the specimens were wrapped in a plastic bag and is placed in a freezer for 16 hours. The plastic bag and film were removed from the specimens and they were immediately immersed in a water bath at 60°C for 24 hours. Then the specimens were removed and placed in a water bath at 25°C for 2 hours. The specimens were then removed from the water bath and placed on the testing machine. A load was applied at a constant rate of 51 mm per minute and the load at which specimen fails or cracks was noted. Indirect tensile strength procedure is shown in the Figure 3.15.



(a)



(b)



(c)



(d)

Figure 3.15 Indirect tensile strength test procedure a) ITS dry samples in Water Bath 25°C - 2 hr, (b) Samples in Vacuum Chamber, (c) ITS samples in freezer (16 hr) & Water Bath 60°C - 24 hr and (d) ITS Testing Machine

3.9.3 Tensile Strength Ratio

The tensile strength ratio of bituminous mixes reflects their resistance to moisture susceptibility. According to AASHTO, a TSR value of 0.8 or above is recommended for mixtures having resistance to moisture susceptibility. Tensile strength ratio was calculated using the equation 3.21.

$$\text{Tensile Strength Ratio (TSR)} = \frac{S_2}{S_1} \dots\dots\dots(3.21)$$

Where, S_1 = Average tensile strength from dry test

S_2 = Average tensile strength from wet test

3.10 SELF-HEALING CAPACITY ANALYSIS

To check the self-healing capacity of mixes, the samples were casted at optimum binder content as per Marshall mix design. The casted specimens were conditioned like ITS dry test and tested in the ITS testing machine and found its peak load. Then unloaded specimens were allowed to heal with a certain confining pressure of 100 psi using a confining pressure apparatus (Figure 3.16) and varying temperature(softening point, softening point+10°C and softening point+20°C).



Figure 3.16 Confining Pressure Apparatus

After subjected to a rest period of 1 day, those samples were again conditioned like ITS dry test. Then reloading was applied to the samples at the same rate. The healing index can be calculated using the equation 3.22.

$$\text{Healing Index (HI)} = \frac{L_2}{L_1} \dots\dots\dots(3.22)$$

Where, L_1 = Average peak load from dry test before confinement

L_2 = Average peak load from dry test after confinement

3.11 SUMMARY

In order to find the optimum castor to be added with 30% and 60% RAP mixes, the physical and rheological properties of respective binder blends was conducted and compared with that of VG 30. For this, penetration test, softening point test, ductility test and viscosity test of VG 30, 30% RAP binder with 5%, 8% and 10% castor oil and without rejuvenator and 60% RAP binder with 5%, 8% and 10% castor oil and without rejuvenator were conducted. The optimum castor oil to be added were finalized by conducting its rheological properties. The performance of mixes was evaluated by Marshall stability test, indirect tensile strength test and self-healing capacity test.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

This section emphasis on the results obtained after conducting the laboratory tests to determine the physical properties of bitumen, aggregates, RAP binder and rejuvenated RAP binder. Results on volumetric properties, moisture susceptibility and rutting characteristics of the mixes were also discussed here.

4.2 PHYSICAL PROPERTIES OF BITUMEN

Table 4.1 represents the results obtained after conducting the physical tests of bitumen. Tests were conducted according to IS 73: 2013 specifications. Test results shows that the physical properties of the bitumen meet the requirements specified by BIS.

Table 4.1 Physical Properties of Bitumen

Property	Value	Required value
Penetration at 25°C	63	Min 45
Softening point (°C)	52	Min 47
Ductility (cm)	82	Min 75
Specific gravity	1.024	Min 0.99
Viscosity (cst)	526	Min 350
Loss on heating	0.728	Less than 1

4.3 PHYSICAL PROPERTIES OF AGGREGATES

Table 4.2 indicates the results obtained after conducting the physical properties of aggregates. Tests were conducted according to IS: 2386 Part 1, Part 3 and Part 4 specifications. Tests results show that the physical properties of aggregates meet the requirements specified by BIS.

Table 4.2 Physical Properties of Aggregates

Property	Value	Required value
Aggregate crushing value	28	Less than 30
Aggregate impact value (%)	26	Max 24
Los Angeles abrasion value (%)	22	Max 30
Combined flakiness and elongation index (%)	26	Max 35
Specific gravity	2.72	2.5 to 3
Water absorption (%)	0.82	Max 2

4.4 PROPERTIES OF RAP MATERIALS

Properties of RAP materials include binder content determination, crushing strength test, impact strength test and physical properties of RAP binder. The test results are shown in the Table 4.3 which indicates that the properties of collected RAP binder are not within the limit and it demands proper rejuvenation for the recovery of lost properties.

Table 4.3 Physical Properties of RAP Materials

Property	Value
Binder Content (%)	5.37
Impact Strength (%)	15.9
Crushing Strength (%)	28
Penetration at 25 (0.1 mm)	8.3
Softening point (°C)	78
Ductility (cm)	1.5
Viscosity at 180(cp)	320

4.5 OPTIMUM CASTOR OIL CONTENT

4.5.1 Physical Property Analysis

In order to find out the optimum percentage of addition of castor oil which can efficiently regain the lost properties of RAP binder, mainly four physical property analysis like softening point test, ductility test, penetration test and Brooke field viscosity test were conducted. The results obtained are shown in the Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4. The obtained results of all the RAP binder blends with rejuvenator were compared to that of fresh binder. Due to the presence of high asphaltene content in RAP binder, which are less temperature sensitive, results low penetration, ductility, viscosity and high softening point. Due to the presence of asphaltene floccules the colloidal nature of the aged binder was lost and it became very stiff. With the addition of castor oil, the stiffness can be reduced by the interaction between binder and polar solvent. The castor oil imparts more aromatic and resins to the blends and thereby ensure high maltene to asphaltene ratio.

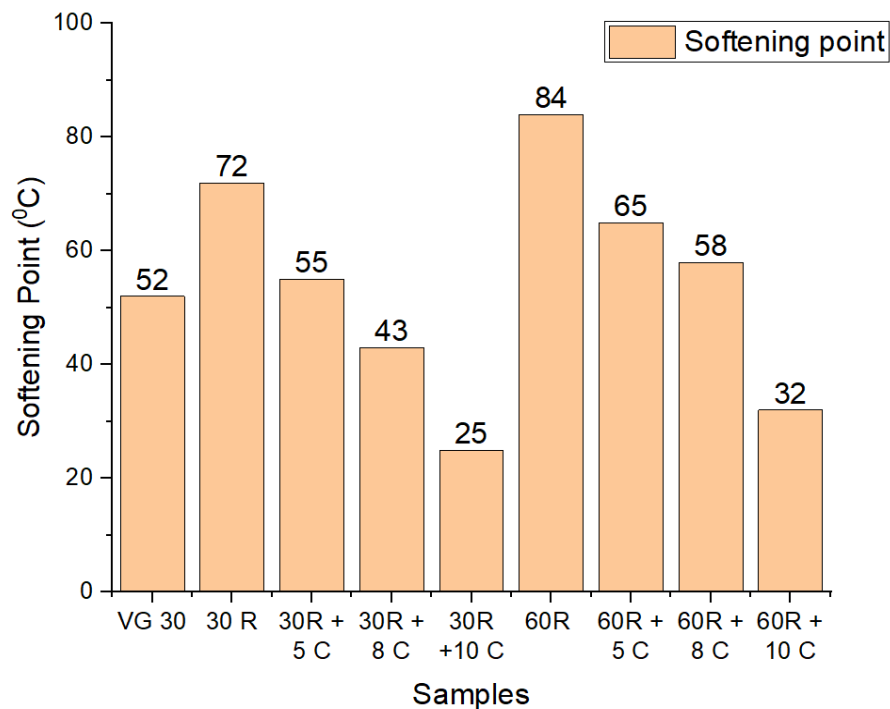


Figure 4.1 Softening Point Test Result

In the Figure 4.1, the softening point of 30% and 60% RAP was obtained as 72°C and 84°C which was very much higher than that of the fresh binder, VG 30. As the percentage of addition of castor oil increases, the softening point decreases. With the addition of 5% castor oil to 30% RAP, the softening point reduced to 55°C which was comparable to that of VG 30. Further addition of castor oil to 30% RAP blend, decreases the softening point to lower values which is not acceptable. For 60% RAP with 5% castor oil the softening point is 65°C and with 8% castor oil it was about 58°C which is comparable to VG 30. With 10% castor oil 60% RAP shows softening point of 32°C which is lower than acceptable limit.

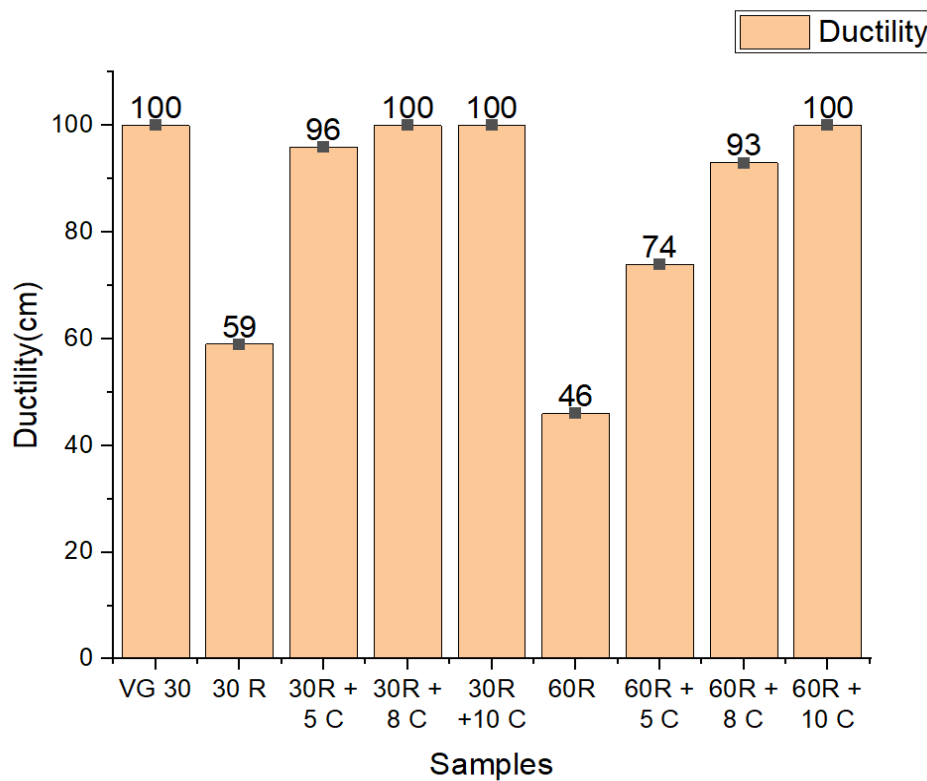


Figure 4.2 Ductility Test Result

In the Figure 4.2, the ductility of 30% and 60% RAP was obtained as 59cm and 46cm which was very much lower than that of VG 30. As the percentage of addition of castor oil increases, the ductility also increases. With the addition of 5% castor oil to 30% RAP, the ductility increased to 96cm which was comparable to that of VG 30. Further addition of castor oil to 30% RAP blend, increases the ductility to 100cm. In the case of 60% RAP blend with 5% castor oil the ductility

value is 46cm which could increase to 93cm with 8% castor oil. For 30% and 60% RAP binder with 10% castor oil the ductility reaches 100cm.

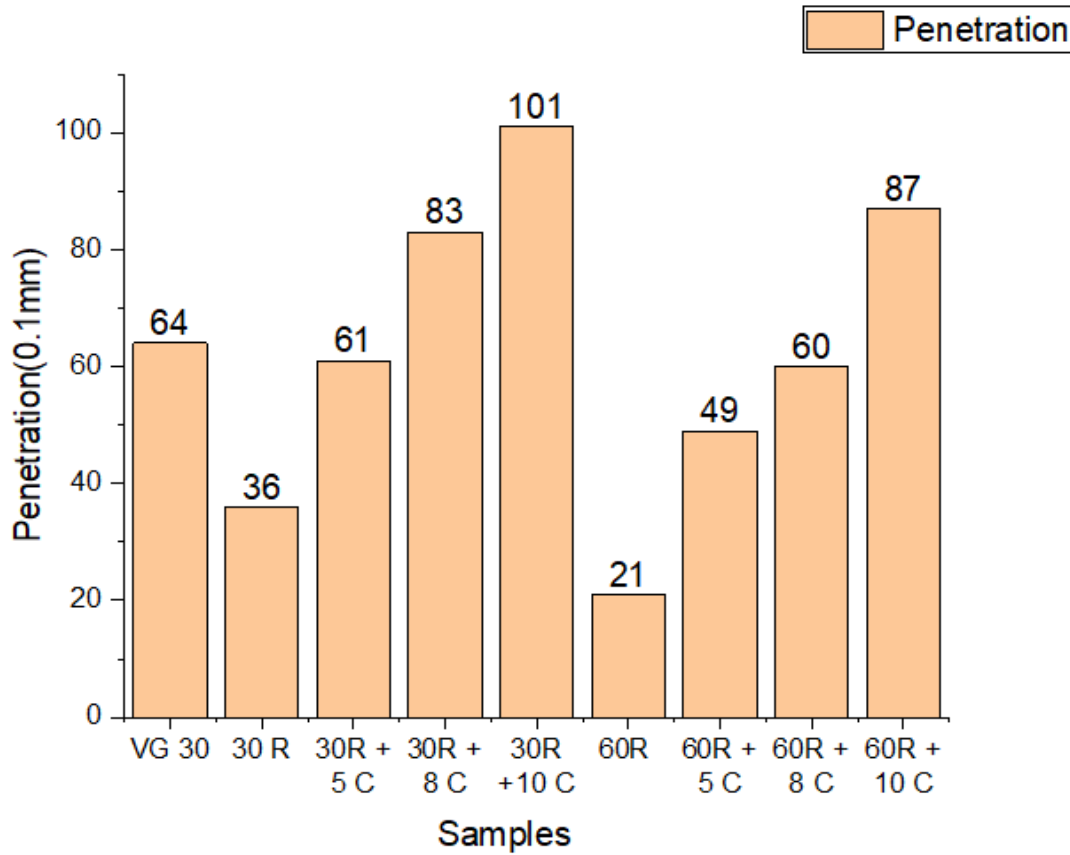


Figure 4.3 Penetration Test Result

In the Figure 4.3, the penetration of 30% and 60% RAP was obtained as 36mm and 21mm which was very much lower than that of VG 30. As the percentage of addition of castor oil increases, the penetration also increases. With the addition of 5% castor oil to 30% RAP, the penetration increased to 61mm which was comparable to that of VG 30. Further addition of castor oil to 30% RAP blend, increases the penetration to 83mm and 101mm. In the case of 60% RAP blend with 5% castor oil the penetration value is 49cm which could increase to 60cm with 8% castor oil. For 60% RAP binder with 10% castor oil the penetration obtained as 87mm which was higher than that of VG 30.

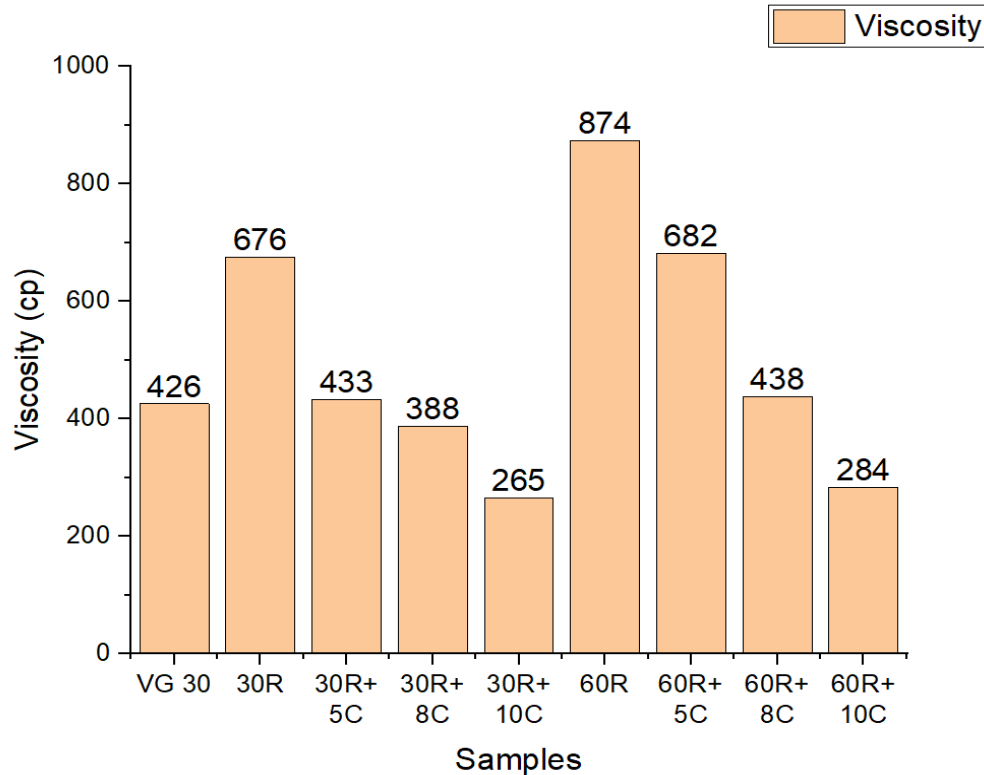


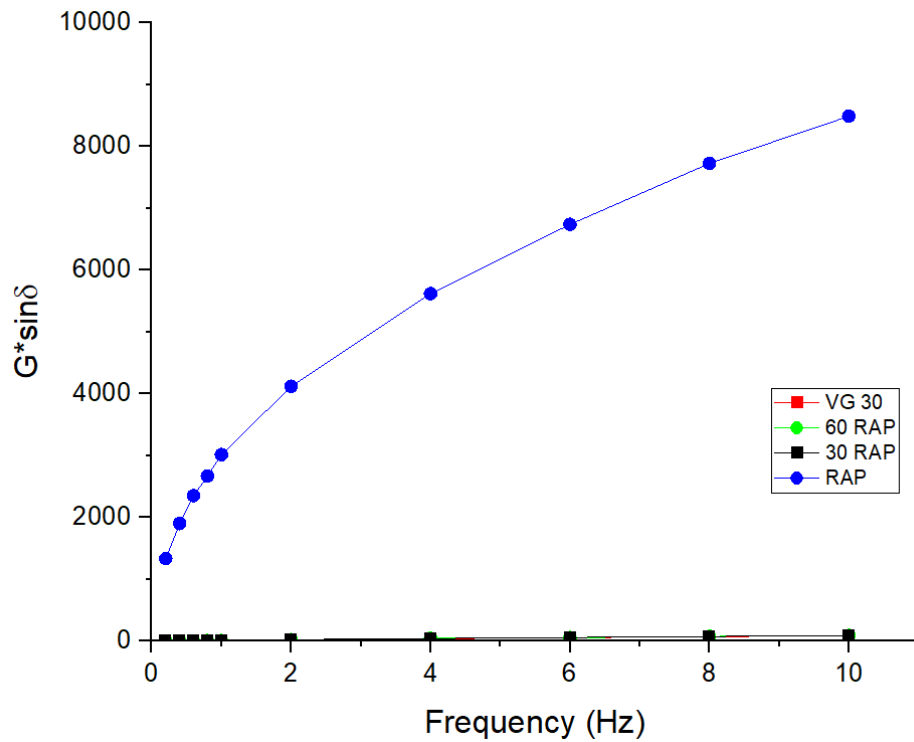
Figure 4.4 Viscosity Test Result

In the Figure 4.4, the viscosity of 30% and 60% RAP was obtained as 676cp and 874cp which was very much higher than that of VG 30. As the percentage of addition of castor oil increases, the viscosity also decreases. With the addition of 5% castor oil to 30% RAP, the viscosity decreased to 433cp which was comparable to that of VG 30. Further addition of castor oil to 30% RAP blend, decreases the viscosity to 388cp and 265cp which is lower than that of VG 30. In the case of 60% RAP blend with 5% castor oil the viscosity is 682cp which could decrease to 438cp with 8% castor oil. For 60% RAP binder with 10% castor oil the viscosity obtained as 284cp which was lower than that of VG 30.

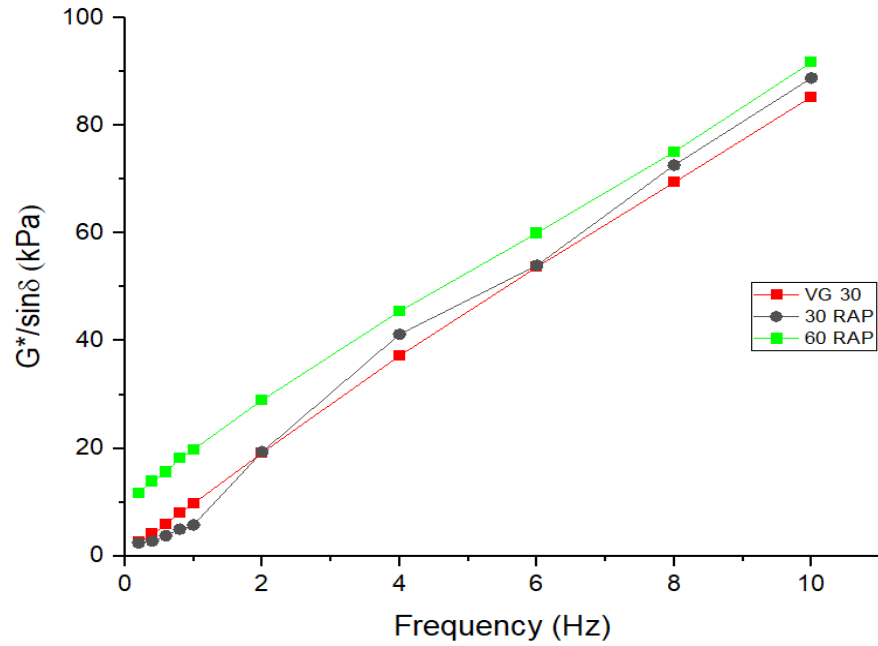
From the above graphs, 30% RAP with 5% castor oil and 60% RAP with 8% castor oil showed similar results that of virgin VG 30 for softening test, ductility test, penetration test and viscosity test. The optimum rejuvenator content in the RAP binder is highly significant since too much quantity will affect the rheological property. By comparing the results, it was observed that the optimum percentage of castor oil needed to rejuvenate 30% RAP is 5% and that of 60% RAP is 8%.

4.5.2 Rheological Property Analysis

Rheological property analysis using dynamic shear rheometer were conducted on the binder with optimum castor oil percentage obtained from physical property analysis. From Frequency sweep test complex shear modulus and phase angle of each sample with respect to the frequency range of 0.2Hz to 30 Hz. From these values rutting parameter at 60°C and fatigue parameter at 40°C were calculated. Variation of rutting parameter and fatigue parameter with respect to frequency range is shown in the Figure 4.5 and Figure 4.6 respectively.



(a)



(b)

Figure 4.5 Rutting Behavior of Samples (a) Comparison of all samples, (b) Comparison of VG 30 and rejuvenated RAP binders

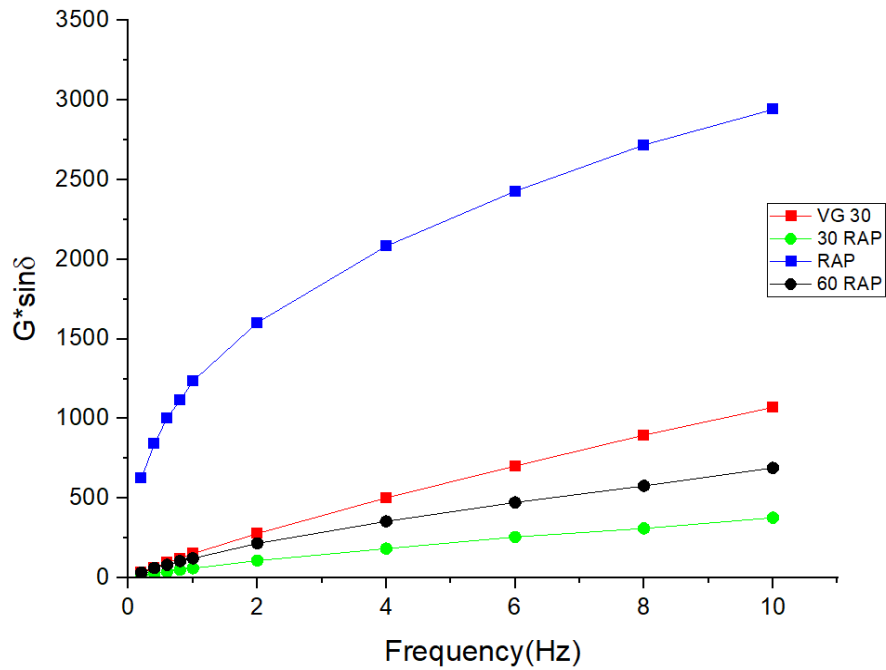


Figure 4.6 Fatigue Behavior of samples

In the Figure 4.5, both rejuvenated RAP binders show higher rutting values compared to VG 30 while RAP binder shows very high rutting values due to the presence of high asphaltene content. By the addition of 5% and 8% castor oil to 30% RAP and 60% RAP binder respectively could reduce the asphaltene content and thereby increase the maltene asphaltene ratio. From the Figure 4.6, both rejuvenated RAP shows low fatigue values compared to VG 30 which indicates that after the addition of castor oil to the RAP binder the fatigue resistance of RAP binder was increased. Rutting and fatigue parameters from Frequency Sweep test is shown in the Table 4.4.

Table 4.4 Frequency Sweep Test Results

Samples	Rutting Parameter (kPa)		Fatigue Parameter (kPa)	
	Max	Min	Max	Min
VG 30	238.9	2.1	2511.8	35.0
RAP	13752.4	1331.0	4332.1	626.7
30R + 5C	423.5	2.9	172.1	2.8
60 R + 8C	411.0	2.6	97.0	1.7

From the above results, the bitumen blends, 30R +5C and 60R+ 8C shows comparable results that of VG 30. The maximum and minimum rutting parameters of both rejuvenated RAP binder is higher than that of virgin binder and maximum and minimum fatigue parameter is lower than that of the virgin binder respectively. This indicates that rejuvenated RAP binder has more rutting and fatigue resistance than virgin binder.

In order to check the fatigue life of rejuvenated RAP binder linear amplitude sweep test at 40°C were conducted. The output obtained were shear stress and shear strain. The graphical representation of LAS test is shown in the Figure 4.7

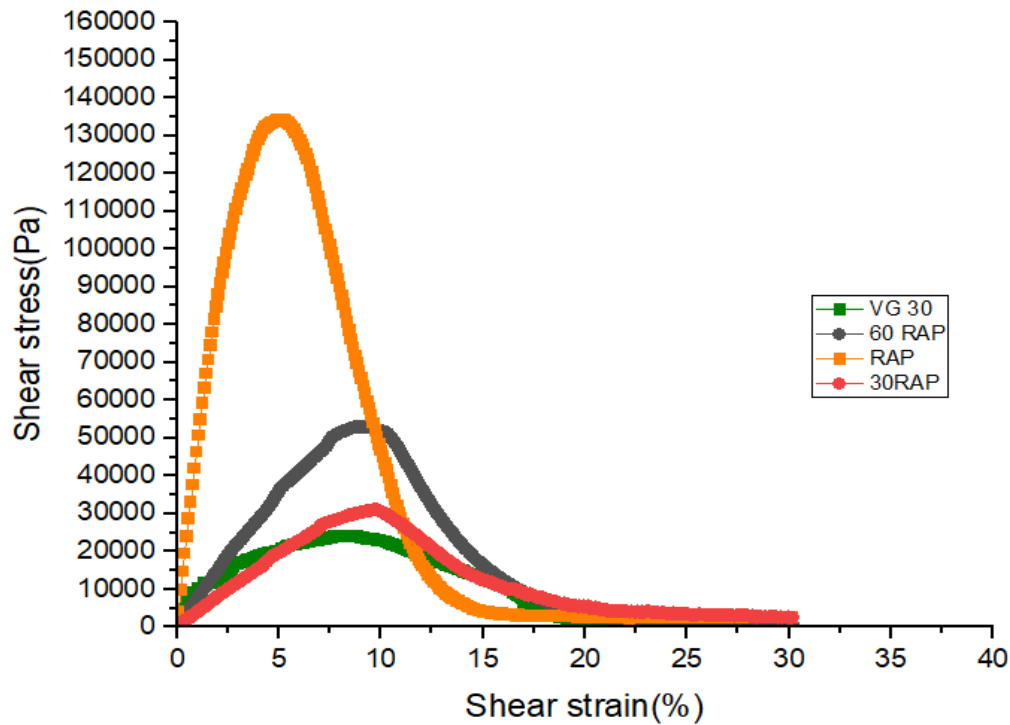


Figure 4.7 LAS Test Result

In the Figure 4.7, the peak shear stress for RAP binder was obtained as 134116.1Pa with a strain value of 8.28. Due to the presence highly stiffened polar molecules, the RAP binder with stand high stress but it is highly brittle due to low elasticity and strain value. After the addition of optimum castor oil to 30% and 60% RAP binder, the peak stress value obtained as 31140.98 Pa and 53078.7 Pa with peak strain value of 9.74 and 8.97 respectively. Both the peak stress and strain values are higher than the VG 30 which indicated that, castor oil can impart optimum rejuvenating power to the aged binder by modifying its physical and chemical components, so that it can undergo wide range of fatigue stress without losing its viscoelastic nature. It can be said that, sufficient fatigue life can be imparted to the aged binder by castor oil as a rejuvenator.

4.6 MARSHALL TEST RESULTS

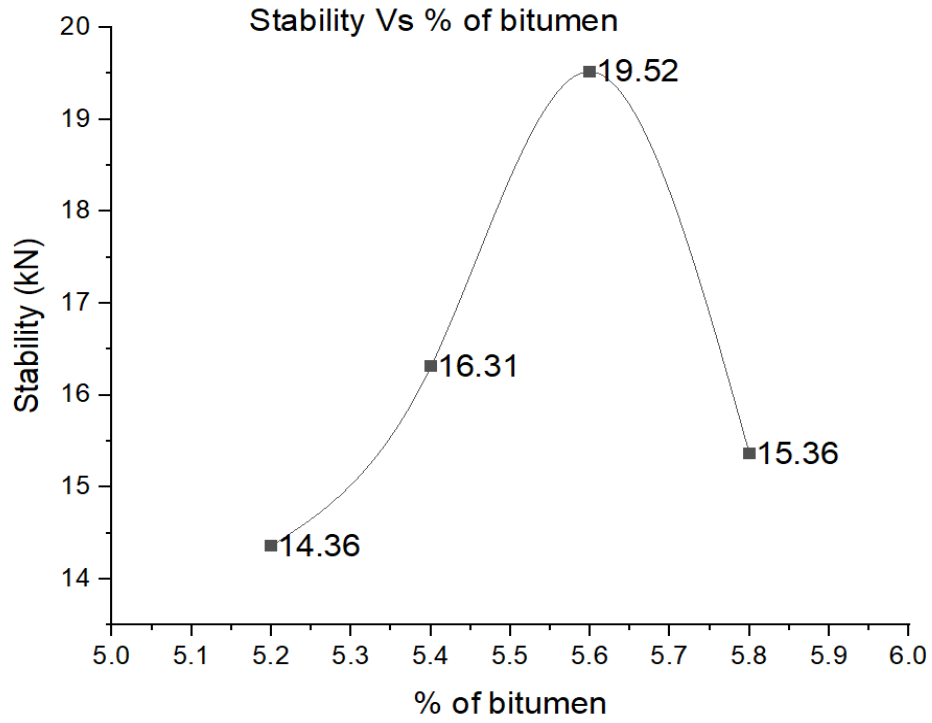
4.6.1 Marshall Test Results for Control Mix

For the determination of volumetric properties of normal and modified bituminous mixes, Marshall samples were prepared at 5.2%, 5.4%, 5.6% and 5.8% of bitumen with optimum amount of castor oil obtained from the analysis of RAP binder. Three samples were prepared for each bitumen content and the volumetric properties of rejuvenated RAP binder were determined. Table 4.5 shows the results of volumetric properties of control mix.

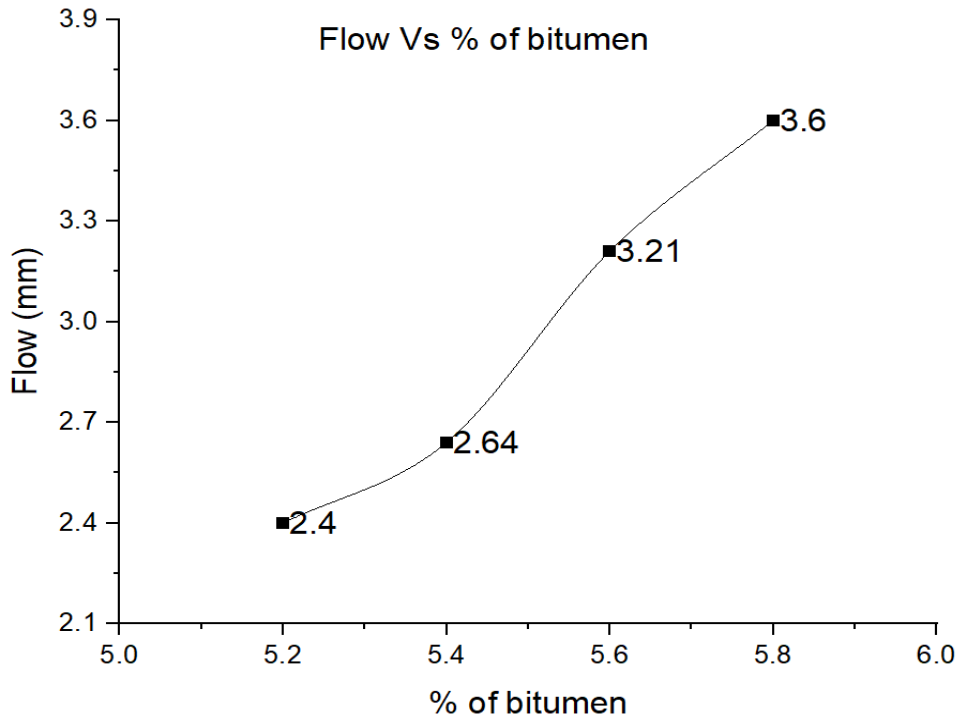
Table 4.5 Volumetric Properties of Control Mix

% of binder	Stability (KN)	Flow (mm)	Gmm	Gmb	Va (%)	VMA (%)	VFB (%)
5.2	14.36	2.40	2.483	2.323	6.44	18.30	64.80
5.4	16.31	2.64	2.495	2.350	5.81	18.0	67.70
5.6	1952	3.21	2.565	2.454	4.33	17.80	75.70
5.8	15.36	3.60	2.471	2.383	3.56	18.2	77.60

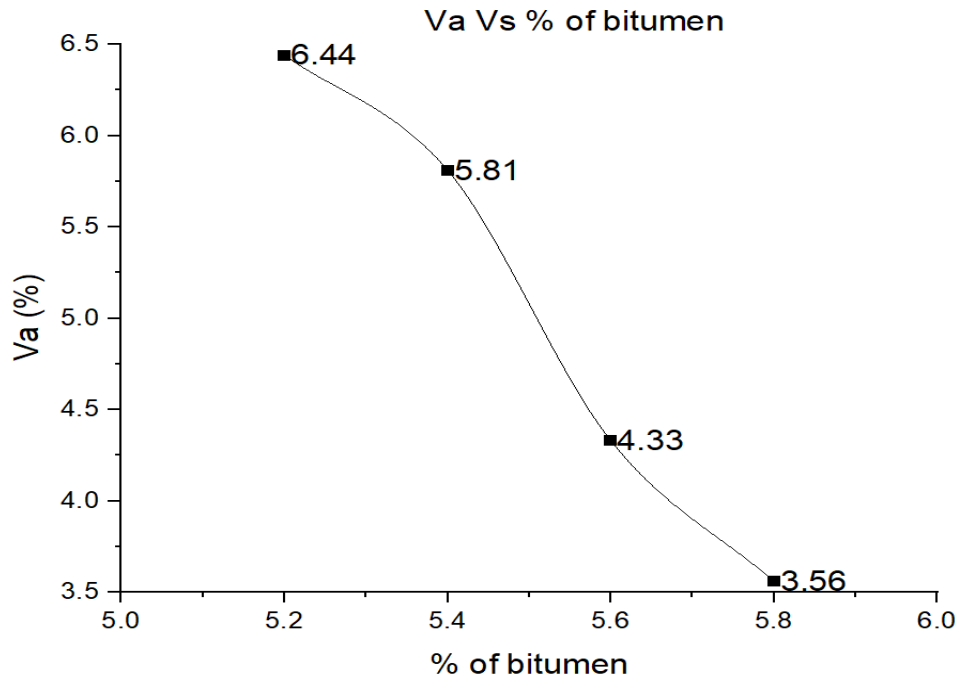
The relationship between Marshall stability, flow value, bulk density (Gmb), air voids(Va), voids in mineral aggregates(VMA), voids filled with bitumen(VFB) is shown in Figure 4.8(a, b, c, d, e and f).



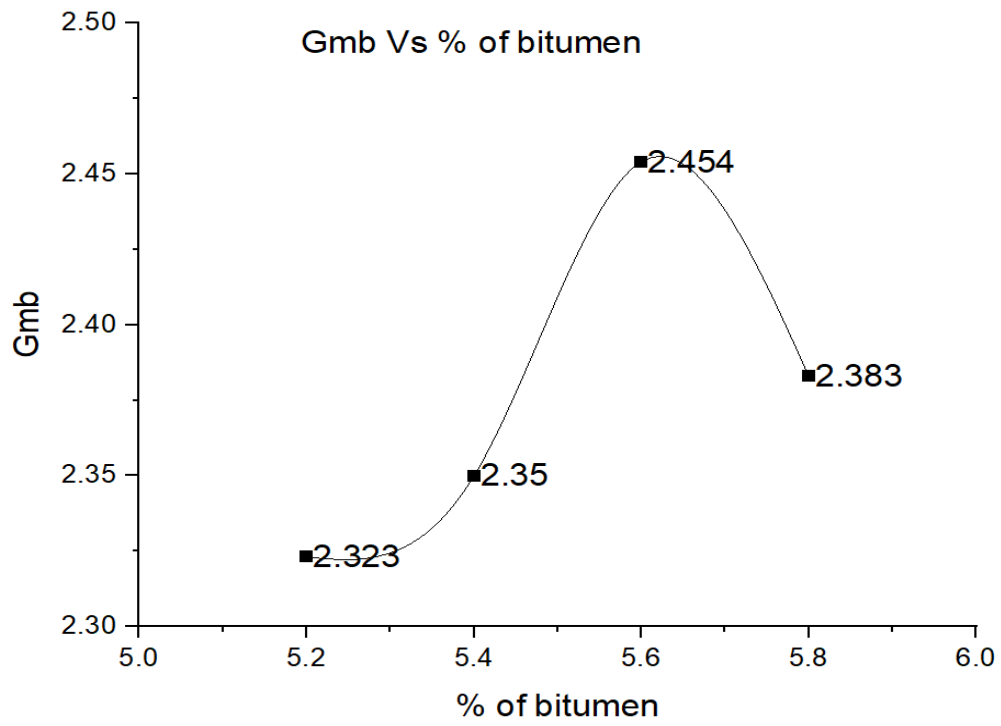
(a)



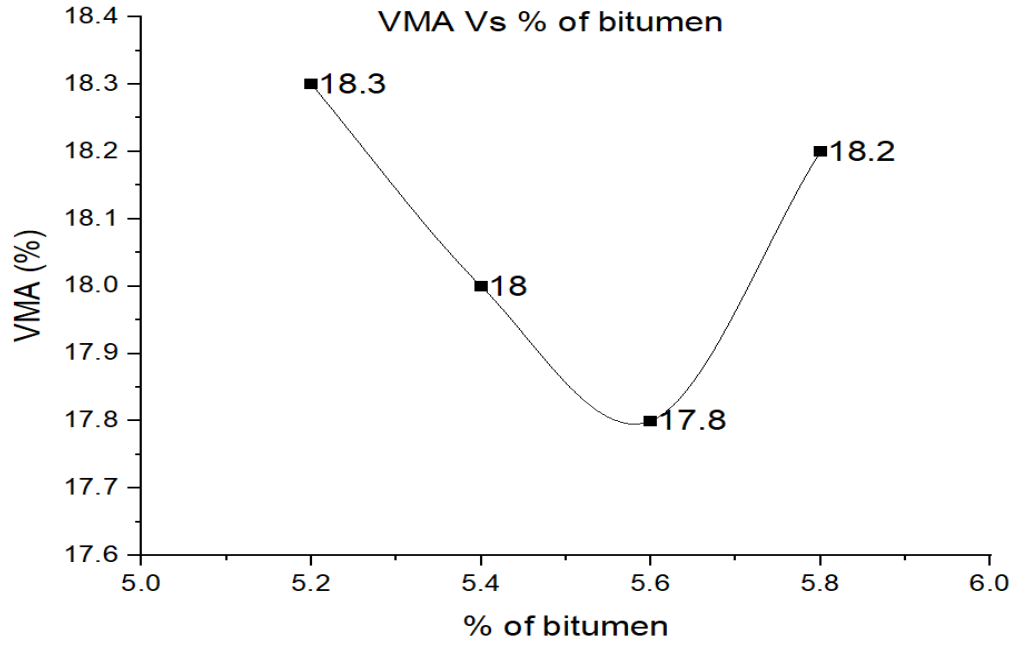
(b)



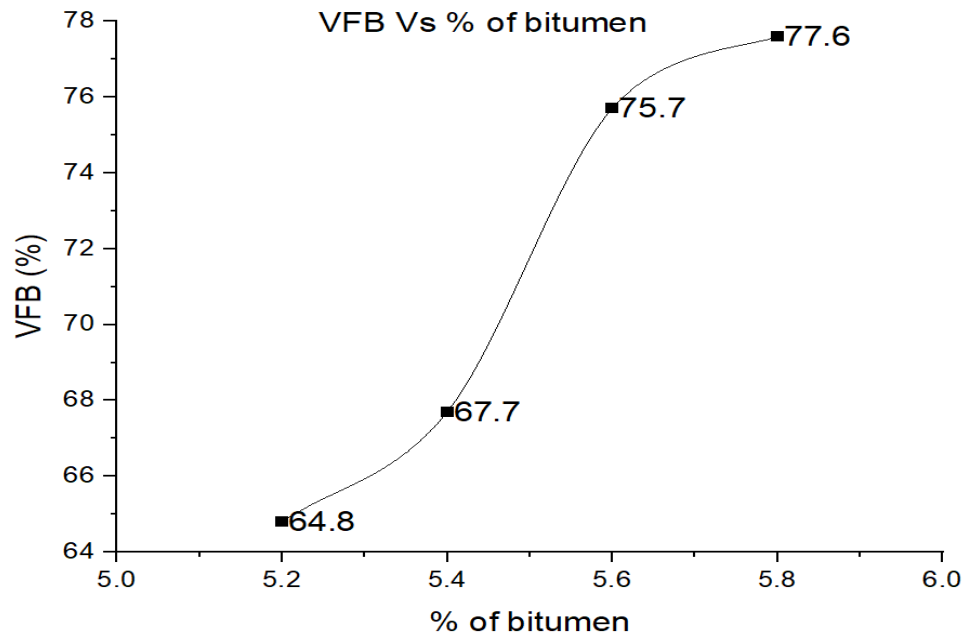
(c)



(d)



(e)



(f)

Figure 4.8 Volumetric Properties of Control Mix (a) Stability Vs % of bitumen, (b) Flow Vs % of bitumen, (c) Va Vs % of bitumen, (d) Gmb Vs % of bitumen, (e) VMA Vs % of bitumen, and (f) VFB Vs % of bitumen,

From the Figure 4.8, it was observed that stability of control mixes increased by increasing the percentage of bitumen up to 5.6% and then decreasing. The flow value increases from 2.83 mm to 3.88mm as the binder content increases from 5.2% to 5.8%. V_a for laboratory mixture should be 4% to fix the optimum binder content. As the binder content increases, the air voids decrease since the voids are filled with bitumen. In the case of VMA at 5.6% binder content the mix attains a lowest peak value of 17.50% and then rises. This is because relatively higher specific gravity material like aggregate is displaced and pushed apart by lower specific gravity material like bitumen. VFB is used in the mix to ensure proper asphalt thickness. If it is too low or too high, the mix will be unstable. As binder content increases the VFB also increases from 64.70% to 78.79%. The optimum binder content for control mix was calculated as the average of bitumen content corresponding to maximum stability, minimum voids ion mineral aggregates, maximum bulk density and air voids of 4% and the obtained value is 5.66% .

4.6.2 Marshall mix design of 30% and 60 % RAP

4.6.2.1 Aggregate Blending

Various blending trails were conducted for 20mm down stock pile, stone dust stockpile and RAP stockpile to meet the requirements of BC G-II as per MoRTH (2013) specification. The trial with minimum least squared error were selected for trial mix preparation. The design blend proportion for 30% RAP is obtained as 30% and 40% for 20 mm down stockpile and stone dust stockpile respectively. The design blend proportion for 60% RAP is obtained as 20% and 20% for 20 mm down stockpile and stone dust stockpile respectively. The optimum gradation of mixes with 30% RAP and 60% RAP materials are shown in the Figure 4.9 and Figure 4.10.

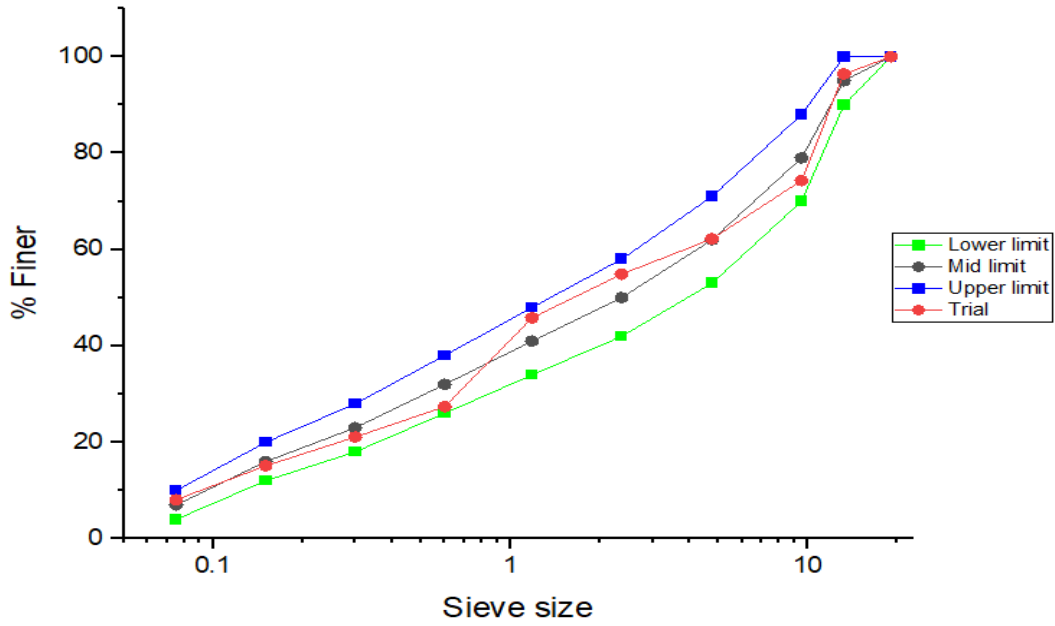


Figure 4.9 Aggregate blending chart with 30% RAP materials

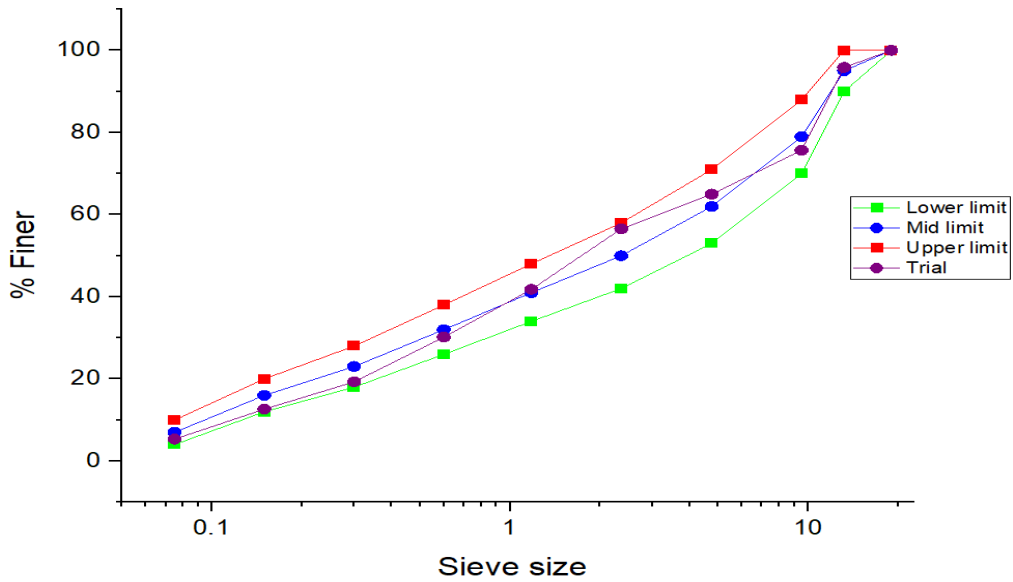


Figure 4.10 Aggregate blending chart with 60% RAP materials

4.6.2.2 Batching of Aggregates

The quantity of RAP binder present in the RAP should be consider while batching the fresh aggregates. For 30% RAP materials, only 28.38% is aggregates and remaining is its binder content.

Similarly for 60% RAP materials, 56.76% contributes to aggregates. So, the fresh aggregate proportion should be altered based on this. Batching of 20 mm down stockpile and stone dust stock pile with respect to the available RAP materials are shown ion the Table 4.6.

Table 4.6 Batching of Aggregates

% RAP	Available RAP Aggregates (%)	Combined Weight of Fresh Aggregates (%)	20 mm down stockpile (%)	Stone Dust (%)
30	28.38	71.62	30.69	40.93
60	56.76	43.24	21.62	21.62

4.6.2.3 Specific Gravity of Aggregates

Specific gravity of aggregates is shown in the Table 4.7.

Table 4.7 Specific Gravity of Aggregates

Materials	Specific Gravity	Method
20 mm down	2.803	ASTM C128
Stone Dust	2.998	ASTM C128
RAP Coarse	2.851	ASTM C128
RAP Fine	2.745	ASTM C128
RAP	2.766	$\frac{P_{coarse} + P_{fine}}{\frac{P_{coarse}}{G_{coarse}} + \frac{P_{fine}}{G_{fine}}}$
30% RAP Blend	2.868	$\frac{100}{\frac{RAP}{G_{RAP}} + \frac{wt\ of\ 20\ mm}{G_{20mm}} + \frac{wt\ of\ stone\ dust}{G_{stone\ dust}}}$
60% RAP Blend	2.821	$\frac{100}{\frac{RAP}{G_{RAP}} + \frac{wt\ of\ 20\ mm}{G_{20mm}} + \frac{wt\ of\ stone\ dust}{G_{stone\ dust}}}$

4.6.2.4. Fresh Binder Requirement

Fresh binder requirement of binder for preparing the mix is shown ion the Table 4.8.

Table 4.8. Fresh Binder Requirement

Binder Content	RAP Binder Available (g)	Total Binder Requirement (g)	Fresh Binder to be Added (g)
5.0	22.68	63.16	40.48
5.2	22.68	65.82	43.14
5.4	22.68	68.5	45.82
5.6	22.68	71.19	48.51
5.8	22.68	73.89	51.21

4.6.3 Marshall Test Results of 30% RAP Mixes

MoRTH (2013) specifies that a minimum binder content of 5.4% corresponds to aggregates specific gravity of 2.7. Specific gravity of aggregate blend with 30% RAP materials was obtained as 2.868 which is higher than 2.7, the minimum binder content should be reduced proportionately to 5.08%. Based on the this, the mix design with 30% RAP materials were conducted with binder content of 5.0%, 5.2%, 5.4% 5.6% and 5.8% and the Figure 4.11 indicates the samples casted by Marshall mix design procedure. Volumetric Properties of Mix with 30% RAP Materials Table 4.9.

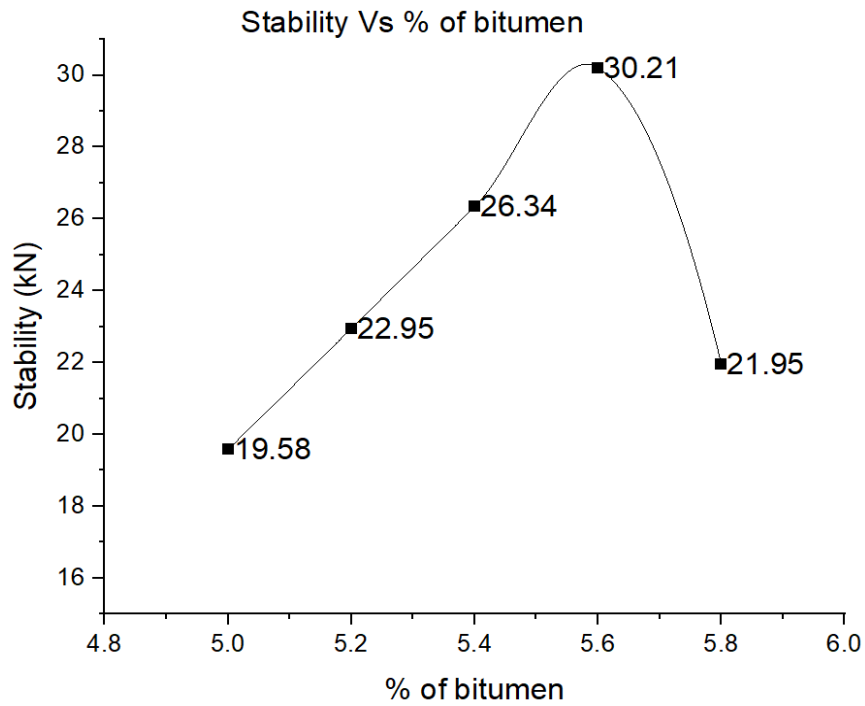


Figure 4.11 Samples with 30% RAP materials

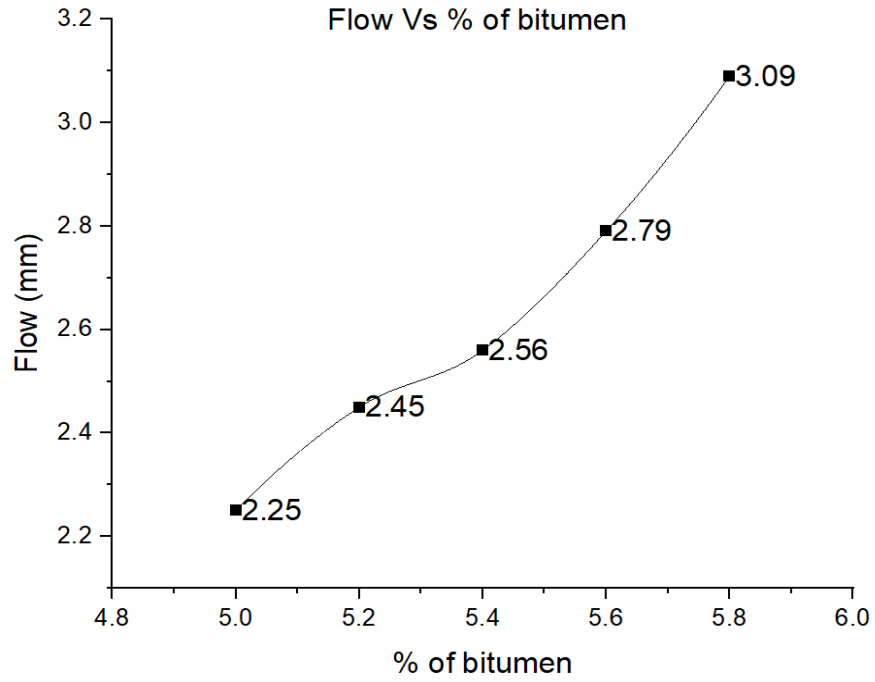
Table 4.9. Volumetric Properties of Mix with 30% RAP Materials

% of Bitumen	Stability (KN)	Flow (mm)	Gmm	Gmb	Va (%)	VMA (%)	VFB (%)
5.0	19.58	2.25	2.511	2.342	6.73	18.2	63.0
5.2	22.95	2.45	2.481	2.348	5.36	17.3	69.1
5.4	26.34	2.56	2.479	2.372	4.32	16.9	74.4
5.6	30.21	2.79	2.446	2.374	2.94	16.0	81.6
5.8	21.95	3.09	2.439	2.371	2.79	16.3	82.9

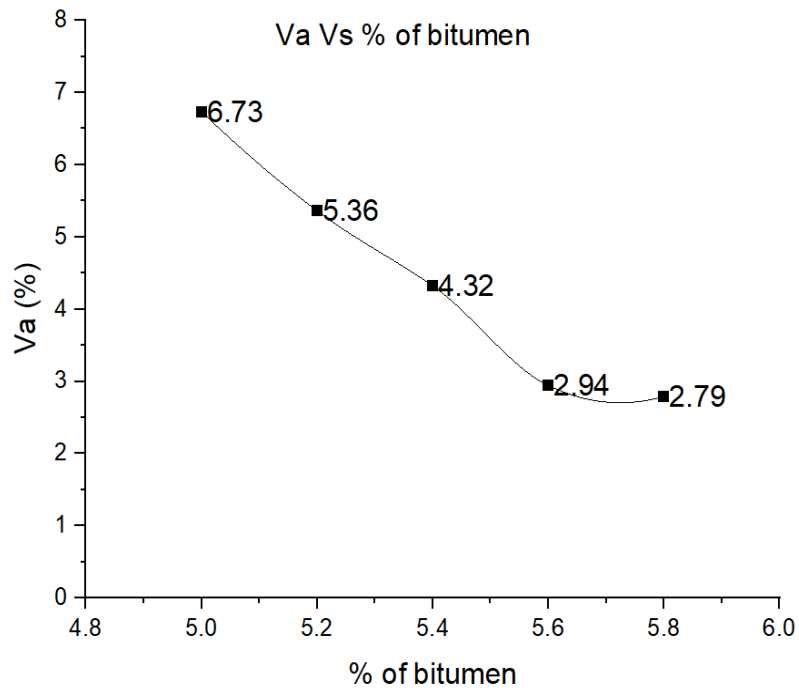
The relationship between Marshall stability, flow value, bulk density (Gmb), air voids (Va), voids in mineral aggregates(VMA), voids filled with bitumen(VFB) is shown in Figure 4.12 (a, b, c, d, e and f).



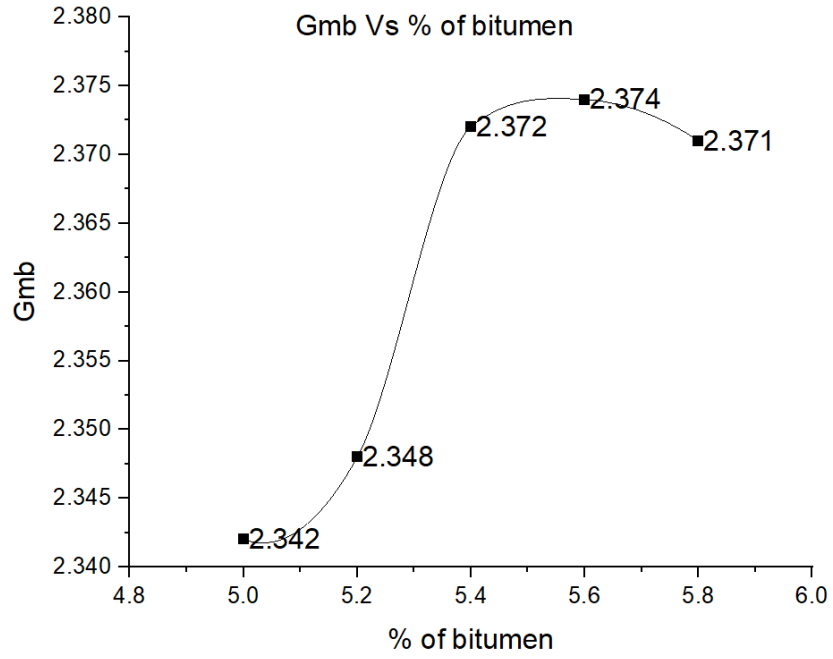
(a)



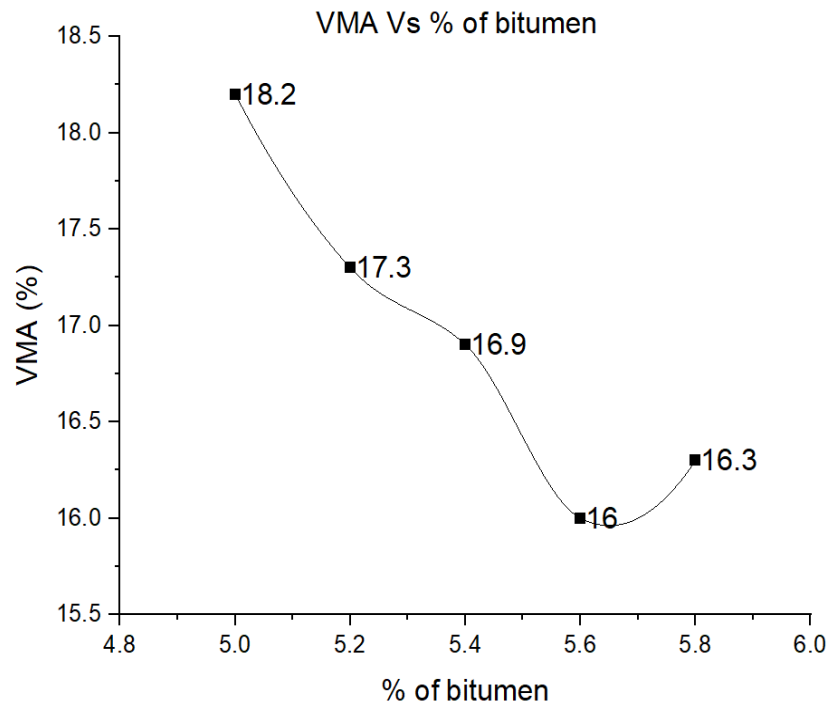
(b)



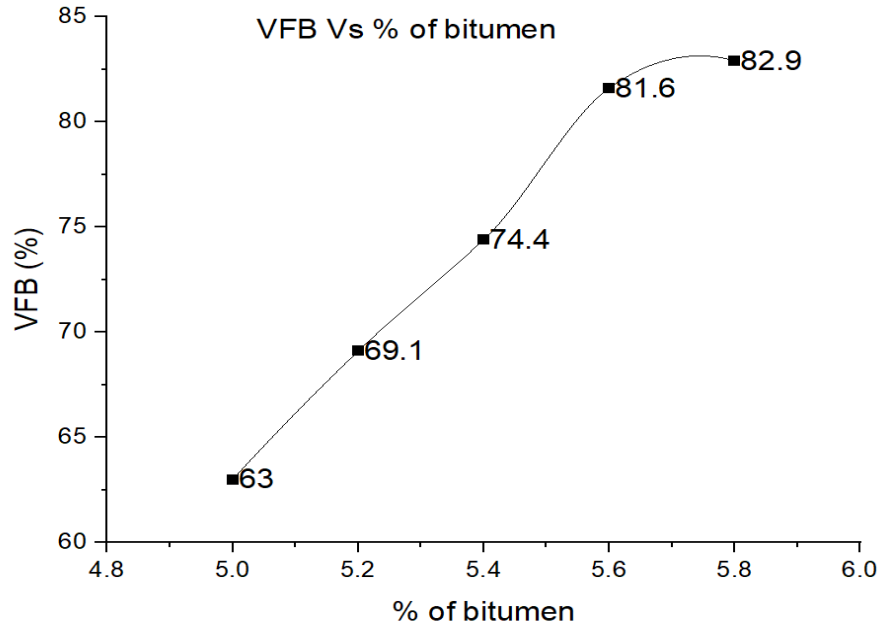
(c)



(d)



(e)



(f)

Figure 4.12 Volumetric Properties of 30% RAP Mix (a) Stability Vs % of bitumen, (b) Flow Vs % of bitumen, (c) Va Vs % of bitumen, (d) Gmb Vs % of bitumen, (e) VMA Vs % of bitumen, and (f) VFB Vs % of bitumen,

From the Figure 4.12, it was observed that, the replacement of fresh materials by RAP increases the stability of mix to a higher level compared to the control mix. This is due to the presence of binder coated RAP aggregates. Stability of mix with 30% RAP increases with increasing the percentage of bitumen up to 5.6% and then decreasing. The flow value increases from 2.25 mm to 3.08 mm as the binder content increases from 5.0% to 5.8%. As the binder content increases, the air voids decrease more compared to the control mix, since the voids are filled with bitumen which is already present in the RAP aggregates. In the case of VMA at 5.6% binder content the mix attains a lowest peak value of 16.0% and then rises. This is because relatively higher specific gravity material like aggregate is displaced and pushed apart by lower specific gravity material like bitumen. VFB is used in the mix to ensure proper asphalt thickness. If it is too low or too high, the mix will be unstable. As binder content increases the VFB also increases from 63.0% to 82.90%. The optimum binder content for 30% RAP mix was 5.44% with 4% air voids.

4.6.4 Marshall Test Results of 60% RAP Mixes

MoRTH (2013) specifies that a minimum binder content of 5.4% corresponds to aggregates specific gravity of 2.7. Specific gravity of aggregate blend with 60% RAP materials was obtained as 2.821 which is higher than 2.7, the minimum binder content should be reduced proportionately to 5.17%. Based on this, the mix design with 60% RAP materials were conducted with binder content of 5.0%, 5.2%, 5.4%, 5.6% and 5.8% and the Figure 4.13 indicates the samples casted by Marshall mix design procedure. Volumetric Properties of Mix with 30% RAP Materials Table 4.10.

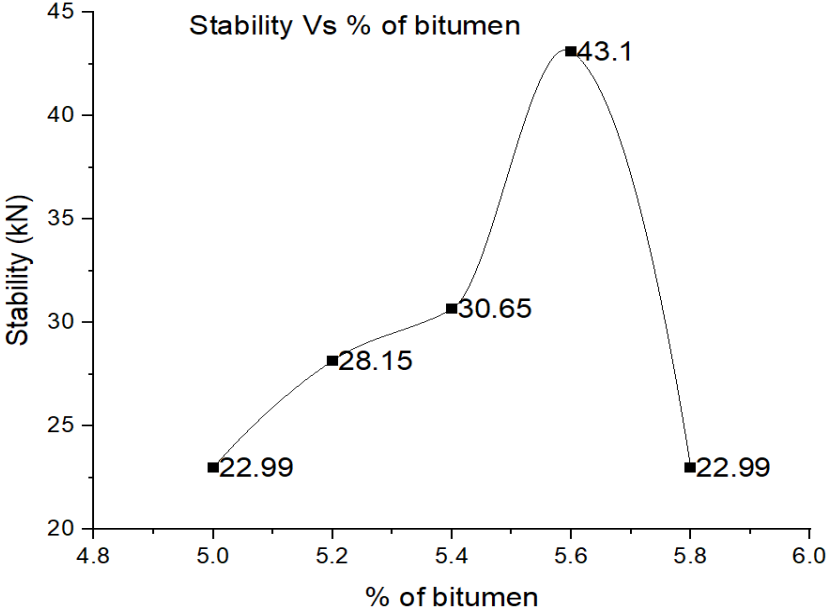


Figure 4.13 Samples with 60% RAP materials

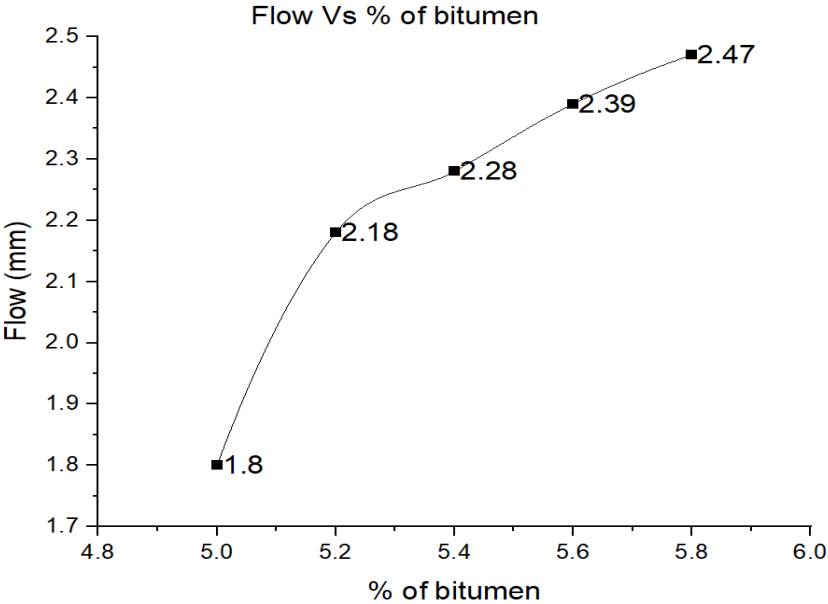
Table 4.10 Volumetric Properties of Mix with 60% RAP Materials

% of Bitumen	Stability (KN)	Flow (mm)	Gmm	Gmb	Va (%)	VMA (%)	VFB (%)
5.0	22.99	1.80	2.444	2.310	5.48	16.8	67.4
5.2	28.15	2.18	2.438	2.349	3.65	15.6	76.6
5.4	30.65	2.28	2.448	2.383	2.66	15.3	82.6
5.6	43.10	2.39	2.436	2.384	2.13	15.2	86.0
5.8	22.99	2.47	2.427	2.379	1.98	15.5	87.2

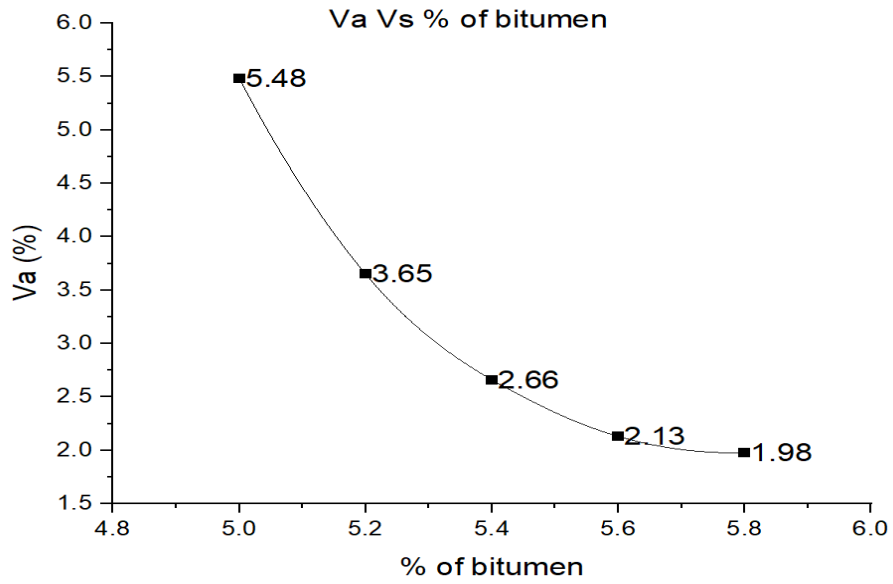
The relationship between Marshall stability, flow value, bulk density (Gmb), air voids (Va), voids in mineral aggregates (VMA), voids filled with bitumen(VFB) is shown in Figure 4.14(a, b, c, d, e and f).



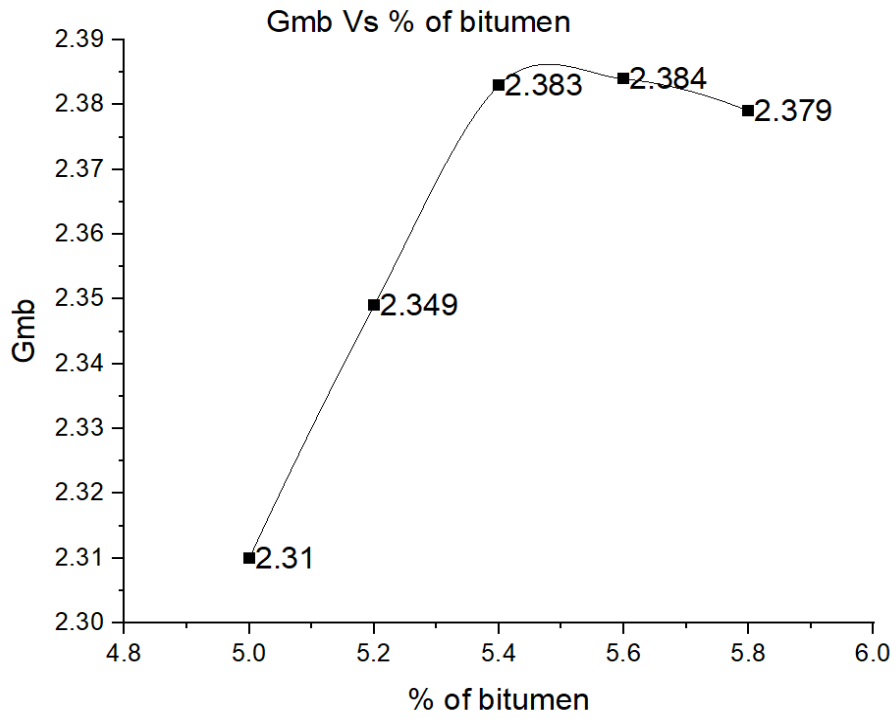
(a)



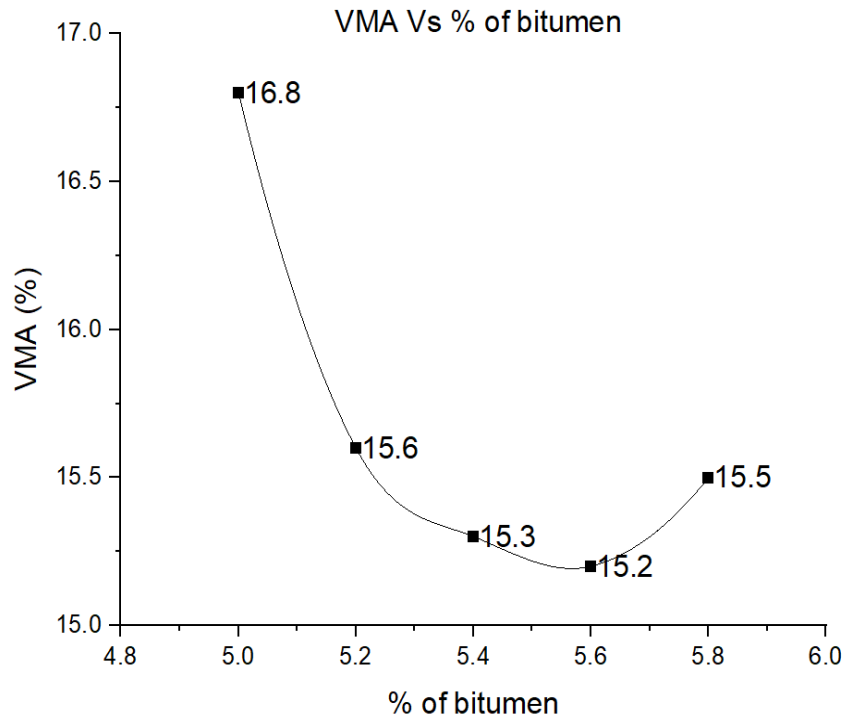
(b)



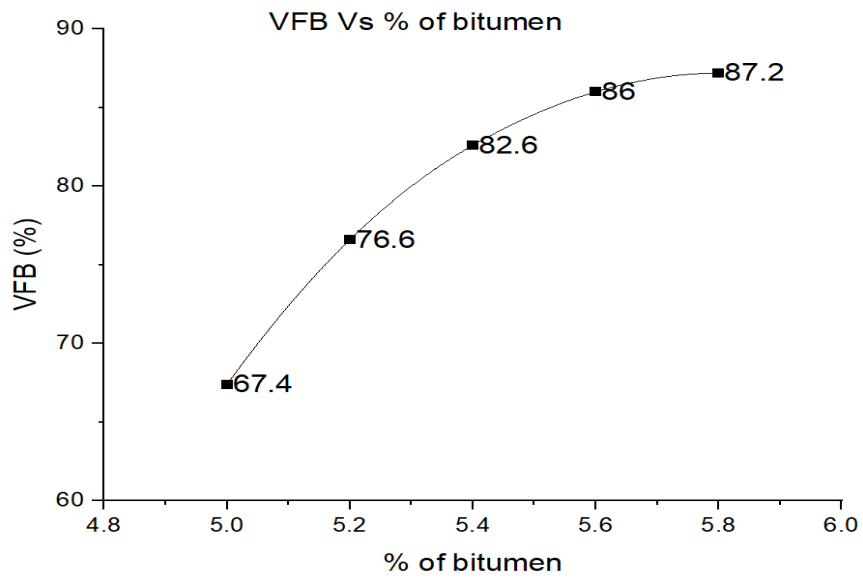
(c)



(d)



(e)



(f)

Figure 4.14 Volumetric Properties of 60% Mix (a) Stability Vs % of bitumen, (b) Flow Vs % of bitumen, (c) Va Vs % of bitumen, (d) Gmb Vs % of bitumen, (e) VMA Vs % of bitumen, and (f) VFB Vs % of bitumen

From the Figure 4.14, while using 60% RAP materials the stability increases than that of 30% RAP mix. This is due to the presence of binder coated RAP aggregates. Maximum stability of mix with 60% RAP obtained as 43.1kN with the bitumen content at 5.6% and then decreasing. The flow value increases from 2.25 mm to 3.09 mm as the binder content increases from 5.0% to 5.8%. As the binder content increases, the air voids decrease from 5.48% to 1.98% which is less compared to the control mix, since the voids are filled with bitumen which is already present in the RAP aggregates. In the case of VMA at 5.6% binder content the mix attains a lowest peak value of 15.20% and then rises. This is because relatively higher specific gravity material like aggregate is displaced and pushed apart by lower specific gravity material like bitumen. VFB is used in the mix to ensure proper asphalt thickness. As binder content increases the VFB also increases from 67.4% to 87.2%. The optimum binder of 60% RAP mix was obtained as 5.63% at 4% air voids.

4.6.5 Marshall Test Results of Mixes with 30% RAP and 5% Castor oil

Mix design with 30% RAP with 5% castor oil were conducted with binder content of 5.0%, 5.2%, 5.4% 5.6% and 5.8% and the Figure 4.15 indicates the samples casted by Marshall mix design procedure. Volumetric Properties of Mix with 30% RAP Materials Table 4.11.

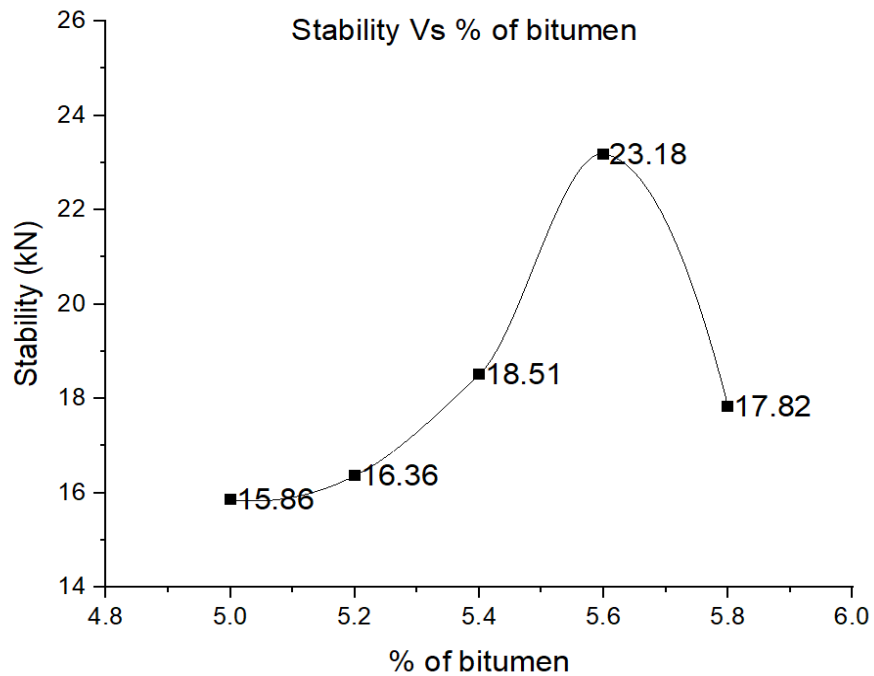


Figure 4. 15 Samples with 30% RAP+ 5%Castor oil

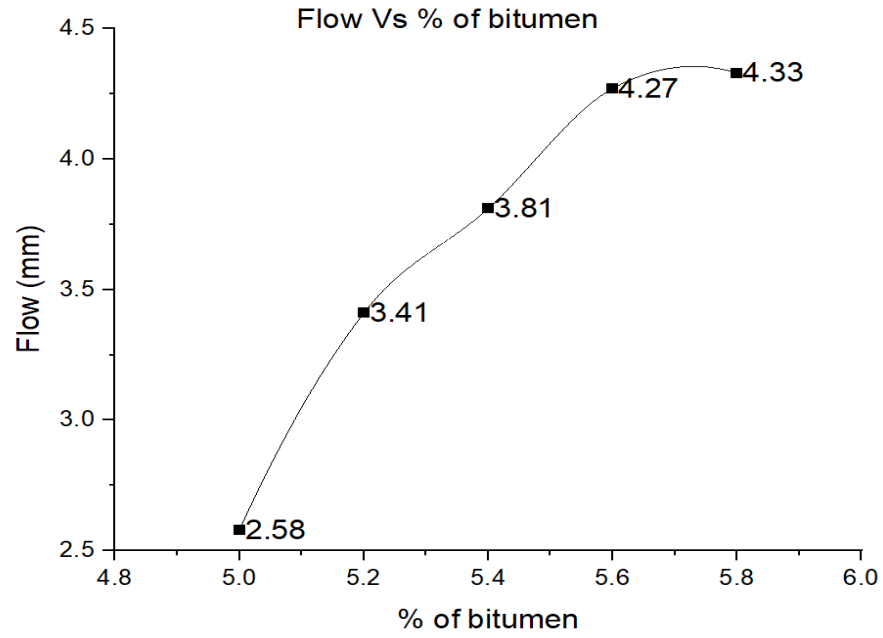
Table 4.11 Volumetric Properties of Mix with 30% RAP+ 5% Castor oil

% of Bitumen	Stability (KN)	Flow (mm)	Gmm	Gmb	Va (%)	VMA (%)	VFB (%)
5.0	15.86	2.58	2.445	2.311	5.48	16.8	67.4
5.2	16.36	3.41	2.478	2.364	4.60	16.7	72.4
5.4	18.51	3.81	2.486	2.392	3.78	16.4	77.0
5.6	23.18	4.27	2.465	2.405	2.43	15.6	84.4
5.8	17.82	4.33	2.419	2.364	2.27	15.7	85.5

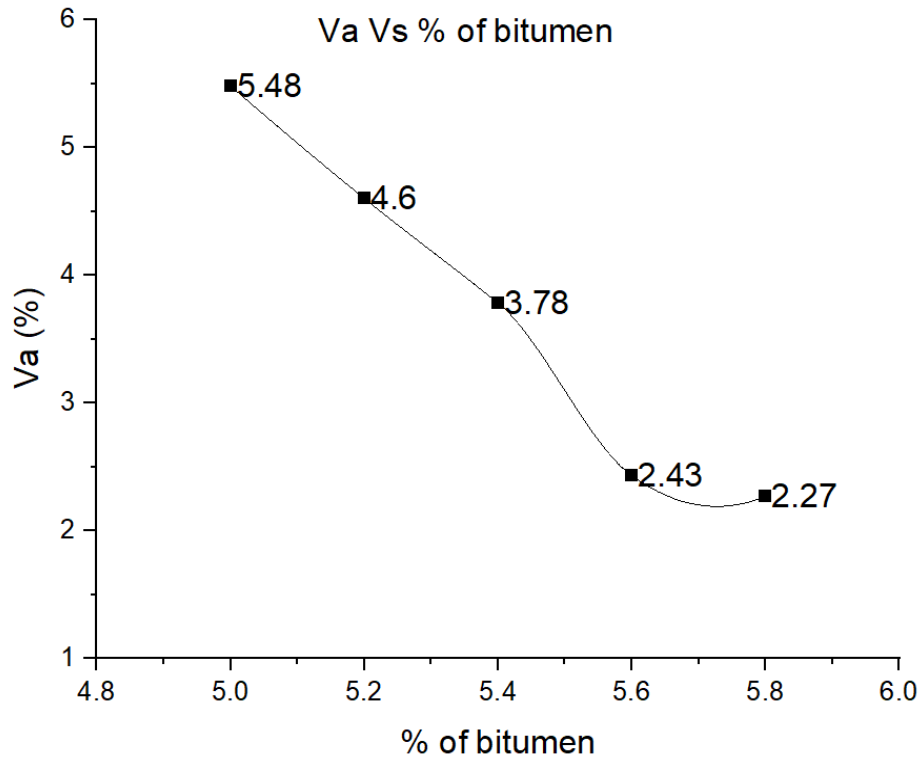
The relationship between Marshall stability, flow value, bulk density (Gmb), air voids (Va), voids in mineral aggregates(VMA), voids filled with bitumen(VFB) is shown in figure 4.16 (a, b, c, d, e and f).



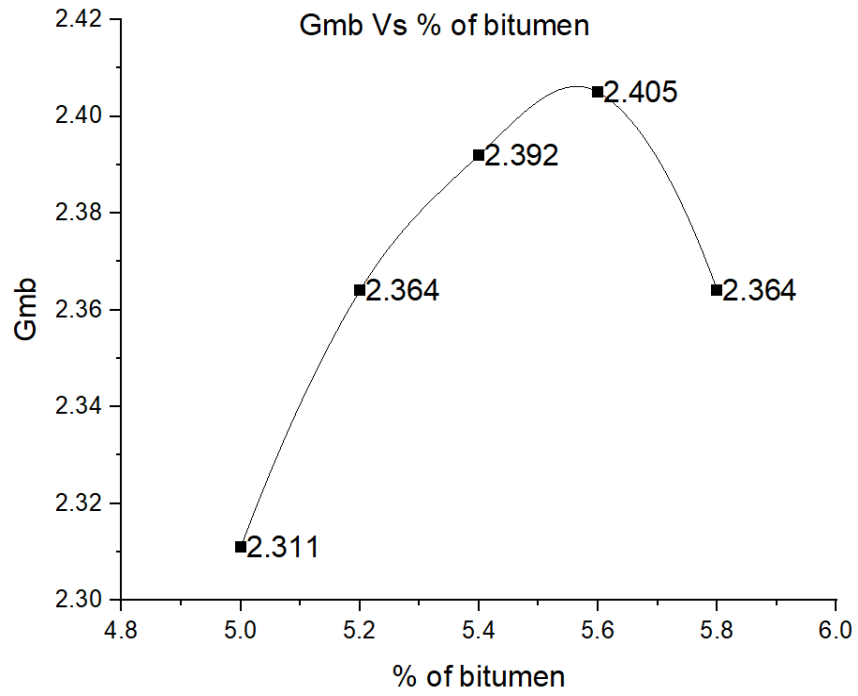
(a)



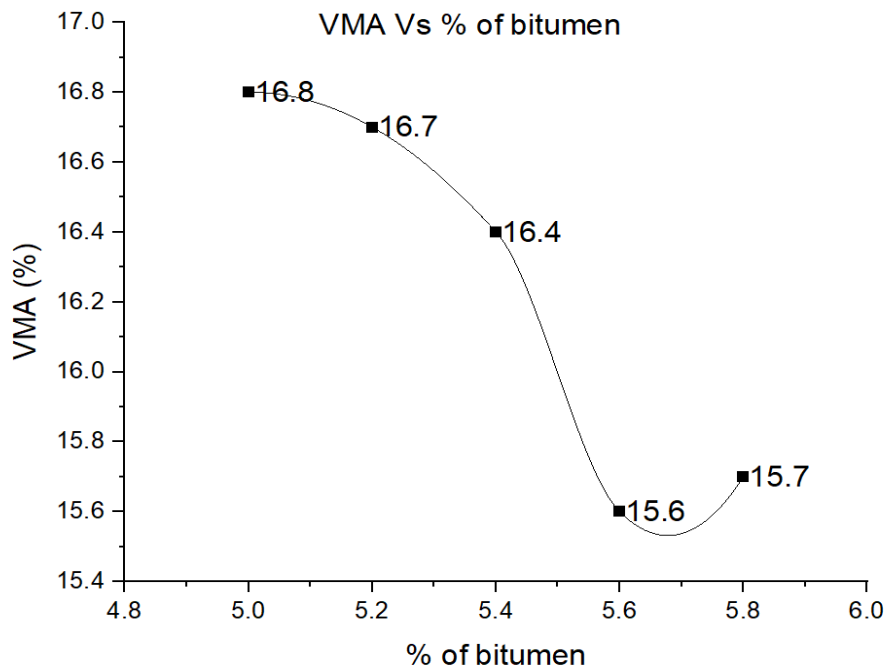
(b)



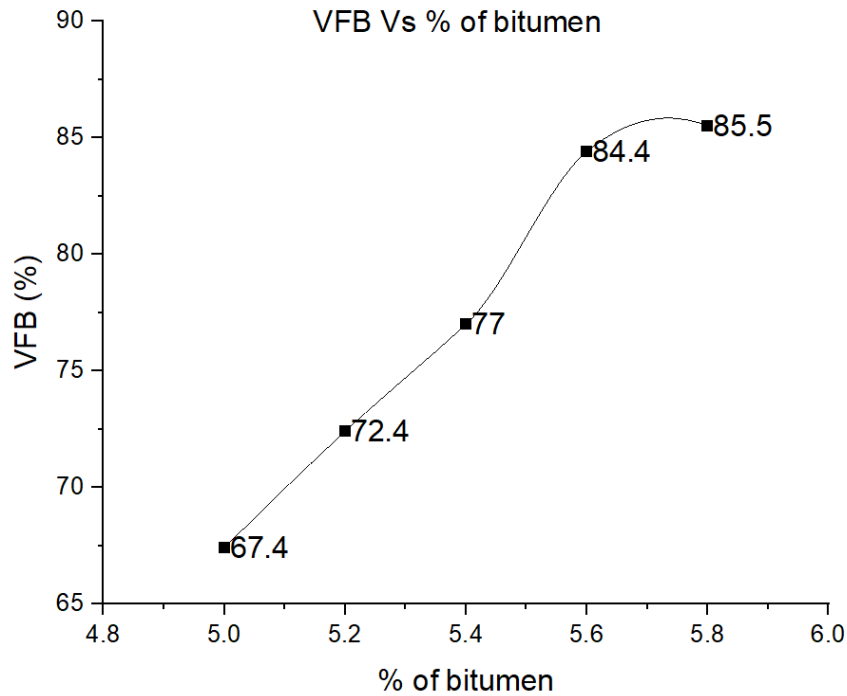
(c)



(d)



(e)



(f)

Figure 4.16 Volumetric Properties of Mix with 30% RAP and 5% Castor oil (a) Stability Vs % of bitumen, (b) Flow Vs % of bitumen, (c) Va Vs % of bitumen, (d) Gmb Vs % of bitumen, (e) VMA Vs % of bitumen, and (f) VFB Vs % of bitumen

From the Figure 4.16, with the addition of 5% castor oil to 30% RAP mix, the stability value reaches 23.18 kN at 5.6% binder content which is higher than control mix. The flow value increases from 2.58 mm to 4.33 mm as the binder content increases from 5.0% to 5.8%. By the addition of optimum castor oil to this mix the rigidity index comes to 4.89 which is within the acceptable limit. As the binder content increases, the air voids decrease from 5.48% to 2.27% which is less compared to the control mix, since the voids are filled with bitumen which is already present in the RAP aggregates. In the case of VMA at 5.6% binder content the mix attains a lowest peak value of 15.60% and then rises which is lower than that of the control mix. It indicates that voids in the mineral aggregates were filled more uniformly in the rejuvenated 30% RAP mix. As binder content increases the VFB also increases from 67.4% to 85.5%. The optimum binder content for 30% rejuvenated RAP mix was 5.34% corresponding to air voids of 4%.

4.6.6 Marshall Test Results of Mixes with 60% RAP and 8% Castor oil

Mix design with 60% RAP with 8% castor oil were conducted with binder content of 5.0%, 5.2%, 5.4% 5.6% and 5.8% and the Figure 4.17 indicates the samples casted by Marshall mix design procedure. Volumetric Properties of Mix with 30% RAP Materials Table 4.12.

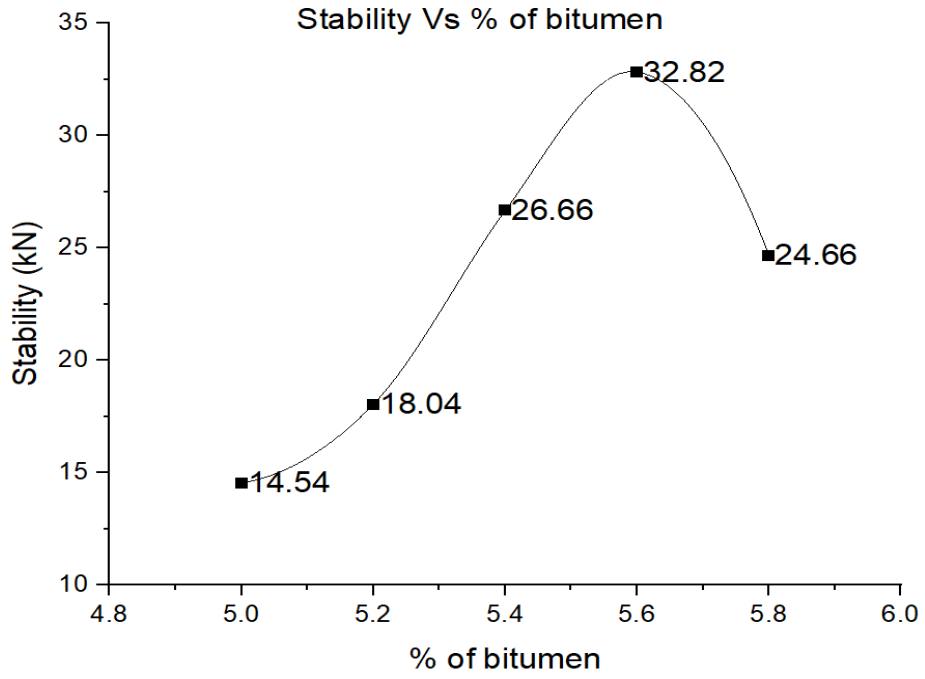


Figure 4. 17 Samples with 60% RAP+ 8%Castor oil

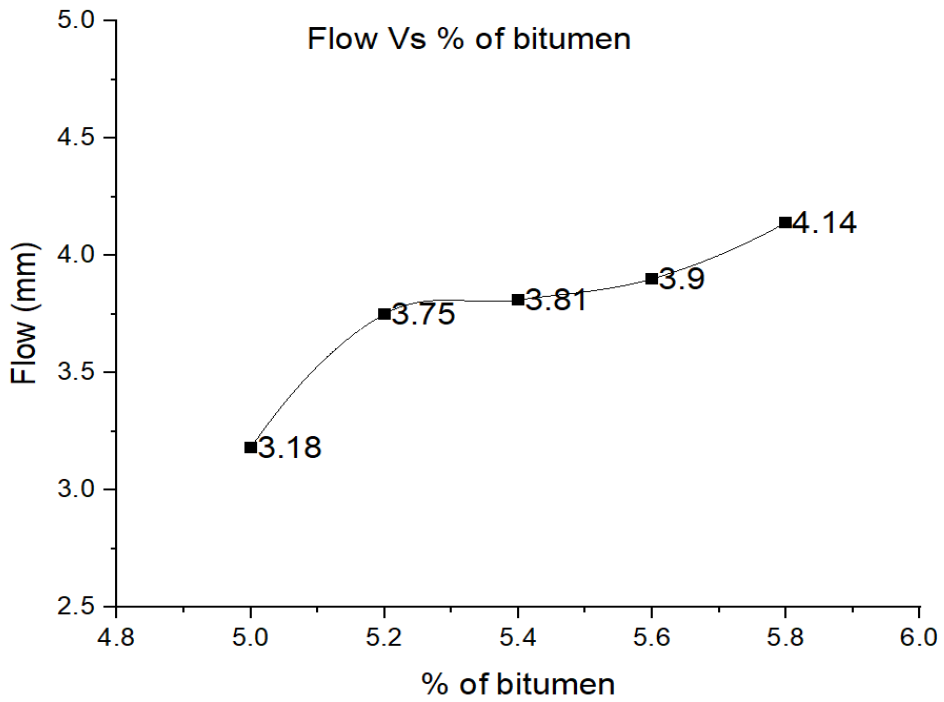
Table 4.12 Volumetric Properties of Mix with 60% RAP+ 8%Castor oil

% of Bitumen	Stability (KN)	Flow (mm)	Gmm	Gmb	Va (%)	VMA (%)	VFB (%)
5.0	14.54	3.18	2.511	2.366	5.77	17.4	66.8
5.2	18.04	3.75	2.478	2.372	4.28	16.4	73.9
5.4	26.66	3.81	2.451	2.376	3.06	15.6	80.4
5.6	32.82	3.90	2.432	2.383	2.01	15.1	86.7
5.8	24.66	4.14	2.425	2.379	1.90	15.4	87.7

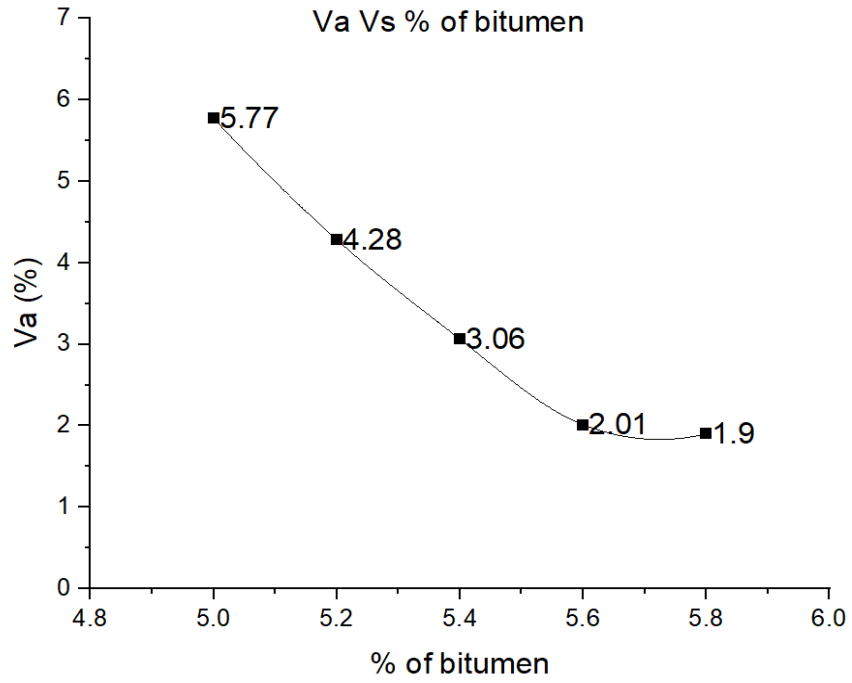
The relationship between Marshall stability, flow value, bulk density (Gmb), air voids(Va), voids in mineral aggregates(VMA), voids filled with bitumen(VFB) is shown in Figure 4.18 (a, b, c, d, e and f)..



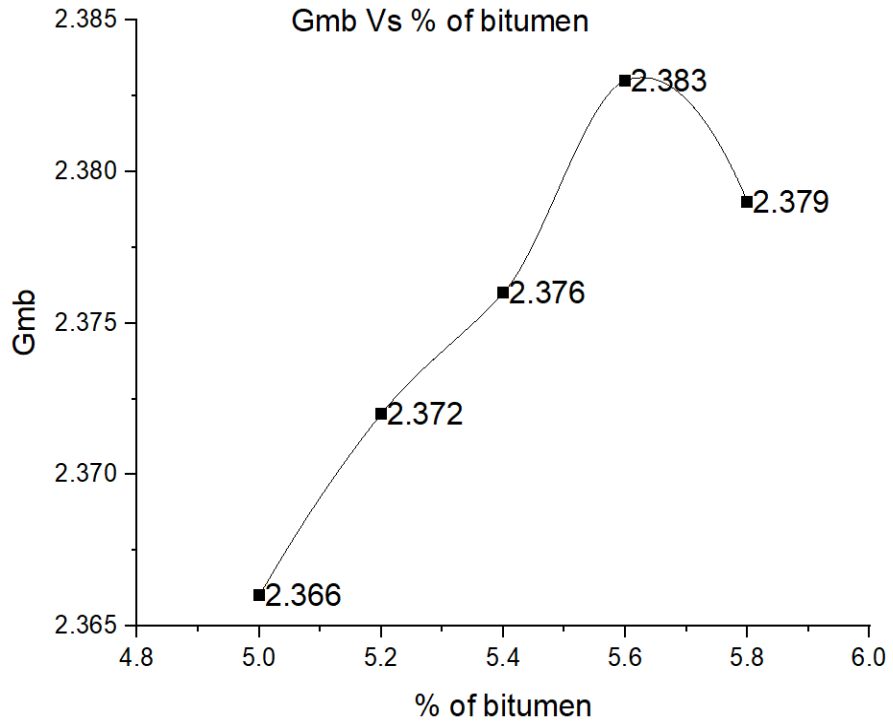
(a)



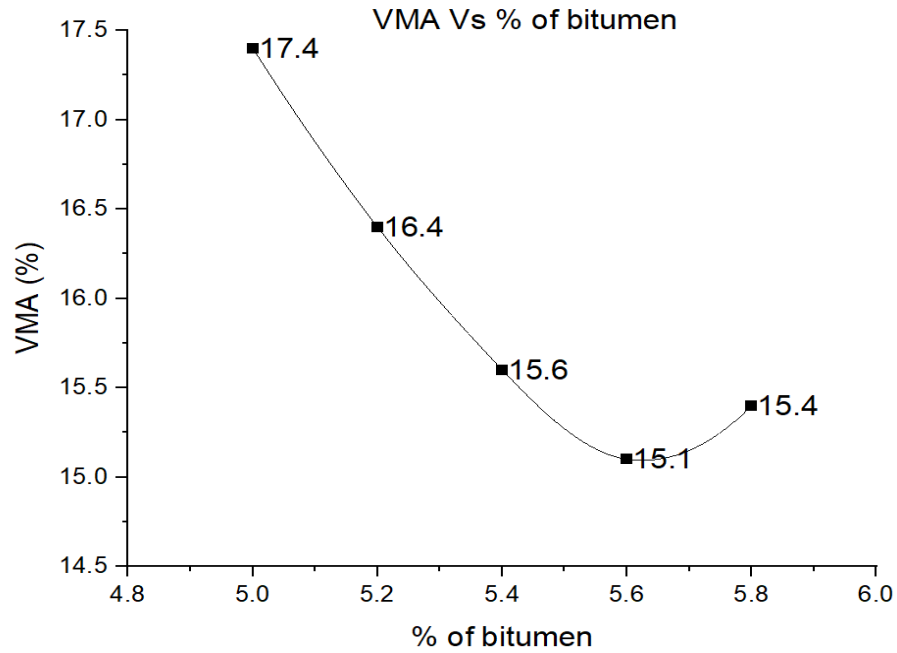
(b)



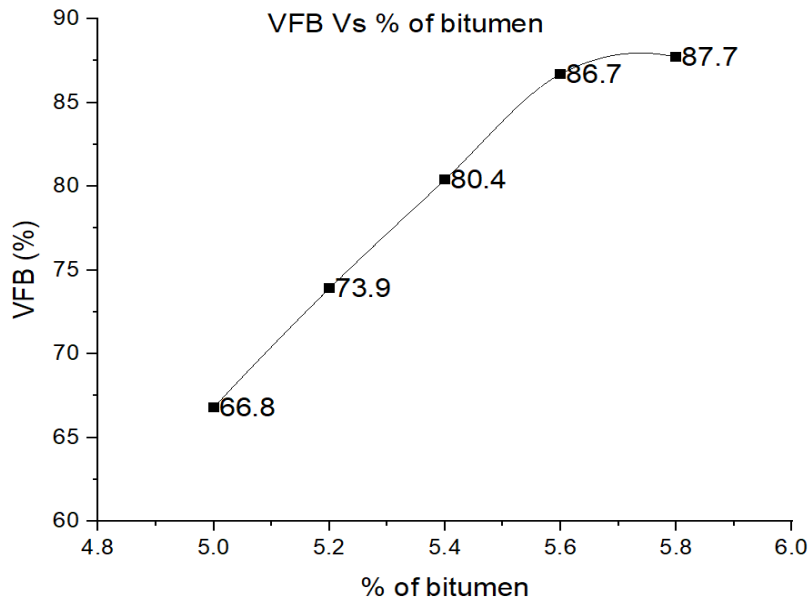
(c)



(d)



(e)



(f)

Figure 4.18 Volumetric Properties of Mix with 60% RAP and 8% Castor oil (a) Stability Vs % of bitumen, (b) Flow Vs % of bitumen, (c) Va Vs % of bitumen, (d) Gmb Vs % of bitumen, (e) VMA Vs % of bitumen, and (f) VFB Vs % of bitumen

From the Figure 4.18, with the addition of 8% castor oil to 60% RAP mix, the stability value reaches 32.82 kN at 5.6% binder content which is higher than control mix due to the presence of binder coated RAP aggregates. The flow value increases from 3.18 mm to 4.14 mm as the binder content increases from 5.0% to 5.8%. With the addition of 8% castor oil to this mix the rigidity index comes to 4.89Kn/mm² which is within the acceptable limit. As the binder content increases, the air voids decrease from 5.77% to 1.90%, since the voids are filled with bitumen which is already present in the RAP aggregates. In the case of VMA at 5.6% binder content the mix attains a lowest peak value of 15.10% and then rises which is lower than that of the control mix. It indicates that voids in the mineral aggregates were filled more uniformly in the rejuvenated 60% RAP mix. As binder content increases the VFB also increases from 66.8% to 87.7%. The optimum binder content for 60% rejuvenated RAP mix was 5.17%.

The comparison of volumetric properties of 30 % RAP with and without optimum castor oil, 60% RAP with and without optimum castor oil and control mix is shown in the Table 4.13.

Table 4.13 Comparison of Volumetric Properties of Mixes

Property	Control mix	30 R	60R	30R+5C	60R+8C	Required Value (MoRTH)
OBC (%)	5.66	5.44	5.63	5.34	5.17	-
Stability	18.07	28.5	37.1	18.12	18.59	Min 9 kN
Flow value	3.7	2.9	2.6	3.7	3.8	2 - 4
% Air voids	4	4	4	4	4	3 – 8 %
VMA	17.51	16.70	17.44	16.56	16.30	Min 11%
VFB	73.42	76.10	77.00	73.60	72.12	65 - 75
Gmb	2.440	2.374	2.380	2.392	2.368	-
Rigidity Index	4.88	9.83	14.27	4.89	4.89	2.94 - 4.91 kN/mm ² (Eltwati et al., 2022)

From Table 4.13, as RAP content increases the optimum binder content decreases and stability value increases. RAP mixes attain higher stability value without the addition of rejuvenator which

is the primary advantage of the incorporation of RAP to the mix. For RAP mixes major concern is given for rigidity index. Rigidity index is the ratio of stability to flow. As compared to the RAP mixes without rejuvenation, the control mix and rejuvenated RAP mixes attained lower rigidity index which is within the required limit of 2.94 to 4.91 kN/mm². The softening effect of oil can be the reason of the reduction in the stability of rejuvenated HMA mixes. Also, the flow value of rejuvenated RAP mixes was comparable with that of control mix. Since castor oil contains various chemical compounds with polar groups, it can dissolve the asphaltene in the RAP. The colloidal nature of aged binder can regain by the chemical interaction between the polar groups of castor oil and asphaltene atoms in the RAP binder and thereby reduce the flow behavior. The air voids in a paving mixture are small pockets of air between the bitumen coated aggregate particle. The air voids decrease, as bitumen contentment increases. A certain percentage of air voids must be present in the finished HMA to allow for additional compaction under the traffic load and environmental conditions. A laboratory compacted sample of HMA has a design air void level of 4%. The minimum VMA required is 11%. As the RAP content increases from 30% to 60% the VMA also reduces from 16.56% to 16.30% which indicates that as RAP increases the voids in the mineral aggregate reduces. The required limit of voids filled with bitumen is 65-75%, which were satisfied by rejuvenated RAP mixes due to the reduction of stiffness of aged binder by dissolving the its asphaltene content. Overall, the mix contain 30% RAP with 5 % castor oil and 60% RAP with 8% castor oil shows better volumetric properties compared to that of control mix and mix contain only RAP materials.

4.7 INDIRECT TENSILE STRENGTH TEST RESULTS

Indirect tensile strength was conducted for both conditioned and unconditioned samples. Three set of samples were prepared for each mix for both conditions. Table 4.14 shows the results of indirect tensile strength for optimum mixes. Tensile strength ratio of mixes was also calculated to determine the moisture susceptibility of the mixes.

Table 4.14 Indirect tensile strength for optimum mixes

Samples	Unconditioned Strength (MPa)	Conditioned Strength (MPa)	Tensile Strength Ratio
Control Mix	0.517	0.435	84.20
Mix with 30 R + 5C	0.720	0.613	85.09
Mix with 60 R + 8C	0.696	0.570	81.94

From Table 4.14, it is observed that RAP mixes meet the minimum tensile strength ratio of 80% recommended by AASHTO T-283. Before conditioning, the control mix attained a tensile strength of 0.517MPa which were reduced to 0.435MPa after conditioning. For 30% rejuvenated RAP mix, the tensile strength without conditioning were obtained as 0.720MPa which were reduced to 0.613MPa after conditioning. Similarly for 60% rejuvenated RAP mix, the tensile strength without conditioning were obtained as 0.696 MPa which were reduced to 0.570MPa after conditioning. As RAP content increases from 30% to 60%, the tensile strength and moisture susceptibility decreases due to the high stiffness of RAP binder. Tensile strength ratio of 30 % RAP with 5% castor oil mix was 85.09% and that of 60% RAP with 8% castor oil mix was 81.94% suggesting a better moisture resistance. This behavior can be explained by fact that the aggregates and RAP binder are covered with the rejuvenator, which reduces the penetration of water to the interface of aggregate and binder and resulting better cohesive and adhesive binding between materials. Therefore, it can be concluded that mix with 30% RAP with 5% castor oil and 60% RAP mix with 8% castor oil has attain sufficient moisture resistance with the influence of castor oil. Even though the mix with 60% RAP comply with standard requirements, due to its high surface roughness, the TSR ratio is lower than that of the control mix.

4.8 SELF-HEALING CAPACITY TEST RESULTS

Self-healing capacity test was conducted by indirect tensile strength of unconditioned samples. Three set of samples were prepared for the control mix and rejuvenated mixes with 30% and 60% RAP materials. Table 4.15 shows the healing index of optimum mixes.

Table 4.15. Self-healing capacity test results of optimum mixes

Type of mixes	Max load - before confinement (kN)	Temperature	Max load - after confinement (kN)	Healing Index
Control Mix	5.512	Softening Point	1.918	0.348
		Softening point + 10°C	3.554	0.645
		Softening point + 20°C	1.473	0.267
Mix with 30 R + 5C	7.212	Softening Point	4.420	0.573
		Softening point + 10°C	4.725	0.655
		Softening point + 20°C	3.985	0.552
Mix with 60 R + 8C	7.078	Softening point	3.800	0.537
		Softening point + 10°C	4.665	0.659
		Softening point + 20°C	3.545	0.501

From the above results, the self-healing capacity of rejuvenated RAP mixtures are higher than that of control mix. The confinement at softening point with 100psi pressure, healing index is lower than the case of conditioning with a temperature of softening point + 10°C and higher than that of temperature equals to softening point + 20°C. Maximum healing index obtained for control mix, 30% rejuvenated RAP mix and 60% rejuvenated RAP mix were 0.645, 0.655 and 0.659 respectively at the same temperature condition; 10°C higher than its softening point. The healing index of 60% rejuvenated RAP mix shows highest value followed by 30% rejuvenated RAP mix. As the temperature increases above its softening point, the RAP aggregates coated with binder itself melt and fill up the cracks. This can be explained by the ability of castor oil which promote the diffusion of aged binder with enhanced binding property and wrap around the surface of aggregates by lowering the viscosity and raising the fluidity of aged binder. Castor oil itself act as a moderator between fresh and aged binder and improves the compatibility between these binders. After a certain temperature limit, the increase in temperature adversely affects the mixes and loosen the bond strength of its materials with high fluidity of binders and aggregates and thereby reduce peak load values and healing index.

4.9 SUMMARY

The lost properties of RAP binder were regained by castor oil as a rejuvenator. For the replacement of 30% fresh materials by RAP, 5% castor oil is needed and for 60% RAP the optimum castor oil required is 8%. Both the physical and rheological properties of these binder blends satisfy VG 30 specifications. The optimum binder content of RAP mixes was reduced in comparison to the control mix and among which, 60% rejuvenated RAP mixes require less fresh binder than all other mixes. With optimum rejuvenator, both mixes attained desirable rigidity index and volumetric properties. Volumetric properties of both rejuvenated RAP mixes were within the MoRTH specification. Indirect tensile strength and moisture sensitivity of 30% rejuvenated RAP mixes were significantly higher than the control mix while 60% rejuvenated mix satisfied the minimum tensile strength ratio as per AASHTO T283. Healing index of both rejuvenated RAP mix were higher than the control mix in which 60% RAP attained highest value. The results reveal that with optimum amount of castor oil as a rejuvenator, the RAP can be efficiently used in the preparation of the BC mixes.

CHAPTER 5

CONCLUSIONS

5.1 GENERAL

The present study investigates the impacts of castor oil as a rejuvenator on recycled asphalt pavement with 30% and 60% replacement of fresh materials by RAP materials. In this study, BC mixes were prepared with optimum castor oil obtained from physical and rheological property analysis of respective binder blends. The following are the main conclusions made after conducting the laboratory investigations:

- The physical properties of the bitumen (VG-30), aggregates and rejuvenated RAP materials were determined and found to be suitable for road construction as per MoRTH and IS specifications.
- Optimum castor oil for 30% RAP mixture were obtained as 5% and that for 60% RAP mixture were 8% by conducting the physical and rheological property analysis of respective binder blends.
- The optimum binder content of all RAP mixes was reduced in comparison to control mix, among which 60% rejuvenated RAP mix requires less fresh binder than all other mixes like control mix, 30% and 60% RAP mixes and 30% rejuvenated RAP mix in order to achieve desired volumetric properties.
- 30% and 60% rejuvenated RAP mixes showed better performance than BC control mix in terms of strength, moisture sensitivity and healing index.
- Replacement of fresh materials by 30% rejuvenated RAP was found to be better on indirect tensile strength in both dry and wet conditions indicates that it can be efficiently applied to arid and heavy rainfall areas.
- Maximum healing index were shown by the 60% rejuvenated RAP mix followed by 30% RAP mix and the control mix. Since the RAP aggregates were already coated with bitumen, it may be attributed to the enhancement of self-healing capacity of mixes at specific conditions like temperature and pressure.

5.2 SPECIFIC CONCLUSIONS

- The binder blend of 30% RAP with 5% castor oil and 60% RAP with 8% castor oil showed better rutting and fatigue properties than that of fresh VG 30 binder. The maximum and minimum rutting values of VG 30 were 358.5 kPa and 1.2 kPa respectively. Both of these values were increased with the addition of optimum castor oil percentage obtained from physical property analysis. Maximum and minimum fatigue values of rejuvenated RAP blends were obtained as 2.8 kPa and 1.7 kPa which is lower than VG 30 with maximum fatigue value of 1421.3 kPa and minimum 18.0 kPa. It indicates that the rejuvenated RAP binders show better rutting and fatigue parameters than VG 30 binder.

- Optimum binder content of the control mix was obtained as 5.66%. On the other hand, optimum binder content of rejuvenated 30% and 60% RAP mixes were obtained as 5.34% and 5.17% respectively. The optimum binder content reduced by 5.66% and 8.66% for 30% and 60% rejuvenated RAP mixes compared to that of control mix. It indicates that by the addition of rejuvenated RAP materials, bitumen content of mixes can be reduced.

- Marshall stability of control mix was found to be 18.09 kN while that for 30% RAP mix and 60% RAP mix was 18.12 kN and 18.59 kN respectively. It indicates that stability increases by 0.16% for 30% RAP mix and 2.76% for 60% RAP mix. Thus, the rejuvenated RAP mixes were durable and stable compared to control mix.

- Tensile strength ratio of optimum RAP mixes attained the minimum criteria; 80% as per AASTO T-283. Also, the TSR ratio of 30% rejuvenated RAP mix was higher than that of control mixes and it indicates higher moisture resistance.

- Maximum Healing Index of the control mixes was found to be 0.645 mm and that of 30% RAP and 60% RAP mixes were found to be 0.655 and 0.659 respectively at the temperature 10°C higher than the softening point of respective binder blend. It indicates that healing index of 60% rejuvenated RAP binder is higher than that of control mix and 30% rejuvenated RAP mix.

5.3 FUTURE SCOPE

The impacts of castor oil with 100% dosage of RAP can be conducted. The chemical property analysis of the rejuvenated RAP binder and chemistry behind the rejuvenator binder blends can be studied. Comparative study of field aging and laboratory aging using short term aging by Rolling

Thin Film Oven Apparatus and long-term aging by Pressure Aging Vessel can be conducted. The rutting and fatigue resistance of rejuvenated RAP mix can be evaluated. The self-healing capacity with various confinement conditions of pressure and rest period can be evaluated. The impact of composite rejuvenator usage and its performance study should be included in future. MIST conditioning with variation of cycles, pressure and temperature can be done to study the severe moisture conditions of pavement.

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APPENDIX-A

Specific Gravity of Aggregates

Specific gravity of 20mm down aggregates- ASTM C128 (ASTM 2015)

Sl No.	Mass of pycnometer +sample+water	Mass of pycnometer+ water	Mass of SSD sample in air	Mass of oven-dry sample	Specific gravity
1	2099	1584	763	762	3.073
2	2105	1599	782	780	2.826
3	2040	1574	774	773	2.510

Average =2.803

Specific gravity of stone dust- ASTM C128-2015

Sl No.	Mass of pycnometer +sample+water	Mass of pycnometer+ water	Mass of SSD sample in air	Mass of oven-dry sample	Specific gravity
1	2013	1593	604	603	3.277
2	2005	1622	588	587	2.863
3	1999	1622	580	579	2.852

Average =2.998

Specific gravity of RAP coarse aggregates

Sl No.	Mass of pycnometer +sample+water	Mass of pycnometer+ water	Mass of SSD sample in air	mass of oven-dry sample	Specific gravity
1	2109	1624	752	751	2.813
2	2145	1623	799	797	2.873
3	2110	1625	743	740	2.868

Average =2.851

Specific gravity of RAP fine aggregates

Sl No.	Mass of pycnometer +sample+water	Mass of pycnometer+ water	Mass of SSD sample in air	mass of oven-dry sample	Specific gravity
1	2055	1624	683	682	2.706
2	2068	1624	698	695	2.737
3	2085	1624	717	715	2.793

Average =2.745

APPENDIX-B

Marshall properties of Control mix

% binder	Spec. Ht (mm)	Weight in Air	Weight in Water	Sat. Surface Dry in Air	Bulk S G, Gmb	Max S G, Gmm	Vb	% Air Voids	% VMA	% VFB	Stability	Flow
5.2	63	1232	714	1241	2.338						14.34	2.35
5.2	64	1233	713	1244	2.322						14.36	2.46
5.2	65	1240	712	1249	2.309						14.38	2.39
Average	64				2.323	2.483	11.8	6.4	18.3	64.8	14.36	2.40
5.4	65	1230	713	1239	2.338						15.94	2.64
5.4	66	1238	720	1246	2.354						16.66	2.61
5.4	64	1241	723	1249	2.359						16.34	2.67
Average	65				2.350	2.495	12.2	5.8	18.0	67.7	16.31	2.64
5.6	64	1248	742	1250	2.457						18.99	3.19
5.6	64	1249	748	1255	2.464						19.88	3.24
5.6	63	1250	745	1256	2.446						19.69	3.21
Average	64				2.454	2.565	13.5	4.3	17.8	75.7	19.52	3.21
5.8	66	1250	736	1255	2.408						15.82	3.56
5.8	65	1250	741	1268	2.372						15.32	3.59
5.8	64.5	1249	742	1269	2.370						14.95	3.65
Average	65.2				2.383	2.471	13.6	3.5	18.2	77.6	15.36	3.60

Marshall properties of 30% RAP

% binder	Spec. Ht (mm)	Weight in Air	Weight in Water	Sat. Surface Dry in Air	Bulk S G, Gmb	Max S G, Gmm	Vb	% Air Voids	% VMA	% VFA	Stability	Flow
5.0	64	1228	707	1233	2.335						20.51	2.22
5.0	63.5	1232	715	1241	2.342						18.98	2.28
5.0	63.5	1235	719	1245	2.348						19.25	2.25
Average					2.342	2.511	11.5	6.73	18.2	63.0	19.58	2.25
5.2	62.5	1238	719	1246	2.349						24.64	2.42
5.2	63	1242	721	1250	2.348						22.23	2.44
5.2	62.5	1234	715	1241	2.346						21.99	2.48
Average					2.348	2.481	12.0	5.36	17.3	69.1	22.95	2.45
5.4	64.5	1249	730	1250	2.402						27.23	2.55
5.4	65	1250	728	1258	2.358						25.65	2.48
5.4	63	1250	724	1252	2.367						26.15	2.65
Average					2.372	2.479	12.6	4.32	16.9	74.4	26.34	2.56
5.6	64.5	1248	724	1251	2.368						31.33	2.77
5.6	65	1250	731	1255	2.385						30.54	2.82
5.6	64	1249	725	1253	2.366						28.77	2.79
Average					2.374	2.446	13.0	2.94	16.0	81.6	30.21	2.79
5.8	63.5	1250	732	1265	2.345						20.23	2.92
5.8	65	1249	728	1252	2.384						23.44	3.12
5.8	64.5	1250	731	1255	2.385						22.18	3.23
Average					2.371	2.439	13.5	2.79	16.3	82.9	21.95	3.09

Marshall properties of 60% RAP mix

% binder	Spec. Ht (mm)	Weight in Air	Weight in Water	Sat. Surface Dry in Air	Bulk S G, Gmb	Max S G, Gmm	Vb	% Air Voids	% VMA	% VFA	Stability	Flow
5.0	63.5	1240	718	1257	2.301						22.35	1.96
5.0	64	1237	713	1259	2.266						24.33	1.65
5.0	64	1243	728	1254	2.363						22.29	1.78
Average					2.310	2.444	11.3	5.48	16.8	67.4	22.99	1.80
5.2	63.5	1245	726	1257	2.345						28.56	2.14
5.2	63.5	1242	725	1258	2.330						27.77	2.19
5.2	65	1246	730	1255	2.373						28.12	2.2
Average					2.349	2.438	12.0	3.65	15.6	76.6	28.15	2.18
5.4	64	1250	732	1257	2.381						29.14	2.31
5.4	64	1249	731	1258	2.370						30.82	2.29
5.4	65	1250	733	1255	2.395						31.98	2.24
Average					2.383	2.448	12.6	2.66	15.3	82.6	30.65	2.28
5.6	65	1247	741	1265	2.380						42.58	2.36
5.6	65	1249	746	1269	2.388						43.77	2.42
5.6	64.5	1250	734	1268	2.341						42.95	2.39
Average					2.384	2.436	13.1	2.13	15.2	86.0	43.10	2.39
5.8	64	1250	738	1255	2.418						38.63	2.41
5.8	64	1249	734	1265	2.352						37.88	2.52
5.8	65	1250	736	1268	2.350						38.55	2.49
Average					2.379	2.427	13.5	1.98	15.5	87.2	38.35	2.47

Marshall properties of mix with 30% RAP and 5% Castor oil

% binder	Spec. Ht (mm)	Weight in Air	Weight in Water	Sat. Surface Dry mass in Air	Gmb	Gmm	Vb	% Air Voids	% VMA	% VFA	Stability	Flow
5.0	63.5	1233	711	1249	2.292						16.59	2.61
5.0	63	1235	715	1245	2.330						15.31	2.70
5.0	63	1231	705	1238	2.310						15.67	2.44
Average					2.311	2.445	11.3	5.48	16.8	67.4	15.86	2.58
5.2	64	1246	724	1248	2.378						15.96	3.35
5.2	64	1244	720	1249	2.352						16.81	3.46
5.2	63.5	1240	719	1244	2.362						16.32	3.43
Average					2.364	2.478	12.1	4.60	16.7	72.4	16.36	3.41
5.4	65	1250	732	1254	2.395						18.96	3.78
5.4	65	1250	738	1260	2.395						19.15	3.73
5.4	63.5	1247	727	1250	2.384						17.42	3.92
Average					2.392	2.486	12.7	3.78	16.4	77.0	18.51	3.81
5.6	65	1250	734	1257	2.390						23.16	4.17
5.6	64.5	1245	741	1255	2.422						26.41	4.36
5.6	63.5	1247	746	1265	2.403						19.98	4.25
Average					2.405	2.465	13.2	2.43	15.6	84.4	23.18	4.27
5.8	65	1243	744	1271	2.359						16.88	4.36
5.8	65	1248	727	1260	2.341						17.91	4.25
5.8	64	1250	738	1261	2.390						18.66	4.39
Average					2.364	2.419	13.4	2.27	15.7	85.5	17.82	4.33

Marshall properties of mix with 60% RAP and 8% Castor oil

% binder	Spec. Ht (mm)	Weight in Air	Weight in Water	Sat. Surface Dry in Air	Gmb	Gmm	Vb	% Air Voids	% VMA	% VFA	Stability	Flow
5.0	63	1235	713	1240	2.343						13.88	3.27
5.0	63	1239	718	1242	2.365						14.99	2.97
5.0	64.5	1245	728	1249	2.390						14.74	3.31
Average					2.366	2.511	11.6	5.77	17.4	66.8	14.54	3.18
5.2	64	1244	725	1246	2.388						18.38	3.78
5.2	64	1249	728	1255	2.370						16.74	3.55
5.2	64	1250	731	1261	2.358						18.99	3.91
Average					2.372	2.478	12.1	4.28	16.4	73.9	18.04	3.75
5.4	65	1248	728	1251	2.386						25.49	3.46
5.4	64.5	1250	735	1258	2.390						29.22	3.74
5.4	6.45	1247	725	1255	2.353						25.28	4.22
Average					2.376	2.451	12.6	3.06	15.6	80.4	26.66	3.81
5.6	65	1249	732	1254	2.393						33.3	4.01
5.6	65.5	1250	736	1260	2.385						34.51	3.97
5.6	64	1248	726	1252	2.373						30.65	3.73
Average					2.383	2.432	13.1	2.01	15.1	86.7	32.82	3.90
5.8	64	1250	736	1258	2.395						24.56	4.07
5.8	64	1247	730	1257	2.366						27.62	4.14
5.8	65	1250	740	1266	2.376						21.8	4.22
Average					2.379	2.425	13.5	1.90	15.4	87.7	24.66	4.14

APPENDIX C

Indirect Tensile Strength Test

ITS test of Control mix - Dry condition

Sl No.	% Binder	Gmm	Gmb	% Air Voids	Height	Diameter	Load,kN	Tensile Strength,MPa
1	5.66	2.644	2.455	7.15	64	100	5.436	0.511
2	5.66	2.644	2.410	8.85	65	100	5.311	0.499
3	5.66	2.644	2.425	8.28	64.5	100	5.789	0.541

ITS test of Control mix – Wet condition

SL NO.	% Binder	Gmb	% Air Voids	Weight in air,g	Va	sample weight after saturation,g	weight of water,g	% saturation	Load,kN	Tensile Strength
1	5.66	2.450	7.34	1230	36.57	1256	26	71.09	4.144	0.462
2	5.66	2.422	8.40	1232	43.50	1266	34	78.16	4.011	0.433
3	5.66	2.410	8.85	1234	45.16	1267	33	73.08	3.777	0.411

ITS test of 30 RAP with 5% Castor oil - Dry condition

Sl No.	% Binder	Gmm	Gmb	% Air Voids	Height	Diameter	Load, kN	Tensile Strength, MPa
1	5.34	2.615	2.442	6.62	64	100	7.281	0.725
2	5.34	2.615	2.429	7.11	63	100	7.128	0.721
3	5.34	2.615	2.425	7.27	64.5	100	7.226	0.714

ITS test of 30 RAP with 5% Castor oil - Wet condition

SL NO.	% Binder	Gmm	Gmb	% Air Voids	Weight in air,g	Va	sample weight after saturation,g	weight of water, g	% saturation	Load,k N	Tensile Strength ,MPa
1	5.34	2.615	2.435	6.88	1231	34.31	1256	25	72.86	6.232	0.625
2	5.34	2.615	2.422	7.38	1235	38.24	1265	30	78.46	6.211	0.599
3	5.34	2.615	2.426	7.23	1240	36.31	1268	28	77.11	6.173	0.614

ITS test of 60% RAP with 8% Castor oil - Dry condition

Sl No.	% Binder	Gmm	Gmb	% Air Voids	Height	Diameter	Load	Tensile Strength
1	5.17	2.541	2.365	6.93	64	100	7.118	0.708
2	5.17	2.541	2.361	7.08	65.8	100	7.226	0.699
3	5.17	2.541	2.355	7.32	64.5	100	6.891	0.680

ITS test of 60% RAP with 8% Castor oil - Wet condition

Sl No.	% Binder	Gmm	Gmb	% Air Voids	Wt in air	Va	sample weight after saturation	weight of water	% saturation	Load	Tensile Strength
1	5.17	2.541	2.359	7.16	1235	35.42	1262	27	76.22	5.328	0.538
2	5.17	2.541	2.362	7.04	1236	35.67	1261	25	70.09	5.905	0.597
3	5.17	2.541	2.367	6.85	1234	34.67	1259	25	72.11	5.826	0.575