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A Final Study: The Role of Plastic-Modified Bitumen in Enhancing Durability and Sustainability in Road Construction

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Abstract: This study systematically evaluates the influence of integrating varying percentages of plastic waste into bitumen on the mechanical properties and performance characteristics of bituminous pavements. Experimental results indicate that the incorporation of plastic waste enhances the performance of bitumen up to an optimal threshold of 8% by weight; exceeding this concentration results in negligible improvements or deterioration in performance. Rigorous laboratory assessments, including Dynamic Shear Rheometer (DSR) analyses, demonstrate that plastic-modified bitumen exhibits a significantly elevated complex modulus (G*) and a reduced phase angle (δ) in comparison to unmodified bitumen, with the 8% modification yielding the most favourable outcomes. Enhanced Marshall Stability, improved flow values, reduced penetration, and increased softening points further signify superior resistance to load and thermal variations. The elevated viscosity of plastic-modified bitumen contributes to enhanced pavement strength and durability. Future investigations should encompass additional evaluations, such as ductility, elastic recovery, and flash/fire point tests utilizing the wet process, alongside an exploration of the dry process involving the coating of aggregates with shredded plastic. The findings substantiate that the incorporation of plastic waste into bitumen not only augments pavement performance but also presents a viable eco-friendly solution for plastic waste management, thereby fostering sustainable construction methodologies. The findings confirm that using plastic waste in bitumen improves pavement quality and offers an eco-friendly solution for plastic waste management, promoting sustainable construction practices.
Keywords: Plastic-Modified Bitumen; Recycled Plastics; Sustainable Road Construction; Mechanical Properties of Bitumen

I. INTRODUCTION

Bitumen, often known as asphalt, is a very thick, black, and sticky liquid or semi-solid form of petroleum. It can be found in refined products or in natural deposits. It fits the definition of a pitch. About 70% of bitumen is utilized in the construction of roads and highways as a binder and in combination with aggregate particles to make asphalt concrete. It can also be used for sealing roofs and producing bituminous waterproofing materials, such as roofing felt. Since bitumen is water-insoluble, it works well as a waterproofing sealant. It can be used to line watercourses because it has the ability to withstand most acids, alkalis, and salts and doesn't contaminate water. Similar to thermoplastic materials, bitumen softens and transforms into liquid with the application of heat and hardens as it cools. In India, flexible pavements are the norm. They are affordable in terms of both the original cost of building and ongoing upkeep. Commonly used bituminous binders in surface courses are modified binders made of polymers (PMBs) and unmodified binder bitumen, which varies based on the temperature. Bitumen treated with polymers has the potential to enhance its resistance to permanent deformation, temperature susceptibility, and fatigue life (Panda and Mazumdar, 2002; Jew and Woodhams, 1986).

Fernandez-Diaz et al. (2024) Innovative approaches have been explored for integrating recycled plastic waste into new construction techniques beyond conventional asphalt mixes. For example, explored the use of plastic waste in cementitious materials for road infrastructure, aiming to enhance durability and sustainability. Li et al. (2023), Studies have evaluated the performance of plastic-modified pavements under extreme weather conditions and heavy traffic loads. Investigated the fatigue and rutting resistance of asphalt mixes containing recycled plastics, demonstrating improved performance in high-temperature environments and under heavy vehicle loads. Ongoing field trials and long-term monitoring studies have provided valuable insights into the durability and performance of plastic-modified pavements in real-world conditions. These studies, such as those conducted in collaboration with transportation agencies and industry partners, contribute to validating the feasibility and benefits of using recycled plastics in road construction. Chen et al. (2023), Advances in recycling technologies have facilitated the processing of diverse types of plastic waste for road construction applications.

Explored the use of microwave-assisted pyrolysis and chemical recycling methods to convert waste plastics into high-quality additives for asphalt mixes, enhancing sustainability and resource efficiency. Pizzol et al., (2023), Multi-criteria decision analysis has been applied to assess the environmental, economic, and social impacts of using recycled plastics in road construction. Recent studies have employed MCDA frameworks to compare alternative materials and technologies, aiding decision-making processes for sustainable infrastructure development

European Asphalt Pavement Association, (2023), Efforts to promote the adoption of recycled plastics in road construction have expanded globally, supported by policy initiatives and regulatory frameworks. Countries such as India, the United States, and several European nations have implemented guidelines and incentives to encourage the use of recycled materials, fostering innovation and collaboration across the construction industry. These recent research studies and advancements underscore the ongoing evolution and diversification of approaches in utilizing recycled plastic waste for sustainable road construction. They reflect a comprehensive effort to enhance performance, durability, and environmental stewardship in infrastructure development, paving the way for a more circular and resilient construction sector. Singhal and Singh (2022), highlighted advancements in processing techniques for incorporating recycled plastics into asphalt binders. They discussed methods such as wet and dry processes for blending plastics with bitumen, aiming to optimize compatibility and performance. Recent field studies in different regions have provided practical insights into the application of plastic-modified asphalt mixes. For example, projects in Australia and the Netherlands have demonstrated successful implementation, showcasing benefits such as reduced road maintenance and enhanced pavement lifespan (Plastics for Change, 2023). Studies have continued to emphasize the environmental benefits of using recycled plastics in road construction. Recent assessments have highlighted reductions in carbon footprint and landfill waste, aligning with sustainable development goals (European Commission, 2023). Dutta et al., 2022, Recent LCAs have evaluated the overall environmental impacts of plastic-modified pavements throughout their life cycle. These assessments consider factors such as energy consumption, greenhouse gas emissions, and potential impacts on ecosystems, providing insights into the sustainability of these materials. Economic evaluations have explored the cost-effectiveness of using recycled plastics in road construction. Studies have shown potential savings in material costs over time, coupled with extended pavement life and reduced maintenance expenses, contributing to overall economic viability. Ellis et al., 2021, Efforts have been made to develop comprehensive guidelines and standards for using recycled plastics in road infrastructure. National bodies and international organizations have collaborated to establish protocols for quality control, material specifications, and performance testing. Banerjee and Saha, (2021), Studies have also evaluated the economic aspects of incorporating recycled plastics in road construction. Although initial costs may be slightly higher due to processing and material handling, long-term benefits such as reduced maintenance costs and extended pavement life are often cited as significant advantages. Recent efforts have focused on establishing standards and guidelines for using recycled plastics in road construction. Organizations such as ASTM International and BSI have been involved in developing specifications to ensure the quality and safety of plastic-modified asphalt mixes. Sharma et al. (2020), examined the use of various types of plastic waste, including polyethylene terephthalate (PET) and polypropylene (PP), in asphalt concrete mixes. They evaluated the mechanical properties and performance characteristics, noting improvements in stability, durability, and resistance to moisture damage. Sabatini et al. (2018) compared the life cycle impacts of conventional road construction materials with those incorporating recycled plastics. They concluded that using recycled plastic in road construction significantly reduced carbon emissions and energy consumption. Veeraragavan et al. (2016) investigated the mechanical properties of asphalt mixes modified with recycled plastic. They found that the addition of plastic waste improved the fatigue resistance and reduced rutting in roads. Vasudevan (2014), explored the use of shredded waste plastic in bituminous mixes for road construction. It highlighted improvements in the resistance to deformation and cracking, attributing these benefits to the enhanced binding properties of the plastic-modified bitumen. These recent reviews and studies underscore the growing interest and advancements in the field of utilizing recycled plastic waste in road construction. They highlight not only technical innovations and performance improvements but also the broader environmental and economic benefits associated with sustainable infrastructure solutions. Continued research and development are crucial for further optimizing these technologies and facilitating their widespread adoption in the construction industry. Vasudevan et. al. (2013), found that waste plastics collected from different sources could be used in modifying bitumen. Their softening point is above 100 degrees Celsius and they do not emit poisonous gas when mixing with bitumen. When plastic is spread over heated aggregate then it gets coated on the aggregate and this is found to be a better raw material for constructing pavement. They then mixed bitumen with this raw material in standard condition then was tested. This shows Marshall Stability higher than the actual aggregate mix bitumen. The sample shows high Marshall Stability value in the range of 18-20KN. Devi et. al. (2013), investigates the method of coating aggregate using plastic. They first collected plastic from different sources like dumping zone, household then shredded it into smaller particles. Bitumen of grade 60/70 was used during investigation and mixes were made.

Normal bitumen was coated with plastic and then by Marshall Method OBC was calculated for normal and plastic coated bitumen. Poweth et. al. (2013), discussed the suitability of plastic waste materials for pavement construction. The waste is mixed in different proportions to the soil sample and their influences on geotechnical properties were studied. The results of the tests indicated that plastic alone is not suitable for pavement subgrade. When quarry dust was added along with soil plastic mix, it maintains the CBR value within the required range. Punith and Veeraragavan (2011), studied the procedure for modification of 80/100-paving grade bitumen using recycled plastic derived from low-density polyethylene carry bags collected from domestic waste. Wet process was adopted to test different empirical test. They found that viscosity increases and penetration decreases with increasing amount of plastic. He observed that maximum bitumen content is 6% by weight of bitumen. Dynamic shear rheometer test results revealed that PE-modified binders (when subjected to the same stress) experienced lower strains than the neat asphalt; in addition, tan δ values of PE-modified binders considerably decreased as the PE content was increased. It was found that 6% PE content in modified asphalt by weight is adequate in terms of enhanced binder properties studied. Gawande (2012), explained the method of modifying bitumen with plastic. The modified bitumen was used in flexible pavement and he found that the plastic could be used up to 6-10 % by weight of bitumen. He also found that the Marshall Stability value was high enough from unmodified sample. Khan and Gundaliya (2012), confirmed that waste plastic when spread on hot aggregate then it gets coated around the aggregates to form a layer. Due to this coating the porosity, water absorption reduces and binding property get enhanced. The bitumen modified by 6 % plastic waste showed best result. The Marshall Stability was also increasing with plastic content and it has maximum value at 6%. At 6% Marshall Value was 35 % higher than unmodified mix. Kaur et. al. (2011), found that the waste plastics can be good modifier for the bitumen used for the road construction. Like the virgin polymers (PE, PP, and PS), waste plastic also shows adhesion property in its molten state, besides improving hardness (softening point of bitumen, viscosity, etc.) and strength and rut resistance of bituminous mixes. The Marshall Mix design is conducted on mixes with and without waste plastics. The Marshall stability of 8% plastics is 1.5 times higher than the mix without plastics in one of the case study. The indirect tensile strength of bituminous mixes with waste plastics is found to be 1.54 times higher than without waste plastics at 25°C. It is observed that the fatigue life is doubled under laboratory condition at 25°C by adding 8 % waste plastics by weight of bitumen and fatigue. Zhu Xiao-qing et. al. (2009), used the mechanochemically devulcanized ground tire rubber (m-GTR) prepared by solid-state mechanochemical reactor is used in the modification of bitumen with styrene-butadiene-styrene block (SBS) copolymer powder. The conventional property _such as penetration index, softening point, 5°C ductility, and aging test$$and rheological properties of bitumen modified by 8, 10, and 12 wt. %m-GTR/SBS were investigated in this paper. Rheological data demonstrated that all of the testing results of 10 wt. %m-GTR/SBS modified bitumen were better than those of SBS modified bitumen under the condition of high temperature. Verma (2008), studied plastic wastes could be used in road construction and the field tests withstood the stress and proved that plastic wastes used after proper processing as an additive would enhance the life of the roads and also solve environmental problems. Waste plastic is ground and made into powder; 3 to 4 % plastic is mixed with the bitumen. Plastic increases the melting point of the bitumen and makes the road retain its flexibility during winters resulting in its long life. Use of shredded plastic waste act as a strong “binding agent” and makes the asphalt last long. By mixing plastic with bitumen the ability of the bitumen to withstand high temperature increases. The plastic waste is melted and mixed with bitumen in a particular ratio. Normally, blending takes place when temperature reaches 45.5°C but when plastic is mixed, it remains stable even at 55°C. The vigorous tests at the laboratory level proved that the bituminous concrete mixes prepared using the treated bitumen binder fulfilled all the specified Marshall mix design criteria for surface course of road pavement. There was a substantial increase in Marshall Stability value of the BC mix, of the order of two to three times higher value in comparison with the untreated or ordinary bitumen. Another important observation was that the bituminous mixes prepared using the treated binder could withstand adverse soaking conditions under water for longer duration. Panda and Mazumdar (2002), found that Polymer-modified binders (PMBs) would improve several properties of paving mixes such as temperature susceptibility, fatigue life, and resistance to permanent deformation. In his investigation, reclaimed polyethylene obtained from LDPE carry bags was used to modify asphalt cement. The basic properties of modified binder and mixes containing such binders were studied and compared with those of bitumen. Three tests, namely the Marshall test, repeated load indirect tensile test, and moisture susceptibility test, were carried out to determine the optimum asphalt cement and polymer contents and to evaluate the modified binder in respect to the mix properties. They found that all the Marshall characteristics of mixes containing modified binder satisfy the criteria specified by the Indian Roads Congress (1988). Imtiyaz (2002), in his observation he found that modified bitumen has higher strength and deforms lesser at high temperature. He compared the different properties of plastic modified bitumen and normal bitumen up to 15% by wt. of the bitumen. It was observed that the plastic modified bitumen shows better results towards softening point, stability and rutting. Murphy et. al. (2001), examined the possibility to incorporate waste polymer into bitumen as a modifier.

II. MATERIALS AND METHODS

The plastic wastes that can be used for the work was collected from different places. Normal mix specimens were prepared with bitumen contents of 2.0%, 4.0%, 6.0%, 8.0%, and 10.0%. Tests were conducted on the modified bitumen to find out the changes in its properties like viscosity, penetration value, softening point, DSR test and Marshall Stability and Marshall Flow values. by empirical methods. The Optimum Bitumen Content (OBC) was found out using Marshall Test. Plastic modified mix specimens with plastic contents of 2 percent, 4 percent, 6 percent, 8 percent and 10 percent by weight of bitumen were prepared through Wet process by adding plastic to heated bitumen at a temperature of 180°C and a homogeneous mixture was formed by stirring it with a stirrer at high speed (3000 rpm) for 20-25 minutes.

The wet process involves blending shredded plastic material with bitumen before producing modified bituminous mixes. The chemical processes that produce binders include the swelling of plastic particles as they absorb some of the more volatile compounds from the bitumen, followed by the degradation of the plastic through de-vulcanization and polymerization. The preparation of the blend begins with obtaining plastic waste from various sources, which is then cleaned and dried. Unwanted materials such as vegetable matter, paper, and cloth are removed. The cleaned plastic is shredded by a machine into pieces measuring 3 mm in dimension, with a maximum length of 7 mm. These shredded plastics are mixed with hot bitumen at a temperature of 170-180°C. The mixture is initially stirred manually for about 4-5 minutes, and then stirred with a high-speed stirrer at approximately 3000 rpm for 20-25 minutes to achieve a homogeneous mixture, ensuring the temperature remains between 170-180°C. Once the mixing is complete, the blend is allowed to cool to room temperature, and blends of different compositions are prepared. The dry process involves mixing an appropriate quantity of dry shredded waste plastic with hot aggregate before producing bituminous mixes at a hot mix plant. The percentage of plastic varies by the weight of the mix. In this process, the dry aggregate is first heated to a temperature of 150-160°C. The required amount of plastic is then spread onto the aggregate, where the high temperature causes the plastic to melt and coat the aggregate. Bitumen is subsequently added to this modified aggregate. The coating of plastic on the aggregate helps cover voids, increasing resistance to acid and water infiltration, which ultimately results in better pavement performance.

III. RESULTS AND DISCUSSION

A. Bitumen

Physical properties of unmodified bitumen which was used are illustrated in the following table. (Source- Justo et. al., Highway materials and pavement testing.)

Property	**Range**
Penetration 0.1 mm @25°c	60-70
Softening point (°c)	49-60
Minimum Marshall strength (kg)	900
Viscosity @ 150°c (poise)	3-6

1) Recycled Plastic Waste

In this investigation, plastic waste in 2%, 4%, 6%, 8% and 10% (by weight of bitumen) was used as a modifier. The Waste Plastic and its Sources of plastic waste are presented in this table:

Type of Waste Plastic and its Sources (Source- IRC: SP: 53-2010)

Waste Plastic	Origin
Low Density Polyethylene (LDPE)	Carry bags, Sacks, milk pouches.
High Density Polyethylene (HDPE)	Carry bags, bottle caps, house hold articles etc.
Polyethylene Teryphthalate (PET) ^	Drinking water bottles etc. ^
Polypropylene (PP) ^	Bottle caps and closures, wrappers of detergent, biscuit, wafer packets etc.

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Polystyrene (PS) ^	Food trays, egg boxes, disposal cups, protective^packagine etc.
Polyvinyl Chloride (PVC) ^	Mineral water bottles, credit cards, toys, pipes, folders and pens, medical disposal etc.

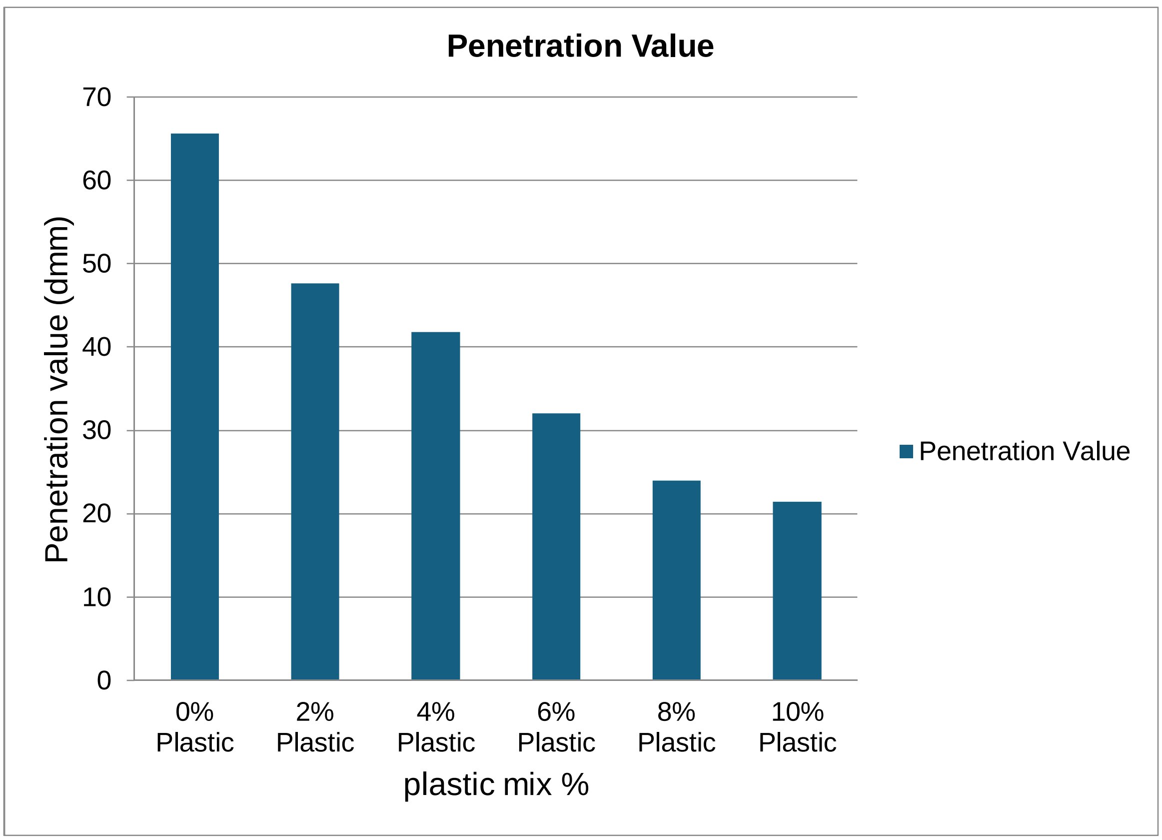
B. Physical Test on Plastic Waste Modified Bitumen

1) Penetration Test

In this test, various percentage of plastic (%) was added to the original bitumen. The test showed the variation of penetration value with the various percentage of plastic modified bitumen and it presented that consistency increases with addition of plastic. The penetration values for the modified bitumen decrease as the plastic content in the mix increase. The addition of plastic made the modified bitumen harder and more consistent. The variation of penetration value of plastic modified bitumen in shown in figure:

% of plastic mixed	Penetration Value (dmm)
0% Plastic	65.60
2% Plastic	47.60
4% Plastic	41.83
6% Plastic	32.00
8% Plastic	24.00
10% Plastic	21.40

Table-4.1, Shows variation of penetration with plastic mixed Bitumen



Graph-4.1, Shows graph of penetration value with plastic mixed Bitumen

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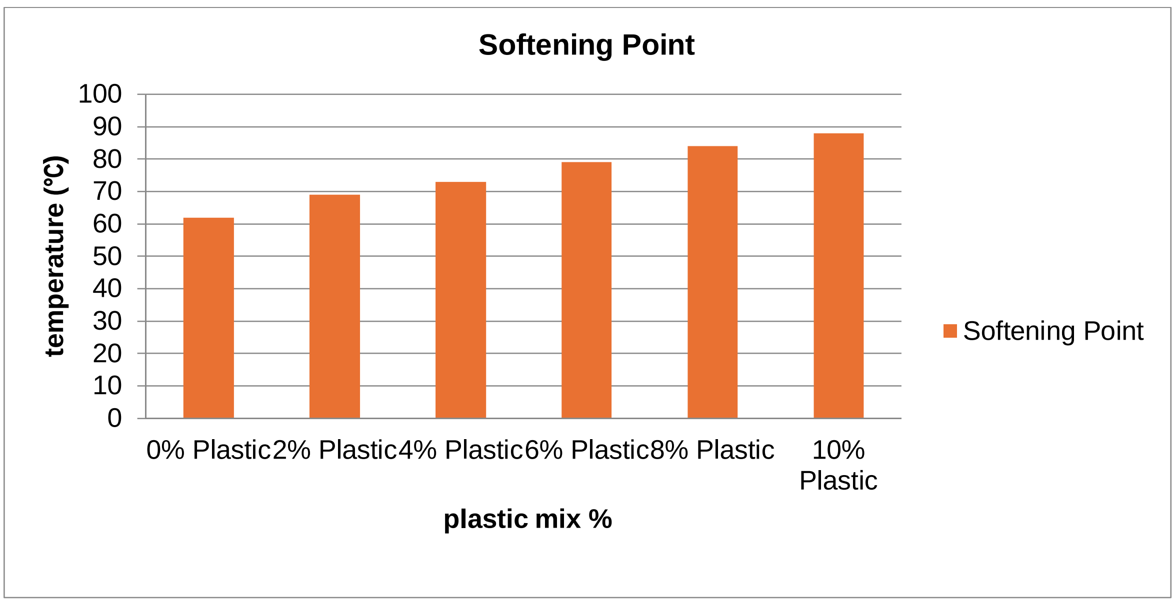
2) Softening Point

In this test, various percentage of plastic was added to the original bitumen. The test showed the variation of softening point with the various percentages of plastic modified bitumen. It was observed that softening point increases with the increasing amount of plastic content (%). This occurrence indicates that the resistance of the bitumen to the effect of heat is increased and it will decrease its tendency to soften in warm weather. Variation of softening point with increasing value of plastic content (%) is shown in figure:

% of plastic mixed	Softening Point (°C)
0% Plastic	62
2% Plastic	69
4% Plastic	73
6% Plastic	79
8% Plastic	84
10% Plastic	88

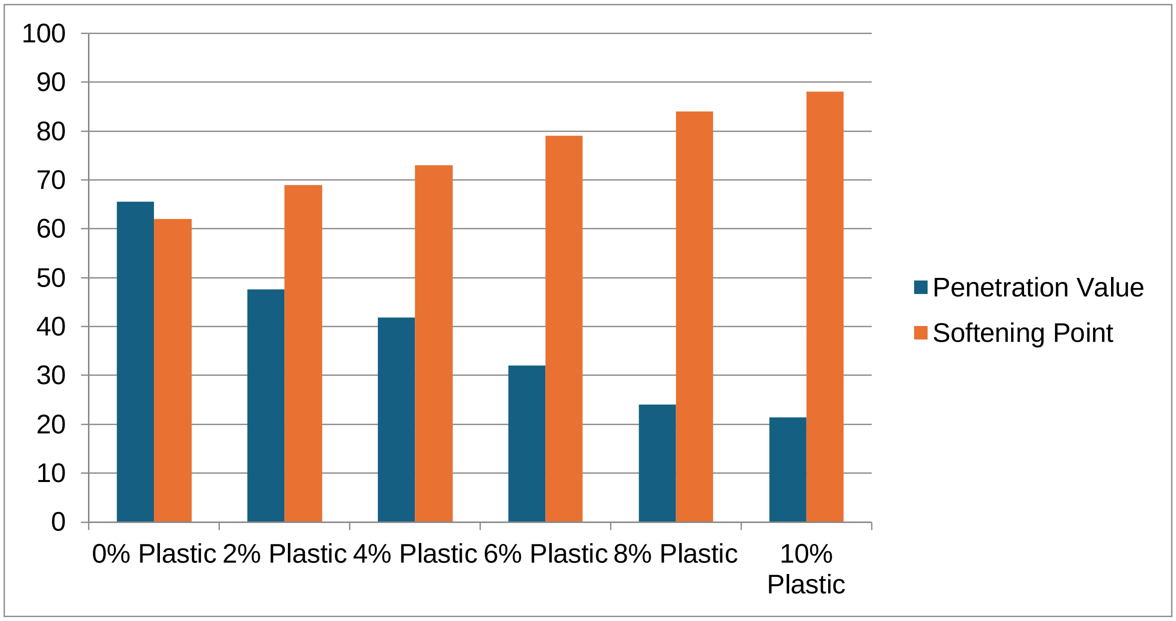
Table-4.2, Shows variation of softening point with different plastic content



Graph-4.2, Shows graph of softening point with different plastic content

Mix Bitumen	Penetration Value (dmm)	Softening Point(°C)
0% Plastic	65.60	62
2% Plastic	47.60	69
4% Plastic	41.83	73
6% Plastic	32.00	79
8% Plastic	24.00	84
10% Plastic	21.40	88

Table-4.3, Shows variation of Penetration value and Softening Point at different %age of plastic mix Bitumen



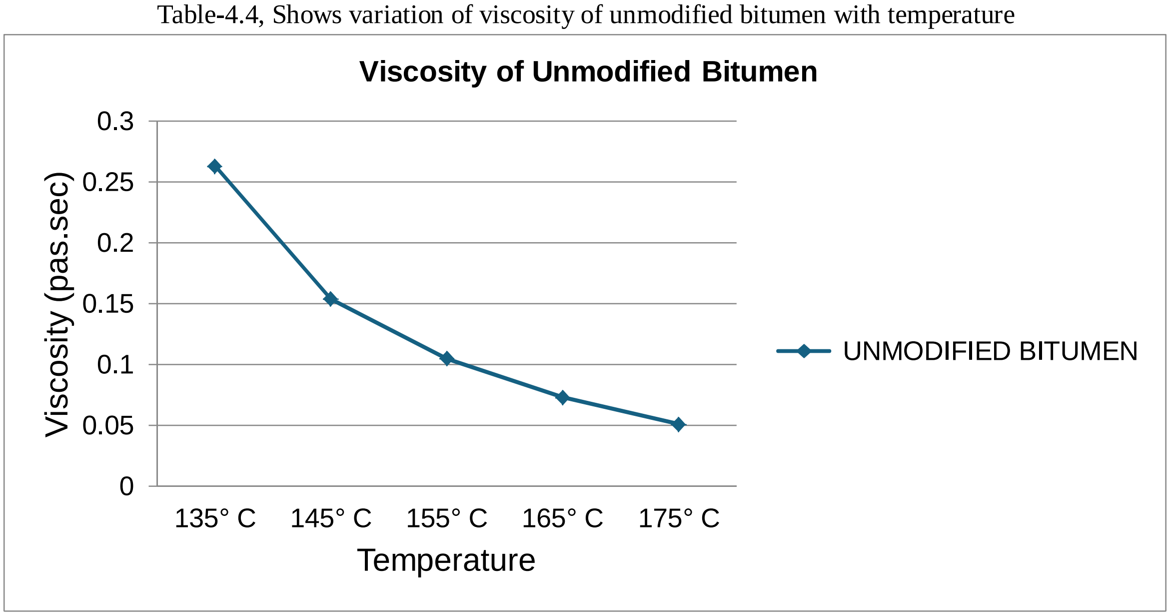
Graph-4.3, Shows graph of Penetration value (dmm) and Softening point (°C) of modified Bitumen

3) Viscosity Test

Viscometer test was conducted by using Visco-88 Viscometer. The apparatus was used to measure viscosity characteristics of conventional and plastic modified bitumen. The viscosity measurement was made at different temperature.

Temperature	Viscosity of unmodified bitumen (pas.sec)
135° C	0.263
145° C	0.154
155° C	0.105
165° C	0.073
175° C	0.051

Table-4.4, Shows variation of viscosity of unmodified bitumen with temperature



Graph-4.4, Shows graph of Viscosity of unmodified bitumen with temperature

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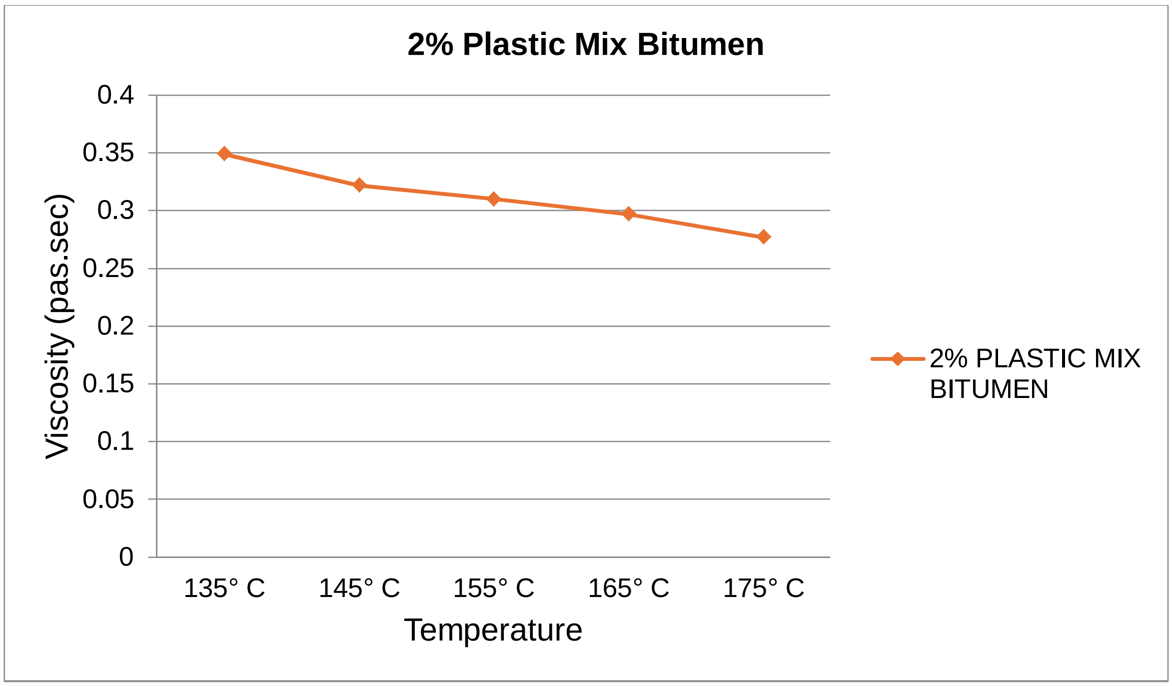
Temperature	Viscosity (pas.sec)
135° C	0.349
145° C	0.322
155° C	0.310
165° C	0.297
175° C	0.277

Table-4.5, Shows variation of Viscosity of 2% plastic mix bitumen with temperature



Graph-4.5, Shows graph of Viscosity of 2% plastic mix bitumen with temperature

Temperature	Viscosity (pas.sec)
135° C	0.324
145° C	0.262
155° C	0.255
165° C	0.268
175° C	0.256

Table-4.6, Shows variation of Viscosity of 4% plastic mix bitumen with temperature

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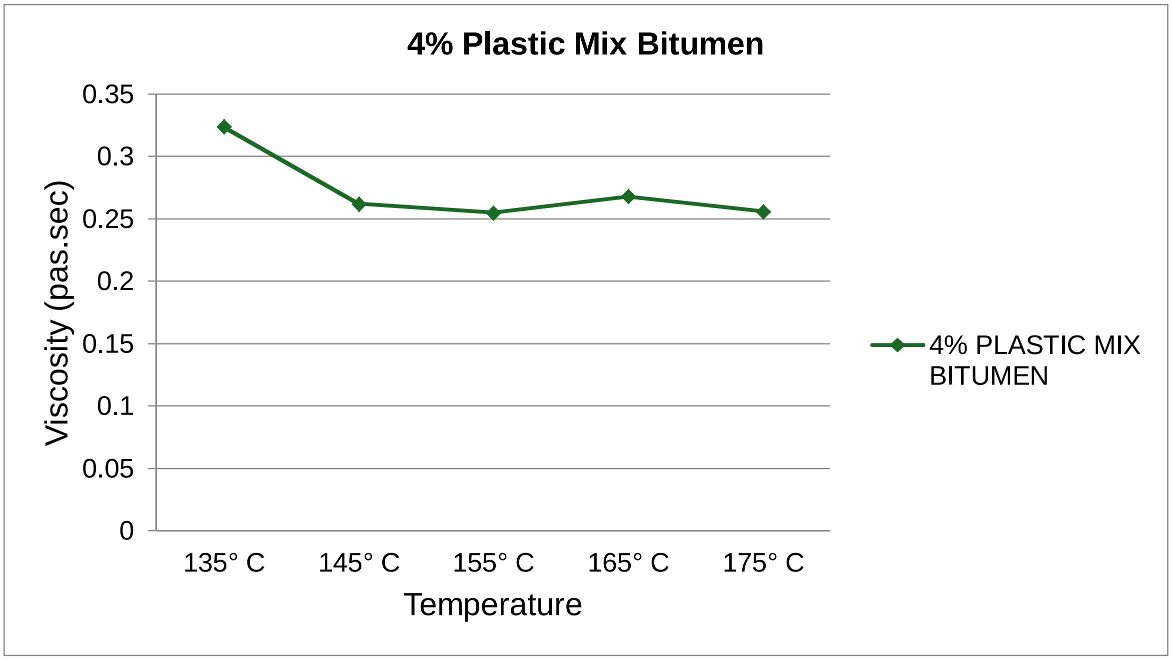

Graph-4.6^Shows graph of Viscosity of 4% plastic mix bitumen with temperature

Temperature	Viscosity (pas.sec)
135° C	0.751
145° C	0.548
155° C	0.321
165° C	0.431
175° C	0.337

Table-4.7, Shows variation of Viscosity of 6% plastic mix bitumen with^temperature

IV. CONCLUSION

Mixing various percentages of plastic in bitumen shows positive results in empirical tests conducted during this dissertation. The test data fluctuates with varying degrees of plastic mixed in bitumen, changing up to an optimum level, beyond which it either shows negative results or remains unchanged. In this study, the optimum plastic content was found to be 8% by weight of bitumen. The DSR test results indicate that the complex modulus (G*) of plastic-modified bitumen is significantly higher than that of unmodified bitumen, with a maximum value at 8% plastic content. The phase angle (δ) is relatively lower for plastic-modified bitumen compared to unmodified bitumen. The Marshall Stability and flow values are greatly enhanced, peaking at 8% plastic-modified bitumen. A decrease in penetration value and an increase in the softening point of modified bitumen indicate better performance under high load and temperature. The high value of complex shear modulus (G*/sinδ) suggests improved resistance to rutting and fatigue. Additionally, the increased viscosity of modified bitumen enhances the strength and durability of pavement layers, leading to greater pavement life and serviceability.

Future studies can perform additional tests such as ductility, elastic recovery, and flash and fire point tests using the wet process. The dry process, which involves applying shredded plastic material to the aggregate before adding bitumen, can also be examined. Laboratory tests like aggregate impact, soundness, crushing value, and specific gravity of aggregates can be conducted to fully understand the behavior of PE-modified binder. The optimum percentage of plastic material may vary upon studying both wet and dry processes. Current study results conclude that PE-modified bitumen offers better strength and resistance to rutting and temperature failure, making it suitable for bituminous pavement construction. This not only enhances pavement quality but also helps reduce plastic waste in the environment, promoting a healthier and less polluted earth.

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