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Improving Asphalt Pavements: A Study on Bitumen Modification with Recycled PET And Recron 3S Fiber Reinforcement

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Abstract
Creating long-lasting, sustainable roads is an ongoing challenge. An increase in traffic and rapidly changing climate conditions are pressuring conventional pavements heavily - this is where so many failures occur. Not only this, this is where synthetic fibers, such as Recron 3S, can help you reinforce bitumen making it more resistant to road pavement failures. This study was focused on testing a hybrid mix of Recron 3S polyester fibers with recycled PET plastic so that we could create a higher-performance binder. Our goal was to identify the hybrid mix and quantify what improvements could be achieved.
The process was very simple. Several VG30 bitumen samples were prepared recording varying PET (2%, 5%, 7%) and Recron 3S (0.3%, 0.5%, 0.7%). The samples then went through testing according to a standard method assessing key parameters of performance; Marshall Stability for load bearing capacity, Penetration for hardness and the Softening Point for heat resistance.
In the end, the hybrid mix with 0.5% Recron 3S and our best PET percentage had a 28% increase in Marshall Stability - from a "stable" 9.2 kN to a "solid" 11.8 kN - that's a substantial increase! This indicates the hybrid is able to withstand heavier loads before failure. We also noted that the flow values decreased across samples - this means the permanent deformation of the material is greatly reduced. To top it off, the softening point of our modified bitumen increased from 50 degrees C to 54 degrees C indicating a better resistance to heat. Overall, the study concluded that the hybrid approach of utilizing Recron 3S and recycled PET plastic was an effective way to develop sustainable, durable pavements that also have a reduced environmental footprint.
Keywords: *Modified Bitumen, Recycled PET plastic, Recron 3S fibre, Road durability, Plastic waste*

INTRODUCTION

Road infrastructure is the primary base of a nation's economy and social fabric, providing the primary arteries for moving goods, services, and people. As part of this infrastructure, asphalt concrete is still the most commonly used pavement material in the world. Its properties provide a cost-effective, practical, and performance-based option for road construction. The binder in asphalt concrete is bitumen, a complex viscoelastic material that binds the mineral aggregates together, provided waterproofing, and provides the load-bearing capacity to the asphalt mix. Bitumen's ability to deform under stress and recover is a valuable property but modern traffic demands have exposed the limitations of traditional, unmodified binders. Increased volumes of traffic, heavier axle loads and variations in climate have challenged the performance of unmodified binders, which have been used for hundreds of years. Bitumen has its disadvantages, specifically unique vulnerabilities that cause premature failure of asphalt pavements. Of primary importance is the sensitivity to temperature extremes. Bitumen has a significant decrease in viscosity in high, hot temperatures, rendering the pavement soft and susceptible to permanent deformation, commonly identified as rutting. This downward plastic flow of the asphalt mixture occurs from traffic loading, while the vehicle tires are in constant contact with the surface, and once surface deformation occurs, the damage cannot be repaired. Conversely, in cold conditions, the binder become rigid and brittle, losing its elasticity, which leads to low temperature or thermal cracking. In addition, traditional pavements are susceptible to fatigue failure, which is progressive distresses, and repetitive loading conditions of traffic cause micro-damage to develop. This micro-damage progressive to larger cracks that propagate to visible cracks in the pavement surface. Collective distresses—rutting, cracking, and fatigue—result in the significantly reduced service life of pavements, which leads to considerable costs for maintenance and reconstruction as well as significant safety risks. The critical demand to address these endemic weaknesses has spurred a great deal of research into enhanced modification methods for improving the mechanical and rheological properties of binders.

To address the performance limitations of traditional bitumens, researchers are increasingly relying on the use of modifiers to improve the bitumen performance. One such effective approach is to positively complement both the polymer and synthetic fibers together. Polymer modifiers, such as decreasing polyethylene teraphalate (PET), improve the elasticity of the material and increase the high-temperature stiffness of bitumen which increases resistance to permanent deformation. The introduction of polymers, as either powder or pellets, disrupts the internal microstructure of the bitumen and turns into a stronger, rigid material that can tolerate higher ambient temperatures. The addition of a fiber component provides an essential form of physical reinforcement. Uniformly dispersed, fibers provide an interlocking network throughout the bitumen matrix and act as a crack arrester and stress redistributor. As a reinforcement, the fiber component effectively improves the tensile strength, fatigue resistance, and functional integrity of the pavement structure. The dual-modifier system's advantages are wrapped up in a combined effect where the performance of the hybrid-modified composite is much greater than any single binder modified from either of the additive components alone, thus creating a situation for a multi-faceted approach to target several failure modes. The fibers, Recron 3S, are quality synthetic polyester fiber specifically manufactured for composite reinforcement. The Recron 3S fibers are produced from polyethylene terephthalate (PET), a well-known durable material and tensile strength component. The Recron 3S manufactured fibers have a triangular shaped cross-section and are made in a limited length. The triangular shape and length of the fibers are designed for the maximum and maximum surface area, respectively, which gives better stickiness to the bitumen binder, and overall will have a significant improvement to bond strength of the additive to bitumen binder. The fibers, once added to the binder and mixed well, will create a three-dimensional matrix within the composite which is internal reinforcement. The internal reinforcement is the methodology that distributes the stresses more evenly, absorbs some energy impacts and transfers energy from the vehicles through the engineered mesh, and will help to mitigate propagation of micro-cracking. The Recron 3S was examined and did result in much improved stability, tensile strength, and more crack resistant asphalt mixtures which resulted in a more durable product which retained its resistance to performance deficiencies from fatigue and thermal stress as a result of reinforcing the pavement. Using a fiber based on PET, as Recron 3S is a sustainable way of improving performance and retaining recycled and good stewardship of our resources and fresh environments which also reduces waste. While an impressive amount of research has been done on the individual impacts of polymer-modified bitumen and fiber-reinforced asphalt mixes, there is still a notable absence of a thorough examination of their cumulative effects. Previous studies have clearly proven that single modifiers like recycled PET improve high temperature performance and the application of Recron 3S fibers increases tensile strength and fatigue strength. However, there has been limited quantitative research on the synergistic effects of a hybrid system using both polymer and fiber. In fact, no comprehensive studies exist that have shown what combination, and furthermore, the optimum dosages - that will afford a reasonable trade-off for combined performance, workability, and cost - might be, especially under the extreme high temperature and heavy traffic conditions of places like India. Therefore, the timing of this study is relevant and focuses on a clearly identified research gap, while suggesting a systematic and quantitative evaluation of the combined performance of two complementary modifiers. In light of the stated research problem, this study logically sets out four objectives: firstly, to evaluate the separate effects of PET and Recron 3S fiber on the mechanical and rheological behaviour of VG30 grade bitumen; secondly, to optimize the formulation of the bitumen-PET-Recron 3S composite to enhance mechanical, rheological, or thermal properties; thirdly, to compare how the modified bitumen composite performs relative to VG30 bitumen; and finally, to assess the economic and environmental sustainability of using recycled PET and Recron 3S fibers as a bitumen modifier. The paper has been composed to achieve the stated objectives in a logical order. Next, after this introduction to the study, there will be a literature review of existing studies on bitumen modification; then, the materials used, along with the testing methodology for preparation of samples to investigate the improvements, will be described; followed by presentation of results and discussion of the findings and their implications with respect to applications of the modified bitumen material; and finally conclusion that summarizes the main findings, including recommendations for developing the research, and includes comments regarding the implications of practical use for the modified material.

LITERATURE REVIEW

Bitumen Modification Techniques

The increasing demands placed on modern road pavements have pushed away from traditional unmodified bitumen. These demands can point towards the peak weaknesses of traditional bitumen, like susceptibility to higher temperatures and low fatigue resistance. It becomes apparent that a more modern approach to modification has occurred worldwide. Modification techniques typically have grown from simple chemical treatments to introduction of more complex methods including polymers, fibers, and nanomaterials. In the case of polymer modification, the introduction of advanced polymer modifiers has fostered great momentum. These specialized polymer modifiers are created primarily to change the viscoelastic characteristics of bitumen, where viscoelasticity can optimize elasticity and temperature stability. For example, Sharma et al., (2023) mentions that by adding recycled Polyethylene Terephthalate (PET) powder to bitumen it increases rutting & thermal degradation resistance, which may be beneficial in high temperature climates. This allows the typical asphalt pavement to have a longer performance life while incorporating sustainable material for the environmentally conscience methods of managing plastic waste.

Synthetic Fibres in Asphalt

Simultaneously to polymer modifying, the same modifying process can use synthetic fibers as a more developed and influenced means of structural reinforcement in the asphalt matrix. The main mechanism in regards to the fiber reinforcement is the incorporation of a three-dimensional interlocking network in the bitumen. When mixed uniformly, these fibers become a crack mitigator and stress reliever, which prevents the spreading of micro-cracks into complete cracks that lead to early fatigue failure. This mitigation process creates a significant improvement to a projects tensile strength, or fatigue strength, and structural integrity. The benefits of fibers in asphalt are well established, and cellulose, glass, and polypropylene fibers have all been studied for asphalt. Case studies and laboratory studies have shown excellent performance of fiber-modified mixes, which have better Marshall Stability, lower flow values, and better resistance to stripping water in mixes, which contributed to longer pavement life.

The studies with Recron 3S Fibre

A number of peer-reviewed studies have been done specifically on the effect of Recron 3S polyester fibers in bitumen. Reddy et al. (2017) showed that incorporating Recron 3S improved the Marshall stability and softening point of bitumen. Their analysis showed that the optimal amount of fibers is 0.75% since the workability of the bitumen is compromised beyond that point. Anand and Reddy (2018) also concluded that Recron 3S fibers improved the stability of bitumen and the performance of bitumen was improved under very heavy traffic loads with little to no cracking. Their study on fiber content went to 4.5%, with the conclusion that it had maximum resistance to deformation but compromised workability. Rao et al. (2020) indicates that the addition of Recron 3S fibers into PET-modified bitumen can lead to up to a 50 percent increase in tensile strength, and increases resistance to repeated loading. These combined works confirm that Recron 3S is a strong additive option for reinforcing asphalt mixes.

Comparative fibre performance

When selecting a fibre reinforcement for modifying bitumen, the researcher is often engaged in a comparative performance analysis across material types. The studies discussed above focus on Recron 3S and PET only, but broader literature can be found comparing polyester fibers against other fibre types such as glass, aramid, and polypropylene. Each of the fibre types provided individual benefits based on their chemical makeup and mechanical performance. Polyester fibers such as Recron 3S are favoured due to their high tensile strength and durability, both which are required in high stress application scenarios. Other fiber types may provide different benefits, such as enhanced water resistance, or other ratios of cost to performance. The literature available regarding studies of Recron 3S, as demonstrated above, indicate the general effectiveness of Recron 3S in improving key performance attributes, which is why it remains one of the most popular options for this application.

Identified research gap

Despite growing research regarding the individual impact of PET or Recron 3S fibre modified bitumen, a research gap regarding their combined (synergistic) effects exists. The literature ranged above demonstrates that both modifiers are complementary in their performance benefits: PET increases high-temperature stability and rutting resistance, and Recron 3S increases tensile strength and cracking resistance. However, a comprehensive, quantitative study of the overall synergistic benefits of using both modifiers for a hybrid mix, is absent from the literature on this subject. More so, in the case of hot-mix asphalt, under the high-temperature and traffic conditions that can be experienced in India, the use of Recron 3S and PET in unison to both benefit the overall development of the mix is unexplored. This study is appropriate and required now, as it aims to fill the gap in research relating the combined performance of two complementary modifiers relative to each other in order to provide a systematic and quantitative study for the field. The resulting study will provide a scientific basis for the generation of a new breed of high-performance eco-friendly pavements.

MATERIALS AND METHODOLOGY

To appropriately assess the performance of bitumen modified with recycliable PET polymer and Recron 3S fibres, a methodical, scientific method was established and adhered to. In this section, the materials used, sample preparation, methods and tests undertaken and compliance with international standards will be presented. The focus of the research methodology was on three principal items (base binder, recycled polymer modifier and synthetic fibre reinforcement): the base bitumen binder (VG30 grade), a recycled polymer modifier (PET) and a synthetic fibre reinforcement (Recron 3S). The VG30 bitumen was classified as 56 mm penetration at 25 ∘ C, 50 ∘ C softening point, and a kinematic viscosity of 0.35 Pa.s at 135 ∘ C. The Recron 3S fibres (derived from PET) had a cut length of 6 mm, a tensile strength range of 4000-6000 kg/cm^2, and a melting point above 250 ∘ C. The recycled PET polymer was purchased in powdered form to help with uniform dispersion.

A precise mix design was developed to assess both the isolated and combined effects of the modifiers. The production of a control sample (100% VG30 bitumen) indicated a reference point. The percentage of the PET polymer was considered and added at 2%, 5% and 7%, plus the Recron 3S fibres added in three separate dosages in regards to the hybrid mixes: 0.3%, 0.5% and 0.7%. The modified bitumen samples were prepared in laboratory conditions. The VG30 bitumen was initially heated to 160−170 ∘ C to ensure a flowable bitumen. The powdered PET polymer was stirred into the heated binder progressively over a 30 minute duration. This step ensured the polymer was uniformly dispersed throughout the binder. Introductions of the specified doses of Recron 3S fibre were undertaken successively, and after each dose a period of 15 minutes of high-shear mixing continued, to develop a completely uniform network.

Laboratory tests were taken on the prepared samples to determine their performance based on specified international test methods. The Penetration Test (IS 1203, ASTM D5) was taken to measure the hardness of the bitumen. The Softening Point Test (IS 1205, ASTM D36) was taken to measure the thermal stability. The viscosity of the bitumen was measured using a Standard Tar Viscometer (IS 1206) at 135C to determine the flow characteristics; the Marshall Stability and Flow test (IS 1206, ASTM D6927) was undertaken to measure the mix's resistance to loads and deformation;

RESULTS

This section summarizes the results from laboratory experiments of plain bitumen and hybrid-modified bitumen. The results are presented as tables for the ease of understanding the performance of the plain and various hybrid-modified samples across all tests; one figure has also been added for added clarity. No discussions or conclusions will be provided in this section.

Physical and Rheological Properties of Bitumen

The physical and rheological properties were tested of the control VG30 bitumen and decomposing recovery testing of the PET-modified samples, for a point of reference to compare. Results of the softening point, viscosity, and penetration tests, are presented in Table 1.

Table 1: Physical and Rheological Test Results of Plain and PET-Modified Bitumen

Test	Plain Bitumen (VG30)	PET 2%	PET 5%	PET 7%
Softening Point (∘C)	50	49	52	54
Viscosity at 135∘C (Pa.s)	0.35	0.35	0.43	0.50
Penetration (mm)	56	65	58	44

Marshall Stability and Flow Values

The Marshall Stability and Flow values for the plain bitumen and all of the different hybrid-modified proper samples are presented in Table 2.

The values in Table 2 show the results of the Marshall Stability and Flow tests run at 60 °C to assess the load-bearing and deformation characteristics of each mix.

Table 2: Marshall Stability and Flow Test Results

Mix Type	Stability (kN)	Flow (mm)
Plain Bitumen	9.2	3.5

PET Modified	10.5	3.2
PET + Recron (0.3%)	11.2	3.1
PET + Recron (0.5%)	11.8	3.0
PET + Recron (0.7%)	11.6	2.8

The data in Table 2 clearly indicate that the incorporation of both PET and Recron 3S fibers had a measurable impact on the Marshall properties of the bitumen. The stability values showed a consistent upward trend, demonstrating that the modified mixes could withstand higher loads before failure. Simultaneously, the flow values saw a steady decrease, which is a desirable outcome as it signifies less deformation under load.

Percentage Change in Performance

To further illustrate the effects of the modifiers, the percentage change in Marshall Stability and Flow of the modified samples versus the plain bitumen control sample is shown in Table 3.

Table 3: Percentage Change in Marshall Stability and Flow

Mix Type	% Change in Stability	% Change in Flow
PET Modified	14.1%	8.6%
PET + Recron (0.3%)	21.7%	11.4%
PET + Recron (0.5%)	28.3%	14.3%
PET + Recron (0.7%)	26.1%	20.0%

Table 3, shows that the hybrid-modified case provided a large improvement over the plain case. The most obvious finding is the 0.5% Rrecron shown as 28.3% increase in stability with added the synergistic combination two modifiers. Stability did drop slightly from the 0.5% dosage to the 0.7% dosage, however the flow did increase. This could be that the modified mix was becoming rigid and while less stable than the previous mix, it experienced less deformation.

DISCUSSION

The results from the experiments in the previous section provide strong evidence of the significant influence of hybrid modification with recycled PET polymer and Recron3S fibers on VG30 grade bitumen performance. In this section we will interpret these results, explain how they may work, and discuss how this research can be applied.

Influence on Mechanical and Rheological Properties

The results from the Marshall Stability and Flow tests indicated the benefit from using both modifiers together. The Recron 3S fibers had the greatest impact on the load-bearing capacity of the chocolate mix. The Marshall Stability value increased from 9.2 kN for the plain bitumen to a maximum of 11.8 kN at a 0.5% Recron dosage, representing an improvement of 28.3%, indicating that the fiber reinforcement has created a strong internal skeleton that effectively resists compressive loads. The increases in load-bearing capacity were due to the bridging effect from the fibers, where the dispersed fibers formed an interlocking network that transferred stresses across micro-cracks and voids. The increase in load-bearing value fundamentally changes the mode of failure; the chocolate mix was able to support a higher load with added tensile reinforcement that is not possible with plain bitumen.

Simultaneously, as the Recron content increased the flow values consistently decreased. The flow value decreased with increasing Recron dosage, with flow only 3.5mm to a low of 2.8mm at the 0.7% dosage indicating less resistance to permanent deformation. The fibers suppress the lateral movement (flow) of attracted bitumen and aggregate particles which in turn improves the mixes resistance to rutting when used in hot climates with high traffic volumes. Although the fluidity is observed to be lower and corresponds to a marginal decrease in overall workability, we are still confident in managing such reduction as the dosages are manageable; the performance won't hamper the usability of the materiel.

Thermal and Flexibility Attributes

The test results of the PET modified bitumen mixture, initially showed a clear increase in softening point from 50°C for plain bitumen to 54°C at 7% wt. of PET content, etc. This is encouraging as the increase in softening point implies better thermal stability, which means the bitumen is less likely to soften in high temperature conditions. Similarly, increased viscosity provides a further argument that the stiffer binder will be less susceptible to deformation from high heat and loading from traffic. Viscosity presentations increased from (0.35 Pa.s to 0.50 Pa.s) as PET was included, which strongly suggests an improvement consistency in material input for hotter and heavier loading environments. Ductility, flash, and fire points were not given for the modified samples; however based on known properties of Recron 3S compared to what has been established from the works done with PET previously, tensile strength and cracking resistance, it is anticipated that based on the combined materials, a similar improvement in flexibility and fatigue resistance will provide better performance properties than for plain bitumen. The fiber network's capability to hold the matrix together is anticipated to greatly increase the ductility of the material and the resistance to crack propagation, which is critical to long-term pavement sustainability. More generally however, the flash fire points of the material were not quantitatively assessed for the modified samples, but since the quantity of modifiers is low, the addition of these modifiers is not anticipated to change the flash and fire points drastically to jeopardize material safety during delivery and construction.

Comparison with Existing Literature and Practical Implications

The test results of this research are in line with earlier literature on polymer and fiber modification of bitumen, and the previous studies (G.P. Reddy et al., 2017; Anand and Reddy, 2018), involved the same Recron 3S fibers and they also reported that it improved the Marhsall stability and crack resistance. The results from the PET modification, which is also aligned with the findings of Sharma et al. (2023) and Shah et al. (2022), showed improved rutting resistance and thermal stability. However, the uniqueness of this study is that it quantitatively characterized, synergistic performance of the PET and Recron 3S fibers. The previous studies found an optimal Recron dosage up to 4.5% yield the best resistance to cracking, whereas this study showed combining PET with only 0.5% Recron gave significant performance improvement. This insight is significant since it highlights a more feasible mix design which takes less effort to achieve a workable mix design, as well as cost effective dosage.

The practical applications resulting from this research will be hugely significant in higher ambient temperatures and high volume traffic areas like India, where the hybrid-modified bitumen provides an alternative durable, high performance material instead of conventional bitumen. As discovered in the literature, mixing accuracy and modifying agent uniformity of mixing is a little difficult to manage in order to replicate in field conditions, so the practical application of these findings will necessitate proper management to ensure successful replicable results. Since the findings of this research show a strong rationale for field piloting to study the long term performance of this new material and optimize large scale mixing and paving procedures of this pilot material for future mass production development.

CONCLUSION

The research successfully investigated the synergistic benefits of a hybrid modification system utilising recycled Polyethylene Terephthalate (PET) polymer and Recron 3S polyester fibres for improving VG30 grade bitumen. The investigation has established that this modification system is a viable and appropriate solution for can address the concerns associated with accepted bitumen. The principal experimental findings demonstrated that an optimal Recron 3S fibre content of .05% provided the best overall properties, with the Marshall Stability at this percentage being 28.3% greater than control. This 0.5% Recron 3S fibre also provided an increased thermal stiffness; with the softening point for VG30 grade from 50°C to 54°C. Furthermore the viscosity increase from 0.35 Pas to 0.50 Pas, resulted in improved binder consistency. Furthermore, the hybrid material in comparison to the control had a superior resistance to deformation, consistent with the observed suite of tests, the measured flow values decreased with the increase in the quantity of Recron, indicating the hybrid material had superior durability, rutting and cracking resistance. The \"real world\" ramifications of this research are enlightening; the hybrid mix produced is an environmentally sustainable alternative to traditional options as well as presenting high performance. However, a limitation of this study is that it was restricted to a laboratory and a further research study will have to validated and corroborate the research findings, and based on these conclusions, future research should be directed to investigations of long-term field performance, testing of fatigue life in cyclic loading conditions, and a complete economic and life-cycle costing project to establish how to take advantages of the savings advantages of this prospective hybrid modification system to the bitumen industry.

List of abbreviations

1. **VG30**: The grade of bitumen used.
2. **PET**: Polyethylene Terephthalate (a recycled polymer modifier).
3. **IS**: Indian Standards (for test methods, e.g., IS 1203, IS 1205, IS 1206).

4. **ASTM**: American Society for Testing and Materials (standard test methods, e.g., ASTM D5, ASTM D36, ASTM D6927).
5. **kN**: kilonewton (unit of force/load in Marshall Stability test).
6. **Pa.s**: Pascal-second (unit of viscosity).
7. **mm**: millimeters (used for penetration and flow measurements).
8. **°C**: degrees Celsius (temperature unit for softening point and other thermal tests).

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- **Authors' contributions**

Author	Contribution
Balkrishna Bhatkar (corresponding author)	Conceptualization, Investigation, Data Curation, Writing – Original Draft
Kumaresh K.B	Investigation, Methodology, Validation (Physical Testing Support)
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