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Analysis on Engineering Behavior of Dense Bituminous Mixes Using Coal Ash with Natural Fiber Reinforcement

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Abstract - Bituminous mixtures generally consist of coarse aggregates, fine aggregates, filler, and a binder. Hot Mix Asphalt (HMA) refers to bituminous mixtures in which all components are heated, mixed, placed, and compacted at elevated temperatures. HMA can be categorized into dense-graded mixes (Bituminous Concrete, BC) and gap-graded mixes such as Stone Matrix Asphalt (SMA). SMA typically requires stabilizing additives—cellulose fibres, mineral fibres, or polymers—to prevent drain-down. In the present study, slow-setting emulsion (SS1)–coated sisal fibre was incorporated at varying dosages of 0, 0.25, 0.5, 0.75, and 1% by weight of the mix, with fibre lengths of 0, 5, 10, 15, and 20 mm. The optimum composition—comprising the optimum bitumen content, fibre content, and fibre length—was identified based on the test results. Marshall characteristics were evaluated to determine the optimum binder and fibre parameters. A maximum Marshall stability of 15 kN was achieved at an optimum bitumen content of 5.57%, an optimum sisal fibre content of 0.5%, and a fibre length of 10 mm. To further assess pavement performance, additional tests such as moisture susceptibility, indirect tensile strength (ITS), creep behaviour, and tensile strength ratio (TSR) were conducted. Considering the environmental concerns associated with coal ash disposal, its use as a partial replacement for natural sand and stone dust offers a sustainable and economical alternative. Performance evaluation through ITS, moisture susceptibility, TSR, and retained stability confirmed the suitability of the modified bituminous mixes..

Keywords: Bituminous mixture, Bottom ash, Fly ash, Tensile strength ratio

1.INTRODUCTION

Aggregates in coarse, fine, and filler fractions form the primary components of bituminous paving mixes. However, the unavailability of suitable aggregates near construction sites often demands long-distance procurement, increasing construction costs. Meanwhile, coal-based thermal power plants, which contribute nearly 70% of India's electricity, generate about 112 million tons of coal ash annually, creating severe challenges related to land use, health risks, and environmental pollution. This study explores the productive utilization of coal ash by partially replacing fine aggregates with bottom ash and mineral filler with fly ash. To further improve mix performance, sisal fibre—naturally available, economical, and locally sourced—was incorporated as a stabilizing additive. Previous studies highlight improvements in resilient modulus, stripping resistance, and mix stability using coal ash and fibres, yet no research combines bottom ash, fly ash, and natural fibres in a single bituminous mix. In this study, dense-graded mixes were designed using the Marshall method and evaluated through indirect tensile strength and moisture susceptibility tests.

1.2 RESEARCH SIGNIFICANCE

Bituminous paving has evolved from simple dust-control techniques to scientifically designed mixtures capable of withstanding modern traffic and climatic demands. With increasing traffic loads, conventional bituminous mixes face challenges such as rutting, moisture damage, and premature cracking. The integration of waste materials and performance-enhancing additives offers a sustainable pathway to improve pavement durability. This research is significant as it explores the use of coal-based bottom ash and fly ash—major industrial by-products—as partial replacements for fine aggregates and filler, addressing both material scarcity and environmental concerns. Additionally, incorporating natural sisal fibre and polymers enhances rutting resistance, strength, and long-term performance. By optimizing mix composition through established design methods, the study contributes to developing cost-effective, sustainable, and high-performance bituminous mixtures suitable for modern road infrastructure.

1.3 Objectives of the Present Study

The present study aims to develop a sustainable dense graded bituminous macadam (DBM) mix by incorporating coal ash and sisal fibre to improve performance and address material scarcity. The primary objective is to evaluate the suitability of coal ash—used as a partial replacement for fine aggregates and filler—as an alternative material in bituminous mixes. Additionally, the study examines the effectiveness of natural sisal fibre as a stabilizing additive to enhance strength, durability, and resistance to cracking and moisture damage. The mix design is carried out using the Marshall method to determine the optimum binder content, fibre content, and fibre length. Further objectives include assessing the Marshall characteristics of mixes with and without coal ash and fibre, and evaluating performance through moisture susceptibility tests, tensile strength ratio, retained stability, indirect tensile strength, and static creep tests. Overall, the study seeks to develop an economical, durable, and environmentally sustainable bituminous paving mix.

2. LITERATURE REVIEW

Ankita Sonkar, S. Srividhya, et al.,(2017) This study investigates the influence of randomly distributed palm fibers on the strength and swelling behaviour of expansive soil, along with the stabilizing effects of bagasse ash. Expansive soils are known for their high plasticity and significant volume changes, making them unsuitable for construction without proper stabilization. In this research, palm fibers were introduced into the soil at four different proportions—0.25%, 0.5%, 1%, and 1.25%—to evaluate their ability to enhance soil strength and modify its index and compaction properties.

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Mohammad Altaf Bhat et al. (2013) investigated the influence of fillers on the performance of bituminous mixes, emphasizing the need for effective mix design to ensure adequate stability and durability. Bituminous mixtures consist of dense-graded coarse aggregates, fine aggregates, fillers, and bitumen binder. Fillers play a crucial role in occupying voids and modifying both physical and chemical properties of the mix. When combined with bitumen, fillers form a mastic that binds aggregates together, significantly affecting mix behavior. Since materials passing through the 0.075 mm sieve are most effective as fillers, their proportion becomes critical. The study reported that increasing filler content leads to a direct increase in Marshall stability, with the Asphalt Institute recommending 4–8% filler in asphalt concrete. Concrete dust and brick dust—abundant and economical in India—were used as fillers, and their effectiveness was evaluated using the Marshall method. Results showed improved physical properties, including enhanced stability and flow values of the bituminous mixes.

3.MATERIAL AND METHODOLOGY

3.1 CHARACTERISTICS OF MATERIAL USED IN BITUMINOUS MIX:

A wide variety of mineral aggregates can be used in bituminous mixes, sourced either from natural deposits such as glacial formations and quarries or from processed materials that improve their performance characteristics. Natural aggregates may be used directly or undergo further processing to achieve the required properties. Industrial by-products like steel slag and blast furnace slag are also incorporated in mixes to enhance mechanical performance. Reclaimed bituminous pavement serves as another valuable aggregate source, contributing to sustainable construction practices. Aggregates play a crucial role in providing strength to asphalt mixtures, as they form the major portion of the mix and contribute significantly to structural stability. In Stone Matrix Asphalt (SMA), coarse aggregates constitute about 70–80% of the total stone content, forming a skeleton-like framework. This stone-on-stone contact improves interlock, resulting in superior shear strength and higher rutting resistance compared to Bituminous Concrete (BC).

3.2 MATERIALS &MIXTURE CONSTITUENT:

3.2.1 Aggregates:

Aggregates are fundamental components of bituminous mixes, contributing the maximum load-bearing capacity and overall strength of the mixture. Their physical properties and quality significantly influence pavement performance. Bituminous mixes generally use three categories of mineral aggregates: coarse aggregates, fine aggregates, and mineral fillers.

3.2.2 Bitumen:

Bitumen acts as a viscoelastic and adhesive binder, filling voids and providing impermeability. It behaves elastically at low temperatures and becomes viscous at higher temperatures, enabling effective aggregate coating.

Bitumen Emulsion: Bitumen emulsion is a two-phase system in which fine bitumen droplets are dispersed in water with stabilizing agents. Upon application, the emulsion breaks and binds aggregates. It is commonly used for patching and maintenance and is available in rapid, medium, and slow setting grades.

4. ANALYSIS OF RESULTS AND DISCUSSION

4.1 Marshall stability

Atterberg limits define the fundamental relationship between moisture content and the behaviour of fine-grained soils. These limits include the shrinkage limit, plastic limit, and liquid limit, which indicate how soil transitions through different states—solid, semi-solid, plastic, and liquid—as water content increases. Introduced by Albert Atterberg and later refined by Arthur Casagrande, these limits are essential for identifying and classifying silts and clays.

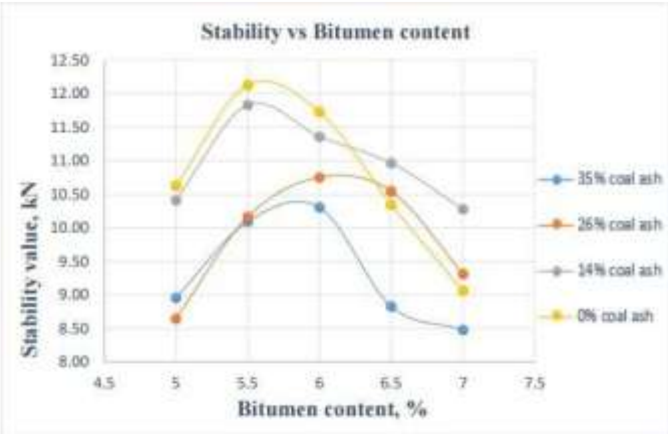

Fig 4.1 Effect of Bitumen Content on Marshall Stability for Various Coal Ash Percentages

The graph shows the variation of Marshall stability with bitumen content for mixes containing 0%, 14%, 26%, and 35% coal ash. Across all mixes, stability initially increases with rising bitumen content, reaches an optimum value, and then decreases due to excess binder causing loss of internal friction. The highest stability is achieved in the 0% coal ash mix, peaking at approximately 12.1 kN at around 5.7% bitumen content, indicating superior aggregate interlock and binder–aggregate adhesion. The mix with 14% coal ash shows the next highest performance, reaching about 11.7 kN, suggesting that moderate replacement can still maintain adequate strength. Mixes with 26% and 35% coal ash exhibit lower peak stability values (~10.7 kN and ~10.2 kN, respectively), indicating that higher ash content weakens the structural skeleton of the mix. Overall, stability decreases significantly beyond 6% bitumen, confirming that excess binder leads to reduced load-bearing capacity.

4.2 Indirect tensile strength test:

The Indirect Tensile Strength (ITS) test is used to evaluate the resistance of bituminous mixes to cracking and their susceptibility to moisture-induced damage. According to ASTM D4867, the Tensile Strength Ratio (TSR) is defined as the ratio of the average ITS of conditioned specimens to that of unconditioned specimens. Test samples were prepared with approximately 7% air voids as per standard requirements. Conditioned specimens were immersed in a 60°C water bath for 24 hours and then kept at 25°C for 1 hour, whereas unconditioned specimens were placed in a 25°C water bath for 30 minutes. The load at failure was recorded, and ITS was computed using Equation 1. TSR was then calculated using Equation 2 to assess moisture sensitivity. Results indicate that air voids increase with higher coal ash content; however, at 14% coal ash, air voids remained comparable to those of the conventional mix. Additionally, the unit weight of DBM samples decreased with increasing coal ash due to its lower density, influencing overall mix performance.

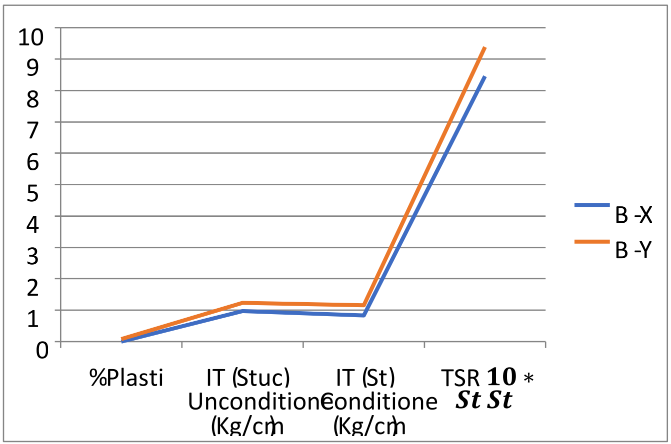

Fig 4.2 Indirect tensile strength (ITS) and TSR variations

The graph illustrates the variation in % plastic, indirect tensile strength (ITS) of unconditioned and conditioned specimens, and the resulting tensile strength ratio (TSR) for mixes BC-X and BC-Y. Both mixes show similar trends, with BC-Y consistently exhibiting slightly higher values, indicating improved moisture resistance. The unconditioned ITS values for both mixes increase initially, reflecting good tensile strength under normal conditions. However, after conditioning, ITS values decrease slightly due to moisture exposure, demonstrating the weakening effect of water on binder–aggregate adhesion. Despite this reduction, BC-Y maintains a marginally higher conditioned ITS, suggesting better stability in wet conditions. The TSR values show a steep rise, with BC-Y achieving the highest TSR, indicating superior resistance to moisture damage. Overall, the results reveal that BC-Y performs better than BC-X in terms of tensile strength and moisture susceptibility, making it more durable for field applications.

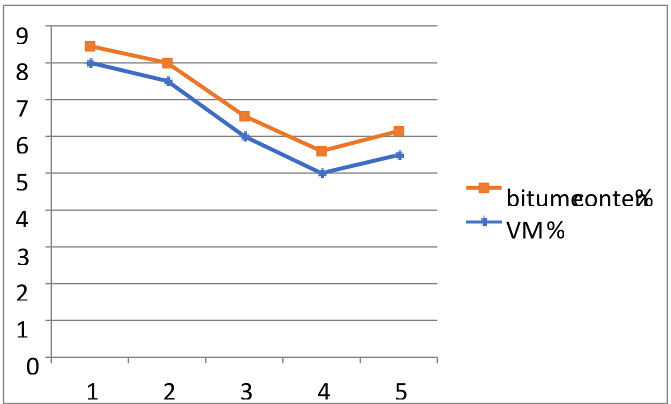

Fig 4.3 Variation of VFB value with bitumen content at different coal ash content

The graph shows the relationship between bitumen content (%) and Voids in Mineral Aggregate (VMA %) for five mix conditions. Both parameters exhibit a similar decreasing trend from Point 1 to Point 4, followed by a slight increase at Point 5. Initially, the bitumen content is high (around 85%) and gradually decreases to approximately 58% at Point 4. VMA follows the same pattern, reducing from about 80% to nearly 50%. This indicates that as the bitumen content decreases, the total available void space within the aggregate structure also reduces due to improved packing and reduced binder demand. At Point 5, both values show a marginal rise, suggesting slight loosening in aggregate structure or increased binder absorption. Overall, the results indicate that VMA is strongly influenced by bitumen content, and an optimum zone exists around Point 3 to Point 4 where the mix achieves a balance between adequate binder volume and aggregate interlock.

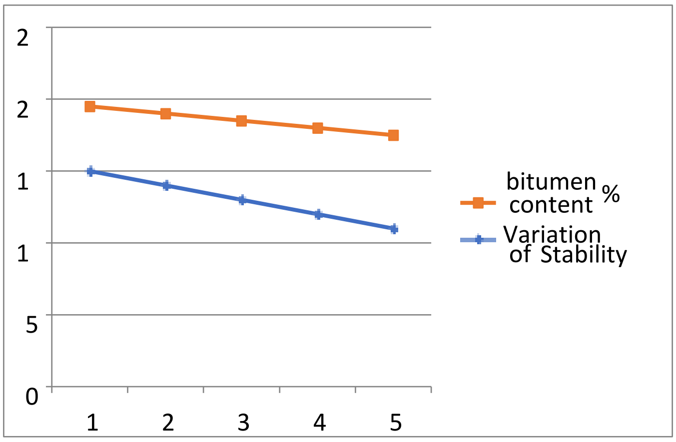

Fig 4.3 Variation of Stability with Bitumen Content

The graph shows a gradual decrease in both bitumen content and Marshall stability from Point 1 to Point 5. As bitumen content drops from approximately 20% to 17%, the stability value also declines from about 16 kN to nearly 12 kN. This indicates that insufficient binder reduces cohesion and aggregate interlock, leading to lower load-bearing capacity. The consistent downward trend confirms that the mix becomes weaker as binder availability decreases.

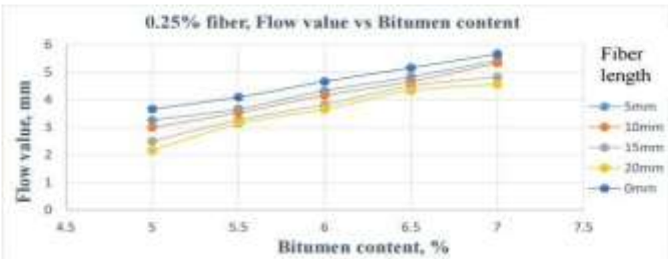

Fig 4.4 Flow Value vs Bitumen Content for 0.25% Sisal Fibre

Flow values increase progressively with higher bitumen content for all fibre lengths. Mixes with 5 mm fibre show the highest flow, indicating greater deformation capacity, while 20 mm fibre provides the lowest flow values. At 7% binder, flow ranges between 4.5–5.3 mm. This shows that short fibres enhance flexibility more than long fibres at low fibre dosage.

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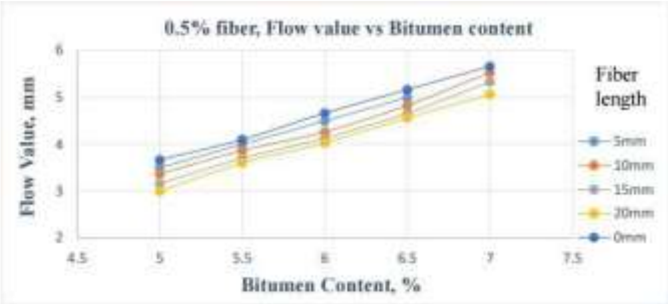

Fig 4.5 Flow Value vs Bitumen Content for 0.5% Sisal Fibre

Flow values increase steadily with bitumen content, and mixes with 5 mm fibre again show the highest deformation response. Compared to 0.25% fibre mixes, the flow values here are slightly higher, indicating improved binder–fibre interaction. At 7% bitumen, flow reaches approximately 5.5 mm for 5 mm fibres and about 4.8 mm for 20 mm fibres.

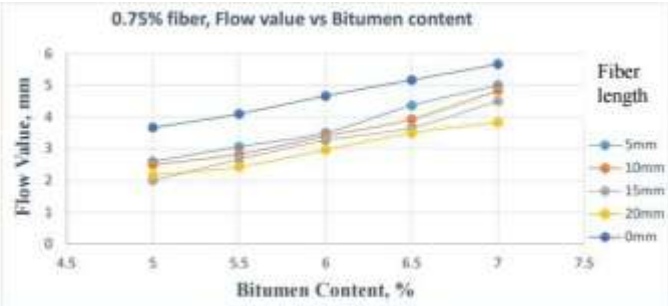

Fig 4.6 Flow Value vs Bitumen Content for 0.75% Sisal Fibre

A strong upward trend in flow values is observed with increased bitumen content. The 5 mm fibre length continues to provide the highest flow, followed by 10 mm, 15 mm, and 20 mm. Greater fibre dosage results in more noticeable flow increase at higher binder contents, indicating improved ductility but slightly reduced stiffness.

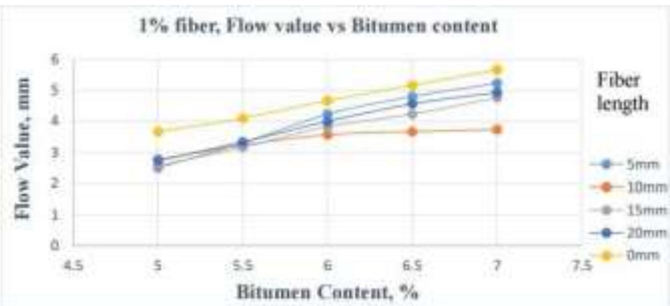

Fig 4.7 Flow Value vs Bitumen Content for 1% Sisal Fibre

At 1% fibre content, the effect of fibre length becomes more pronounced. The 20 mm fibre length shows the highest flow values at all bitumen percentages, reaching nearly 5.8 mm at 7% binder. Longer fibres create higher internal voids, resulting in greater deformation under load. Short fibres (5 mm and 10 mm) show moderate flow, indicating better structural stability.

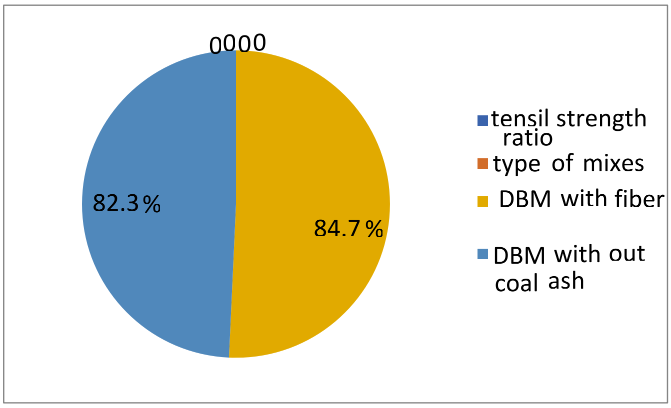

Fig 4.8 TSR Variation Between Fibre-Reinforced and Conventional DBM Mixes

The pie chart compares the tensile strength ratio (TSR) of two bituminous mixes: DBM with fibre and DBM without coal ash. The DBM mix containing fibre shows a TSR value of 84.77%, while the DBM mix without coal ash exhibits a slightly lower TSR of 82.35%. This indicates that incorporating fibre in the bituminous mix improves resistance to moisture-induced damage. A higher TSR value signifies better retention of tensile strength after conditioning, demonstrating enhanced durability and improved binder–aggregate bonding. Therefore, the fibre-reinforced DBM mix performs better under moisture susceptibility conditions compared to the conventional DBM mix.

5. CONCLUSIONS

1. Marshall test results showed that DBM mixes incorporating bottom ash (300–75 micron) and fly ash (passing 75 micron) exhibited optimal performance when prepared with a bitumen content of 5.6%, fibre content of 0.5%, and fibre length of 10 mm.
2. Marshall stability and flow values remained within acceptable limits when coal ash content was maintained below 15%, indicating its suitability as a partial replacement material.
3. Increasing fibre content and fibre length led to a reduction in air voids and flow values, while the Marshall Quotient increased due to enhanced stability.
4. Higher fibre dosage and longer fibre lengths required greater amounts of bitumen and emulsion to ensure proper fibre coating.
5. Incorporation of fly ash–plastic waste composite improved the indirect tensile strength and resilient modulus at both 35°C and 45°C. It also reduced rutting during wheel-track testing and enhanced creep modulus and creep recovery, demonstrating improved deformation resistance and durability of the bituminous concrete mix.

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