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A Study on Development in Engineering Properties of Dense Grade Bituminous Mixes with Coal Ash by Using Natural Fiber

M. Venkateshwara rao[1], [2] Dr.P. Bala Krishna, Ph.D.,

[1]M. Tech Student, Department of Civil Engineering, MVR College of Engineering and Technology (autonomous) Paritala, India.

[2]Associate Professor, and Head of the Department (HOD), Department of Civil Engineering, MVR College of Engineering and Technology, Paritala, India.

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Abstract - Coal-based thermal power plants in India produce significant waste, primarily fly ash and bottom ash, which poses environmental and health risks when disposed of in large quantities. This research explores the effective use of these waste products in bituminous paving mixes, substituting natural aggregates to conserve resources. Dense-graded bituminous macadam (DBM) specimens were prepared using natural coarse aggregates, bottom ash as fine aggregate, and fly ash as filler, with sisal fiber as a reinforcing additive. Varying percentages (0–1%) and lengths (5–20 mm) of SS1 emulsion-coated sisal fiber were tested to optimize the mix's engineering properties. VG30 bitumen, chosen for its superior Marshall characteristics, resulted in an optimum binder content of 5.57%, fiber content of 0.5%, and fiber length of 10 mm, achieving a Marshall stability of 15 kN.

Additional performance tests, including moisture susceptibility, indirect tensile strength (ITS), creep, and tensile strength ratio assessments, confirmed that the coal ash and sisal fiber mix significantly enhances pavement durability. This approach offers an eco-friendly and economical solution for bituminous pavement construction, addressing coal ash disposal challenges and conserving natural aggregates.

Keywords: Bottom ash, Fly ash, Sisal fiber, Emulsion, Indirect tensile strength, Static creep test, Tensile strength ratio.

1.NTRODUCTION

Road infrastructure forms the backbone of a nation's progress, with durable pavements essential for efficient transportation. In India, highways are a key mode of transport, prompting substantial investments from the government in road construction and maintenance. The focus on flexible pavements necessitates careful consideration of both pavement and mix design, with bituminous mix design playing a crucial role in creating strong, long-lasting pavements.

Bituminous mix design involves selecting and proportioning aggregates, bitumen, and additives to create a mixture that is durable, resilient, and skid-resistant. Aggregates form the structural base, while bitumen acts as a binder, and both components are optimized to ensure performance. Various bituminous mixes, including Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), Cold Mix Asphalt (CMA), Cut-back Asphalt, and Mastic Asphalt, cater to different applications. HMA, a common choice for high-traffic roads, is mixed at high temperatures for optimal compaction and durability. WMA, produced at lower temperatures, reduces emissions and is suited for urban environments. CMA is a practical, low-temperature option for remote or emergency repairs.

HMA includes specific types such as Dense Graded Bituminous Macadam (DBM), known for its impermeability and strength in base layers, Stone Matrix Asphalt (SMA), designed to resist rutting under heavy loads, and Open-Graded Mixes, which allow water drainage and reduce noise.

Advanced methods of mix design, like Marshall and Hveem methods, aid in optimizing the proportion of materials for improved performance. These developments, along with sustainable practices like using nonconventional materials, are shaping the future of road construction, supporting economic, environmental, and structural goals.

1.1 Problem Statement

India's coal-based thermal plants produce around 120 million tons of ash annually, often disposed of in open areas or dumping yards, leading to environmental damage, land use issues, and health risks. Additionally, limited availability of aggregate materials for bituminous mixes requires costly procurement from distant locations. Utilizing coal ash as a substitute in bituminous mixes offers a sustainable solution, potentially lowering costs, conserving resources, and reducing the ecological impact of ash disposal. This approach could address pressing environmental challenges while meeting societal infrastructure needs responsibly. A detailed study on this application could unlock significant benefits.

1.2 Objectives of Research

This experimental study investigates the feasibility of using coal ash as a nonconventional aggregate in bituminous mixes, enhanced with natural Sisal fiber as an additive. The main objective is to create an effective blend that meets performance requirements for fatigue resistance, moisture susceptibility, and creep value in bituminous pavements. Incorporating coal ash aims to address the limited availability and high cost of conventional aggregates, presenting a sustainable approach for road construction. The study also examines the role of Sisal fiber in improving the mechanical and structural properties of the asphalt. A key focus is determining the optimal fiber content and length to maximize performance characteristics, durability, and longevity of the mix. By evaluating various fiber proportions and lengths, this research seeks to identify the ideal mix that strengthens pavement engineering properties, potentially reducing maintenance costs and promoting sustainability in road construction.

1.3 Scope of the Study

This study examines the integration of coal ash as a fine aggregate in Hot Mix Asphalt (HMA) to create durable, eco-friendly pavements. Replacing conventional materials like sand and stone dust with coal ash presents an economically viable alternative, reducing reliance on natural resources and addressing environmental issues linked to coal ash disposal. Incorporating coal ash in HMA mix design can yield high-quality pavements with smooth, weather-resistant surfaces, supporting sustainable road construction and offering potential for commercial application.

Additionally, the study explores the innovative use of non-conventional materials such as coal ash and natural fibers like Sisal to enhance bituminous pavement construction. This approach, which substitutes traditional materials, introduces a sustainable, cost-effective method for asphalt road construction. The combined use of coal ash and natural fibers could conserve resources and reduce environmental impact, supporting the shift towards green construction practices while mitigating coal ash disposal and pollution concerns.

A comparative analysis on Dense Graded Bituminous Macadam (DBM) mixes is conducted across four scenarios: DBM with both fiber and coal ash, with fiber alone, with coal ash alone, and with neither. This analysis aims to identify the optimum combination for improved pavement performance, providing insights into the role of each component in achieving structural integrity and durability.

The study further assesses the performance characteristics of bituminous mixes under moisture, thermal, and load-bearing conditions. Moisture resistance is evaluated through tests like Tensile Strength Ratio (TSR) and Retained Stability to gauge the mixes' durability against moisture-related damage, crucial for maintaining stability in wet environments. Thermal cracking resistance tests determine the mixes' ability to withstand temperature fluctuations, essential for extending pavement lifespan in variable climates. Lastly, Static Creep Tests assess resistance to permanent deformation, a factor critical for road safety and longevity under heavy traffic. By comparing mixes with and without coal ash and fiber, the study seeks to identify formulations that optimize durability, sustainability, and cost-effectiveness in road construction.

2. MATERIALS

This study investigates the formulation of a bituminous mix using various materials to optimize pavement durability and sustainability. The primary components of a bituminous mix include a blend of graded aggregates and bitumen binder, designed to form a dense, elastic structure that is both impermeable and durable when compacted. The goal of mix design is to achieve the optimal ratio of coarse and fine aggregates, mineral fillers, and additives to meet specific performance standards.

Aggregates play a key role, with coarse aggregates (retained on a 4.75 mm IS sieve) providing structural stability and load-bearing capacity. Quality coarse aggregates should be durable, angular, and free of impurities to ensure proper bonding and interlocking, which enhances the mix's resistance to wear, deformation, and environmental stresses. Fine aggregates, smaller than 4.75 mm, fill voids between coarse aggregates, stabilizing the mix and contributing to its resistance to cracking and raveling. Both types must be clean and well-graded to optimize load distribution and enhance rigidity within the pavement.

Mineral fillers, such as particles smaller than 0.075 mm, fill the smallest voids, boosting cohesion and reducing permeability. Fillers like fly ash or lime improve moisture resistance and the mix's durability under traffic loads by enhancing bonding between aggregate and binder. This study utilizes bottom ash and fly ash as mineral fillers, addressing both structural needs and environmental sustainability.

Bitumen, a viscoelastic binder, plays a critical role by binding aggregates and filling voids to create a durable, impermeable surface. It prevents moisture infiltration, essential for pavement longevity, and responds well to temperature variations. For enhanced performance, bitumen's properties can be modified with additives to improve elasticity, tensile strength, and resistance to deformation.

Additives like Sisal fiber improve tensile strength, flexibility, and resistance to cracking. An SS-1 emulsion serves as a fiber coating agent, aiding in fiber distribution and stability within the mix. The materials used include stone chips, bottom ash, fly ash, VG-30 bitumen binder, Sisal fiber, and SS-1 emulsion, carefully selected and sourced from nearby facilities.

Figure 3.3 Stone chips

Figure 3.2 Bottom ash

Figure 3.1 Fly ash

Table 3.1 Physical property of coarse aggregate and fine

Property	Code specification	Test Result	
		Natural Aggregate	Bottom ash
Aggregate impact value, %	IS:2386 part-IV	14	-
Aggregate crushing value, %	IS:2386 part-IV	13.5	-
Los Angles Abrasion test, %	IS:2386 part-IV	18	-
Soundness test (five cycle in sodium sulphate), %	IS:2386 part-V	3	8.2
Flakiness index, %	IS:2386 part-I	11.9	-
Elongation index, %	IS:2386 part-I	12.5	-
Water absorption, %	IS:2386 part-III	0.14	10.75
Specific gravity	IS:2386 part-III	2.7	2

Table1. Physical property of aggregate

2.1 Bitumen

In this study, VG-30 paving bitumen (viscosity grade) was selected due to its superior performance in high-traffic pavement applications. Initial trials with both VG-30 and VG-10 grades indicated that VG-30 pr ovided better Marshall characteristics, notably increased Marshall stability, when combined with bottom ash, fly ash, and emulsion-coated fiber. The higher viscosity of VG-30 enhances load-bearing capacity and deformation resistance, making it ideal for heavy-duty pavements. Key properties of VG-30, such as penetration, softening point, and ductility—tested as per IS standards—further affirm its suitability for creating durable, resilient bituminous mixes for modern road construction.

Physical Properties	IS Code	Test Result
Penetration at 25ºC/100gm/5s, 0.01mm	IS:1203-1978	46
Softening Point, ºC	IS:1205-1978	46.5
Specific gravity, at 27ºC	IS:1203-1978	1.01
Absolute viscosity, Brookfield at 160ºC, Centi Poise	ASTM D 4402	200

Table .2 Physical property of binder

Chemical composition	
Composition	**Test result**
Cellulose, %	65
Hemicellulose, %	12
Lignin, %	9.9
Waxes, %	2
Physical property	
Property	**Test result**
Density, gm/cc	1.51
Tensile strength, MPa	510-640
Young’s modulus, MPa	9.5-2.0
Elongation at break, %	2.0-2.5

Table.3 Physical and chemical property of sisal fiber

3. EXPERIMENTAL WORK

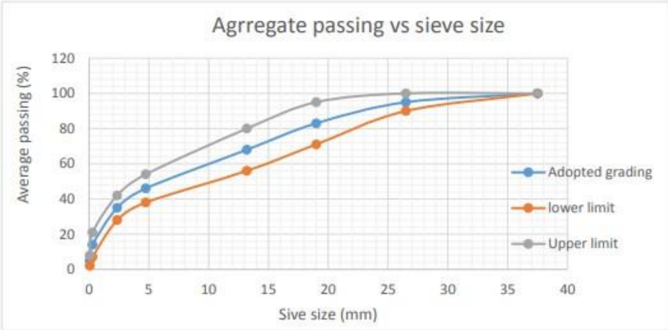

Figure 4.1 Aggregate gradation curve.

3.1 Mix Design:

The DBM mixtures were prepared in accordance with the Marshall procedure specified in ASTM D6927-2015. All ingredients of mixture, such as coarse aggregates, fine aggregates, filler, fiber and VG-30 bitumen were mixed in a specified procedure. Before preparing the samples, fibers were coated with SS-1 emulsion and stored in a hot air oven at 110^{0}C as shown in Figure 4.3. Coated fiber are stored for 24 hours to ensure proper coating around each fiber and to drain downextra bitumen that may adhere to fiber.

3.2ANALYSIS OF RESULTS AND DISCUSSION

Marshal stability

The incorporation of coal ash in Dense Graded Bituminous Macadam (DBM) mixes showed reduced stability, peaking at 11.83 kN with 14% ash content. This decline is likely due to coal ash's different physical properties, necessitating further research to optimize its use and enhance DBM performance for sustainable pavement solutions.

Marshal flow value

The flow value versus bitumen content graph (Figure 5.2) reveals a notable trend: both flow value and coal ash content increase with rising bitumen levels, indicating that higher bitumen content improves the workability and fluidity of Dense Graded Bituminous Macadam (DBM) mixes. Increased bitumen levels enhance the flexibility and deformation capacity of the mix, which is essential for withstanding traffic-induced stresses. However, at 14% coal ash by weight of the mix, a significant reduction in flow value is observed compared to the conventional mix, highlighting potential limitations in the mix's performance at this level of coal ash content.

This reduction in flow value suggests that the coal ash may disrupt the mix’s deformation properties, possibly due to differences in particle size, porosity, or the physical and chemical properties of coal ash compared to traditional aggregates. These properties may impede the mix’s capacity to retain flexibility, potentially compromising overall performance, particularly in terms of resilience to traffic-induced deformations.

To optimize DBM mixes with coal ash, further investigation into the interactions between bitumen and coal ash at various proportions is necessary. Such research may help identify optimal formulations that balance workability and durability

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while incorporating sustainable materials like coal ash in asphalt pavement construction.

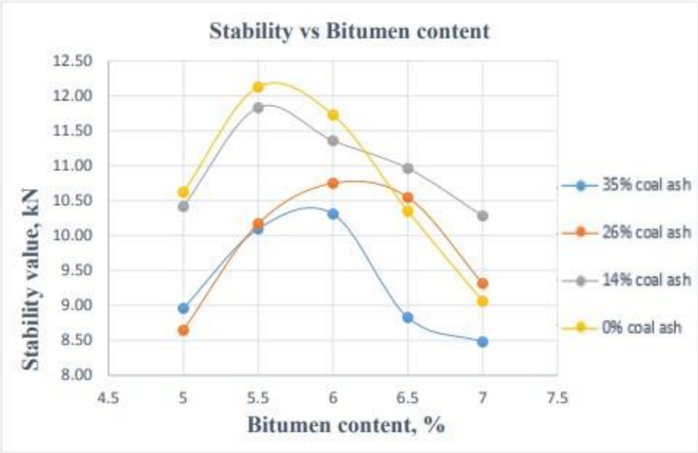

Figure 5.1 Variation of Stability value with bitumen content at different coal ash content

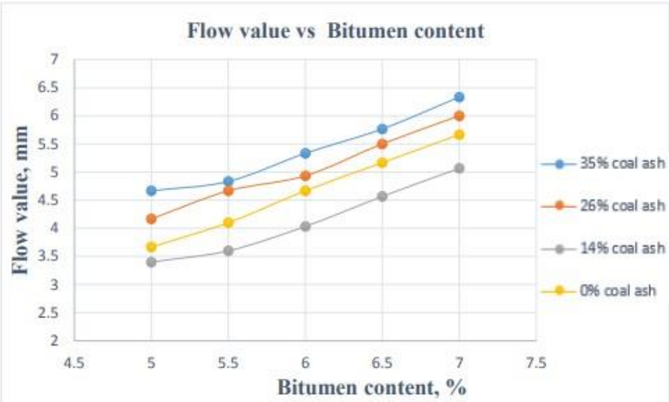

Figure 5.2 Variation of Flow value with bitumen content at different coal ash content

Fig.2 shows marshall flow and marshal stability

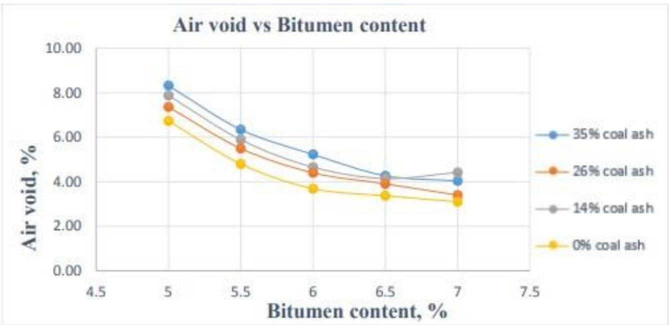

Figure 5.3 Variation of Air void value with bitumen content at different coal ash content

Incorporating coal ash into Dense Graded Bituminous Macadam (DBM) mixes leads to an increase in air voids, a critical factor influencing durability and compaction in bituminous pavements. High air void levels can reduce the pavement's resistance to moisture, accelerate aging, and potentially compromise long-term stability. Interestingly, at 14% coal ash by weight of the mix, the air void content aligns more closely with that of conventional DBM mixes, suggesting that coal ash can be a viable component if carefully managed.

To optimize the performance of DBM with coal ash, adjustments such as refining aggregate gradation, optimizing bitumen content, or incorporating stabilizing agents may help maintain ideal air void levels and structural integrity. These modifications could enable coal ash to partially replace conventional aggregates while preserving the pavement's durability.

This approach promotes a more sustainable construction practice by reducing reliance on natural aggregates and recycling coal ash, an industrial byproduct, without compromising pavement quality. By adapting the DBM mix design, coal ash could offer a cost-effective and environmentally friendly alternative, balancing air voids to ensure a durable and resilient pavement structure suited to long-term highway and roadway applications.

Table 5.1 Marshall properties analysis

Fiber content, %	Fiber length, mm	OBC, %	Optimum stability, kN	Flow value, mm	VA, %	VMA, %	VFB, %	Gmb
0.25	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.70	14.20	4.00	3.60	16.70	79.00	2.28
	10	5.78	13.20	3.50	3.60	17.00	76.00	2.28
	15	5.87	12.80	3.80	3.10	16.60	80.00	2.27
	20	5.73	11.90	3.80	4.00	17.00	77.00	2.27
Fiber content, %	**Fiber length, mm**	**OBC, %**	**Optimum stability, kN**	**Flow value, mm**	**VA, %**	**VMA, %**	**VFB, %**	**Gmb**
0.5	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.57	13.80	3.85	2.90	17.10	75.00	2.26
	10	5.60	15.00	3.50	2.80	15.80	82.00	2.30
	15	5.80	11.50	3.60	4.30	17.60	76.00	2.25
	20	6.13	12.00	4.90	4.00	17.90	78.00	2.24
Fiber content, %	**Fiber length, mm**	**OBC, %**	**Optimum stability, kN**	**Flow value, mm**	**VA, %**	**VMA, %**	**VFB, %**	**Gmb**
0.75	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.90	12.20	3.70	3.60	17.30	80.00	2.26
	10	5.77	13.30	3.10	2.20	15.90	86.00	2.30
	15	6.00	12.50	3.40	4.00	17.90	78.00	2.25
	20	6.13	12.30	3.50	4.30	18.35	77.00	2.24
Fiber content, %	**Fiber length, mm**	**OBC, %**	**Optimum stability, kN**	**Flow value, mm**	**VA, %**	**VMA, %**	**VFB, %**	**Gmb**
1	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.93	12.30	4.20	3.70	17.60	80.00	2.24
	10	5.77	12.50	3.40	4.40	17.65	76.00	2.24
	15	5.55	13.40	3.20	2.90	16.10	82.00	2.28
	20	5.63	12.65	3.8	2.40	16.20	83.00	2.28

The static creep test results indicate that DBM samples with an optimized mix—comprising 0.5% fiber at a 10mm length, 14% coal ash (split as 9% bottom ash and 5% fly ash), and 5.6% binder—show significantly reduced deformation under prolonged loading. This suggests enhanced resistance to permanent deformation, outperforming both modified and conventional DBM mixes.

The data also reveal that using either coal ash or fiber individually in the mix contributes to reduced deformation compared to unmodified DBM, highlighting each material's positive impact on load-bearing durability. Coal ash and fibers appear to bolster the mix's resistance to deformation, indicating potential for their combined use in strengthening asphalt pavements. These findings support the viability of coal ash and fiber as additives to improve the durability of DBM mixes, potentially leading to more resilient and sustainable pavement solutions.

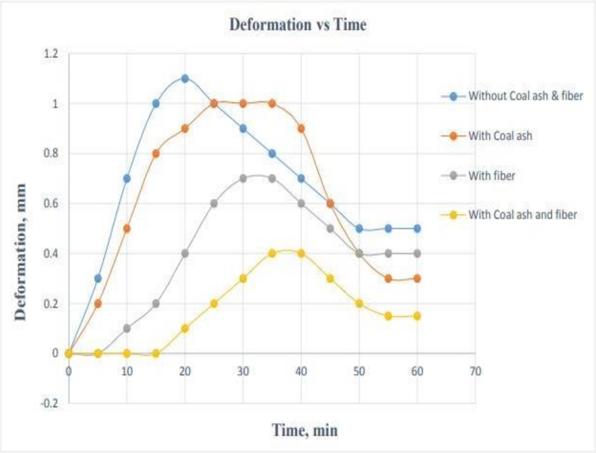

Figure 5.33 Variation of Deformation value at 40^{0}C for DBM sample with respect to time

4.Conclusion

1. Marshall test results revealed that DBM mixes using bottom ash and fly ash in 300-75-micron sizes and passing 75-micron fractions achieved optimal results, meeting Marshall criteria when bitumen content, fiber content, and fiber length were 5.6%, 0.5%, and 10mm, respectively.

2. Marshall stability and flow values remained within acceptable limits when coal ash content did not exceed 15%.

3. Increased fiber content and length led to a decrease in air voids and flow, while raising the Marshall Quotient due to higher stability values.

4. Higher fiber content and length required increased optimum bitumen content and emulsion for effective fiber coating.

5. Indirect tensile strength tests showed enhanced tensile strength in samples with emulsion-coated fibers and coal ash, providing DBM samples with excellent resistance to thermal cracking.

6. Emulsion-coated fiber, coal ash, or their combination improved moisture resistance in DBM mixes, as evidenced by higher tensile strength ratios and retained stability values.

Future Scope

1. Since sisal fiber performed well in bituminous mixes, additional natural fibers like jute and coconut should be evaluated to understand their impact on DBM mixes.

2. Only SS-1 emulsion was used to coat sisal fiber in this study; future research should explore the effects of rapid-setting (RS) and medium-setting (MS) emulsions through further testing.

3. The influence of mineral fillers such as lime (for anti-stripping) and cement (as a stabilizer) on DBM mixes should also be examined in future studies.

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