International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Experimental Study on the Effects of Coal Ash and Emulsion Coated-Sisal Fibers in Hot Mix Asphalt

Bhavna Upadhyay[1], Akhand Pratap Singh[2], Dr. R.R.L. Birali[3]
M.Tech. Scholar, Assistant Profesor, Professor
Department of Civil Engineering
Shri Rawatpura Sarkar University, Raipur

Abstract:-India's coal-fired thermal power plants produce substantial amounts of fly ash and bottom ash, leading to critical environmental and disposal challenges. This experimental study investigates the integration of these waste by-products into Hot Mix Asphalt (HMA) by utilizing fly ash as a mineral filler and bottom ash as a fine aggregate. Emulsion-coated natural sisal fibers were incorporated to improve the mix performance and provide a sustainable alternative to conventional materials.

Dense graded bituminous mixes (DBM) were prepared as per MORTH (2013) specifications, using VG-30 bitumen and a nominal maximum aggregate size (NMAS) of 26.5 mm. Sisal fibers coated with SS-1 emulsion were added at varying contents (0%–1%) and lengths (5 mm–20 mm). The Marshall Mix Design method was employed to evaluate the optimal binder content, fiber dosage, and fiber length. The optimum mix, with 5.57% binder, 0.5% fiber content, and 10 mm fiber length, achieved a peak Marshall Stability of 15 kN.

Performance evaluation through tensile strength ratio (TSR), indirect tensile strength (ITS), static creep, and moisture susceptibility tests indicated marked improvements in mechanical properties. The results affirm that the combined use of coal ash and treated sisal fiber not only enhances pavement performance but also presents a cost-effective and environmentally responsible method of ash utilization.

Keywords: Fly ash, Bottom ash, Sisal fiber, Emulsion, Marshall Stability, TSR, ITS, Creep test

1. Introduction

1.1 Background of the Study

The construction and maintenance of durable and high-performance pavements are critical to a nation's infrastructure and economic growth. In India, where the highway network forms the core of transportation, there is a continuous push to improve the quality and sustainability of road construction materials. Bituminous pavements, being widely used for flexible road surfaces, demand careful mix design to ensure longevity, load-bearing capacity, and resistance to environmental stresses.

Traditionally, natural aggregates and conventional binders have been the primary components of Hot Mix Asphalt (HMA). However, growing environmental concerns, material scarcity, and high construction costs have led to the exploration of alternative and sustainable materials. Coal-fired thermal power plants in India generate large quantities of fly ash and bottom ash, posing serious environmental and disposal challenges. At the same time, natural fibers like sisal offer biodegradable and locally available reinforcement options.

This study focuses on the experimental evaluation of bituminous mixes modified with coal ash (fly ash and bottom ash) and emulsion-coated natural sisal fibers. By partially replacing conventional materials with industrial by-products and renewable fibers, the research aims to enhance the mechanical properties of HMA while contributing to waste management and resource conservation. The investigation centers on the impact of these additives on the performance characteristics of Dense Graded Bituminous Macadam (DBM) mixes, in alignment with sustainable pavement engineering practices.

1.3 Problem Statement

The production of bituminous mixes traditionally relies on natural aggregates of various sizes to meet performance specifications. However, in many regions, the availability of coarse, fine, and filler-grade aggregates is limited, requiring long-distance transportation that significantly increases project costs. Simultaneously, India's growing dependence on coal-based thermal power plants generates an estimated 120 million tonnes of fly ash and bottom ash annually. These waste products are typically disposed of in open lands, ash ponds, or dumping yards methods that pose serious threats to land use, human health, and the environment.

Despite the vast availability of coal ash, its potential as a viable construction material remains underutilized. Furthermore, the use of natural fibers like sisal in bituminous pavements is limited, though they offer renewable, biodegradable, and locally accessible solutions for enhancing asphalt mix performance. Emulsion-coated natural fibers may address issues related to moisture damage and improve binder-aggregate interaction.

Therefore, there is an urgent need to investigate the feasibility of incorporating coal ash and emulsion-treated sisal fibers in Hot Mix Asphalt. This study seeks to address the dual challenge of material scarcity and environmental sustainability by exploring these alternatives in Dense Graded Bituminous Macadam (DBM) mixes. Through experimental analysis, the research aims to identify cost-effective and performance-enhancing solutions for modern pavement construction.

1.4 Objectives of Research

The primary objective of this research is to evaluate the performance of Hot Mix Asphalt (HMA) modified with coal ash (fly ash and bottom ash) and emulsion-coated natural sisal fibers. The study aims to utilize fly ash as a mineral filler and bottom ash as a fine aggregate to reduce reliance on natural resources and address environmental concerns related to ash disposal.

This experimental investigation also focuses on assessing the effects of emulsion-coated sisal fibers on the mechanical and volumetric properties of Dense Graded Bituminous Macadam (DBM) mixes. The specific goals of the study include:

- ➢ To determine the optimal proportion of coal ash (fly ash and bottom ash) as filler and fine aggregate in DBM mixes.
- ➢ To evaluate the influence of emulsion-coated sisal fibers on the strength, stability, and durability of the asphalt mix.
- ➢ To identify the optimum fiber content and fiber length that enhance the mix's resistance to moisture damage, thermal cracking, and permanent deformation.
- ➢ To analyze key performance parameters such as Marshall Stability, Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), and Static Creep.

The overall objective is to develop a sustainable and cost-effective bituminous mix design that incorporates industrial waste and natural fibers without compromising pavement performance.

1.5 Scope of the Study

- ➢ Utilising coal ash as a fine material in Hot Mix Asphalt (HMA) mix design is the study's main focus. This will result in high-quality, smooth-surfaced roads that can survive a variety of environmental conditions and be commercially successful.
- ➢ Furthermore, unconventional materials like coal ash and natural fibres combined can open the door for creative bituminous pavement design. This method offers a cost-effective replacement for natural resources like sand and stone dust with coal ash, addressing the major issues surrounding the disposal of coal ash and environmental contamination

In this research work a comparative study has been done on Dense graded bituminous macadam (DBM) by focusing on the following highlight.

1. Marshall properties study of mixes on DBM using,
   a) With fiber and coal ash
   b) With fiber and without coal ash

c) Without coal ash and with fiber
d) Without fiber and coal ash

2. The performance characteristics of bituminous mix
   (a) Under moisture condition with and without fiber and coal ash ·
   - Tensile strength ratio test
   - Retained stability test

   (b) Under thermal cracking (Tensile strength test) of DBM mix with and without fiber and coal ash.

2. Review of Literature

Hadiwar doyo, Sigit Pranowo (2013) studied that the failure at the surface layers of road is due to the change in temperature and the load of the traffic. He performed an experiment on Short coconut fibers in bitumen mix. He executes the experiment with various percentages of coconut fibers ranging from 0.5% to 1.50% with the increment of 0.25%. The fiber size was also varied with 5mm, 7.5mm, 10mm, and 12.5 mm. He tests the bitumen characteristic with coconut fibers.

From the result obtained in Marshall Properties test he found that the Marshall stability increased by 10-15%, when 0.75% of fiber content and 5-mm of fiber length was added by weight of the mixture. He also observed that with the addition of fiber in bitumen; change the bitumen propertywith a lower penetration value.

Santhosh and Mohammed (2019) explored the use of natural fibers in dense grade bituminous mixes with coal ash. The research indicated that combining bottom ash as fine aggregate, fly ash as mineral filler, and natural fibers like sisal can improve the engineering properties of bituminous paving mixes.

Dwivedi and Joshi (2022) investigated the effect of natural fibers on the engineering properties of dense grade bituminous mixes with coal ash. The study demonstrated that incorporating bottom ash as fine aggregate and fly ash as mineral filler, along with natural fibers like sisal, can enhance the performance characteristics of bituminous paving mixtures.

Ullah et al. (2022) examined the eco-friendly incorporation of crumb rubber and waste bagasse ash in bituminous concrete mixes. The findings suggested that these waste materials could be effectively used to improve the mechanical properties of asphalt mixtures, promoting sustainability in road construction.

Maurya et al. (2022) investigated the recycling and reinforcement potential of fly ash and sisal fiber reinforced hybrid polypropylene composites. The study demonstrated that hybridization with fly ash has a benign effect on reducing property degradation in recycled composites, suggesting potential applications in asphalt mixtures.

Sun et al. (2023) analyzed the feasibility of using waste incineration fly ash in asphalt pavement materials. The research highlighted the potential of fly ash to improve the mechanical properties of asphalt mixtures while addressing environmental concerns related to heavy metal leaching.

Kar et al. (2023) evaluated the use of sisal fibers in dense asphalt mixes and stone mastic asphalt. The study found that adding 0.3% sisal fibers improved the Marshall stability of asphalt mixes.

Kumar (2023) observed that the stability and tensile strength of control stone mastic asphalt were comparable to those containing 0.3% sisal fibers, indicating the fibers' effectiveness in enhancing mix performance.

Singh et al. (2023) concluded that using 0.4% sisal fibers in stone mastic asphalt significantly improved tensile strength and stability while reducing drain down.

2.1 Summary

1. The review of existing literature reveals that the incorporation of bottom ash in bituminous mixes has shown promising results in terms of performance characteristics such as stability and durability. However, in Marshall Property analysis, certain limitations were observed particularly increased air voids and decreased mix density, which can affect long-term pavement performance.
2. Although individual studies have investigated bottom ash and fly ash separately in asphalt mixes, limited research exists on their combined utilization in a single bituminous mix. This gap in literature forms the primary motivation for the present study, which aims to evaluate the collective effect of coal ash (fly ash + bottom ash) on the performance of Hot Mix Asphalt.
3. Furthermore, the use of natural fibers in bituminous paving has been primarily restricted to Stone Mastic Asphalt (SMA) and Bituminous Concrete (BC) due to their higher void content. In most previous works, fibers have been employed as additives or stabilizers rather than as performance-enhancing reinforcements. This study seeks to extend their application by using emulsion-coated sisal fibers in Dense Bituminous Macadam (DBM), addressing performance limitations and enhancing structural integrity.

3. Raw Materials

3.1 Mixture Constituent

Aggregate, graded from maximum fraction to lower fraction (often less than 25mm IS sieve to the mineral filler, smaller than 0.075mm IS sieve), is combined with bitumen binder to create a uniform mixture that is known as a bituminous mix. After that, this mixture is put down and compacted to create an elastic, rigid, and flawlessly impermeable body. The goal of mix design research is to determine the ideal ratios for bitumen, aggregate, and any additional additives that may be needed.

3.1.1 Aggregates

Aggregates play an important part in bituminous mix. Maximum aggregate by weight of mixture is added to take the maximum load bearing & adding strength characteristics to the mixture. Hence, the physical properties and quality of the aggregates are considerably important to pavement. There are three types of mineral aggregates used in bituminous mixes, which are given below.

Coarse Aggregates

Aggregates which are retained on 4.75 mm IS sieve are called as coarse aggregates. A good quality coarse aggregate should have physical characteristic like hardness, angular in shape, toughness, durability, free from dust particles, clay, vegetation and organic matters. Aggregate with these above physical properties offers quite good compressive strength and shear strength and shows good interlocking characteristic.

Fine Aggregates

Aggregates size ranging from 4.75 mm to 0.075 mm IS sieves are called Fine aggregates. As with course aggregate, Fine aggregate should be free from dusts, clay, vegetation, loam or organic matter. Fine aggregate fills the voids between the coarse aggregate and stiffens the binder.

Mineral Filler

Aggregates those are smaller than 0.075 mm IS sieve is called as mineral filler. Filler are used to fills the voids in mix, which cannot be filled by fine aggregates. And also used to increase the binding property between the aggregates in the preparation of specimens.

3.1.2 Bitumen

Bitumen is essential in bituminous mix because of its visco-elastic and adhesive property. It binds the aggregate and fills the small voids which offer impermeability in mixture. At low temperature it acts like an elastic body and at high temperatures it behaves like a viscous liquid [22].

3.1.3 Additives

Additives are used in the mixture to provide better strength characteristic and engineering property. Now a day's different additives such as fibers, polyethylene, minerals, polyester etc. are added either to stabilize or to improve performance property of the pavement.

3.1.4 Bitumen Emulsion

A bitumen emulsion is two phase system in which a significant amount of finely divided bitumen is suspended over an aqueous medium and stabilized by one or more suitable material. When the bitumen emulsion is applied on aggregate, it breaks down and starts binding the aggregate. The first sign of break down occur when the color of bitumen emulsion film change from chocolate brown to black. Bituminous emulsions are especially used in patch and maintenance work [22]. Three types of emulsion are there i.e.

(i) Rapid setting (RS),
(ii) Medium setting (MS), and
(iii) Slow setting (SS)

3.2 Materials Used in Study

In this study following materials are taken in to consideration to prepare the bituminous mix.

- Stone chips (as coarse aggregate)
- Bottom ash (as fine aggregate)
- Fly ash (as mineral filler)
- VG-30 (as bitumen binder)
- Sisal fiber (as additives)
- SS-1 emulsion (as fiber coating agent)

3.2.1 Aggregate

Coarse aggregates comprised of stone chips were procured from a nearby crusher and were stored by sieving in to different sizes. For this study, stone chips comprising coarse aggregate fractions and upper size fractions of fine aggregates ranged from 26.5 mm to 0.3 mm were used as shown in Figure 3.3. For lower fractions of fine aggregates and mineral filler, bottom ash and fly ash wererespectively used to the extent of 9% and 5% by weight of total mix. Bottom ash was procured from the nearby NSPCL thermal power plant (shown in Figure 3.2), while fly ash was collected from the nearby Adhunik Metaliks Power plant (shown in Figure 3.1). The physical properties of coarse aggregates and fine aggregates which are primarily required for paving are given in Table3.1.

Figure 3.1:- Fly Ash

Figure 3.2:- Bottom Ash

Figure 3.3:- Stone Chips

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	13.4	-
Los Angles Abrasion Test, %	IS:2386 part-IV	18	-
Soundness Test (Five Cycle In Sodium Sulphate), %	IS:2386 part-V	3	8.1
Flakiness Index, %	IS:2386 part-I	11.8	-
Elongation Index, %	IS:2386 part-I	12.4	-
Water Absorption, %	IS:2386 part-III	0.13	10.73
Specific Gravity	IS:2386 part-III	2.6	2

3.2.2 Bitumen

The paving bitumen grade VG-30 (VG-viscosity grade) was used in this experimental study. Initially, two bitumen grades such as VG-30 and VG-10 were used to study the Marshall characteristics of mixes with the materials considered. These initial trials resulted better Marshall characteristics, especially the Marshall stability in respect of mixes made up of bottom ash, fly ash and emulsion coated fiber with VG-30 bitumen as binder. The physical characteristics of VG-30 bitumen tested as per IS standards are given in Table-3.2.

Table 3.2 Physical Property of Binder

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

3.2.3 Additives (Sisal Fiber)

A naturally occurring substance that is readily available in the area, sisal fibre has been employed as a modifier to enhance the engineering qualities of traditional DBM combinations. In the course of this experiment, sisal fibres were coated with a slow-setting emulsion (SS-1) and kept in a hot air oven for 24 hours at 110 degrees Celsius. Emulsion coating was taken into account because of the material's biological makeup. Sisal fibre is a gentle yellow-colored cellulose fibre. Figure 3.4 (a) depicts the sisal fibre that was employed in this investigation. It is recyclable, long-lasting, and anti-static [13]. Table -3.3 lists the sisal fiber's physical and chemical characteristics.

Figure 3.4 (A) Sisal Fiber Used.

Figure 3.4 (B) Sisal Fiber Plant [15]

Table 3.3 Physical and Chemical Property of Sisal Fiber

Chemical Composition	
Composition	**Test Result**
Cellulose, %	65
Hemicellulose, %	12
Lignin, %	9.8
Waxes, %	2
Physical Property	
Property	**Test Result**
Density, Gm/Cc	1.50
Tensile Strength, Mpa	510-640
Young's Modulus, Mpa	9.5-2.0
Elongation At Break, %	2.0-2.5

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Los Angles Abrasion Test, %	IS:2386 part-IV	18	-
Soundness Test (Five Cycle In Sodium Sulphate), %	IS:2386 part-V	3	8.1
Flakiness Index, %	IS:2386 part-I	11.8	-
Elongation Index, %	IS:2386 part-I	12.4	-
Water Absorption, %	IS:2386 part-III	0.13	10.73
Specific Gravity	IS:2386 part-III	2.6	2

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Density, Gm/Cc	1.50
Tensile Strength, Mpa	510-640
Young's Modulus, Mpa	9.5-2.0
Elongation At Break, %	2.0-2.5

3.2.4 Emulsion (SS-1)

SS-1 is an anionic based slow setting bitumen emulsion, which is extensively used for tack coat, fog seal, dust control, and in fine graded mix. Slow setting emulsions are the steadiest emulsions,which usually can be diluted with water and mixed with aggregates and mineral fillers and for all paving uses. To allow the emulsion to fully cure, the pavement temperatures at construction should be sufficiently high [12]. The percentage residue content in SS-1 emulsion is found to be 71.48%in 100ml of emulsion by residue evaporation method mentioned in IS 8887 (2004).

5.4.6 Voids Filled With Bitumen (VFB)

From the figure 5.27 to figure 5.30 it was observe that with increase in binder content VFB increase. It was also observe that for all fiber content and fiber length the VFB value with respect to binder contents are shown better result when compared to the conventional mix.

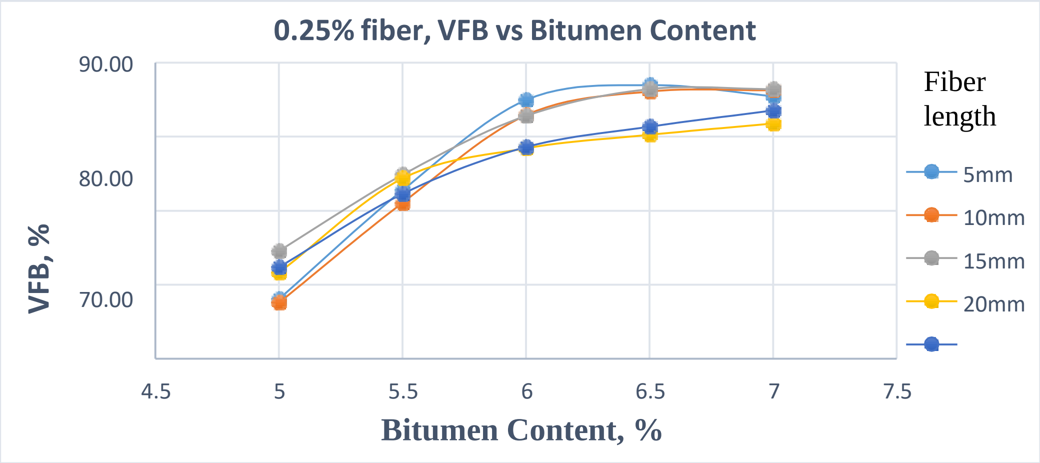


Figure 5.27:- Variation of VFB Value with Bitumen Content In 0.25% Fiber Content at Different Fiber Length

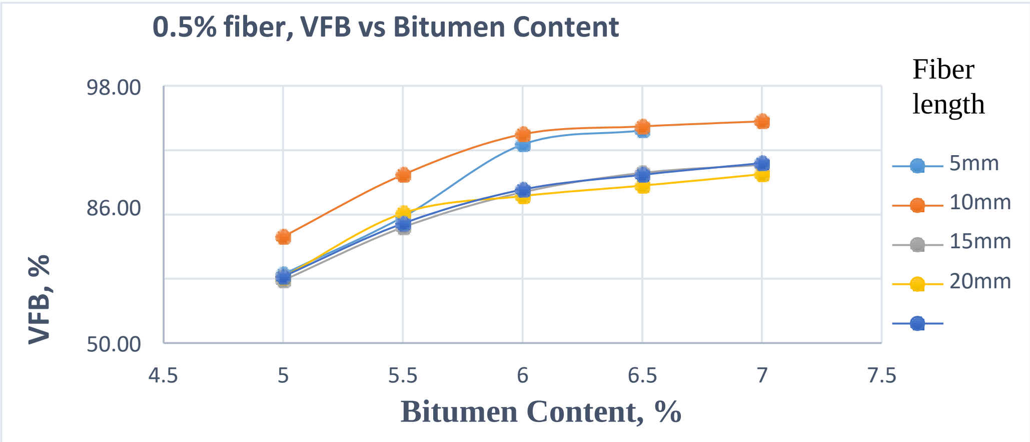


Figure 5.28:- Variation of VFB Value with Bitumen Content In 0.5% FiberContent at Different Fiber Length

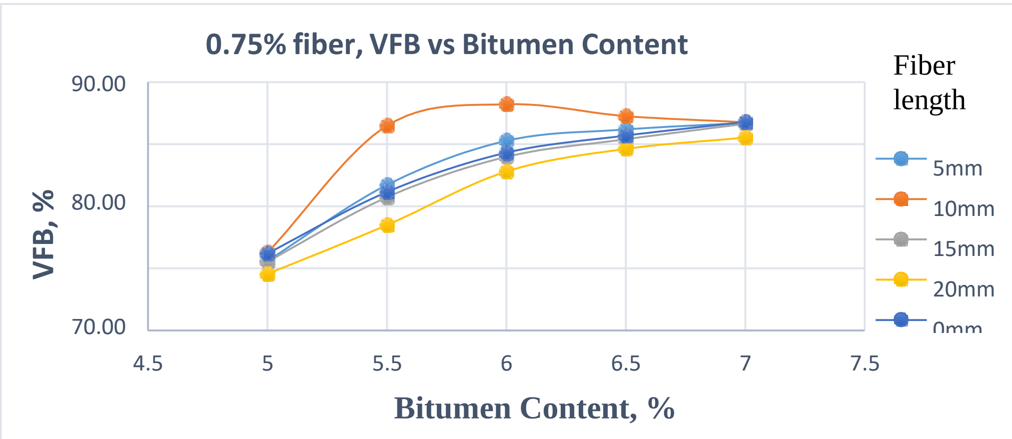


Figure 5.29:- Variation of VFB Value with Bitumen Content In 0.75% Fiber Content at Different Fiber Length

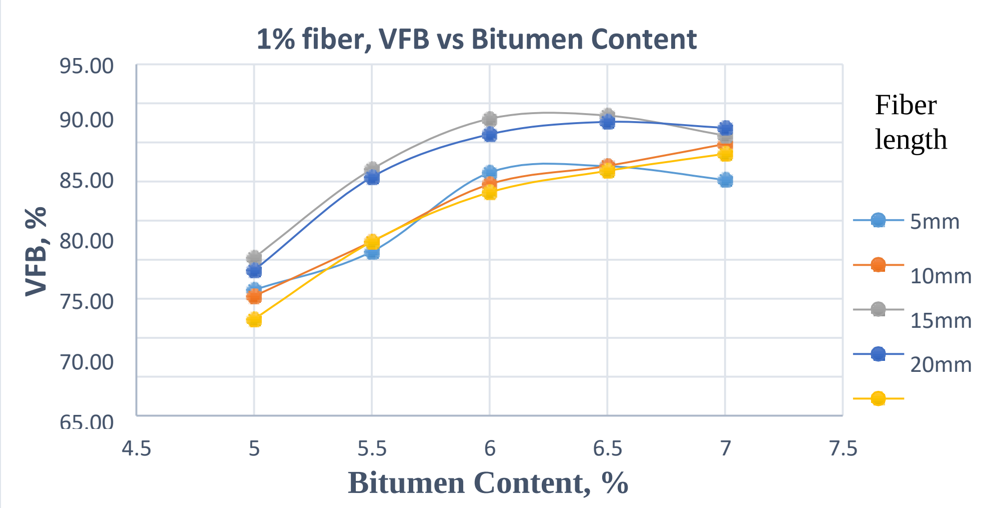


Figure 5.30:- Variation of VFB Value with Bitumen Content In 1% FiberContent at Different Fiber Length

Table 5.1 Marshall Properties Analysis

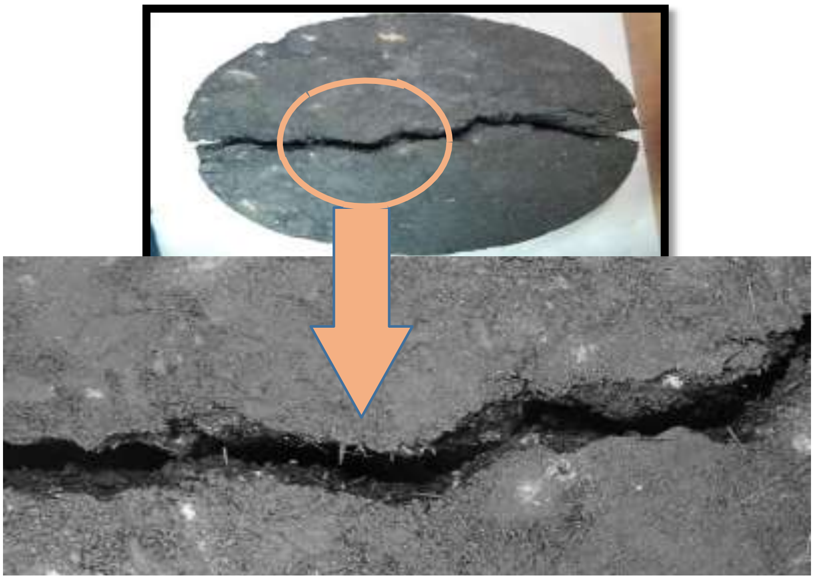
Fiber Content,%	Fiber Length, mm	OBC, %	Optimum Stability, kN	Flow Value, mm	VA, %	VMA, %	VFB, %	Gmb
0.25	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.70	14.20	4.00	3.60	16.70	79.00	2.28
	10	5.78	13.20	3.50	3.60	17.00	76.00	2.28
	15	5.87	12.80	3.80	3.10	16.60	80.00	2.27
	20	5.73	11.90	3.80	4.00	17.00	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 Stabili ty,kN**	**Flow Valu e,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

5.5 Static Indirect Tensile Test

The static indirect tensile test was carried out on four types of samples given below.

- Sample with fiber and coal ash
- Sample with coal ash
- Sample without fiber and coal ash
- Sample with fiber

As seen from the graph given in Figure 5.32, as usual with increase in temperature, the indirect tensile strength of any bituminous mix decreases. But with addition of coal ash along with emulsion coated fiber the indirect tensile strength of DBM sample is increased as compared to unmodified conventional mix. This may be possible due to the



criss-cross pattern of fibers presentin various parts of the mixture resulting in higher strength in tension as shown in figure 5.31. It isalso observed that the coal ash also contributes to a marginal increase in tensile strength comparedto unmodified conventional mix, which is an advantage.

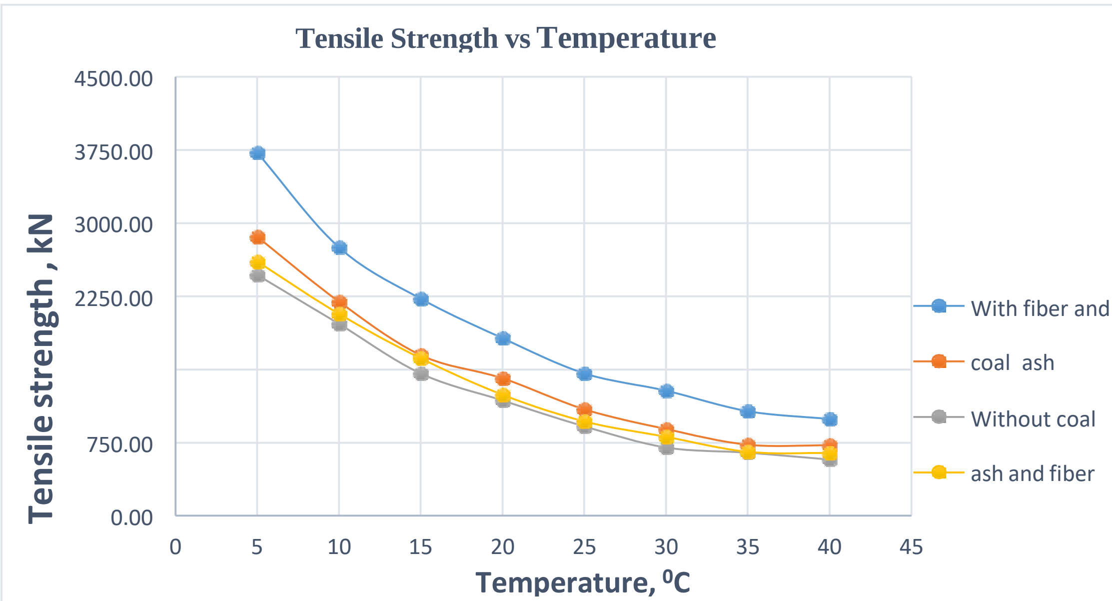


Figure 5.32:- Graph Between Tensile Strength Vs Temperature.

5.6 Resistance to Moisture Damage (Tensile Strength Ratio (TSR))

The results of tensile strength ratio (TSR) in respect of two different types mixes, one modified and other unmodified are presented in Table 5.2. It was observed that with addition of both fiber and coal ash together, resistance to moisture induced damage was increased as compared to the conventional DBM mixture. This may due to the lesser amount of air voids in modified DBM mixture than unmodified mixture, when prepared with emulsion coated sisal fiber. Similarly from the table 5.1, it is observed that a minimal value of resistance to moisture damage is achieved whenthe mix was prepared with either fiber or coal ash.

Table 5.2 TSR of DBM Mixes With and Without Fiber and Coal Ash.

Tensile Strength Ratio			Design Requirement
Type of Mixes	**DBM With Coal Ash**	**DBM Without Coal Ash**	Minimum 80% (as per MORTH specification)
DBM With fiber	84.77%	82.04%	
DBM Without fiber	82.35%	80.26%	

5.7 Retained Stability Test

Retained stability was evaluated for DBM sample which were prepared with fiber, coal ash and conventional aggregate and given in table 5.3. It was observed that the sample containing both emulsion coated fiber and coal ash has given higher result than conventional DBM sample. Butthe sample prepared only with coal ash and conventional aggregate has shown less resistance tomoisture and hence given reduced stability than design requirement.

Table 5.3 Retained Stability of DBM Mixes with and Without Fiber and Coal Ash

Retained Stability				Design Requirement
Type of Mixture	**Average Stability After Half an Hour in Water at 60^0c (Kn)**	**Average Stability After 24 Hours in Water at 60^0c (Kn)**	**Average Retained Stability (%)**	*Minimum 75% (As per Morth Specification)*
DBM with Fiber and Coal Ash	14.78	13.21	89.37	
DBM with Coal Ash	13.88	10.17	73.21	
DBM with Fiber	12.63	10.10	79.94	
DBM without Fiber and Coal Ash	13.56	10.45	77.03	

5.8. Static Creep Test

Static creep test is a measure of permanent deformation due to constant loading for a long period of time. It was observed from the deformation and time graph shown in figure 5.33 that the deformation value for DBM sample that

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

is prepared with 0.5% fiber content, 10mm fiber length, 14% coal ash (9% bottom ash and 5% fly ash) by weight of the mix and optimum binder content of 5.6% by weight of the mixture decreased when compared with other modified and unmodified DBM mix. It is also seen that with either addition of coal ash or fiber in the mixture, the deformation value decrease when compared to conventional mixture.

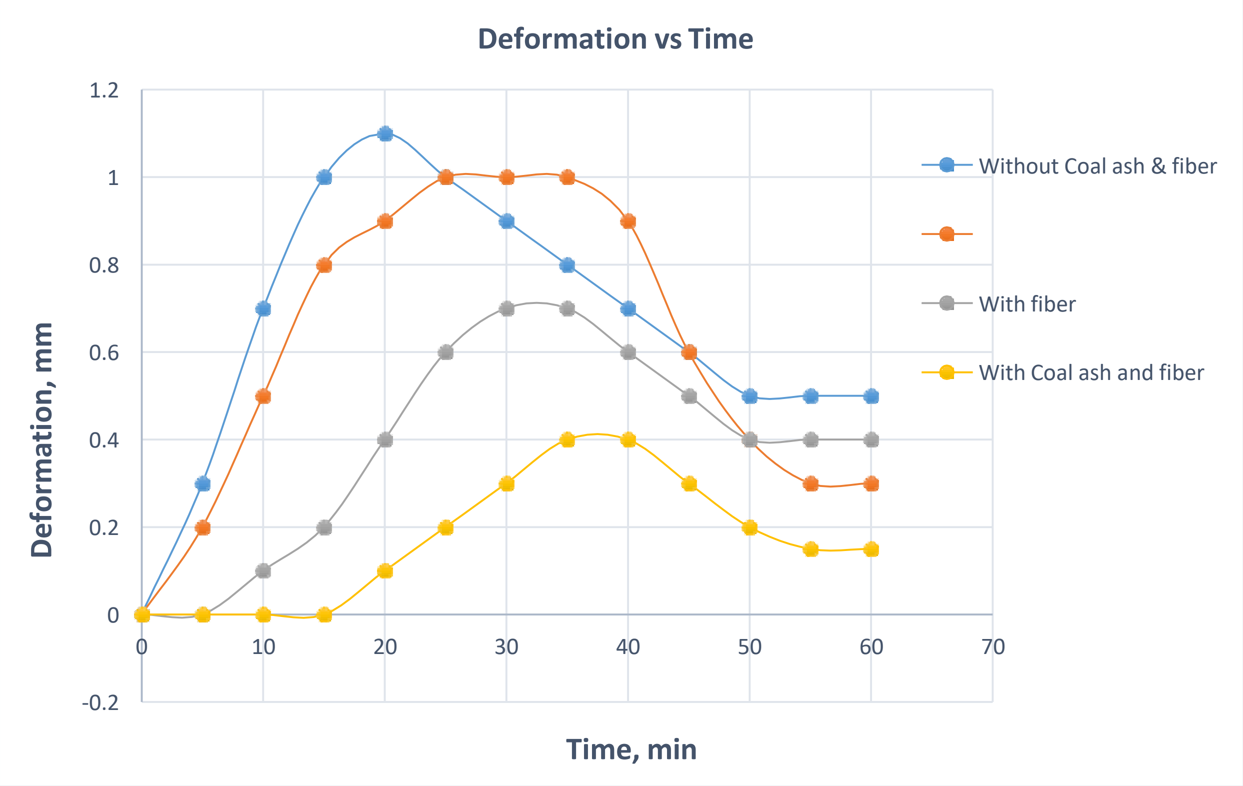


Figure 5.33:- Variation of Deformation Value at 40^{0}C for DBM Sample With Respect ToTime

6. Conclusion and Future Scope

6.1 Conclusion

Based on the experimental investigation of Dense Bituminous Macadam (DBM) mixes modified with coal ash (fly ash and bottom ash) and emulsion-coated sisal fibers, the following conclusions are drawn:

1. The optimum mix comprising bottom ash (300–75 µm), fly ash (passing 75 µm), bitumen content of 5.6%, 0.5% sisal fiber content, and 10 mm fiber length met all Marshall criteria, delivering improved stability and strength.

2. Incorporating coal ash up to 15% by weight of the mix provided acceptable Marshall Stability and flow values, confirming its suitability as a partial substitute for natural aggregates and fillers.

3. An increase in fiber content and length led to a decrease in air voids and flow values, while the Marshall Quotient increased, indicating enhanced stiffness and load-bearing capacity of the mixes.

4. Higher fiber content and length required increased bitumen and emulsion content to ensure adequate coating and bonding, highlighting the importance of balancing mix design parameters.

5. The Indirect Tensile Strength (ITS) test demonstrated that the inclusion of emulsion-coated sisal fibers and coal ash significantly improved thermal crack resistance, enhancing the overall engineering properties of the DBM mix.

6. The Tensile Strength Ratio (TSR) and retained stability values showed marked improvement with the addition of emulsion-coated fibers and coal ash, indicating better moisture resistance and reduced stripping potential.

Overall, the study validates that the combined use of coal ash and emulsion-coated sisal fibers in DBM mixes is a technically viable and environmentally sustainable approach to enhancing pavement performance.

6.2 Future Scope

a) While sisal fiber showed promising results, further research should explore other natural fibers such as jute, coconut, and hemp to evaluate their reinforcing potential in DBM mixes under similar conditions.

b) This study utilized SS-1 (Slow Setting) emulsion for fiber coating. Future investigations should consider the effects of Rapid-Setting (RS) and Medium-Setting (MS) emulsions on fiber performance, bonding behavior, and overall mix characteristics.

c) The role of alternative mineral fillers such as lime and cement should be examined. Lime may improve stripping resistance, while cement could act as a stabilizer. Their effects on the mechanical and durability properties of DBM mixes need to be assessed.

d) Long-term field performance studies of coal ash and fiber-modified DBM mixes should be conducted to validate lab results under real traffic and environmental conditions.

e) Advanced performance tests such as rutting resistance, fatigue life, and dynamic modulus may be included to better understand the behavior of modified mixes under varied loading scenarios.

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