Transp. in Dev. Econ. (2016) 2:4
DOI 10.1007/s40890-015-0008-z

ORIGINAL ARTICLE

# A Study on Use of Natural Fiber for Improvement in Engineering Properties of Dense Graded Bituminous Mixes with Coal Ash

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Received: 29 September 2015 / Accepted: 14 December 2015 / Published online: 2 February 2016


**Abstract** Coal-based thermal power plants have been a major source of power generation in India. The prime waste products of a coal based thermal power plant are fly ash and bottom ash. Heavy dumping of these waste products causes fatal environment pollution to air, water, and land, besides impairing human health. This research work is done to explore the optimum use of ash, namely bottom ash (as part of fine aggregate) and fly ash (as mineral filler) along with natural fiber (such as sisal fiber) used to improvise the engineering properties of bituminous paving mixes. In the present laboratory study, dense graded bituminous mix specimens were prepared using natural aggregates as coarse aggregates, bottom ash as fine aggregates, fly ash as filler and sisal fiber as additive. To strengthen the mix, slow setting emulsion (SS1) coated sisal fiber was added in varying percentages such as 0, 0.25, 0.5, 0.75, and 1 % by weight of the mix, with variations of sisal fiber length such as 0, 5, 10, 15 and 20 mm. The most suitable composition (such as optimum bitumen content and optimum fiber content including the optimum length of fiber in the bituminous mix) was selected based on the results of Marshall tests. Further, for justifying the performances of the bituminous paving mix thus developed, tests for indirect tensile strength and moisture susceptibility in the form of tensile strength ratio and retained stability of bituminous mixes were conducted.

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**Keywords** Fly ash · Bottom ash · Sisal fiber · Dense graded bituminous mix (DBM) · Marshall test · Indirect tensile strength

## Introduction

Aggregates in coarse, fine and filler fractions are the main constituents of the bituminous paving mixes. In many construction sites, aggregates in different size fractions are not easily available, necessitating their procurement from long distances thereby causing exorbitant increase in cost of construction. On the other hand, 70 % of the total power generation in India is due to coal based thermal power plant, that also contribute about 112 million tons of coal ash as by-product waste in every year from 120 coal based thermal power plants (2010–11 data) [5]. Such a huge quantity of this type of waste material does pose challenging problems, in the form of land usage, health hazards and environmental dangers. Hence to suppress the said problems related to these materials, a good number of studies have been attempted to utilize them in a productive way which will satisfy the needs of the society. This particular work is an attempt to utilize these waste materials to some extent by replacing the filler and some fractions of fine aggregates in bituminous paving mixes. In order to enhance the properties of the paving mixes, their modification with different types of fibers is also done. In order to offset the possible drawbacks of using the coal ashes, unlike conventional fibers, naturally, locally and abundantly available sisal fiber has been tried in possible development of sustainable bituminous paving mixes to improve the pavement performance. Sisal fiber is obtained from a plant with a botanical name *Agave sisalana* [12].

Ali et al. observed through an experimental study on the outcome of fly ash on the mechanical properties of bituminous mixtures, that fly ash as mineral filler can be used to increase resilient modulus characteristics and stripping resistance [1]. As per Churchill and Amirkhanian, partial substitution of fine aggregates by coal ash had a moderate detrimental effect on short-term tensile strengths. Results of a limited field study showed that 3 months after placement, metal concentrations in soils were not substantially altered [2]. Colonna et al. studied the feasibility of bottom ash for HMA (Hot Mix Asphalt) mix used in the intermediate courses of flexible pavements. Their results show that the mixtures perform better when 15 % of bottom ash was added to the mixture in replacement of correspond amount of sand [3]. Kar studied the effect of sisal fiber on SMA (Stone Matrix Asphalt) and bituminous concrete (BC) mixtures and he concluded that the optimum bitumen contents for BC and SMA mixes were 5 % and 5.2 % respectively whereas optimum fiber content for each mix was 0.3 % [13]. From the scanty literature available, it is observed that there is no study on utilization of bottom ash and fly ash together in the same bituminous mix and the use of a natural fiber in SMA and BC mixes. Hence, this was the main motivation of the present research work.

In the present study, dense graded bituminous mix specimens were prepared using natural aggregate as coarse aggregates, bottom ash as partial replacement of fine aggregates and fly ash as mineral filler with sisal fiber as a stabilizing additive. Design of the mixtures was done as per Marshall procedure. For characterization of the mixes, various tests such as indirect tensile strength (ITS) and moisture susceptibility test in terms of tensile strength ratio (TSR) and retained stability were taken up.

## Objectives of Study

The prime objective of this study is to use waste materials such as bottom ash and fly ash along with some locally available natural or vegetative fibers in bituminous paving mixes. To achieve this objective, the optimum mix design conditions such as optimum fiber content, optimum fiber length and optimum bitumen content in addition to the appropriate replacement of bottom ash and fly ash are decided as per Marshall method of mix design. Further, the bituminous mixes thus developed have been evaluated in terms of the engineering properties.

## Materials

### Bitumen

Initially, two bitumen grades such as VG-30 and VG-10 (Viscosity Grade) were tried with certain assumed mix compositions and test conditions to study the Marshall characteristics of mixes. The initial trials showed better and satisfactory Marshall characteristics when mixes were made up with bottom ash, fly ash and emulsion coated fiber with VG-30 bitumen as binder. The physical characteristics of VG-30 bitumen used in this study are given in Table 1.

### Aggregate

For this study, stone chips comprising coarse aggregate fractions and fine aggregate fractions ranging from 26.5 mm to 0.3 mm were used. For lower fractions of fine aggregates and mineral filler, bottom ash and fly ash were respectively used to the extent of 9 and 5 % by weight of total mix. Bottom ash procured from the nearby NSPCL (NTPC-SAIL Power Company Limited) thermal power plant and fly ash collected from the nearby Adhunik Metaliks Power plant was used in this study. These material compositions were chosen considering the available quantities in the required size fractions, particularly stressing upon the bottom ash in consideration of the aggregate grading selected. The physical properties of natural aggregates and bottom ash are given in Table 2.

### Additives (Sisal Fiber)

The sisal fiber, a naturally and locally available material which is produced from a plant (shown in Fig. 2) has been used as a stabilizing additive for improving the engineering properties of conventional dense graded bituminous mix (DBM). In this experimental work, sisal fibers were coated with SS-1 (slow setting emulsion) and stored at 110 °C in hot air oven for 24 h [4]. Emulsion coating was made considering the organic nature of the material. Sisal fiber is a cellulose fiber having soft yellowish color. The sisal fiber used in this study is shown in Fig. 1. It is durable, anti-static and recyclable. The chemical composition and physical properties of sisal fiber are given in Table 3.

**Table 1** Physical properties of bitumen used

| SL. No. | Physical properties | IS code/ASTM code | Test result |
|---|---|---|---|
| 1 | Penetration at 25 °C/100 gm/5 s, 0.01 mm | IS:1203-1978 | 46 |
| 2 | Softening Point (°C) | IS:1205-1978 | 46.5 |
| 3 | Specific gravity, at 27 °C | IS:1203-1978 | 1.01 |
| 4 | Absolute viscosity, Brookfield at 160 °C, cP | ASTM D4402 | 200 |

**Table 2** Physical properties of natural aggregate and bottom ash used

| SL. No. | Property | Code specification | Test Result | |
|---|---|---|---|---|
| | | | Natural aggregate | Bottom ash |
| 1 | Aggregate impact value (%) | IS:2386 part-IV | 14 | – |
| 2 | Aggregate crushing value (%) | IS:2386 part-IV | 13.5 | – |
| 3 | Los Angles abrasion value (%) | IS:2386 part-IV | 18 | – |
| 4 | Soundness test result (5 cycles in sodium sulphate) (%) | IS:2386 part-V | 3 | 8.2 |
| 5 | Flakiness index (%) | IS:2386 part-I | 11.9 | – |
| 6 | Elongation index (%) | IS:2386 part-I | 12.5 | – |
| 7 | Water absorption (%) | IS:2386 part-III | 0.14 | 10.75 |
| 8 | Specific gravity | IS:2386 part-III | 2.7 | 2 |

**Fig. 1** Sisal fiber used

**Fig. 2** Sisal fiber plant (Agave sisalana) [12]

**Table 3** Chemical composition and physical properties of sisal fiber used

| SL. No. | Composition | Test result |
|---|---|---|
| Chemical composition [11] | | |
| 1 | Cellulose (%) | 65 |
| 2 | Hemicellulose (%) | 12 |
| 3 | Lignin (%) | 9.9 |
| 4 | Waxes (%) | 2 |
| **SL. No.** | **Property** | **Test result** |
| Physical property | | |
| 1 | Density (gm/cc) | 1.5 |
| 2 | Tensile strength (MPa) | 511–635 |
| 3 | Young's modulus (MPa) | 9.4–2.0 |
| 4 | Elongation at break (%) | 2.0–2.5 |

## Experimental Design

The DBM samples were prepared with aggregates as per gradation specified in MORTH 2013 (Ministry of Road Transport and Highways) [6] given in Table 4 and Fig. 3. The following tests were performed.

- Marshall tests of mixes.
- Static indirect tensile test.
- Resistance to moisture damage in form of TSR and Retained stability test.

## Design Mix

The DBM mixtures were prepared in accordance with the Marshall procedure specified in ASTM D6927-15 [9]. All ingredients of the mixture, such as coarse aggregates, fine aggregates, filler, sisal fibers and VG-30 bitumen were mixed in a specified procedure developed after several trials. However, before preparing the samples, fibers were coated with SS-1 emulsion and stored in a hot air oven at 110 °C for 24 h [4] as shown in Fig. 4a and b and Fig. 5 respectively to drain away the excess emulsion after coating. Then the fibers were cut into specified lengths of about 5, 10, 15 and 20 mm as given in Fig. 6. The aggregates and bitumen were heated separately and maintained at the mixing temperature of 150–160 °C. The temperature of the aggregates was maintained 10 °C higher than that of the binder. Required quantities of bitumen VG-30 and coated emulsion fiber pieces were added to the pre-heated aggregates and thoroughly mixed as shown in Fig. 7a and b. The quantity of binder to be added was calculated from

**Table 4** Gradation of aggregate

| Sieve size (mm) | Adopted gradation (% passing) | Specified limit (% passing) |
|---|---|---|
| 37.5 | 100 | 100 |
| 26.5 | 95 | 90–100 |
| 19 | 83 | 71–95 |
| 13.2 | 68 | 56–80 |
| 4.75 | 46 | 38–54 |
| 2.36 | 35 | 28–42 |
| 0.3 | 14 | 7–21 |
| 0.075 | 5 | 2–8 |

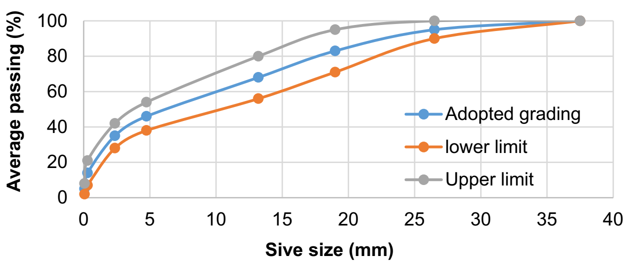


**Fig. 3** Aggregate gradation curve for DBM Mix

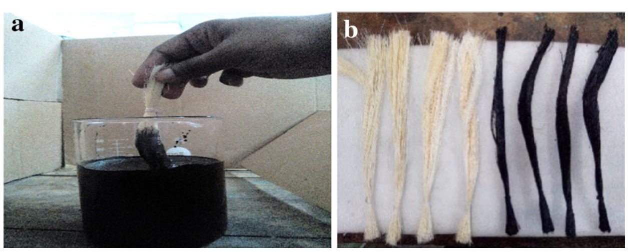


**Fig. 4** Coating of emulsion on fiber

**Fig. 5** Oven dry coated fiber

subtracting the coated emulsion fiber weight from design binder weight. Then thorough mixing was done manually till the colour and consistency of the mixture appeared to be uniform.

**Fig. 6** Cutting of coated fiber

The mixing time and temperature were maintained, i.e. 2–5 min and 150–160 °C respectively. The mixture was then poured into a pre-heated Marshall mould and compacted using Humboldt Automatic Marshall Compactor with 75 compaction blows on each side as shown in Fig. 8. The Marshall samples were extracted from the mould after the specimens were brought to room temperature and thereafter tested in accordance with ASTM D6927-15 procedure [9] as shown in Figs. 9 and 10.

## Static Indirect Tensile Test

Static ITS test of bituminous mixes was performed in accordance with ASTM D6931-12 [8] to assess the resistance to thermal cracking. In this test, Marshall specimens were prepared at optimum composition and loaded in vertical diametrical plane as shown in Fig. 11a, b, c and d. The test temperature was varied from 5 to 40 °C at an increment of 5 °C. The tensile strength values of three mix samples were calculated from Eq. 1 and then the average of results of three samples was reported. The effects of temperature on the ITS of mixes with and without fiber were also studied.

$$St = \frac{2000 \times P}{\pi \times D \times T} \quad (1)$$

where $S_t$ = Indirect Tensile strength, MPa, P = Maximum Load, kN, T = Specimen height before testing, mm, D = Specimen Diameter, mm

## Resistance to Moisture Induced Damage

The resistance to moisture susceptibility of bitumen mixes was measured in terms of TSR and retained stability value.

*Tensile Strength Ratio (TSR)*

In this test, conducted in accordance with the ASTM D4867/D4867 M–09 [7], the specimens of 100 mm

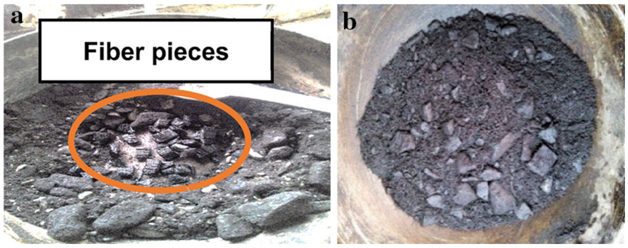


**Fig. 7** Addition of bitumen and fiber followed by thorough mixing

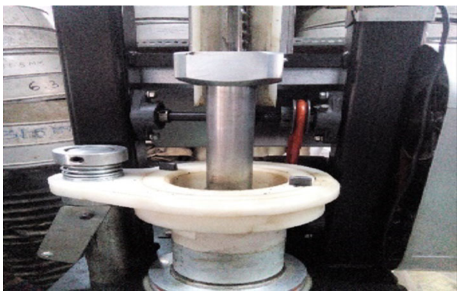

**Fig. 8** Compaction of a Marshall specimen in progress

**Fig. 9** A view of DBM samples before Marshall testing

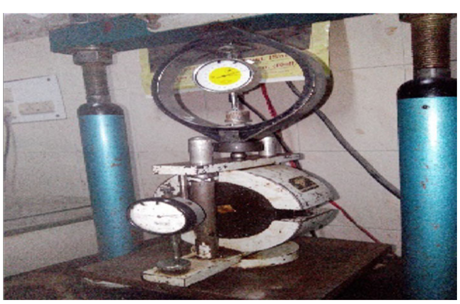

**Fig. 10** Marshall test of a DBM sample in progress

diameter and 62.5 mm height were prepared in gyratory compactor with 7 % air voids as shown in Fig. 12. Six samples of equal average air voids were prepared and divided into two subsets. Samples of one subset were conditioned in water at 60 ± 1 °C for 24 h followed by soaking in water bath at 25 ± 1 °C for 1 h prior to testing and the other set were cured in water bath for 20 min at 25 ± 1 °C. The ITS test was performed at 25 ± 1.0 °C temperature as shown in Fig. 13 for samples of each set. Figure 14 gives a view failed sample with tensile cracks.

The TSR of each sample was calculated from Eq. 2 and the average of results of three samples was reported.

$$\text{Tensile strength ratio (TSR), \%} = \frac{S_{tm}}{S_{td}} \times 100 \qquad (2)$$

where $S_{tm}$ = average tensile strength of the moisture-conditioned subset, kPa, $S_{td}$ = average tensile strength of the dry subset, kPa.

*Retained Stability Test*

The loss of stability in bituminous mixes due to penetration of moisture was measured in the form of Retained stability test. This test was conducted in accordance with the STP 204-22 procedure [10]. In this test, six Marshall specimens were prepared with 4 % air voids and were divided into two sets. Samples of one set were conditioned with water at 60 ± 1 °C for half an hour (unconditioned) and the other set for 24 h (conditioned). Following the conditioning, each sample was tested for Marshall stability value. The retained stability of each sample was calculated from Eq. 3 and the average of three samples of each set was reported.

$$\text{Retained stability, \%} = \frac{S_2}{S_1} \times 100 \qquad (3)$$

where $S_1$ = Unconditioned Marshall stability, kN, $S_2$ = Conditioned Marshall stability, kN

## Results and Discussion

### Mixture Design

From the results of the Marshall tests as presented in Figs. 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 26, it is observed that with an increase in fiber content and fiber length, optimum binder content is increased. The mixtures are more consistent and offer higher stability values with other satisfactory Marshall characteristics when fiber length varies from 5 mm to 20 mm. With an increase in fiber content beyond 0.5 % and fiber length beyond 10 mm in the mixture, the stability decreases. This is corroborated from the experimental observation that during the mixing process, beyond the said fiber conditions, the mixture does not become homogenous enough to result in an appropriate mix.

From the Marshall stability and other characteristics reported above, it is found that the optimum bitumen content of 5.57 % with an optimum fiber content of 0.5 %

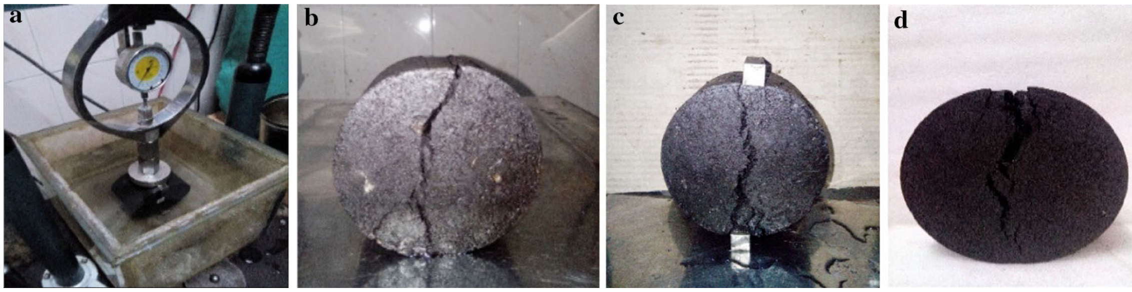


**Fig. 11** Loading of a specimen during ITS Test and different views of specimens after ITS Test

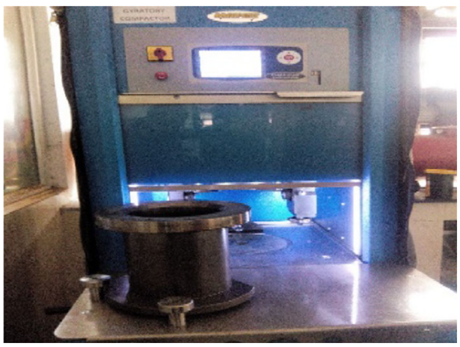

**Fig. 12** A Sample under preparation in a gyratory compactor

**Fig. 13** Moisture susceptibility test in progress

**Fig. 14** View of cracks in DBM sample after failure

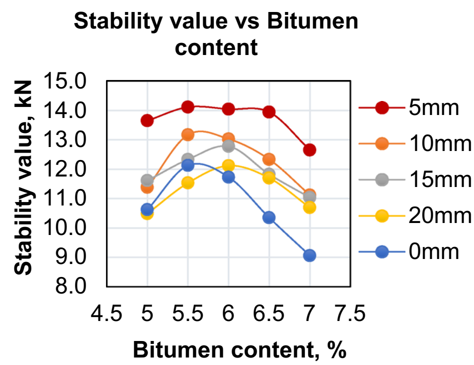


**Fig. 15** Stability value versus bitumen content (0.25 % fiber)

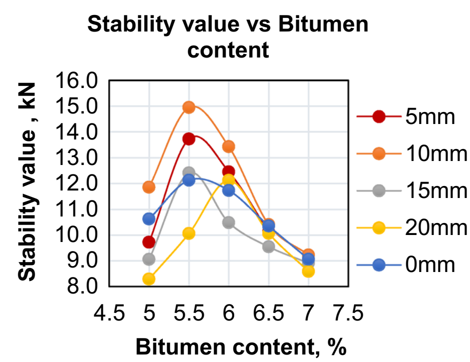


**Fig. 16** Stability value versus bitumen content (0.5 % fiber)

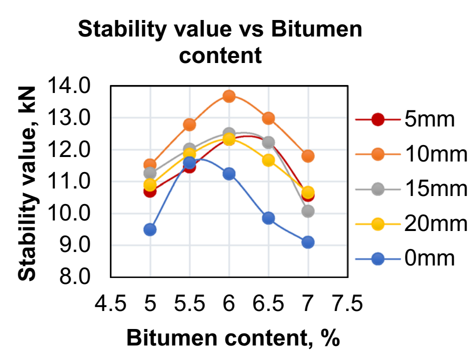


**Fig. 17** Stability value versus bitumen content (0.75 % fiber)

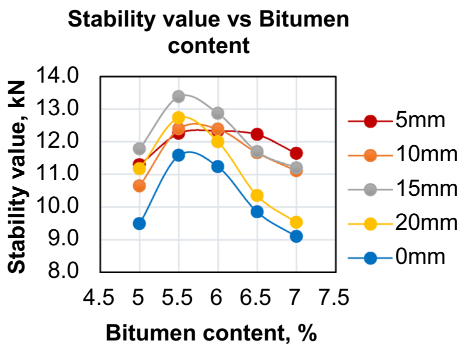


**Fig. 18** Stability value versus bitumen content (1 % fiber)

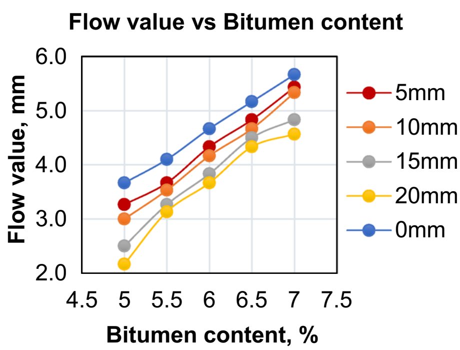


**Fig. 19** Flow value versus bitumen content (0.25 % fiber)

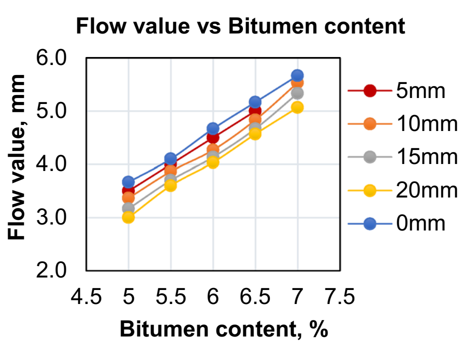


**Fig. 20** Flow value versus bitumen content (0.5 % fiber)

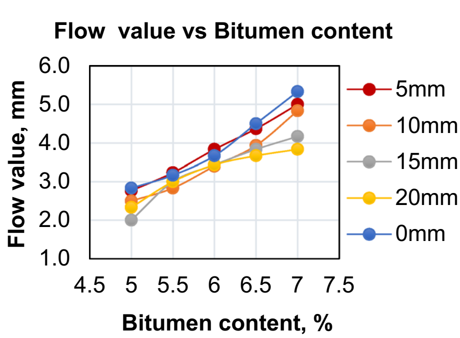


**Fig. 21** Flow value versus bitumen content (0.75 % fiber)

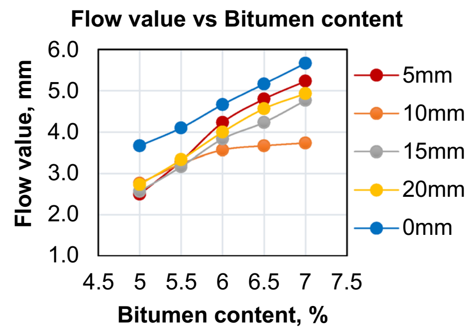


**Fig. 22** Flow value versus bitumen content (1 % fiber)

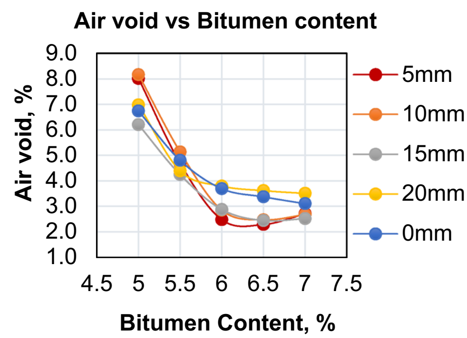


**Fig. 23** Air void versus bitumen content (0.25 % fiber)

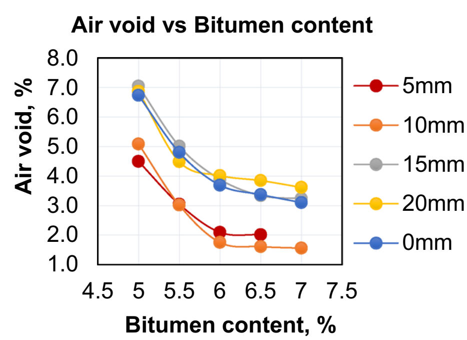


**Fig. 24** Air void versus bitumen content (0.5 % fiber)

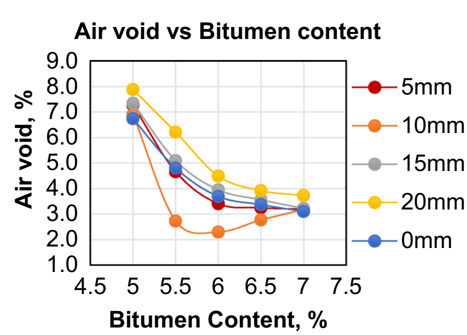


**Fig. 25** Air void versus bitumen content (0.75 % fiber)

by weight of mixture along with fiber length of 10 mm, offers maximum stability value of 15kN satisfying other Marshall criteria. The bitumen requirement is generally observed to be higher as the fine aggregates (partly) and filler comprise of coal-based bottom ash and fly ash in addition to the use of fibers in the paving mixes. Further, this may be due to the fact that as the entirety of the subtracted emulsion is not available to aid in coating of aggregate because possible porosity existing with the sisal fiber.

The summary of results of other Marshall tests not presented above is given in Table 5. Increase of Marshall quotient up to fiber content of 0.5 % indirectly indicates higher resistance to permanent deformation characteristics of bituminous mixes.

### Static Indirect Tensile Test

The variations of ITS with temperature in respect of DBM mixes with or without coal ash and fiber are shown in Fig. 27. As usual, the ITS of any bituminous mix decreases with increase in temperature. But with the addition of coal ash along with emulsion coated fiber, the ITS of DBM sample at any test temperature is higher compared to an un-modified mix. This may be possible due to the criss-cross pattern of fibers present in various parts of the mixture resulting in higher strength in tension. It is also observed that the coal ash contributes to a marginal increase in the tensile strength compared to an un-modified conventional mix, which is an advantage. This may be due to the higher bitumen content in the mix with coal ash.

### Resistance to Moisture Damage

*Tensile Strength Ratio (TSR)*

The results of TSR with respect to different types of mixes considered are presented in Table 6. It is observed that with addition of both fiber and coal ash together, resistance to moisture induced damages improves marginally as compared to the conventional DBM mixture. However, the un-modified mixes satisfy the minimum TSR requirements.

*Retained Stability Test*

The results of retained stability values for unmodified and various modified mixes are presented in Table 7. It is observed that the mix containing both emulsion coated fiber and coal ash results higher retained stability values as compared to the un-modified mix. But the sample prepared only with coal ash and conventional aggregate has shown less resistance to moisture and hence given reduced stability than design requirement.

## Conclusions

Based on the results of a laboratory study the following conclusions are drawn.

(1) From the results of the Marshall tests, it is observed that the DBM mixes prepared with bottom ash and fly ash used respectively in 300-75 micron sizes and passing 75 micron resulted best mixes considering

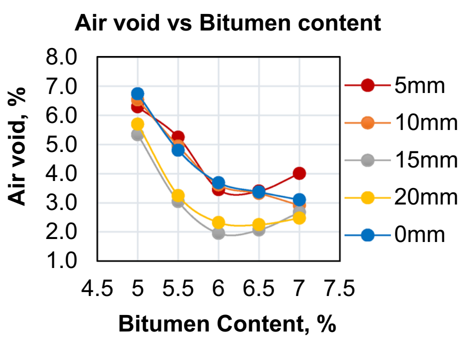


**Fig. 26** Air void versus bitumen content (1 % fiber)

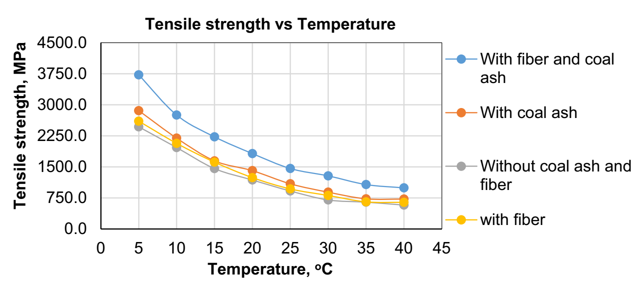


**Fig. 27** Relationship between Indirect Tensile strength and Temperature

**Table 5** Marshall test results

| Sl. nos. | Item/property | Test results | | | | |
|---|---|---|---|---|---|---|
| | Fiber content (%) | 0 | 0.25 | 0.5 | 0.75 | 1 |
| | Fiber length (mm) | 0 | 5 | 10 | 15 | 20 |
| 1 | Bulk specific gravity (kN/m$^3$) | 23.3 | 22.8 | 23.0 | 23.0 | 22.8 |
| 2 | Marshall quotient (kN/mm) | 3.62 | 3.55 | 4.29 | 4.29 | 4.19 |
| 3 | Voids in mineral aggregate (VMA) (%) | 15.30 | 16.70 | 15.80 | 15.90 | 16.10 |

**Table 6** TSR of mixes with and without fiber and coal ash

| Tensile strength ratio | | | Remarks |
|---|---|---|---|
| Type of mixes | DBM With coal ash | DBM without coal ash | |
| DBM with fiber | 84.77 % | 82.04 % | Minimum 80 % (as per MORTH specification) |
| DBM without fiber | 82.35 % | 80.26 % | |

**Table 7** Retained stability of mixes with and without fiber and coal ash

| Retained stability (%) | | | Remarks |
|---|---|---|---|
| Type of mixes | DBM with coal ash | DBM without coal ash | |
| DBM with fiber | 84.05 | 79.94 | Minimum 75 % (as per MORTH specification) |
| DBM without fiber | 73.21 | 77.03 | |

the Marshall criteria as per MORTH specifications when bitumen content, fiber content and fiber length were 5.6, 0.5 % and 10 mm respectively and satisfying other engineering properties studied. A higher value of bitumen content is observed in contrast to the normal requirement of 4.5 % for DBM mix; this is due to the increase in fiber content and fiber length and also due to the use of coal ash in aggregate mixture in the present work.

(2) It is also observed that with increase in fiber content and fiber length up to a given level, air-void and flow value decreases whereas Marshall quotient increases. The latter is a good indication of rutting resistance of bituminous paving mixes in case of the recommended mix composition.

(3) From the ITS test it is observed that the ITS of sample increases due to the addition of emulsion coated fiber and coal ash which gives an excellent engineering property for DBM samples to endure thermal cracking.

(4) It is further observed the use of either emulsion coated fiber or coal ash or both in DBM mix, increases the resistance to moisture induced damages as determined in terms of the TSR and retained stability value.

(5) From the observations made, it can be concluded that the coal ash in finer fractions can be used in DBM layer of a pavement. There can be further improvement in engineering properties of DBM mixes by utilizing non-conventional, yet abundantly and locally available natural sisal fibers.

(6) The coal ash dumping which is a serious concern to everyone associated in respect of its disposal and environmental pollution, can find a possible approach for its reuse in a partial manner in an economical way by substituting natural resources of sand and stone dust which are depleting fast.

## Future scope

(1) In this study, only SS-1 emulsion was considered as a coating medium for sisal fiber, therefore the effects of other types of emulsions such as rapid setting emulsion (RS) and medium setting (MS) emulsion should be taken into account and subsequent tests should be performed for future study.

(2) In this work, the paving mixes as prepared with coal ash and sisal fibers have been studied for all basic engineering properties and they need to be studied for some characteristics under repeated load condition such as resilient modulus, fatigue life and permanent deformation characteristics.

(3) Furthermore, some experimental stretches should be constructed in the field with appropriate traffic situation comprising DBM mixes with the prescribed composition for verifying the results obtained through this laboratory study.

**Acknowledgments** The authors record appreciation of sincere cooperation provided by the staff and PG & research students of the Transportation Engineering section of NIT Rourkela for conduct of this research work. The authors acknowledge the opportunity to present the research work that forms the basis of this article at the 3rd Conference of the Transportation Research Group of India (TRG) held at Kolkata (India) from 17 to 20 December, 2015.

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