Performance of bio-bitumen produced using sugarcane molasses

Dheeraj Mehta
Research Scholar, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, INDIA- 24766, d_mehta@ce.iitr.ac.in

Nikhil Saboo
Associate Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, INDIA- 247667, nikhil.saboo@ce.iitr.ac.in

ABSTRACT: Bio-bitumen has emerged as a sustainable alternative to petroleum bitumen. The renewable nature of bio-bitumen coupled with greener production has garnered significant attention in the pavement industry. This study presents the rheological and mixture performance of bio-bitumen produced using sugarcane molasses. Multiple stress creep recovery (MSCR) and linear amplitude sweep (LAS) tests were undertaken to evaluate the rheological performance, while mixture performance was assessed using wheel rut test and indirect tensile asphalt cracking test (IDEAL CT). The results of the investigation showed that the addition of SM lowered the accumulation of strain. The non-recoverable creep compliance (J_{nr}) was found to be lower in bio-bitumen as compared to conventional bitumen indicating enhanced rutting resistance. The number of cycles to failure (N_f) of bio-bitumen increased, indicating improved fatigue life. Overall, the mixture's performance against rutting and fatigue cracking was found to be satisfactory.

1 INTRODUCTION

The demand for crude oil derived bitumen is on steep rise due to rapid highway construction. The annual consumption of bitumen for the year 2022 stood at 122 million tonnes, as per the report of the International Bitumen Emulsion Federation (Asphalt Institute and Eurobitume 2022). From an Indian viewpoint, the consumption was 8.87 million metric tonnes. The non-renewable nature and ever-increasing price of crude oil generates search for sustainable paving materials. One such renewable material of interest is sugarcane molasses (SM).

SM is a viscous liquid obtained as a by-product of sugar production industry. Typically, SM is made up of sucrose, fructose, and glucose. Additionally, SM has few traces of minerals and has moisture in the range of 15 % - 25 %. India is the world's second-largest producer, with an estimated annual output of 14 million tons. SM is used in soil stabilization, as a retarder in concrete, and is being explored as a partial replacement of bitumen. Hareru and Ghebrab (Hareru and Ghebrab 2020) evaluated the rheological properties of sugarcane molasses modified binders. The results revealed that the addition of SM leads to improved rutting resistance. Phuc Le (Le 2021) studied the performance of sugarcane molasses replaced bituminous mixtures. The resistance against permanent deformation and moisture susceptibility was found to improve. Saboo et al. (Saboo et al. 2023a) explored the feasibility of using sugarcane molasses as a partial replacement of bitumen. Through a set of tests on bitumen and mixtures, they concluded that the incorporation of SM improved resistance against permanent deformation without compromising fatigue resistance. Mehta and Saboo (Mehta and Saboo 2024) assessed the effect of SM source on properties of physical and chemical properties of bio-bitumen. The findings showed that the SM source did not affect the properties of bio-bitumen. Based on the existing literature, it can be seen that limited studies are available on the performance of bio-bitumen. Therefore, the aim of the study is to evaluate the performance characteristics of bio-bitumen binders and mixtures against rutting and fatigue.

2 OBJECTIVES

- To assess the rutting and fatigue resistance performance of bio-bitumen blends using multiple stress creep recovery and linear amplitude sweep tests.
- To evaluate the performance of bio-bitumen mixtures against rutting and fatigue via wheel rut and indirect tensile asphalt cracking test (IDEAL-CT)

3 MATERIALS

Viscosity graded bitumen VG 40 which is widely used in Indian condition was used as a base binder in

the study. Table 1 shows the properties of bitumen as per IS 73.

Table 1 Physical properties of VG 40

Properties	Results	Specifications
Penetration at 25°C, 100 g, 5 s, 0.1 mm	41	35*
Absolute viscosity at 60°C, Poises	4219	3200-4800
Flash point (Cleveland open cup), °C	285	220*
Solubility in trichloroethylene, percent	99.95	99*
Softening point (R&B), °C	52.4	50*
Ductility at 25°C, cm	>100	25*

* Minimum

Sugarcane molasses (SM) is a thick dark brown liquid obtained via sugar refining process. Figure 1 shows the appearance of SM. Table 2 represents the properties of SM.

Figure 1 Appearance of SM

Table 2 Basic properties of SM

Property	Value
°Brix	79
Moisture content, %	15.42
Specific gravity, g/cc	1.402
pH	4.72

4 OPTIMUM DOSAGE AND PRODUCTION PROCEDURE OF BIO-BITUMEN

4.1 *Optimum dosage of SM*

The selection pertaining to optimum dosage of SM was decided based on (a) change in the stiffness of the binder (true fail temperature), (b) flowability (tar viscometer), and (c) moisture sensitivity (10 min boiling test). At each dosage of SM (10 % to 40 % by weight of bitumen), all three criteria were checked sequentially. Until 30 % replacement, all the criteria were satisfied. At 40 % replacement, issues related to flowability were observed, limiting the pumpability of bio-bitumen. Based on the above criteria the optimum dosage was fixed at 30 % of SM by weight of bitumen. In the interest of brevity, the details regarding the criteria are not presented here and can be found elsewhere (Mehta and Saboo 2024; Saboo et al. 2023b; a).

4.2 *Preparation procedure of bio-bitumen*

Bio-bitumen was produced by heating the base binder (VG 40) to a temperature of 130 °C – 140 °C, followed by addition of SM. The blend of bitumen and SM is mixed with a low shear mixer at an rpm of 500 for a duration of 15 – 20 mins.

5 EXPERIMENTAL FLOWCHART

To accomplish the aforementioned objectives the following research plan was adopted as shown in figure 2

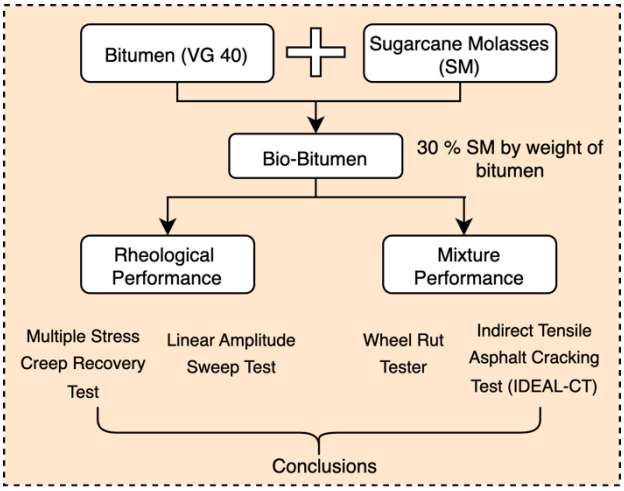

Figure 2 Research methodology flowchart

6 EXPERIMENTAL METHODS

6.1 *Rheological Performance*

The permanent deformation characteristics of bio-bitumen were evaluated using multiple stress creep recovery test as per AASHTO T350. The samples were short-term aged (STA) using rolling thin film oven test. The test was conducted at 50°C, 60 °C, and 70 °C. The range of temperature were considered to account for average maximum pavement temperature. Ten cycles of loading are given at each stress level (0.1 kPa and 3.2 kPa). A small non-recoverable creep compliance (J_{nr}) and higher percentage recovery (%R) are desired for enhanced rutting performance. The intermediate temperature performance of bio-bitumen was evaluated using linear amplitude sweep test (AASHTO TP 101). STA samples were subjected to long term ageing via pressurized ageing vessel. Intermediate test temperature 20 °C was considered. LAS is a two-step wherein a frequency sweep test followed by an amplitude sweep test is performed. The obtained values are used as input to develop relation between number of cycles to failure (N_f) and strain (γ), as depicted in equation 1

$$N_f = A\gamma^B \quad (1)$$

Where A and B are model parameters.

6.2 *Mixture Performance*

The bio-bitumen mixtures were subjected to wheel rut test and IDEAL CT test to evaluate the resistance against rutting and fatigue. For wheel rut tester samples were compacted to 7 % air voids wherein a wheel load of 700 N was made to pass back and forth over the specimen in accordance with EN 12697. The rut depth versus number of passes was recorded. IDEAL CT test was performed on the specimen prepared at 7 % air voids. Three replicates were tested for each mixture. A vertical load on diametrical axis of sample is applied to record the displacement versus load curve. CTindex and asphalt flexibility ratio (AFR), which is ratio of l_{75} by m_{75}. A higher AFR is an indication of better flexibility of the bituminous mixture.

7 RESULTS AND DISCUSSIONS

7.1 *Strain accumulation of bio-bitumen*

Figure 3 depicts the accumulated strains of bio-bitumen at 3.2 kPa^{-1} stress level for test temperatures of 60 °C and 70 °C. The results shown are average of three replicates. As seen, the addition of SM reduced the rate of strain accumulation in bio-bitumen compared to the base binder. At higher temperature, the smaller accumulation of strain ensures good rutting performance.

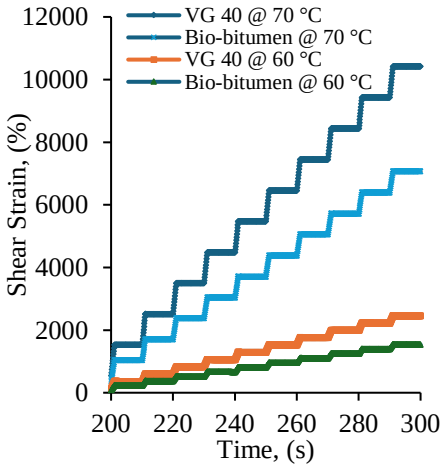

Figure 3 Strain accumulation of bio-bitumen

7.2 *Non recoverable creep compliance (J_{nr}) and percentage recovery (%R)*

The permanent deformation characteristics of bio-bitumen were quantified using non-recoverable creep compliance (J_{nr}) and percentage recovery (% R). A lower value J_{nr} indicates a small irrecoverable strain of bitumen. Figure 4 shows the variation of J_{nr} at 3.2 kPa stress level. It can be seen that the J_{nr} value increases with increase in test temperature whereas % R decreases (refer table 3). In general, regardless of the test temperature, the bio-bitumen showed better rutting resistance than the base binder. For instance, at 70 °C, the J_{nr} of bio-bitumen was found to be 32 % lower than VG 40. As seen, the %R value reduced with increase in temperature. At 50 °C and 60 °C, bio-bitumen showed equivalent or slightly better recovery than base binders. However, at 70 °C no binder showed recovery. In summary, the enhanced rutting resistance could be linked to the chemical interaction between SM and bitumen leading to lower non-recoverable creep compliance.

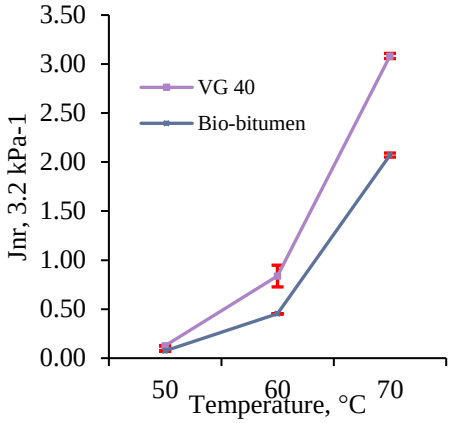

Figure 4. Non-recoverable creep compliance of bio-bitumen

Table 3 Percentage recovery of bio-bitumen

	@50 °C	@60 °C
VG 40	16.3 %	3.2 %
Bio-bitumen	21 %	5 %

7.3 *LAS*

The fatigue life of bio-bitumen was assessed using number of cycles versus strain as presented in figure 5. Two replicates were considered. The fatigue life of bio-bitumen increased with the addition of SM. For bio-bitumen sample at 20 °C (5 % strain), the fatigue life increased by 3.55 %. The improvement in fatigue life can be attributed to gummy interaction imposed by SM to bitumen resulting in enhanced elasticity. Overall, it was found that the addition of SM led to improved intermediate temperature performance.

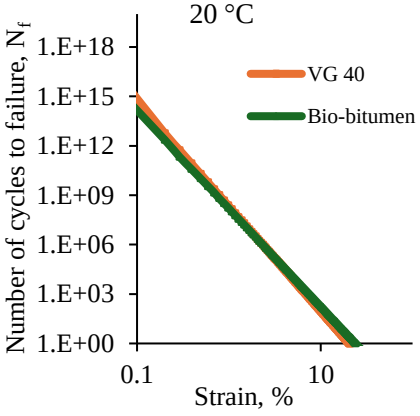

Figure 5 Variation of number of cycles to failure versus strain of bio-bitumen

7.4 *Rutting resistance of mixtures*

Figure 6 shows the variation of rut depth over the course of 20000 passes at 60 °C. As can be seen, the rut depth progression of bio-bitumen was lower than the base binder. At the end of 20000 passes, the rut depth of bio-bitumen and VG 40 was 4.91 and 5.58 mm, respectively. Overall, the incorporation of SM resulted in enhanced resistance against permanent deformation.

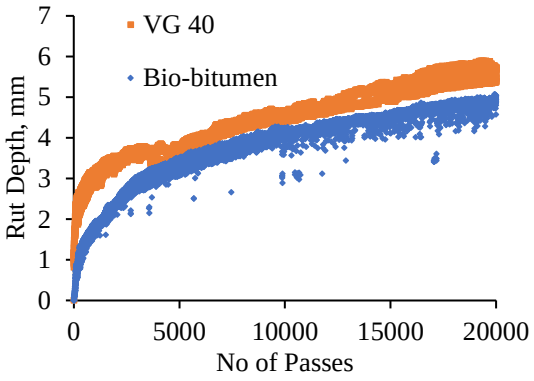

Figure 6 Rut depth versus number of passes of bio-bitumen

7.5 *Fatigue resistance of mixtures*

Figure 7 shows the IDEAL CT index and AFR of VG 40 and bio-bitumen mixtures. As can be seen, the incorporation of SM resulted in higher CT_{index} and AFR. The CT_{index} values of bio-bitumen were 20 % higher than control mixture. The higher values of AFR indicate improved cracking resistance of bio-bitumen. The formation of elastic compounds during interaction of SM and bitumen is expected to enhance elasticity, resulting in higher AFR values. However, the exact nature of interaction needs further exploration.

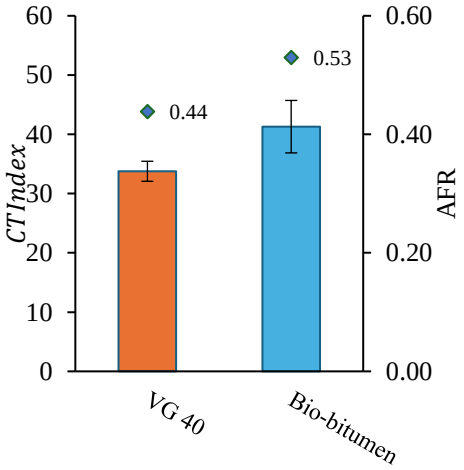

Figure 7 CTindex and AFR variation of bio-bitumen

8 CONCLUSIONS

This study evaluated the rheological and mixture performance of bio-bitumen against permanent deformation and fatigue resistance.

- The addition of SM through MSCR test results revealed that bio-bitumen had lower rate of strain accumulation and lower non recoverable creep compliance.
- The number of cycles to failure slightly increased, indicating an improved fatigue life of bio-bitumen in comparison to base binder.
- Through wheel rut testing, it was found that bio-bitumen mixture had lower rut depth compared to control mixtures.
- The bio-bitumen mixtures had 20 % CTindex than the control mixtures.

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