Fatigue Analysis of Coir Powder Modified Bitumen Using Linear Amplitude Sweep Test

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ABSTRACT

The fatigue resistance of the asphalt binders is significant in the fatigue performance of asphalt pavements. Previously, the Super-pave specification parameter $|G^*|\sin\delta$ was identified and used for rating the asphalt binders based on their fatigue resistance. However, in ensuing research works, it was found that this parameter does not relate well with the accumulation of fatigue damages under strain-controlled conditions and significant efforts had been carried out to accurately measure and characterize the fatigue resistance of binders in a way that had been suitable for inclusion in binder specifications. This led to the suggestion of a new binder fatigue test using the linear amplitude sweep test in the DSR (dynamic shear rheometer) to find out the number of cycles to fatigue failure (Nf) and the effectiveness of this parameter to consider as the criterion for rating the binders based on their fatigue resistance. This study uses the Linear Amplitude Sweep (LAS) test at a temperature of 25°C in which the amplitude of the applied load was continually increased from 0 to 30% over the course of 3100 cycles to accelerate the growth of damage on the short term and long-term aged binders. This study deals with the fatigue analysis of VG30 bitumen with and without varying percentage (0% to 1.2%) of coir powder. Different laboratory tests such as penetration value, softening point, ductility and viscosity have been performed on all the samples. Fatigue performance parameters of binders with and without coir powder were also evaluated. Results of this study showed that the addition of the additive increases the fatigue life and aging resistance of the binders. The results revealed that the addition of additive enhances the binder properties. Besides, the results indicated that the elastomeric modified binder gave the best performance in fatigue.

Keywords: Linear Amplitude Sweep Test, Coir Powder Modified Bitumen, Fatigue life

1. INTRODUCTION

Flexible pavements constitute a critical aspect of modern transportation infrastructure, designed to endure dynamic and repetitive loading conditions. The main component of asphalt, bitumen, is essential to the structural integrity and long-term endurance of these pavements. On the other hand, resistance to fatigue damage has a significant impact on the service life of pavements, and fatigue damage is one of the main distresses in asphalt pavements linked to long-term aging. The primary cause of fatigue damage to asphalt pavement is recurrent loading over the service life [5]. Numerous studies have been carried out to improve bitumen's properties by modification techniques, with the aim of enhancing its resistance to strain and fatigue. Studies using a variety of additions, including chemical and natural additives, have been conducted [4,9]. The utilization of waste materials as additives in building is becoming more and more important in the modern era of sustainable construction. So, it is preferable to use natural additives that are produced as waste or by-product rather than artificial additions.

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The qualities of bitumen have been demonstrated to improve with the use of natural additives such coir powder, a by-product of coconut husk [4,7].

Large-scale studies have concentrated on developing experimental laboratory testing procedures, theoretical model creation, and data analysis to precisely forecast the fatigue performance of asphalt pavements. It is possible to do fatigue study on both the mix and the binder in pavement materials. Investigations show that most efforts have been focused on asphalt aggregate mixes; asphalt binders have been the subject of less recent investigations [12]. The Dynamic Shear Rheometer (DSR) has been the equipment of choice for many researchers that are developing an experimental testing approach to assess the fatigue of asphalt binders. By measuring the asphalt binder's response to applied stresses or deformations, the DSR, a kind of rotating rheometer, uses oscillatory shear to evaluate the material's rheological behavior. Numerous material functions, such as the complex modulus $|G^*|$, phase angle δ, storage modulus G', loss modulus G", and practical combinations of these values, are used to characterize the viscoelastic characteristics of the asphalt binder [5,6,8]. The Superpave standard suggests using the parameter $|G^*|\sin\delta$ at a specified frequency and temperature to gauge the asphalt binders' fatigue resistance. Researchers are using a variety of accelerated testing techniques to accurately and swiftly measure the amount that asphalt binders contribute to mixture fatigue [5,8,9]. The Linear Amplitude Sweep (LAS) test, which is now a standard test procedure for binder fatigue evaluation in AASHTO designation, was one among the tests that received strong approval from experts. The current approach to binder fatigue analysis uses the concepts of Viscoelastic Continuum Damage (VECD) mechanics to calculate the binder's fatigue life from the strain in the pavement. The Linear Amplitude Sweep (LAS) test, on the other hand, uses cyclic loading with gradually rising load amplitudes to speed up damage and produce enough data for an in-depth examination [9,10,12]. The test was conducted using oscillatory shear in strain control mode at a frequency of 10 Hz and a temperature of 25^0C in accordance with AASHTO standard TP 101-14. In order to cause fatigue damage in the binder, the load was increased linearly from 0% to 30% over 3100 loading cycles. The fatigue failure point was determined to be the point that matches the reduction in initial $|G^*|$ at the maximum shear stress. It seemed sense to investigate the AASHTO-recommended method as a possible test to see how binders performed under fatigue. When choosing the ideal conditions for the Linear Amplitude Sweep Test in DSR, care should be taken even in the smallest detail, like heating the peltier plate and measuring system to 64^0C, to prevent errors brought on by specimen edge fracture or failure due to insufficient plate adhesion [1,5,6,10].

2. MATERIALS USED

One of the binders most frequently used in India for the building of asphalt pavements is VG30 bitumen; this particular binder was chosen for the study. The binder was obtained from Hindustan Petroleum Pvt. Ltd.; it was delivered in sealed containers to guard against oxidation, premature aging, and contamination from outside sources. The study used coir powder, which has a particle size of less than 75 microns, as an addition. In mills, coir fiber is ground into a powder and then passed through a 75-micron screen. Six samples in all were made with the different additive amounts. The samples prepared were:

i VG 30
ii VG 30 + 0.4% Coir Powder
iii VG 30 + 0.6% Coir Powder
iv VG 30 + 0.8% Coir Powder
v VG 30 + 1.0% Coir Powder
vi VG 30 + 1.2% Coir Powder

3. EXPERIMENTAL INVESTIGATION

The coir powder is mixed with VG 30 bitumen to create the samples. After heating the bitumen to 165^{0}C, different percentages of coir powder—ranging from 0 to 1.2% by weight of bitumen—are added to the bitumen. After that, it is mixed for 30 minutes at 165˚C using a laboratory shear mixer. Since it has been demonstrated in earlier research that adding 0.2% of coir powder has no discernible impact, the 0.2% is left out [4,7,11]. According to the Bureau of Indian Standards (BIS), physical property tests such as viscosity using a Brookfield viscometer, ductility, specific gravity, softening point, and penetration are carried out on all these modified and unmodified binders to ensure sample identification and to compare the effects of additives in the binders [4,11]. Next, in compliance with AASHTO T240, these samples are short-term aged utilizing a Rolling Thin Film Oven (RTFO) at 163^{0}C for 85 minutes [2]. The binder is then long-term aged within 72 hours of short-term ageing using pressure ageing vessel at 100^{0}C and 2.08MPa for 20 hours in accordance with AASHTO R28 [3]. The sample was removed, and degasification was carried out at -25Hg/mm pressure and at 170^{0}C for 30 minutes, following which these samples are subjected to the LAS test [6].

The frequency sweep and amplitude sweep tests are the two components of the LAS exam. The undamaged material characteristics, represented by the value α, were determined during a frequency sweep test carried out with the Anton Paar® Dynamic Shear Rheometer as part of the damage analysis. The test was performed at the selected temperature with an applied load of 0.1 percent strain across a frequency range of 0.2 to 30 Hz. It applies oscillatory shear loading at constant amplitude throughout a range of loading frequencies. At each of the frequencies listed, the following data were recorded: phase angle [δ, degrees] and complex shear modulus [|G*|, Pa]. The reciprocal of the slope of the Log (ω) vs. Log G'(ω) curve yields the α value [1,6,8].

To measure the material's damage characteristics, an amplitude sweep test with oscillatory shear in strain-control mode at a frequency of 10 Hz was carried out at the selected temperature. The loading strategy consisted of a continuous oscillatory strain sweep. 3100 loading cycles with a linear increase in loading from 0% to 30% were finished. Peak shear stress and peak shear strain were recorded at each of the ten load cycles (1 sec), together with peak shear modulus [|G*|. Pa] and phase angle [δ, degrees]. The temperature at which the test was performed was 250C. The following damage calculation approach was used to analyse the amplitude sweep test data [1,8,9].

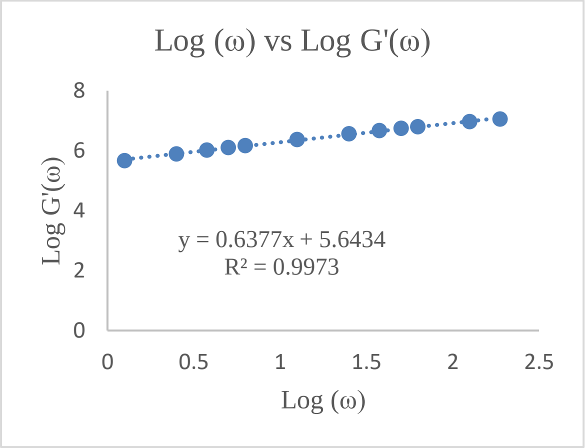

Figure 1: Graphs showing the plot to find alpha values for VG 30

The damage accumulation in the specimen was calculated using the following summation:

$$D(t) = \sum_{i=1}^{N}[\pi\gamma_0{}^2(C_{i-1} - C_i)]^{\alpha/(1+\alpha)}(t_i - t_{i-1})^{1/(1+\alpha)} \qquad (1)$$

Where,

C(t) = G*(t) /G*initial; which is G* at time t divided by the initial "undamaged" value of G*.

γ_o= applied strain for a given data point in percent.

G* = Complex shear modulus, MPa

α=undamaged material properties represented as a parameter.

t = testing time in second.

The failure definition in the LAS test is defined as 35% reduction in the initial modulus. The fatigue parameter N_f is given by

$$N_f = A(\gamma_{max})^B \qquad (2)$$

where A and B are VECD model coefficients that depend on the material characteristics.

The 'A' parameter denotes a material's ability to maintain its integrity over loading cycles and as a result of cumulative damage. This value is proportional to the storage modulus. The 'B' parameter describes the asphalt binder's sensitivity to changes in strain level. Higher absolute values of the B parameter show that when the strain level amplitude increases, the fatigue life reduces at a faster rate. In general, more fatigue resistant binders tend to have higher 'A' values and lower absolute 'B' values [1,12].

4. RESULTS AND ANALYSIS

The physical property tests conducted are penetration, specific gravity, viscosity, ductility and softening point test on binders with different percentages of coir powder. Through penetration and softening point, it was found that coir fiber significantly improved the physical properties of the bitumen. This indicates that the addition of coconut fiber as modifier in bitumen has increased the hardness of the bitumen and has a greater temperature susceptibilitywhich is a similar observation made by Azril et.al. [4]. The LAS test was conducted on all these binders as per standards.

4.1 Change in penetration values with respect to different percentage of additives

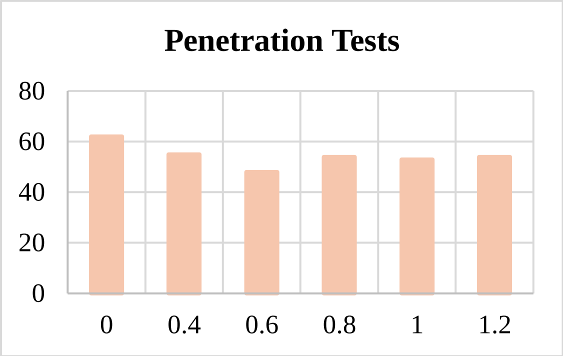

Figure 2: Penetration test

The figure 2 sows the variation of penetration values with respect to the increase in percentage of coir powder wen tested under 25^0C. When the content of coir powder rises to 0.6%, the penetration value appears to be declining until an upward trend is observed. That is, the value of penetration increases from 48 to 54 when the composition of coir powder grows from 0.6 to 1.2%, and decreases from 62 to 48 when it climbs from 0 to 0.6%.

4.2 Change in specific gravity values with respect to different percentage of additives

The figure 3 depicts that the specific gravity seems to be decreasing when the composition of coir powder increases. That is the value of specific gravity reduces from 1.01 to 0.97 when the coir powder composition increases from 0 to 1.2%. But it is seen that all the specific gravity value falls within the limit of 0.96 to 1.02.

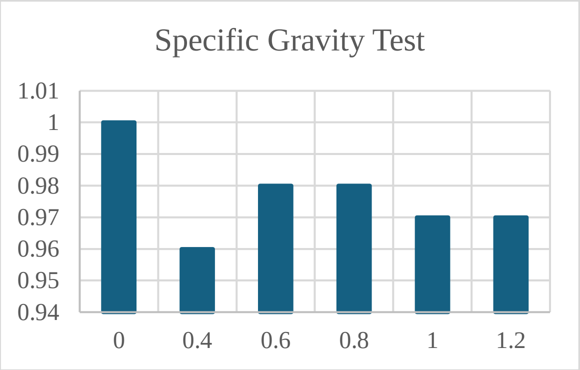

Figure 3: Specific Gravity test

4.3 Change in viscosity with respect to different percentage of additives

The viscosity test is conducted using the Brookfield apparatus at a temperature of 135^{0}C. The results obtained are shown in the figure 4 in which viscosity seems to be increasing when the composition of coir powder increases until 0.6% and then an increasing trend is seen. That is the value of penetration increase from 556 to 935 when the coir powder composition increases from 0 to 0.6% and then decrease from 935 to 776 when the coir powder composition increases from 0.6 to 1.2%.

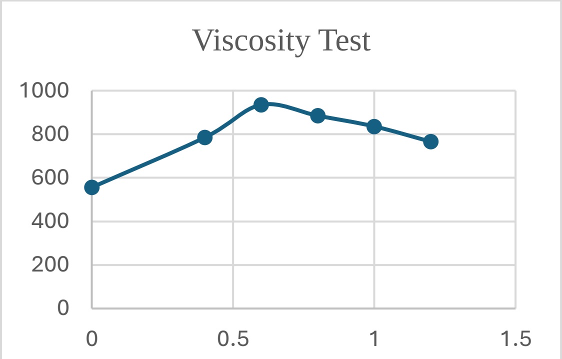

Figure 4: Viscosity test

4.4 Change in ductility with respect to different percentage of additives

The figure 5 shows the results from ductility test in which it is seems to be decreasing when the composition of coir powder increases. That is the value of softening point reduces from 100 to 63 when the coir powder composition increases from 0 to 1.2%.

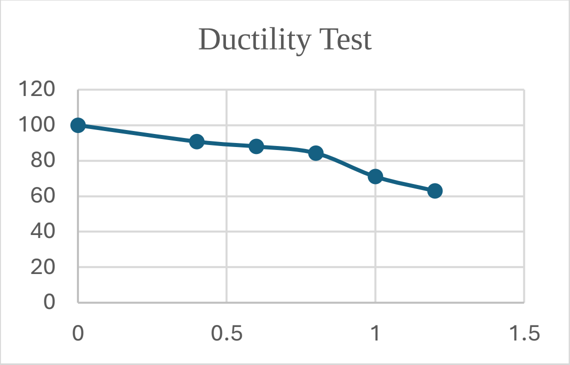

Figure 5: Ductility test

4.5 Change in ductility with respect to different percentage of additives

The softening point seems to be increasing when the composition of coir powder increases until 0.6% and then an increasing trend is seen, as per depicted in the figure 6. That is the value of penetration increase from 49^0C to 52^0C when the coir powder composition increases from 0 to 0.6% and then decrease from 52^0C to 50^0C when the coir powder composition increases from 0.6 to 1.2%.

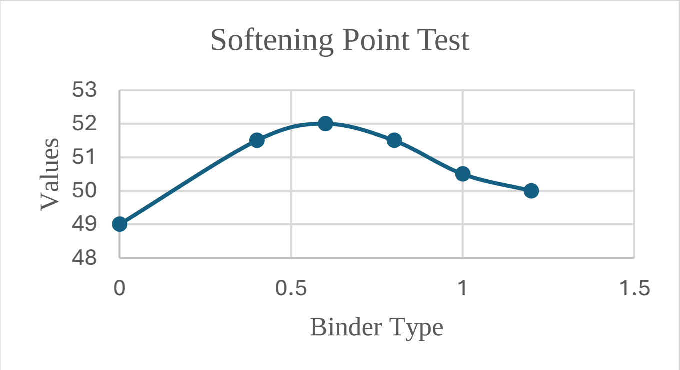

Figure 6: Softening Point test

4.6 Fatigue parameter of binders

The table 1 shows the fatigue parameter N_f of unmodified and coir powder modified VG 30 binders at 5% and 2.5%. It is observed that the addition of coir powder has increased the fatigue life to a certain percentage of additive later on which shows a fall in the trend. There is significant change in fatigue life of VG 30 bitumen when treated with 0.6% of coir powder.

Table 1: N_f Values of Binders at 5% and 2.5% Strain.

Binder	**N_f Values at 2.5% strain**	**N_f Values at 5% strain**
VG30	10,54,708	29,989
VG30+0.4% Coir Powder	10,86,029	27,575
VG30+0.6% Coir Powder	19,83,253	50,110
VG30+0.8% Coir Powder	9,66,417	25,235
VG30+1.0% Coir Powder	2,32,277	5,508
VG30+1.2% Coir Powder	1,35,957	3,412

From the plot of Log Nf VS Log Shear Strain which is provided in the figure 7, it is seen that at lower strains the Nf values are higher and as the strain value increases the Nf values decreases. The addition of 0.4 and 0.6% additives increased the Nf of the neat binder significantly. At higher strains also the effect was significant. But the addition of binders above 0.6% seems to have a negative impact on the fatigue life of the binder. Among the three additives (pure VG30, VG30 + 0.4% coir powder and VG30 + 0.6% coir powder), the effect of VG30 + 0.6% coir powder at lower strains was more dominant as in the case of other binders and followed by VG30 + 0.4% coir powder and then VG30. At higher strains, VG30 showed higher Nf values when compared with VG30 + 0.4% coir powder.

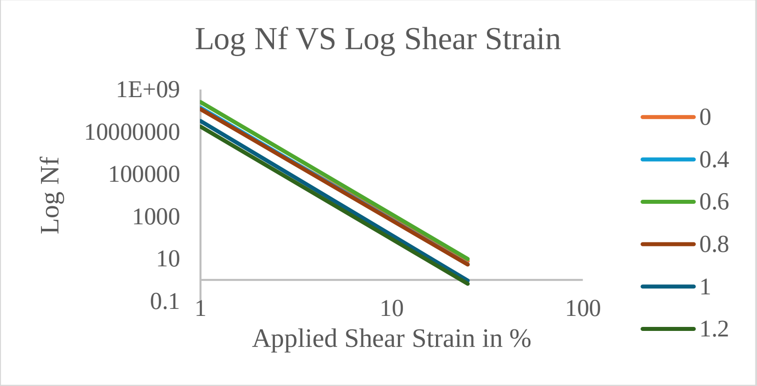

Figure 7: Graph Showing Variation of N_f with Different % of Strain

4.7 Comparison of Nf values, Area under the stress strain curve till failure and G*.sinδ of binders with different percentage of additive

One statistical technique that is utilized for many different types of analysis is the area under the stress-strain curve. The material's energy absorption prior to failure is represented by the area under the stress-strain curve; a larger area suggests that the material can endure higher loading and absorb more energy before failing. In contrast to brittle materials, ductile materials have a larger area beneath the curve. The materials should have an excellent trade-off between strength and ductility in order to have a larger area under the curve. This area under the curve till failure is used to study the fatigue parameter of the binders. The area of the curve is restricted by the x, y, and line connecting the x axis to the fracture point (peak shear stress). The trend in rising binders' Nf values was compared to the trend in rising area under the curve until failure stress and the super-pave fatigue parameter G*.sinδ at 1% strain, as illustrated in figure 8. Rather than the fatigue parameter G*.sinδ, the change in Nf values more closely resembled the pattern that was followed by the areas under the curve till failure.

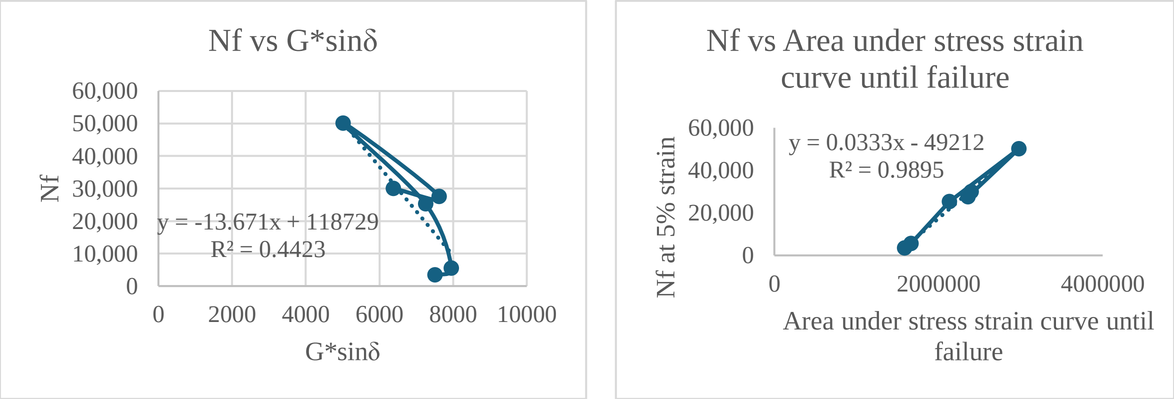

Figure 8: Trend Line for Nf VS G*.sinδ VS Area under the Curve

5. CONCLUSIONS

This study investigated the influence of coir powder additive on the fatigue performance of VG30 asphalt binders. Various percentages of coir powder (0%, 0.4%, 0.6%, 0.8%, 1%, and 1.2%) were added to the binder, and the modified binders were subjected to physical property tests, Frequency Sweep tests, and Linear Amplitude Sweep tests to evaluate fatigue performance. Aging simulations were conducted using Rolling Thin Film Oven (RTFO) and Pressurized Aging Vessel (PAV) to replicate short-term and long-term aging, respectively. Additionally, Stone Mastic Asphalt (SMA) mixes were prepared, and repeated load tests were performed to study the fatigue properties of the mix. The results indicated that the physical properties of bitumen improved with the addition of coir powder, with increased softening point and viscosity but decreased penetration and ductility. The Linear Amplitude Sweep test proved effective in predicting the fatigue performance of bituminous binders, while the indirect tensile fatigue test was identified as a simple and efficient method for determining the fatigue parameters of the mix. The major observations from the tests revealed that the 0.6% coir powder-modified binder exhibited the highest retained penetration and minimal change in softening point, indicating optimal stiffness enhancement. Ductility values decreased with increasing coir powder content, suggesting improved brittleness. Specific gravity values varied, reflecting changes in binder composition, while viscosity increased up to 0.6% coir powder, indicating reduced flowability. Fatigue cracking resistance improved up to 0.6% coir powder, as evidenced by G*sinδ values, but declined at higher percentages. The fatigue parameter followed a trend similar to the area under the stress-strain curve, indicating a stronger correlation with fatigue performance than the Superpave fatigue parameter. Overall, the study demonstrated that coir powder additives, particularly at 0.6%, significantly enhance the fatigue performance and stiffness of asphalt binders, making them a promising material for improving pavement durability.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research was conducted independently, and no funding or support was received from any organization or entity that could pose a conflict of interest.

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