Effects of Waste Denim Fibre (WDF) on the physical and rheological properties of bitumen

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Abstract. About 15% of the denim jeans are waste materials during the cutting processing in the manufacturing. That is considering a huge waste need to be managed and recycled in a sustainable manner. In this research, waste denim fibre modified binders were prepared at 0.5%, 1%, 1.5% and 2% concentration of waste denim fibre by weight of bitumen. Effects of waste denim fibre on physical and rheological properties of bitumen were investigated by conducting penetration, softening point, ductility, temperature susceptibility, complex modulus, phase angle and permanent deformation parameters evaluations. Results show that the addition of waste denim fibre reduces the penetration, ductility and temperature susceptibility and increases the softening point of bitumen, which indicating improved permanent deformation resistance of bitumen. Based on dynamic shear rheometer analysis, it was found that, waste denim fibre improved the rheological properties of bitumen from a temperature range of 40ºC to 70ºC. Furthermore, rutting parameter evaluation indicated that denim fibre modified bitumen has high resistance to rutting due to the enhancement of its elastic behaviour with increased of denim fibre content in the modified binder. It was also noted that 2% WDF is the optimum content for improving the rutting resistance of base bitumen.

1. Introduction

Bitumen is a complex viscoelastic material that has the main essential role in the asphalt pavements performance [1]. It contributes in about 95% of pavements construction among the all-world pavements. These pavements suffer from different types of failures over time due to the increasing of the axial loads, heavy traffic, and change in the environmental conditions during the last few decades. Among those failures, the rutting, fatigue and low temperature cracking distresses are the most common [2]. The researchers and engineers are continuously looking for improvement the properties of the bitumen and then the performance of asphalt mixtures and pavements. The most common approach is the modification of bitumen [3, 4]. Bitumen industries are also looking for the sustainable modifications alternative ways to improve the performance of the asphalt road pavements, as well as reduce its carbon footprint [5]. In general, fibers and polymers are the most two substantial cases used for this purpose [4, 6, 7].

Recently, there is a great interested in using the composite materials, especially, those related with the environmental and sustainability aspect which has a great impact on the society. one of such materials is waste denim fibre [8]. Waste Denim fiber (WDF) is considered a new waste fibre introduced in construction field to reinforce the concrete and building materials and to solve the environmental problem due to denim waste from the garments that have been purchased then disposed and from the
textile waste of the factories and the garments goods that have not been sold [9, 10]. Biocomposite also produced from waste of denim and bio-resin to replace the certain petroleum-based products applications which turn to reduce the petrochemical materials, and reduce the environmental damaged by waste denim materials [10]. The most common standard fibers used in asphalt are too expensive which leads to increasing the total cost of the asphalt mixture [11, 12]. Researchers and Governments are looking for new fiber materials from urban waste, industries or agricultural to be applied in the industrial and engineering applications to reduce the final cost of such engineering products and contribute in reduction the environmental pollutions [11, 13]. Therefore, in this study, Waste denim fiber (WDF) was introduced and evaluated as a new modifier for improving the physical and rheological characteristics of base bitumen.

2. Materials and Modification Process

2.1. Materials
The base bitumen 60/70 penetration grade was used which supplied by PETRONAS refinery, Malacca, Malaysia. Waste denim fibre (WDF) was obtained from waste of Jeans labelled by the manufacturer as 100% cotton. The WDF was cut to small pieces then a Knife mill used to reduce the size. The end size of WDF used in this study was from 1000 to 1500 µm.

2.2. Modification Process
Base bitumen was melted at temperature of 160 °C till becomes sufficiently fluid. A weighted 0.5%, 1%, 1.5%, and 2% of waste denim fibre by the weight of base bitumen binder were gradually added to the base bitumen. The blends were prepared using high shear mixer at 160 °C and blending rate of 4000 rpm for 90 minutes to obtain a homogenous mixture.

3. Experimentation Method

3.1. Penetration Test
The penetration test was carried out based on ASTM D5-13 standard at 25 °C and time period of 5 seconds under a load of 100g to establish the consistency of base and modified bitumen. The penetration depth was recorded in units of 0.1 mm as the penetration value of the specimens of binders.

3.2. Softening Point Test
The softening point of various samples of bitumen was measured based on ASTM D36-12. is used for establishing the temperature at which bitumen softens. Softening point was taken as the temperature at which bitumen cannot longer support the weight of a 3.5 g steel ball at the uniform rate of temperature (5°C/min).

3.3. Ductility Test
Ductility test can indicate the performance of bitumen in high and low temperature. According to ASTM 113, the ductility test was conducted to measure the stretching length of base and modified bitumen samples. Test carried out at 5cm/min deformation speed and 25 °C temperature.

3.4. Temperature Susceptibility
Temperature susceptibility for base bitumen and WDF-modified bitumen was evaluated according to penetration index parameter. Softening point and penetration tests results were used in estimation of PI according to Eq. 1. shown below.

\[
PI = \frac{1952 - 500 \times \text{Log Pen} - 20 \times SP}{50 \times \text{Log Pen} - SP - 120}
\]  

(1)

When pen is the penetration at 25 °C and SP is the softening point in °C.
3.5. Dynamic Shear Rheometer Test

Rheological characteristics of base and modified bitumen were determined by a Malvern Kinexus rheometer according to ASTM D7175-15 standard. Temperature sweep test was carried out under frequency of 10 rad/s over a temperature range of 40 to 70°C and controlled strain loading mode. The plate of 25 mm diameter and 1 mm gap geometry were applied. The testing temperatures were selected at 40, 46, 52, 58, 64, and 70°C considering the objective of this study to investigate the high-temperature performance of WDF-modified asphalt binders.

4. Results and Discussions

4.1. Penetration Test

Effects of waste denim fibre on penetration of base and WDF-modified bitumen binders are shown in Figure 1. It was observed that as the content of waste denim fibre increases the penetration value of WDF-modified binder decreases. That reduction in penetration may result in an improvement of modified bitumen resistance to temperature defects by the increasing of durability of modified binders during service life. The large decrease in penetration value due to addition of waste denim fibre indicates that WDF makes the base bitumen harder and consistent; this might improve the rutting resistance of bitumen. These findings further support the idea of significant reduction in penetration value of asphalt binder with addition of cellulose fibre [14].

4.2. Softening Point Test

Figure 2 presents the softening point values for base and WDF-modified bitumen. It can be seen that waste denim fibre addition leads to increase softening point temperatures of modified bitumen. It was observed that as the WDF amount increases the softening point increases. The highest softening point of 57°C was shown at 2% of WDF content. These results match those observed in the previous study conducted by Mohammed et al. [14]. The increasing in softening point of WDF-modified bitumen indicates that viscosity of modified bitumen under influence of temperature was improved, and that will make the bitumen higher rutting resistant.

4.3. Ductility Test

Elasticity and tensile deformation of bitumen can be evaluated by ductility test. Figure 3 shows the influence of adding waste denim fibre on the ductility of bitumen 60/70 at various portions of WDF. Compared with the standard requirements of ductility for Malaysian specifications (≥100 cm), WDF-modified bitumen has lower ductility. It was observed that as WDF content increases the ductility of modified bitumen decreases. This decreasing indicates that waste denim fibre will improve intermediate temperature performance of WDF-modified bitumen.

Figure 1 Penetration values vs. WDF content  Figure 2 Softening point values vs. WDF content
4.4. Temperature Susceptibility

Figure 4 shows the penetration index values as an indicator of temperature susceptibility for base and modified bitumen. It is observed that, with addition of waste denim fibre up to 1.5%, the PI increases, then PI values decreases with increases of WDF, however it still higher than PI value of base bitumen. This indicates that WDF-modified bitumen is high temperature resistance and the resistance increases as the WDF increases up to 1.5%. That improvement in temperature susceptibility of WDF-modified bitumen will lead to enhancement in rutting and low temperature resistance and service temperature range of pavement [15].

![Figure 3](image1.png)  
**Figure. 3** Ductility values vs. WDF content

![Figure 4](image2.png)  
**Figure. 4** Penetration Index vs. WDF content

4.5. Rheological Properties

Figures 5 and 6 show the complex modulus (G*) and phase angle (δ) of base and modified asphalt binders against temperature. It was observed that complex modulus increases with increases of waste denim fibre, however, phase angles decreases. It was also noted that there is higher increment in G* at lower amount of waste denim fibre, but slight increases at higher concentrations. It was also observed that at lower temperature there was a higher increase in G* with increasing of WDF, however in high temperature the increment was slight lower, but improvement in high temperature performance grade was noted with increasing the WDF. That indicates that, addition of waste denim fibre increases complex modulus at high temperature which enhances the rutting resistance of binders. From Figure 6, it can be seen that, phase angle values significantly decreased as waste denim fibre concentration increased at range of test temperature (40 °C to 70 °C). The reduction of phase angle indicates in improvement of permanent deformation resistance, because lower phase angle binders show more elastic behaviour. So that also signifies an increase in WDF can results in continues elastic behaviour of WDF- modified binder. These findings are in agreement with Mohammed’s (2018) findings which showed the same behaviour of complex modulus and phase angle of the modified bitumen with cellulose fibre.
4.6. Rutting Parameters

The influence of temperature on rutting parameter \((G^*/\sin\delta)\) of waste denim fibre modified binders is illustrated in Figures 7 and 8. Rutting parameter is an indicator for evaluating the rutting resistance of both base and fibre modified binders. It was found that the addition of waste denim fibre improved the high temperature stability of binders. It was also observed that as the concentration of waste denim fibre increases the value of \(G^*/\sin\delta\) increases, and it decreases with an increase of the test temperature. The superpave requirements of minimum rutting resistance for unaged binder is \(G^*/\sin\delta \geq 1\text{kPa}\). It can be seen that in Figure 7, the base binder fulfils the requirements of superpave up to 64 °C, however the waste denim modified binders have the highest \(G^*/\sin\delta\) ratio which exceed the 1 kPa up to 70 °C as shown in Figure 8, which indicates that WDF-modified binders are applicable for rutting resistance at more than 70 °C pavement service temperature. Bitumen modified with 2.0 % WDF showed the highest \(G^*/\sin\delta\) ratio among the base and other WDF-modified bitumen samples. Therefore, it can be concluded that waste denim fibre could improve the rutting resistance of asphalt binders and then asphalt mixtures rutting resistance will be improved to contribute in solving the rutting problem in asphalt pavement, especially at high temperature regions. The findings observed in this study seem to be consistent with another research found that the addition of fibre resulted in the improvement of high temperature performance of asphalt binder [14].
5. Conclusion
This research investigated the influence of waste denim fibre on the physical and rheological properties of bitumen. Results of penetration and softening point tests show that, as the WDF content increases, the penetration values decrease and softening point increases which indicate improving the hardness of binders and then resistance to temperature will enhanced. Ductility test results show lower ductility of modified bitumen which indicates the enhance of intermediate temperature performance of modified binders. Temperature susceptibility investigation indicates that, base bitumen has more susceptibility to temperature than waste denim fibre-modified bitumen, due to higher penetration index value observed in WDF-modified binders. Rheological properties evaluation shows that, waste denim fibre enhances the rheological properties of base bitumen at high service temperatures. Rutting parameters shows that, WDF-modified binders are more resistance to permanent deformation; this indicates that WDF-modified binders are more suitable for high temperature paving applications compared to base binders. From results analysis, 2% WDF can be recommended for modification of base bitumen as optimum content.

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