Mechanical properties of cellulose-fibre reinforced bituminous mix under various loading rates

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Abstract. Fibrous products can be incorporated by both mixing methods, and the dosage of 7%, beyond which excessive usage would give the increase in fibre dosage proportional to the increase in fibre dosage. However, excessive fibre dosage of more than 0.3% would give a replacement effect to the tougher aggregate, leading to decreased toughness and strength [4-11]. Another example is synthetic polymer fibre, which comes in various products such as polyethylene (PE), polyethylene terephthalate (PET), and aramid. PE can be incorporated by both mixing methods, and the outcome has been reported to enhance stiffness, strength, rutting resistance, and fatigue life up to around 24.54% at the lowest rate and 38.2% at the highest rate, signifying better resistance against loading. Moreover, PE can also be combined with aramid fibre to enhance the mechanical properties of bituminous mixes regarding their strength, fatigue life, stiffness, and resistance to rutting at various temperatures by mainly acting as bonding enhancement and a load-carrying agent inside the asphalt matrix [20-27]. Meanwhile, PET is typically used in the form of plastic waste products to either modify binder stiffness or act as an additive in a mixture, both of which were found to increase the resistance to rutting and moisture damage, as well as higher strength and fatigue life of a bituminous mixture [28-33]. There is also a plant-based type of fibre, such as cellulose fibre. The use of cellulose fibre in an asphaltic mixture can come in either fibrous or pelletised form, all of which were reported to elevate the amount of added binder due to its absorption capacity and lead to higher stiffness, stability, and resistance to rutting and moisture damage in the dense asphaltic mixture [34-35], with a relatively equivalent outcome in the gap graded stone mastic asphalt (SMA) mixture [36-40]. However, the effect of modified types of cellulose fibre, such as modification using blended bitumen, as well as the post-cracking behaviour of the modified bituminous mix, remains to be observed to date.

1 Introduction

The use of fibre in an asphaltic mixture has been a widespread practice in the road construction field, where the first dated use of fibre was back in the 1920s using Asbestos, which was found to enhance the mechanical properties of asphaltic pavement structures until being banned due to considerable health hazard concern [1]. Since that, there are various types of fibrous products being used. Fibrous products can be classified according to their source, which can come from either artificial or natural processes [2] can be employed by directly pouring them into the asphaltic mixture, generally known as the dry mix method, or mixed with bitumen to form a polymer-modified bitumen (PMB) product, whose technique is named the wet mix method [3]. One example is the glass fibre, which could be employed using the dry and wet mix methods and evidently could enhance the stiffness of bituminous mixtures, leading to enhanced resistance to rutting and longer fatigue life. Moreover, the observed outcome showed increased binder proportional to the increase in fibre dosage. However, excessive fibre dosage of more than 0.3% would give a replacement effect to the tougher aggregate, leading to decreased toughness and strength [4-11]. Another example is synthetic polymer fibre, which comes in various products such as polyethylene (PE), polyethylene terephthalate (PET), and aramid. PE can be incorporated by both mixing methods, and the outcome has been reported to enhance stiffness, strength, rutting resistance, and fatigue life up to around the dosage of 7%, beyond which excessive usage would result in a non-compatible mixture [12-19].
aggregate, and cellulose fibre. The aggregates used were taken from the local quarry in Parung Panjang, Indonesia, while the binder was provided by Shell Indonesia. Additionally, the cellulose fibre was produced by J. Rettenmaier & Söhne (JRS) under the brand name Viatop® 66 consisting of 66% cellulose fibre coated with 34% bitumen 50/70 [41], shown in Fig. 1 (Left).

Fig. 1. Cellulose fibre Viatop® 66 and (right) raw material testing

All the resources needed to be checked prior to being used for further stages. The aggregates were subjected to specific gravity and absorption examinations, whereas the bitumen underwent several tests such as penetration, softening point, specific gravity, and flash point (Fig. 1, right). All the standard values for the examination are shown in Table 1, taken from the Indonesian national code called BINA MARGA 2018 Rev. 2 requirement, after which the same standard was used to produce the mix design used in this study, with the result presented in Fig. 2.

Table 1. Material properties and Bina Marga 2018 requirement

<table>
<thead>
<tr>
<th>No</th>
<th>Material</th>
<th>Properties</th>
<th>Bina Marga 2018 Req.</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coarse aggregate</td>
<td>Specific gravity (gr/cc)</td>
<td>2.542</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>% Absorption</td>
<td>0.693</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fine aggregate</td>
<td>Specific gravity (gr/cc)</td>
<td>2.550</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>% Absorption</td>
<td>2.795</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Filler</td>
<td>Specific gravity (gr/cc)</td>
<td>2.506</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>% Absorption</td>
<td>3.445</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bitumen</td>
<td>Penetration in 25°C</td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Softening point (°C)</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flashpoint (°C)</td>
<td>&gt; 230</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific gravity (gr/cc)</td>
<td>1.076</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Material production and SCB test

After the initial check, the sample production began using the following steps. Firstly, all components were heated to 160°C for approximately 45 minutes in an oven before being poured into a planetary mixer for blending. Each mixing process lasted for nearly 5 minutes, during which the fibre was placed into the mixture of aggregates shortly before the binder was poured. The well-blended sample was then placed back into the oven for a couple more minutes to maintain the temperature for going into the compaction mould. Then, the compaction could carry over in a standard Marshall compactor, with each sample side subjected to 75 times blow as per the standard approach (Fig. 3, left).

Cylindrical specimens with a diameter of 150mm and height of 50mm were fabricated by this method and then split into two equivalent parts for each cylinder to create SCB samples (Fig. 3, right). Before running into the test, a notch of 5 mm depth and 1mm width was developed in each test sample according to the norm. Afterwards, the SCB tests could be executed using a Universal Testing Machine (UTM) using three rates of loading speed: 0.25, 0.5, and 1 mm/min (Fig. 4).
2.3 Calculation of semi-circular bending result

The typical outcome of an SCB test in a UTM is a set of force-displacement data (Fig. 5). This needs further calculation steps to convert the result into several known mechanical properties, such as tensile strength, flexibility index (FI), and critical strain energy ($J_c$). Tensile strength is calculated using Equation 1, where the maximum load is denoted by $P_{\text{max}}$, $r$ is the specimen radius, and $t$ is the specimen thickness.

\[
\sigma = 4.263 \times \frac{P_{\text{max}}}{2rt} \tag{1}
\]

FI is a parameter that shows the ductility behaviour of a mixture beyond its initial crack propagation, i.e., after the peak force is reached (Fig. 5). The larger FI value indicates a greater extent of deformation in a sample before the failure state, whereas a smaller FI indicates a more brittle behaviour. This parameter is defined by Equation 2, where the parameters can be found by Equations 3-4.

\[
FI = \frac{G_f}{|m|} \times A \tag{2}
\]

\[
G_f = W_f / A_{lig} \tag{3}
\]

\[
A_{lig} = (r - a) t \tag{4}
\]

where $W_f = \text{work of fracture (Joules)}$, $A_{lig} = \text{ligament area (m²)}$, $a = \text{notch depth (m)}$, $|m| = \text{absolute post-peak slope (kN/mm)}$.

Critical strain energy ($J_c$) is the ratio between the total strain energy of a set of specimens and the variation of fabricated notch depth. A higher number of $J_c$ indicates a higher resilience, basically meaning a tougher material, as opposed to a lower $J_c$ value. This parameter is obtained by calculation using Equation 5.

\[
J_c = -\frac{1}{b} \left( \frac{du}{da} \right) \tag{5}
\]

where $\frac{du}{da} = \text{strain energy} / \text{notch depth}$.  

3 Results and discussions

3.1 Volumetric properties of asphalt mixtures

The volumetric properties of the fabricated specimens, namely the air void and VMA, are presented in Fig. 7.
From the graph above, it is apparent that the amount of air void was not significantly affected by the inclusion of the cellulose fibre, as the most considerable difference between the control and modified mixes reached less than 10%. The air void percentage herein fulfilled the national norm Bina Marga 2018 of about 2 – 4% air void. Moreover, VMA also fulfilled the requirement by more than 18%, with the highest difference between the control and the cellulose fibre-modified mixtures being less than 2%. With the average density of 2.24 gr/cm³ for all mixtures, all the information indicates that the effect of fibre on the volumetric properties can be neglected.

3.2 Semi-circular bending (SCB) results

The SCB tests generate the outcomes of tensile strength, flexibility index (FI), and critical strain energy (Jc). All results are presented in Fig. 8-10.

Fig. 8 shows that the cellulose fibre enhanced the strength of the bituminous mixture, where the maximum difference to the control mix was reached at the lowest loading rate by 20% - 45%. Such a phenomenon was possible since the stiffer fibre-matrix interface could influence the mechanical performance, especially at the low-loading rate where the binder became more viscous, as opposed to the more elastic tendency exhibited when subjected to a high loading rate. On the other hand, the difference at the highest rate was only 8.8% – 13.7%. Interestingly, the addition of cellulose fibre with the dosage of 0.3% gave the highest strength in any case, with a difference of 6.5% - 16% to other dosages at the low rate and 1.2% - 4.2% at the high rate. In addition to the binder behaviour explained previously, this could mean that the influence of fibre added to a mixture highly depends on its distribution inside the mix. This needs to be taken into account, especially for combating the type of distress that tends to occur locally, such as cracking and stripping.

Secondly, the flexibility index (FI) shows the extent of deformation that can be governed in a sample after the first crack propagates. The FI of samples blended with cellulose fibre, depicted in Fig. 9, has exhibited an improved state, particularly at the low-speed rate, due to the improved stiffness of the fibre-matrix interface. In this case, the incorporation of cellulose fibre by 0.3% w/t increased the FI value by 30.43%, whereas the dosage of 0.4 and 0.5% gave only 8.9% - 13.33% improvement from the control mix. Adding more fibre seemed to have a detrimental effect here, as the value declined by 13% - 16% compared to the dosage of 0.3%. Similar to the tensile strength, the fibre distribution contributed to this difference. On the other hand, as the binder reached a more elastic state at a high-speed rate, the stiffer interface was found to decrease the degree of deformation, hence making the non-modified sample have an enormous amount of deformation in this case. Naturally, the specimens with the largest modification degree would exhibit the worst behaviour herein, as the decrease almost reached 45%. The mid-loading speed gave a mixed behaviour, where the addition of fibre could still enhance the FI value to a limited extent by 1-2%, whereas adding more fibre decreased the value to a similar fraction to the highest loading rate case.

The last parameter is the critical strain energy (Jc) shown in Fig. 10. A higher Jc indicates a better crack resistance while subjected to tensile deformation. Akin to the previous cases, the inclusion of 0.3% w/t cellulose fibre yielded the best outcome in every loading rate, increasing by 24.5% at the low rate and 38.2% at the high rate compared to the control mix; the improvement was found to range from 5.88% - 24.5% at the low rate and 3.4% - 38.2% at the high-speed rate.

4 Conclusion

This study aims to examine the effect of cellulose fibre with dosages of 0.3% - 0.5% w/t on the mechanical properties of asphaltic mixtures using Semi-Circular Bending (SCB) test under various loading rates from 0.25 to 1 mm/min. The application of cellulose
increased the tensile strength by 20% - 45% at the low loading rate and 8.8% - 13.7%, where the maximum value was achieved by adding 0.3% w/t fibre. Moreover, the critical strain energy ($J_c$) increased by 5.88% - 24.5% at the low rate and 3.4% - 38.2% at the high-speed rate, where a higher dosage of fibre did not contribute positively to the properties of the mixtures. Lastly, the flexibility index (FI) value exhibited a similar trend, where the fibre dosage of 0.3% w/t yielded the highest value at the low-speed level, differing by 30.43%, whereas the dosage of 0.4 and 0.5% gave only 8.9% - 13.33% improvement from the control mix. However, given the highest loading rate, the fibre modification reduced the value to 16.81% - 45% lower than the control mix. To sum up, the extent of improvement in mechanical properties of bituminous mixtures is inversely proportional to the increase of fibre dosage due to the modified fibre-matrix interfacial behaviour, and the fibre inclusion of 0.3% w/t exacts the best outcome in this study.

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**References**
