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Coir Fibers and Micronized Rubber Modified Asphalt Binder

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ABSTRACT

Coir fibers (CFs) and micronized rubber powder (MRP) can be derived from low or negative-value agricultural/industrial waste streams and provide economical and sustainable pathways to develop high-value engineered products. This study investigated the influence of adding these modifiers on the performance characteristics of asphalt binders. Samples were produced using a mixture of slow-setting anionic asphalt emulsion with various quantities of MRP (at 0, 2 and 10 wt. %) and two levels of short CFs (~ 1 mm and 2 mm) with different fiber contents (at 0, 2 and 5 wt. %). The performance of modified asphalt samples was assessed by penetration depth (PD), softening point (SP), and penetration index (PI). Full factorial statistical design was structured to reveal the influence of main effects of the wt. % MRP, wt. % CFs, and CFs length and their interactions on the performance of the modified asphalt. Based on the statistical experimental design, linear regression analysis was performed. The linear regression showed that adding CFs and/or MRP consistently reduced PD, increased SP values and improved PI values. The length of CFs significantly affected the performance, which becomes more distinct with the increased weight content of CFs at 5 wt. %. It was also discovered that the combined addition of short CF and MRP achieved similar PI values at the same weight content of MRP alone.

Keywords: coir fiber; micronized rubber powder; asphalt binder; penetration depth; softening point; penetration index

1. Introduction

As the rapid-growing economy is boosting people's demand for travel, the substantially increased traffic load has been causing more frequent road maintenances and shortened service life due to severe asphalt pavement damages [1]. To improve the performance and durability of asphalt pavement, modifications of the asphalt binder is deemed to be one of the crucial approaches that has been extensively studied [2]. The development of modified asphalt binders by adding various reinforcement materials has been the research focus over the past decades [3–8]. Historically, the use of rubbers and fibers to reinforce asphalt binders has been the most popular methods with evident improvement of strength and durability [9]. Crumb rubbers were stated to improve the viscosity, rheological properties, rutting resistance and thermal cracking resistance of asphalt binders [10]. The performance of rubber reinforced asphalt binder depends primarily on the rubber type, binder and mixing conditions. It was also found that fibers can stiffen asphalt binder by forming a spatial network [11]. The introduction of fibers into asphalt binder alters its viscoelasticity [12,13] and reinforces the binder system, causing it to have improved tensile strength, toughness [14], stability, durability and possibly higher resistance to rutting, creep and fatigue cracking [15] than unmodified asphalt binders. In recent years, as sustainability is gaining immense popularities globally, asphalt modified with recyclable and sustainable materials start to draw growing attentions and demands in the market [16]. The utilization of crumb rubbers made from discarded tires of vehicles can avoid the need of new rubber material production, and provided a solution to the disposal of countless waste tires all over the world which has become a serious global environmental concern. Numerous attempts have been made to modify asphalt binders using crumb rubbers made from discarded tires [3,5,6], and positive results confirmed its capability to enhance asphalt properties as effectively as fresh rubbers. Crumb rubbers with relatively large and inconsistent particle sizes were commonly used to modify asphalt in previous research [17–19]. Yet, micronized rubber powder (MRP) made from discarded tires using advanced processing technology can be thoroughly cleaned and consistently sized to less than 100 µm. As a result, it has the advantage of being easily dispersed into various systems and applications, which makes it more effective to be used for asphalt modification. Since the applications of synthetic fibers have been causing substantial negative environmental impact, natural fibers are more sustainable materials to be used posing no harm to the planet [2]. Researchers have studied many types of natural fiber reinforcements in asphalt binders, including asbestos [11], basalt [20,21], cellulose [22,23], lignin [11,24], kenaf [25], and corn stalk fibers [26]. Coir fiber (CF), which is considered as an agricultural waste also have the potential to be used for modifying asphalt properties. CF is abundantly available in tropical countries and can be easily obtained from coconut shells, which are agricultural byproduct with negative values after the coconut fruits and juice are extracted [2]. Compared with other botanic fibers, coir fibers have lower percentage of cellulose (36% - 43%). However, the amount of lignin is significantly higher (41% - 45%), exhibiting higher strength and hardness compared to other alternatives [22]. Coir is also a cheap fiber, even cheaper than sisal and jute [27]. Research work on coir fibers is currently fairly limited. The work by Vale et al. [22] showed that stone matrix asphalt mixtures modified with coir fibers presented better performance than cellulose fibers which has been the most predominantly used natural fiber reinforcement. However, the size of coir fibers caused the difficult processibility in the sample productions, which motivated more studies on using coir fibers with shorter length (preferably less than 20 mm). The study by S. Hadiwardoyo [28] presented the use of shorter coir fibers (5-12.5 mm) as an asphalt additive with five levels of contents from 0.5 to 1.5 wt. %. The addition of coir fibers resulted in the decrease of penetration depth and ductility as well as the increase of softening point. Penetration index (PI) values showed that all the modified binder were less susceptible to changes in temperature than neat asphalt. In general, increased coir fiber content caused increase of PI values. However, the length of the coir fibers didn't seem to affect the PI values significantly. Meanwhile, the fiber length still caused difficulties in the mixing process with asphalt. Therefore, coir fibers with even smaller length (possibly < 5 mm) should be explored. Modified asphalt binders with the addition of EVA/coir fibers were also investigated [29] and showed improved elasticity and higher viscosity in comparison with the original neat binder. The enhancement was observed to be more significant in the presence of coir fibers and the EVA/coir fiber modified binders exhibited highest resistance to permanent deformation, indicating a potential synergic effect by using coir fibers together with polymer or rubber materials. Tan et al. [2] experimented on coir fibers with and without chemical treatments but observed that the effects of chemically treated coir fibers to the asphalt binders didn’t show significant difference compared with untreated coir fibers. It was found that asphalt modified with coir fibers were consistently better on the penetration, softening point and PI. Hence, untreated coir fibers should be used for simplified process. The influence of adding short CFs less than 5 mm or the combination of CF and MRP on asphalt binder performance has not been investigated, which directed the objective of this work to address the lack of research in this area by examining representative asphalt performance judged by softening point (SP), penetration depth (PD), and penetration index (PI). The novelty of this research lies in the investigation of possible synergic effect of using short CF (< 5 mm) and MRP compared with the effect of adding either CF (< 5 mm) or MRP alone. Meanwhile, the utilization of natural fibers and recycled rubbers generated from agricultural and industrial wastes to improve the asphalt performance is a potential economical alternative as well as a sustainable approach to shape future asphalt pavement industry.

2. Materials and Methods

2.1. Materials

Clean coir long fibers were sourced from local market at Raleigh, NC, USA. Prior to mixing, these long fibers were cut into shorter length by scissors and eventually shredded by using an electric salt grinder into two groups of short fibers with an average length of ~1 mm and ~2 mm (Figure 1(a) and (b)), respectively. These short CFs and MRP were used for modifying a 40/50 penetration grade slow-setting anionic asphalt emulsion (sourced from Dalton Enterprise Inc., Cheshire, CT, USA) to analyze the impact of modifiers on the performance of asphalt. The flashpoint of this grade of asphalt emulsion is above 177 °C, and the specific gravity at 16 °C is between 0.98–1.02 g/cc. The MRP (MicroDyneTM 75-TR acquired from Lehigh Technologies, Inc., Atlanta, GA, USA) is a 200-mesh grade with an average particle size of ~75 µm. As is shown in Figure 1(c), MRP is in powder form and can be easily dispersed in various systems.

Figure 1. Images of short CFs with an average length of (a) ~ 1 mm, (b) ~ 2 mm and (c) MRP.

Table 1. Material variables for asphalt samples.

Material Variables	Values
MRP wt. %	0, 2, 10
CF wt. %	0, 2, 5
CF length	C1 (~1 mm), C2 (~2 mm)
Number of samples	3 × (1 + 2 + 2) = 15

A total of 15 control and modified asphalt samples were produced following the experimental design shown in Table 1.

2.2. Asphalt Modification

The most difficult part of preparing modified asphalt samples from asphalt emulsion is to fully remove all water content from the emulsion. In a previous work, asphalt emulsions were cast on pans to go through a three-day drying process, and eventually forced air heating in an oven. Not only is this process time-consuming, but a complete elimination of water is also not guaranteed in thick samples. The uniform dispersion of modifiers is also not easy to be preserved during the drying phase. In our previous work [30], a new process was established to efficiently make control and modified samples with consistent quality. This process requires slow and constant heating of asphalt emulsion (mixed with additives in case of modified asphalt) to eliminate all water content and melt the asphalt, followed by casting the melt in sample molds. To achieve and retain uniform dispersion of additives in the emulsion, vigorous agitation (with a Thermo Scientific^{TM} (Waltham, MA, USA) Cimarec^{TM} digital stirring hotplate) was initiated upon the addition of modifiers into the emulsion and continued through the entire heating process. The heating process began with water evaporation in asphalt emulsion, followed by the melting of the asphalt at the end. With the increase of temperature, the mixtures with high concentration MRP (>5 wt. %) started to become highly viscose, making it more challenging to thoroughly mix asphalt and modifiers. Consequently, it took more time to prepare these samples. The temperature and weight of the sample were measured every 15 min to check the progress of water evaporation. The sample preparation was considered complete when sample weight remains unchanged for three consecutive measurements suggesting complete evaporation of water. The temperature measured at this moment was ~300 °C, which ensured that the asphalt was in melt form and can be casted in sample molds for penetration depth and softening point testing, shown in Figure 2.

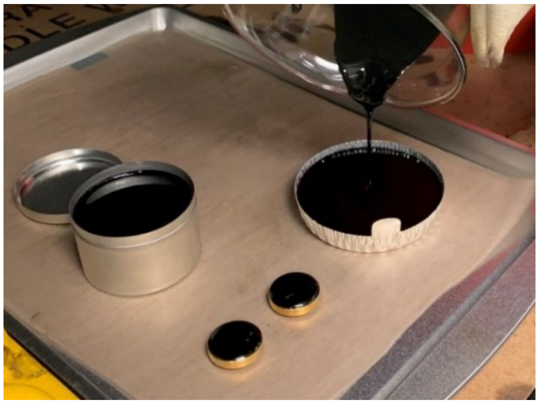

Figure 2. Asphalt in melt form being cast in sample molds for standard tests measuring PD and SP.

2.3. Characterization of Modified Asphalt

Physical properties of the control and modified asphalt samples were evaluated using standard testing methods. Penetration depth tests were performed at 25 °C with a Humboldt Mfg. Co. H-1250 Penetrometer (Norridge, IL, USA), following ASTM D5-05 standard [31]. Per the instructions in this ASTM standard, three measurements were obtained from distinct locations of each sample. Softening point tests were conducted with a Humboldt Mfg. Co. H-1569 Ring and Ball Apparatus, following the ASTM D36-06 standard [32]. For the softening point test, two measurements were taken for each sample with a regularly used double-ring frame. In addition, the penetration index (PI) was calculated according to Equation (1) [33] to assess the temperature susceptibility of the modified asphalt samples:

$$PI = [1952 - 500 * (Pen_{25} - 20 * SP)]/[50 * \log (Pen_{25} - SP) - 120] \quad (1)$$

where Pen_{25} is penetration depth at 25 °C and SP is softening point.

3. Results and Discussion

3.1. Penetration Depth (PD) and Softening Point (SP)

Regression models for PD (Equation (2)) and SP (Equation (3)) were developed using 45 (15 × 3) PD and 30 (15 × 2) SP measurements obtained as described in Section 2.3, respectively. The regression models for PD and SP with R-squared values of 0.80 and 0.97, respectively, showed that all variables, including CF length (C1, C2), CF wt. % and MRP wt. %, significantly affected penetration depth and softening point:

$$PD = - 0.971 * C1 * CF - 2.006 * C2 * CF - 0.667 * MRP + 46.326 \quad (2)$$

$$SP = 0.419 * C1 * CF + 0.844 * C2 * CF + 1.071 * MRP + 38.814 \quad (3)$$

The effect of variables, including MRP content and CF length at different CF weight contents (0 wt. %, 2 wt. % and 5 wt. %) on PD, is shown in Figures 3 and 4, respectively. The effect of these variables on the SP is shown in Figures 5 and 6.

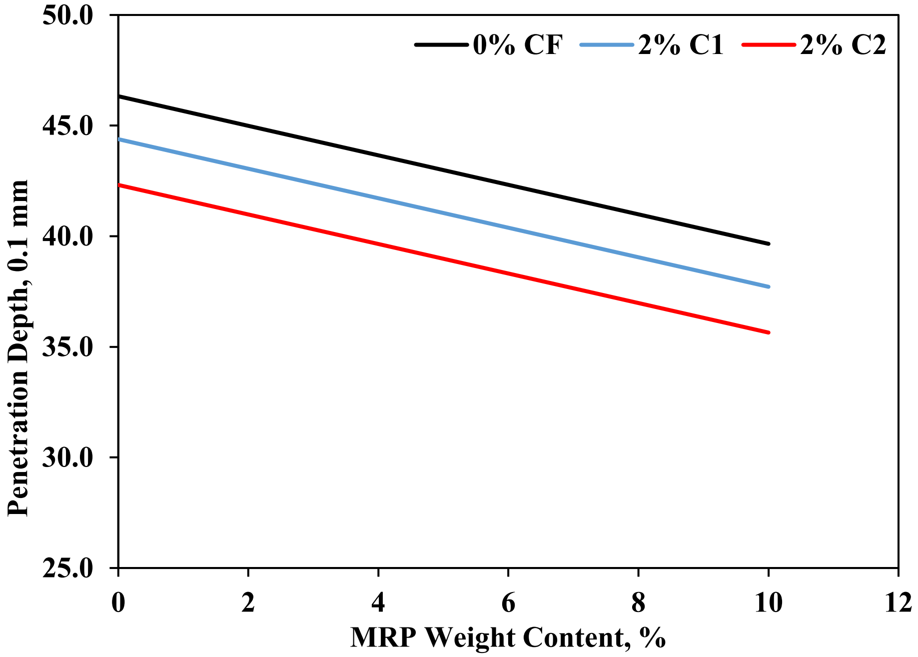

Figure 3. Effect of MRP wt. % and CF length on PD at 0 wt. % and 2 wt. % of CF.

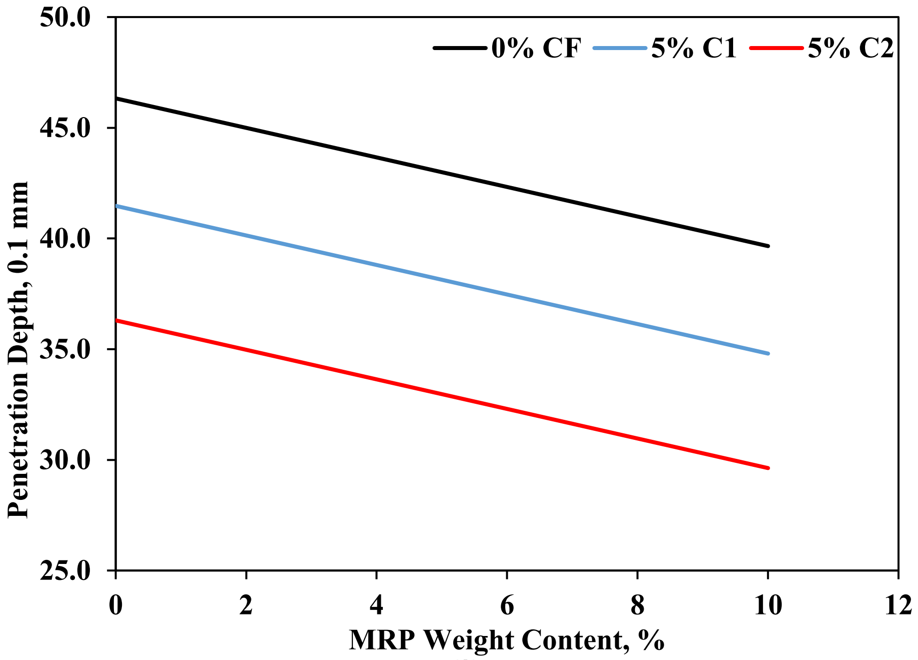

Figure 4. Effect of MRP wt. % and CF length on PD at 0 wt. % and 5 wt. % of CF.

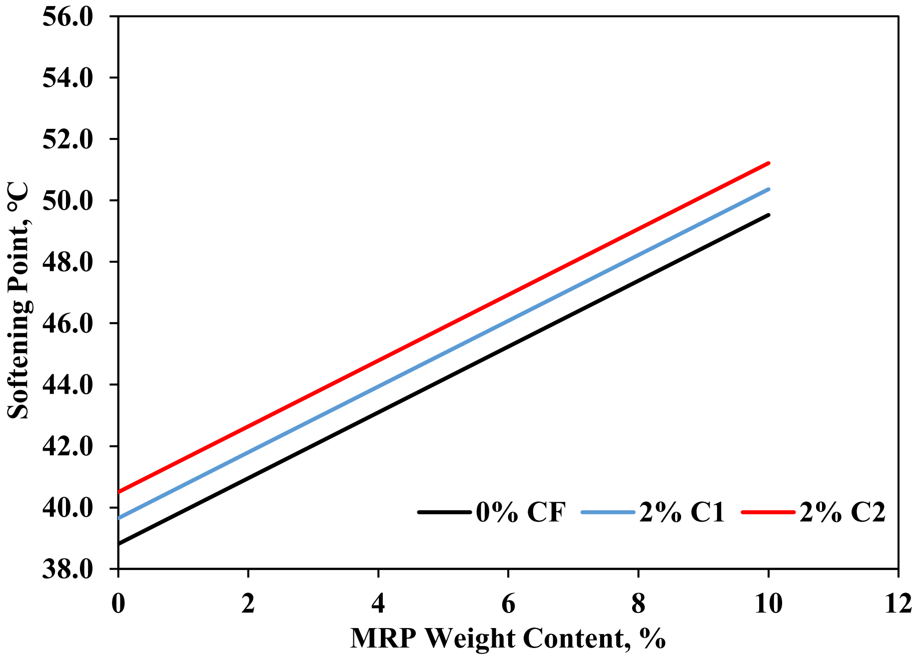

Figure 5. Effect of MRP wt. % and CF length on SP at 0 wt. % and 2 wt. % of CF.

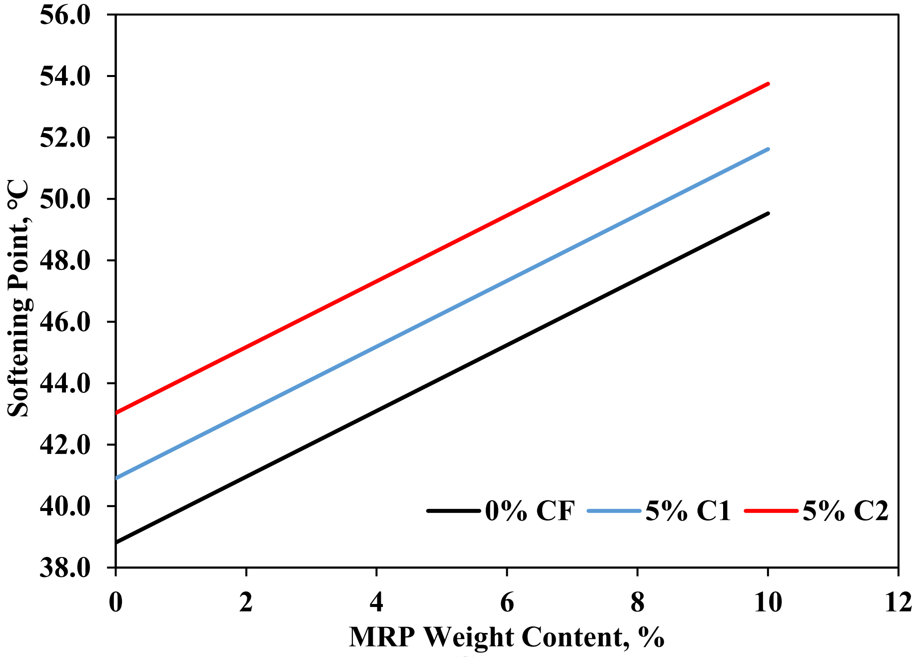

Figure 6. Effect of MRP wt. % and CF length on SP at 0 wt. % and 5 wt. % of CF.

The PD (at 25 °C) and SP of unmodified asphalt sample were measured to be 47.7 (units 0.1 mm) and 39.3 °C, respectively. The addition of MRP and/or CF to asphalt significantly altered its characteristics of PD and SP. The increase in MPR and/or CF content caused PD to decrease, whereas the SP increased proportionally. These phenomena can be explained by the interaction mechanism of asphalt with MPR and CF. When the MRPs are mixed in asphalt at high temperature, rubber particles will swell up to three times their original volume after absorbing the lighter molecular weight component of asphalt [34]. The absorption of the lighter components not only led to reduced space between rubber particles due to swelling, but also stiffens the liquid phase of the binder [35]. The addition of CFs resulted in the further stiffening of the higher molecular component (asphaltene) present in the region between rubber particles. Moreover, the variations of PD and SP were also clearly affected by the length of CFs, with the longer fibers (C2) being more effective in altering the asphalt properties. Additionally, it is also observed that the impact of fiber length is becoming more distinct in modified asphalt with higher CF content (5 wt. %), which is proved by the more spaced curves in Figures 4 and 6. Comparison of asphalt samples with only MRP or CF showed that the addition of CFs resulted in lower PD than that resulting from the addition of MRP regardless of fiber length. This may be attributed to the three-dimensional spatial networking effect of CFs [11]. With relatively low weight contents, the much higher aspect ratio of fibers than rubber particles makes it more capable of forming a spatial network. In contrast, modified samples with only MRP resulted in a higher softening point than that of samples modified with only CFs. Because rubbers are still effective in providing good interfacial adhesion to stabilize the asphalt, which is likely due to the solubility law [11] since the chemical affinity between asphalt and rubbers is fairly high. Stronger interactions between additives and asphalt would result in better high-temperature stability and, therefore, the higher softening point of the mixtures.

3.2. Penetration Index

The effect of CF length, CF wt. % and MRP wt. % on the penetration index (PI) was assessed using the regression model shown in Equation (4). The regression model generated an R-squared value of 0.95 with variables of CF length, CF wt. % and MRP wt. % significantly affecting PI values (at 95% confidence level).

$$PI = 0.089 * C1 * F + 0.154 * C2 * F + 0.229 * R - 3.871 \tag{4}$$

PI value is an important measuring standard that is broadly used to evaluate the temperature susceptibility of asphalt binders with higher PI values indicating lower temperature susceptibility. As an example, the PI values in the range from −2 to +2 are generally considered appropriate for pavement applications. Asphalt binders with PI values below −2 are extremely susceptible to temperature and tend to become brittle at low temperatures, which will have a higher chance of experiencing thermal cracking and rutting [36].

The effect of variables, including MRP wt. % and CF length at different contents (0 wt. %, 2 wt. % and 5 wt. %) on PI is shown in Figures 7 and 8, respectively. Virgin asphalt binder without modifications was measured to have a PI value less than −3.7 and is, therefore, highly prone to turning brittle over time at low temperature. Mixing asphalt with the MRP and/or CF positively changed its temperature susceptibility, causing PI value to increase linearly as the additive weight content is increasing. The variations of PI values were also significantly affected by the length of CF. Slightly longer fibers (C2) were proved to alter PD and SP of asphalt more significantly than shorter ones (C1), therefore PI values from asphalt samples modified with C2 are consistently higher. It was also found that combined addition of CF and MRP will achieve similar PI values compared to the addition of MRP alone. For example, as is shown in Figure 7, asphalt binder modified with 10 wt. % MRP alone achieved a PI value slightly lower than that achieved with 2 wt. % CF (C2) and 8 wt. % MRP combined. In comparison, asphalt binder modified with 10 wt. % MRP alone achieve a PI value slightly higher than that achieved with 5 wt. % CF (C2) and 5 wt. % MRP combined in Figure 8. Therefore, a potential combined synergic effect by using CF and MRF was not observed in this work in terms of PI value improvement.

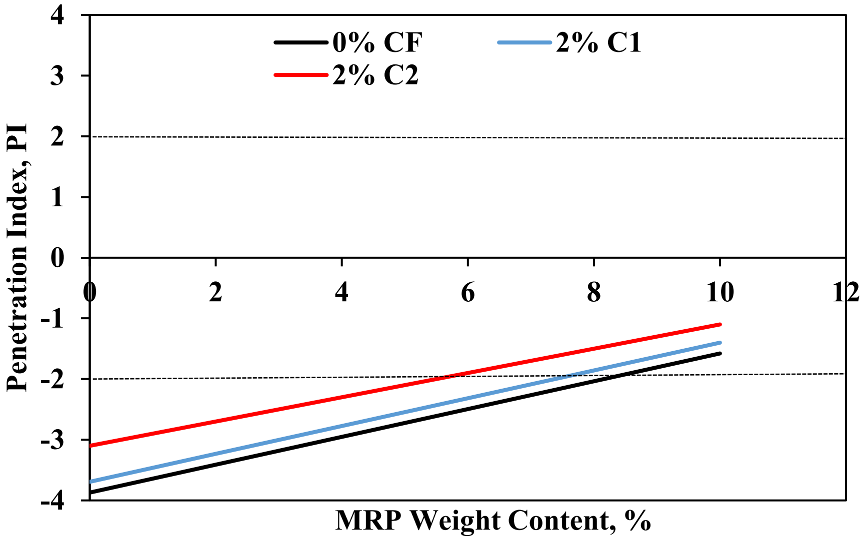

Figure 7. Effect of MRP wt. % and CF length on PI value at 2 wt. % of CF.

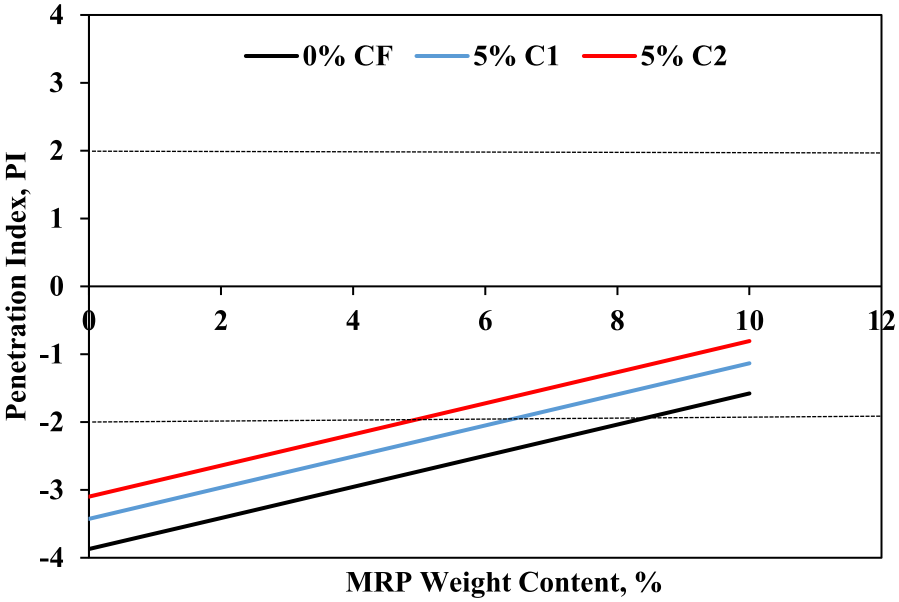

Figure 8. Effect of MRP wt. % and CF length on PI value at 5 wt. % of CF.

It is noteworthy that the weight content of CF at 5% in the modified asphalt sample is more than triple of the highest CF weight content (1.5%) reported in the literatures. Further increase of CF content is possible, yet the rubber content has to be reduced accordingly. Because it is observed in asphalt mixing that addition of higher than 5% weight content of MRP resulted in a substantial increase in the viscosity of the asphalt sample mixture, which started to negatively affect the processibility of the modified asphalt. In contrast, the addition of CF did not have as significant impact on the viscosity of the modified asphalt at the same weight content. Therefore, adjusting the MRP and CF weight content to reduce rubbers and increase fibers in the asphalt mixture can potentially reach a higher combined weight content of the reinforcement materials without sacrificing the performance.

4. Conclusions

The efficacy of modifying asphalt performance characteristics by two sustainable additives, namely coir fibers (CFs) with different fiber length and micronized rubber powder (MRP) was investigated. Linear regression analysis derived from full factorial experimental design showed that the addition of CFs and/or MRP reduced the PD and increased SP of the modified asphalt samples. The length of CFs was found to significantly affect the characteristics of the modified asphalt, which become more distinct with the increased content of CFs. The PI value of neat asphalt was found to be −3.7 (highly susceptible to temperature), yet it was possible to improve the PI value to the range of −2 to 2 (suitable for asphalt applications) by the addition of MRP and/or CFs. The utilization of short CFs (< 5 mm) with our unique mixing method achieved high CF weight content and overcame the workability issue with long CFs reported in the literature. Our work sheds light on opportunities of modifying asphalt performance using inexpensive additives while addressing sustainability issues. It is worth mentioning that the modified asphalt can be recycled, further modified if desired and reused for road pavement and thus achieving circular economy. To further validate the efficacy of CF and MRP modifications on asphalt binder properties, additional future research work is recommended, e.g. SEM imaging analysis and FTIR to evaluate the fiber–asphalt and rubber–asphalt bonding, contact angle measurements and thermal analysis to verify our PI value findings in this work.

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