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Chemical modification of waste cooking oil to improve the physical and rheological properties of asphalt binder

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HIGHLIGHTS

- Chemical modification reduced the acid value of waste cooking oil (WCO).
- Lowest acid value improved the physical and rheological properties of the modified asphalt binder.
- Treated waste cooking oil (WCO) to asphalt binder increase resistance to rutting and reduce temperature susceptibility.

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ABSTRACT

The performance of asphalt binder modified with waste cooking oil (WCO) is affected by the quality of the WCO itself because of the degradation process during frying activity. The quality of WCO can be determined by conducting an acid value test, wherein an increased acid value has caused the decreasing of rheological performance. Therefore, untreated WCO with a high acid value is chemically modified and pre-treated with alkaline catalysts to undergo transesterification. The transesterification of WCO is performed as a pre-treatment to reduce high free fatty acid (FFA) content, which is equivalent to the acid value. The treated WCO sample undergoes a chemical test (acid value), physical test (penetration and softening test), and rheological test through a dynamic shear rheometer (DSR). The rheological performance of rutting, which is analyzed using DSR, is compared between the untreated and treated WCO to determine any improvement in rutting resistance after chemical modification. Results show that the acid value reduces from 1.65 mL/g to 0.54 mL/g after the chemical treatment of WCO. The decrease in acid value affects the improvement of penetration, softening point test, and rheological performance test, wherein increased failure temperature is achieved at 70 °C for treated WCO compared with the untreated WCO at 64 °C.

1. Introduction

Petroleum-based asphalt is produced from the by-product of petroleum refinement, which is commonly used as a main material apart from aggregates for pavement construction. Today, petroleum asphalt is becoming increasingly scarce as a non-renewable resource, resulting in limitations to obtain it because of the shortage in the supply of petroleum source. Therefore, a number of notable studies are conducted worldwide to explore an alternative resource from waste materials for use as an asphalt substitute and replace the conventional binder. Oil-based modification, especially using waste cooking oil (WCO), has recently gained extensive attention because of its satisfactory performance as a potential waste material to replace the limited source of the binder, as reported in a previous research. The recyclability of WCO as a modifier in asphalt binder modification can mitigate major environmental issues, such as waste oil disposal and waste water treatment [1]. An abundance of WCO is an environmental threat; therefore, recycling or reusing WCO in asphalt binder material is considered as the proper utilization and management of this waste. This approach can also ensure economic and environmental benefits [2].

Several studies focused on the WCO performance in asphalt binder have been reviewed. Asli and Karim [3] conducted a study to investigate the potential of WCO as a rejuvenator for

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the aged binder. Their result proved that the addition of WCO resembled the original binder properties from the aged binder, which was brittle and hard at a selected optimum dosage. Eventually, the ability of WCO as a rejuvenator minimized the usage of the novel binder after the aged condition because the WCO restored the aged binder into its original condition. Chen et al. [4] conducted a research to determine the performance of WCO as a rejuvenator for aged asphalt binder in terms of physical, chemical, and rheological properties. An increasing penetration value and a decreasing softening point were recorded with the addition of WCO, and the viscosity was reduced during the physical assessment. During asphalt mixture production, a lower viscosity was acquired, which decreased the mixing and compaction temperature. Wen et al. [5] evaluated the performance of WCO as an alternative binder at high and low temperatures. The rheological performance results showed that the complex modulus (G^*) was reduced, resulting in a low rutting resistance at high temperature. By contrast, an increased resistance to thermal cracking was linearly observed in the low-temperature performance with the addition of WCO. This rheological result coincides with the studies conducted by Maharaj et al. [6], wherein an improved fatigue cracking resistance was recorded at low temperature. Meanwhile, the high-temperature performance showed an adverse effect as the rutting deformation resistance decreased with the addition of WCO.

A significant gap was identified between the previous studies, wherein the fundamental parameter affecting WCO performance was not clearly explained, yet WCO was directly used in the modified asphalt binder without determining the quality of WCO. Basically, the performance regarding the rheological properties and deformation of the modified asphalt binder was affected by the quality of WCO, in which the acid value is a parameter of quality measurement. High acid value has an undesirable characteristic that limits the replacement of WCO in asphalt binder. A pilot study was conducted to obtain fundamental ideas at the early stage of experimental research. The result demonstrated that increasing pattern trends of rutting resistance, with low-temperature susceptibility from high acid value to low acid value of WCO in modified asphalt binder, can be observed. Therefore, the rheological performance of WCO suggests that the improvement of rheological properties is related to WCO quality in terms of acid value. The proven theory initiated several efforts in minimizing the acid value to improve the rheological performance of the modified asphalt binder. Thus, chemical modification is achieved through transesterification [7]. Transesterification is conducted when the untreated WCO is chemically reacted with methanol (alcohol) in the presence of sodium hydroxide (NaOH) as base catalysts. The process results in the separation between treated WCO (ester) and glycerol as end product [8,9]. Thereafter, the treated WCO is purified [10] before it is used for further modification of the asphalt binder. Eventually, this process can minimize the acid value content [7] to enhance the rutting resistance performance. Theoretically, transesterification involves alkali catalysts (homogeneous and heterogeneous), acid catalysts (homogeneous and heterogeneous), and enzymes [11–14]. Selecting the type of transesterification depends on the free fatty acid (FFA) content, which is equivalent to the acid value, to ensure the quality and yield of treated WCO.

This paper investigates the relation between the quality of WCO and its physical and rheological performance, as well as to identify any improvement of modified asphalt binder performance after conducting chemical modification on untreated WCO. Therefore, tests on penetration, softening point, viscosity, and dynamic shear rheometer (DSR) are conducted to study the effects of untreated and treated WCO on the asphalt binder performance.

2. Materials and experimental works

2.1. Asphalt binder

In this study, 60/70 penetration grade asphalt binder was used as control asphalt binder. The binder source was obtained from Wira Bakti Solution Company and met all the requirements of the Jabatan Kerja Raya (JKR) standard.

2.2. Waste cooking oil

WCO was collected from a restaurant three times a year, specifically, during April, August, and December. Different months of WCO collection represent the different frequent duration times WCO was used, which affected the acid value result. The longer the time WCO was used, the higher the resulting acid value [15]. The raw sample of WCO was filtered first by placing filter paper in a beaker to remove food, dirt, and impurities. The filtering process took approximately 1 h to complete before the filtered WCO was obtained. After the process, the impure particles remained on the filter paper, while the residues of the filtered WCO were collected for further testing. The different qualities of WCO were determined through the acid value test, wherein high acidity corresponds to a high FFA [7]. WCO has higher FFA content than fresh cooking oil [16]. Normally, the FFA content ranges from 2% to 7% in WCO [17]. Based on the quality test, WCO from the April sample recorded the highest acid value, whereas the December sample had the lowest acid value as shown in Table 1. Azahar et al. [18] investigated the effects of different qualities (acid value) of WCO on asphalt binder performance. The lowest acid value achieved the most excellent performance with regard to rheological properties. Therefore, the WCO with the lowest acid value (December sample) was selected for further treatment through transesterification to determine any performance improvement when the existing acid value is minimized.

Selecting the type of transesterification process either by using acid or alkali catalysts was determined via the initial acid value content. The acidity in WCO serves as an indicator of the suitability for transesterification and is one of the vital properties for analysis before conducting this process [19]. Normally, transesterification through an alkali homogeneous catalyst is commercially used because of the low cost with high quantity yield in a short duration of reaction time [20–26]. However, the selection of this process depends on the acidity content, in which FFA specifically based on oleic acid should be less than 1% [27]. The alkali catalyst transesterification was conducted for further chemical treatment because the FFA content in WCO from the December sample was less than 1%. The WCOs from the April and August sample were not considered for further chemical modification because their FFA contents were more than 1%, which requires the addition of a chemical process, thereby increasing the cost.

2.3. Transesterification

Transesterification is a type of chemical reaction in which WCO is reacted with methanol and catalyzed using NaOH. Single-step transesterification reaction was selected by using alkali catalysts

Table 1
Acid value.

Sample	Volume of KOH (mL)	Acid Value (mL/g)	Conversion to FFA (based on oleic acid%)
April	31.7	3.55	1.78
August	25.3	2.83	1.42
December	14.8	1.65	0.83