Jurnal Teknologi

Full paper

Evaluation of Pavement Mixture Incorporating Waste Oil

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Article history

Received :5 June 2014
Received in revised form :
25 September 2014
Accepted : 16 October 2014

Graphical abstract

Abstract

Road construction necessitates a high amount of bitumen, which is a non-renewable material. The usage of reclaimed asphalt pavement (RAP) can be seen as a sustainable option, which offers economic benefits and conservation of natural resources. However, the high stiffness offered by RAP which leads to cracking has impelled the application of rejuvenator. The exploration of waste oil as the rejuvenator has gained the interest but they still lack of the information. This paper aims to highlight previous research works conducted on the waste oil application in the pavement materials. Large amount of waste product from the automotive industry and by-product of frying can impose adverse impact if not disposed properly. The properties of two types of waste oil namely waste engine oil (WEO) and waste cooking oil (WCO) were reviewed. Additionally, method incorporating waste oil in pavement materials, effects to the binder and mixture performance also included. It was observed that the effects of WEO and WCO are commonly produced both of the adverse and good effects to the pavement. The temperature, amount of waste oil and RAP are notable to give significant influence on the performance properties.

Keywords: Waste engine oil; waste cooking oil; reclaimed asphalt pavement.

1.0 INTRODUCTION

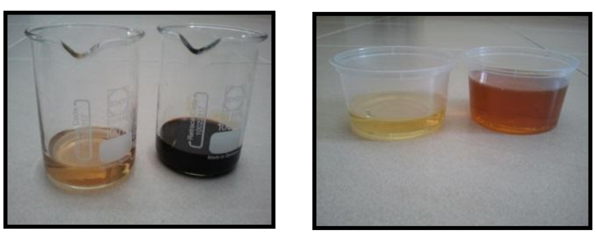
Bitumen is often seen as “black gold” rather than as a waste product from petroleum distillation. This non-renewable material is in high demand following the continuous construction of road. Additionally, fast depletion of natural materials has also impelled asphalt industries to find another alternative source to construct sustainable and economical roads without having to sacrifice on quality. As a result, the use of reclaimed asphalt pavement (RAP) has gained high interest due to less waste produced.

After years of exposure to traffic loads and climate change, a road will experience aging and reduction in the performance of its binder. One distinctive feature of a pavement is that after the end its design life, the pavement’s surfaces can be milled and recycled into reclaimed asphalt pavement (RAP) [1-2]. This renewability process can be done through 'rejuvenation'. Typically, 10% to 60% of RAP is added into asphalt mixture. While a higher RAP content can significantly increase the mixture's stiffness. Through rejuvenation, the properties of the old asphalt pavement (particularly its binder properties) can be improved to restore the original ratio of asphaltenes to maltenes and compensate the hardening effect [3-5]. Asphaltenes is a solid, hard, brittle component that is not affected by oxidation, whereas maltenes is liquid, oily and resinous in appearance [6]. The purpose is to provide sufficient binder coating to the new aggregates from the reclaimed asphalt mixture to produce pavement with consistent performance. The enhancement of asphalt binder is needed as to meet certain level of performance requirement [7].

Waste oil that is discarded into landfill without prior treatments prominently brings adverse impact on the environment. The effect can be seen from eutrophication process in which a thin layer of oil appears on the surface of a river or a lake. This thin layer of oil can block the sunlight, hinder photosynthesis and disrupt oxygen supply to the aquatic life [8-9].
An eutrophication process leads to excessive growth of micro-organism, phytoplankton and algea, all of which use the waste oil as a food source. Consequently, the quality of lake or river deteriorates before disrupting further the intrinsic equilibrium of the aquatic ecosystem. Waste oil that flows into the river can be derived from the engine oil from automotive industry or from the waste cooking oil from a residential area. As the concern of high construction costs and conservation of natural resources increased, the usage of waste oil as rejuvenator becomes the viable alternative in mitigating the problems as mentioned above [9]. Therefore, this paper presents a review on the properties of the waste oil, method of application of waste oil in asphalt pavement, effects to the binder as well as mixture performance.

2.0 CATEGORIES OF WASTE OIL

This section discusses two types of waste oil; waste engine oil (WEO) and waste cooking oil (WCO). Economic improvement has a direct impact on commercial activities and road network facilities in a country. This situation can lead to an increase in the number of vehicles on the road. In Malaysia, a total of 23 million vehicles were registered and this can contribute waste engine oil (WEO) [10], which can lead to environmental pollution if not properly disposed or recycled. In a single automotive oil change, 3 to 4 liters of waste oil can be produced. Engine oil also can be referred as oil lubricants, oil cylinder, crankcase oil and motor oil [7][11] with its main function being to lubricate, protect, reduce friction, clean and prevent the component of an engine from corrosion [12]. Vehicle workshops and factories with heavy machinery are seen as primary sources that generate WEO. If the discharge of waste engine oil is not well managed or disposed, it will affect human's health, aquatic life and ground pollution. A little of waste engine oil is sufficient to depredate millions of gallons of fresh water [13]. Figure 1(a) shows the difference between the color of fresh oil and waste engine oil; the former has gold and translucent color before turning black and opaque after engine's heating process. Meanwhile, Figure 1(b) shows the difference between the color fresh and waste cooking oil. The fresh oil turned to dark brown after the heating process of frying activity. Some common physical changes observed in vegetable oil after frying are (i) an increase in the viscosity, (ii) an increase in the specific heat, (iii) a change in the surface tension, (iv) a change in color, and (v) an increase in the tendency of fat to foam [14].



(a) (b)

Figure 1 (a) New and waste engine oil (b) New and waste cooking oil

In addition to engine oil, many sources of cooking oil can be recycled, and the latter has the potential to be used as an additive in asphalt mixtures. This oil is processed from sources that vary by geographical location; for example, soybean oil and salad oil are available in the United States, animal fat can be found in China, soybean and canola oils can be obtained from England, rapeseed oil and sunflower oil are available in Europe, palm oil can be found in Malaysia and animal fats can be obtained from Canada. Figure 2 shows the total production WCO in various countries. United States is the top producer of WCO, producing 10 million tonnes of WCO per year (55%) whereas Ireland produces the lowest WCO (153,000 tons per year). In Malaysia, palm oil is used as cooking oil due to its low processing cost and high availability, unlike its uses in other countries. Waste cooking oil is a product of the frying at high temperatures, which are usually performed in food industries, restaurants, hotels and residences [15]. These products are usually treated and discharged into the river.

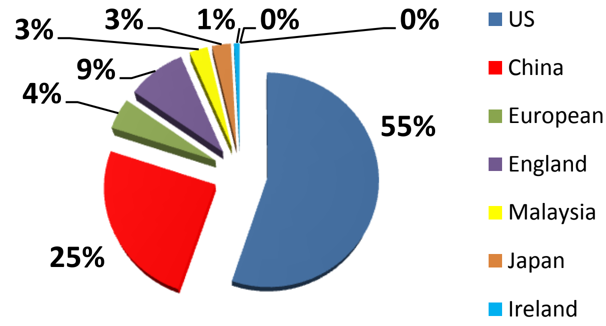


Figure 2 Quantity of WCO generated by various countries [13–15]

3.0 PROPERTIES OF WASTE OIL

This subchapter provides an overview of the physical and chemical properties of WEO and WCO. The properties of WEO depend on its combustion process, operation temperature and contaminant sources such as moisture, soot, diluents, rust, detergents and engine wear metal particles [14–16]. They also depend on the nature of the oil base, type of additives and contaminants [12]. Additive is the activator in oil that contains the detergent, dispersants, rust preventor, corrosion inhibitor, extreme pressure agents, friction modifier, anti-wear additive and anti-foaming agent [21] in order to maintain and meet the intrinsic properties of oil [12], [21].

Table 1 presents the basic properties of waste engine oil. However, these properties can be vary depending on that aforementioned factors. Viscosity is the obvious distinguishing feature between waste engine oil and new engine oil. The viscosity of waste engine oil is decreased or thinner due to the degradation of properties during its service [22]. In pavement construction, safety is the main consideration when dealing with modifiers or additive. The flash point of waste engine oil has been reported to be lower than the required limit for bitumen which is about 200°C and above. Meanwhile, Table 2 shows the maximum limit of chemical properties of waste engine oil. The presence of heavy metal in waste engine oil is always seen as a limitation for it to be used as a modifier [23]. From the view point of waste engine oil alone, it can be considered as a hazardous material. However, these hazardous effects can be immobilized after having the product blended with the asphalt bitumen.

Table 1 Basic properties of waste engine oil [12]

Parameter	Value
Specific Gravity	0.93
Viscosity	0.12 Pa.s
Flash Point	120°C
Ash Content	2.02%
Iron Content	50ppm

Table 2 Maximum allowable level for mixture containing waste engine oil

Constituent	Symbol	US Maximum Allowable [24]	Malaysia Standard Maximum Allowable Level [25]
Arsenic	As	5 ppm	5 ppm
Cadmium	Cd	2 ppm	2 ppm
Chromium	Cr	10 ppm	10 ppm
Lead	Pb	100 ppm	100 ppm
Sulfur	S	NA	NA
Total Halogen	-	4000 ppm	1000 ppm

- NA – Not Available

The chemical properties of waste cooking oil are listed in Table 3. According to U.S Patent No. 20120167802 A1 [26], the organic acid composition in WCO is included in groups of cohesive agents. The main function of cohesive agents is to reduce the high viscosity of aged asphalt binders in RAP, producing a homogenous mixture when integrated with new pavement materials. The reduced viscosity of binder leads to the decreasing surface tension of the aggregate and coated binder. As a result, this process will easily expel the air curtain around aggregate particles in order to assist the cohesion. Therefore, it is interesting to note that WCO is a good rejuvenating agent since it can promote good coating to the aged binder.

Table 3 Chemical properties of waste cooking oil [27]

Type of Free Fatty Acid	% Waste Cooking Oil
Oleic acid	43.67
Palmitic acid	38.35
Linoleic acid	11.39
Stearic acid	4.33
Myristic acid	1.03
ɣ- Linolenic acid	0.37
Lauric acid	0.34
Linolenic acid	0.29
Cis-11-Eicosenoic acid	0.16
Heneicosanoic acid	0.08
TOTAL	100

3.1 Incorporating Waste Oil into Pavement Material

Waste oil into pavement typically incorporated into pavement in liquid form. It can be blended with virgin binder prior to mixing it with an asphalt mixture; it can also be directly poured into the heated aggregate and RAP [27-28]. Table 4 shows the range of mixing temperature between residual oil and asphalt mixture as suggested by previous researchers. This summary is subjected to the mixing process for laboratory evaluation only. The typical value of mixing was found to be around 160°C due to the presence of the stiff aged binder.

Table 4 Mixing process of waste oil in asphalt

Researcher	Summary of findings
Villanueva et al., [30]	The mixing temperature is 160°C with 1 hour time of mixing and mixing speed 500 rpm.
Borhan et al., [31]	The mixing temperature, time of mixing and mixing speed was not stated. This is due to manually mixing with room temperature mixing (cold mix).
Zamhari et al., [22]	The mixing and speeds of mixing was not stated. However, the time mixing is 1 hour per cycle.
Dedene [29]	The mixing temperature is about 150°C. There is no specific mixing speed due to manually stir.
Asli et al., [27]	The mixing temperature 130°C. Time of mixing 0.5 hour and low mixing speed 200 rpm.
Zargar et al., [32]	The mixing temperature 160°C with time of mixing 0.5 hour and mixing speed 200 rpm.
Nurul Hidayah et al., [33]	The mixing temperature 160°C with mixing speed 600rpm by using high shear mixer.

Additionally, a new innovation technique was introduced by Garcia et al. [4], who innovated the product in capsule form in order to mitigate the high skid resistance by the application of rejuvenators. The capsule is fabricated with shell as the outer layer, with the inner being a porous core where the rejuvenators are embedded. The shell is hard but impermeable, and it is made from particles of type I 52.5R cement that is bonded by a liquid epoxy resin (Struers Epofix resin, bisphenol A-epichlorohydrin) and hardener (triethyenetetramine) in a 10.7% weight proportion [4]. Figure 3 shows the mechanism of a capsule that contains the aromatic and dense oil when subjected to traffic load.

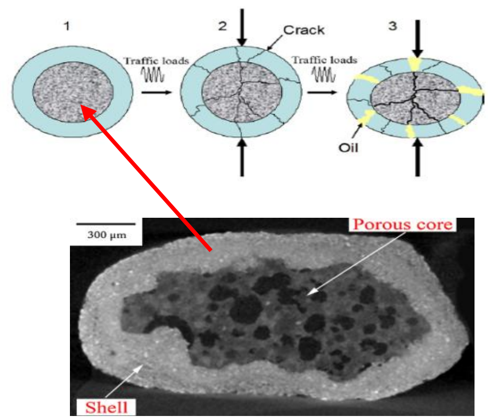


Figure 3 Mechanism of capsule form rejuvenator [4]

4.0 BINDER PERFORMANCE

Waste oil prominently affects the properties of binder. Penetration, softening point, viscosity and dynamic shear rheometer test is frequently used for binder evaluation. Penetration and softening point measure the hardness and softness of a binder. In this test, a 1 mm diameter needle is loaded with a weight of 100 g and the distance is drops in 5 s into a bitumen sample that is maintained at a temperature of 25◦C. According to Read & Whiteoak [34] the maximum difference between the highest and the lowest reading for the penetration group of 50–149 should be 4. Meanwhile, the softening point should not differ by more than 1°C. Otherwise the test should be repeated. These tests are significant in classifying a bitumen grade based on penetration ranges.

Bailey and Philips [28] have patented for asphalt rejuvenation by using waste vegetable oil. The researchers claimed that the waste vegetable oil has the greatest effect to the penetration and softening point value when added to the heated RAP. About 9 -11% waste vegetable oil was recognized to rejuvenate aged samples from field to the targeted 40/60 penetration grade binder. Asli et al. [27] introduced the environmental friendliness usage of WCO from palm oil sources for binder stage evaluation. Binder grade 80/100 was heated in the oven to get the aged samples. The aged binder of bitumen group 50/60 needed 1%, group 40/50 needed 3- 4% and group 30/40 needed 4 – 5% as the optimum WCO to achieve the original penetration value 80/100. Zargar et al. [32] conducted the continuous heating of bitumen 80/100 and produced an aged binder with a penetration value about 45 dmm. This binder needed 3% - 4% of WCO to meet the properties comparable with the original 80/100 bitumen. Meanwhile, the penetration value of aged sample from a motorway with 6.3 dmm, need about 20% of WEO to satisfactory to target grade 60/70 bitumen [5]. Zamhari et al. [22] revealed that the addition of 10% WEO to the artificial aged bitumen with penetration value 31 dmm have facilitated to achieve the target penetration grade 80/100. Here, obviously shows that the range of rejuvenator used to compensate the aging effect is depend on the hardness of aged binder and the target binder. The lower penetration value, need the higher amount of waste oil to achieve the target binder. Generally, the range 1 – 10% of WEO needed to rejuvenate the artificial aging binder and 10 % - 25% for aged sample from field.

Viscosity test is conducted to determine the ability for pumping, coating and placing the asphalt binder. Temperature for mixing and compaction can be obtained from viscosity graph. The unit of viscosity is Pascal seconds (Pa.s). The viscosity reading was taken at one-minute intervals for the total of three minutes which is suggested between 18 – 21 minutes for each evaluated temperature [35]. Zargar et al. [32] conducted the viscosity test according to ASTM D4402 and used the temperature 135°C as the measuring workability. Various percentages of WCO added into penetration grade binder 40/50, which is compared to the original bitumen pen-grade 80/100. The aged bitumen has a higher viscosity value, while the addition of 4% WCO into the aged bitumen penetration group of 40/50 achieves almost the same viscosity as the original bitumen. As stated in literature, a rejuvenator must have the lower viscosity to ensure the sufficient coating of aged binder to aggregates and enhanced the workability. The results by Bailey and Phillips [28] has proven this statement as shown in Table 5. The increasing of oil content and temperature has decreased the viscosity of the samples.

Table 5 Value of viscosity from different temperature [28]

Oil Content (%)	Viscosity (Pa.s)		
	120°C	150°C	180°C
0	1.074	0.231	0.074
2	0.844	0.200	0.064
4	0.723	0.172	0.060
6	0.607	0.151	0.053
8	0.504	0.131	0.046
10	0.429	0.117	0.044

Rheological characteristic is prominently determined by dynamic shear rheometer (DSR) test in order to verify any changes in the behavior of the binders or the shear resistance at temperatures which rutting and fatigue occur due to addition of waste oil. The rheological characteristic of asphalt binder refer to the elastic, viscoelastic and viscous properties [36-37]. The rheology equipment consists of a fixed lower plate and oscillating upper plate through which shear force is applied to the specimen. The unaged and short term aging specimen is loaded with gap 1 mm, meanwhile the sample long term aging used gap of 2 mm. The rheology in binder closely related to viscous and elastic behavior. These two parameters are important to able for a binder to stand firm of permanent deformation and fatigue cracking. DSR measures the complex shear modulus, G* and phase angle, δ of asphalt binders for unaged, short term aging using Rolling Thin Film Oven (RTFO) and long term aging using Pressure Aging Vessel (PAV). G* is divided sin δ or G*/sin δ as indicator of rutting potential at high temperature and G*sin δ as to predict fatigue cracking at intermediate temperature. The compliance of rutting parameter, G*/sin (δ) equal to 1 kpa for un-aged and 2.2 kpa for aged binders after RTFO. Meanwhile, fatigue parameter, G*sin (δ) for 5 MPa, stiffness and m-value of the blend after RTFO + PAV aging [32-33],[35]. The rutting parameter, G*/sin δ was observed to decreased with the addition of oil [24].

Rheological properties also can be represented either by master curve or isochronal curve. Master curve is the variation of complex modulus in shear mode, G* as a function of frequency at a reference temperature. Meanwhile, isochronal curve is the variation in G* and phase angle, δ with temperature at a selected frequency or loading time [40]. Zargar et al. [32] focused on isochronal plot, where phase angle was plotted versus temperature for each sample modified with 0, 1, 2, 3 and 4% waste cooking oil. As the temperature increased from 30°C to 80°C, the complex shear modulus was decreased. Bitumen aging also implies a complex shear modulus, G*, increase and a phase angle δ decrease, providing more resistance to deformation. Dedene et al. [24] conducted a preliminary study of recovered asphalt binder blended with waste engine oil. The concentration used as 4% and 8% by weight of the total mix. The test involved viscosity test and dynamic shear rheometer (DSR). Initially, the presence of waste engine oil has increased the susceptibility to ageing. However, after short term ageing the rutting resistance was increased [33].

5.0 PERFORMANCE OF ASPHALT MIXTURE

Oil has the ability to reduce the bitumen viscosity and soften the bitumen. Rutting is a problem that mainly occurred on the soft mixture. Higher rutting potential is when the large amount of permanent deformation was observed [31]. Creep test is one of the tests that can be used to assess the permanent deformation of asphalt mixtures and it can be conducted either in static or dynamic loading. Borhan et al. [41] conducted laboratory evaluation of low cost cold mix asphalt which modified with 0, 20, 25 and 30% of used cylinder oil by weight of binder content. As the amount of used cylinder oil increased, the creep stiffness decreased. The oil weakens the bonding between the binder and aggregate within the cold mix. The addition of used engine oil to the cold asphalt mixture made asphalt pavement become susceptible against permanent deformation. The stiffness also was reduced about 28% compared to the control mixtures (without waste engine oil) at the temperature of 40°C. This is due to the lower viscosity offered by the waste engine oil deteriorating the mastic bonding.

Stiffness, rutting resistance and cracking resistance are significant properties of bituminous pavement [42]. Higher application of RAP materials, cause higher materials stiffness. Bailey and Philips [28] reported that the used of vegetable oil decreases the stiffness of the aging mixture. The oil was introduced to the mixture at the stage of hot mix recycling. Dedene [29] conducted the rutting resistance test using asphalt pavement analyzer (APA) machine at the temperature 58°C. The sample consist 25% RAP and two amount of WEO (4% and 8%). The sample with WEO showed the increased rutting compare to control. Tran et al. [44] revealed the application of emulsion manufactured from a naphthenic crude stock (Cyclogen® L) to the 50% RAP, increases the mixture resistance against low temperature cracking. By adding 50% RAP with 12% Cyclogen® L, the mixture exhibits lower critical failure temperature compared to control mixture. This finding shows that the application of waste oil will be effective if used with the high RAP percentage.

■6.0 CONCLUSION

As conclusions, this review has revealed that the effects of WEO and WCO are generally produced both of the adverse and good effects to the pavement. These effects depend on the appropriate amount used in the aged mixture material. The high stiffness of mixture require high amount of waste oil. In cold mix, it was reported that the performance was affected such as stability, strength and weakening the bonding between aggregate and binder. Meanwhile, in hot mix asphalt where the oil was integrated with RAP, it offered the stiffness reduction and therefore improved resistance to cracking. The condition is the amount of RAP must be sufficient to produce the stiffness effect on the mixture. The temperature, amount of waste oil and RAP are notable to give significant influence on the performance properties. Therefore, these factors are an intriguing which could be usefully explored in further sustainable research.

Acknowledgement

The authors wish to acknowledge the support Ministry of Education Malaysia, Malaysia, research grant 4F436 of Universiti Teknologi Malaysia and Universiti Tun Hussein Onn Malaysia who sponsored this study.

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