Effect of Bio based rejuvenator on mix design, Energy consumption and GHG Emission of High RAP Mixture

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Abstract. Concerns about the cost, availability, and environmental impact of using petroleum-based materials have led to increased usage of reclaimed asphalt pavement (RAP). Meanwhile, the demand of the road industry to decrease the energy consumptions and reduce the release of greenhouse gases as well as other harmful gases, which cause serious air pollution has increased due to the amount of energy consumed is a major component of pavement construction that significantly contributes to the total cost. This paper evaluates the effects of Biobased rejuvenator known as JCO on the required heat energy and the amount of CO2 produced to increase the temperature of RAP and virgin aggregates and one binder from 25°C to the point of mixing. The results showed that incorporating Biobased rejuvenator (JCO) can potentially reduce the required heat energy and amount of greenhouse gas produced by RAP and virgin, respectively.

1. Introduction
Road pavement can be considered to be the backbone of the transportation system [1]. Today, asphalt binder has become the most commonly used construction material for road construction in the world, making up over 90 percent of the global highways. However, asphalt binder prices have increased over 255% from $235 per ton in 2006 to $635 per ton in 2015, according to the Department of Transportation (DOT) Asphalt Binder Price Index. By Analysis of January 2011 global industries market report, 118.4 million metric tons of asphalt is to reach global asphalt market by 2015. By the year 2020 as predicted by United States Energy Administration (USEA), total energy consumption from petroleum, natural gas, coal, electricity and renewable energy will increase by 32%, 33%, 62%, 22%, 45%, and 26% respectively [2, 3]. It is almost universally accepted that the release of greenhouse gas production (GHG) into the atmosphere coming from these fossil fuels is at least partly responsible for the climate change. Accordingly, transportation agencies are increasingly interested in
investigating new technologies that will reduce the cost of asphalt pavement materials while maximizing long-term and reducing the release of GHG into the atmosphere coming from these fossil fuels [4-6]. Mean-while, public enlightens campaign, global awareness and stringent environmental regulations are actively being implemented to prevent the worsening effects of climate change. Good experiences have been obtained for the Reclaimed Asphalt Pavement (RAP) use so far during last few decades where it can be seen that some researcher’s uses RAP as high as 100% of the new asphalt pavement materials, guidelines have made for the implementation of RAP materials[7]. Increased usage of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) has increased the need for recycling agents intended to return the age-hardened RAP binder (asphalt) to its original state consuming less energy and at the same time emitting less. The main mechanism of this technology involve the use of Biobased rejuvenator that helps to reduce the viscosity of bitumen at lower temperature and improve coating, mixture workability, and compaction [8-10]. In such a way, good workability and reasonable long-term performance of the asphalt mixture should be achieved. Lower mixing and paving temperatures of RAP mixtures, which are an important issue in recent years, with respect to increased energy demand of civil engineering structures during their processing, allow reduction of this demand and result in minimized greenhouse gas production[11, 12]. The lower production temperature also reduces the ageing of the bitumen during the production stage, which results in an improved thermal and fatigue cracking resistance. The results of this study showed that production high RAP content is feasible, contributing to the reduction in energy consumption, GHG and costs.

2. Materials and methods

2.1 Binder and aggregates

The binder used in this study was a conventional 80/100 penetration grade (PG-64) supplied by Petronas Ltd. Table 1 shows the conventional properties of the binder. The granite aggregates supplied by Kuad Quarry Sdn. Bhd were used for this study.

| Test Parameters               | Value                          |
|------------------------------|--------------------------------|
| Penetration at 25 °C (dmm)   | 81 ASTM D5                     |
| Softening point (°C)         | 47 ASTM D36                    |
| Ductility at 25 °C (cm)      | >100 ASTM D113                 |
| G*sinδ at 64 °C (Pa)         | 1332 ASTM D7175                |
| Viscosity at 135 °C (Cp)     | 302 ASTM D4402                 |

Table 1. Conventional binder properties

| Sieve Size (mm) | Percentage of passing by weight (%) |
|----------------|-------------------------------------|
| 20             | 100                                 |
| 14             | 90-100                              |
| 10             | 76-86                               |
| 5              | 50-62                               |
| 3.35           | 40-54                               |
| 1.18           | 18-34                               |
| 0.425          | 12-24                               |
| 0.15           | 6-14                                |
| 0.075          | 4-8                                 |

Table 2. Aggregate gradation for JKR mix type AC 14
2.2 Bio-based rejuvenating agent
A non-edible oil from jatropha curcas seed that cannot be used for nutritional purpose was used as bio-based rejuvenator. The blend was performed by mixing the aged binder with the bio-based rejuvenator. The dosage of the bio-based rejuvenator varies from 1% up to 5% based on the weight of the aged binder. Before adding bio-based rejuvenator into the aged bitumen, the physical properties were investigated as shown in Table 3:

| Property             | Value         |
|----------------------|---------------|
| pH                   | 5.2           |
| Free fatty acids     | 0.0718 mg KOH g–1 oil |
| Specific gravity     | 0.8945        |
| Flash point          | 245°C         |
| Peroxide value       | 7.20 meq g–1 oil |
| Iodine value         | 51.27 g 100 g–1 oil |
| Density at 27°C      | 0.725 g cm–1  |
| Viscosity            | 8.2 cst       |

The specific bio-based rejuvenating agent is an oily liquid that will restore the original ratio of asphaltenes to maltenes and compensate the hardening effect of the aged binder resulting in improved cracking resistance without adversely affecting rutting resistance.

2.3 Sample preparation
All samples prepared and fabricated in the laboratory based on

i. Preparation of RAP material by aggregate fractionation, determination of optimum RAP binder content and mixing with JCO.

ii. Preparation of virgin material such as aggregates.

iii. Preparation of mixture for each set of compaction temperatures, binder content and RAP content.

iv. Heating of all mixtures composition at targeted mixture temperature and then mixed for three minutes under controlled mixer temperature.

v. Short term aging of mixture for two hours at anticipated compaction to imitate the aging of binder in the field before compaction.

vi. Compaction of mixtures using servoPac compactor to simulate the field compaction at 100 gyration with 30 revolution per minute and 1.25° compaction angle.

vii. Measurement of specimen volumetric properties such as air voids, bulk specific gravity (Gmb) and voids filled with asphalt binder (VFA).

2.4 Energy Consumption of RAP with Biobased rejuvenator mixture production
In this study, the required heat energy and fuel requirements were calculated to heat both the aggregate and asphalt binders from the ambient temperature to the mixing temperature. The heat energy required to produce the asphalt mixes was calculated using Equation (1), assuming that the ambient temperature prior to mixing at Penang was 31°C. The temperature at which the aggregate and asphalt binder is blended together is known as the mixing temperature.
Where $Q$ is the sum of heat energy (J), $m$ is the mass of material (kg), $c$ is the specific heat capacity coefficient (J/(kg/°C)), $ΔΘ$ is the difference between the ambient and mixing temperatures (°C), and $i$ and $j$ indicate different material types.

The specific heat capacity coefficient of the aggregate varies according to the temperature. Waples and Waples [13] developed Equations (2) and (3) to calculate the specific heat capacity of aggregate for different temperatures.

$$C_{pnT} = 8.95 \times 10^{-10} T^3 - 2.13 \times 10^{-6} T^2 + 0.00172 T + 0.176$$  \hspace{1cm} (2)

$$C_{p_{T2}} = C_{p_{T1}} \times \frac{C_{pn_{T2}}}{C_{pn_{T1}}}$$  \hspace{1cm} (3)

$$C^* = \int_{t_i}^{t_f} C_{pn} dt$$  \hspace{1cm} (4)

where $T$ is temperature (°C), $C_{pnT}$ is the unit less specific heat capacity of the aggregate at the target temperature; $C_{pnT1}$ is the unit less specific heat capacity of the aggregate at the initial temperature; $C_{p_{T1}}$ is the specific heat capacity of the aggregate at the initial temperature (J/kg/°C); and $C_{p_{T2}}$ is the specific heat capacity of the aggregate at the target temperature (J/kg/°C). In addition, $t_i$ is the specific heat capacity for the selected temperature range (J/kg/°C), and $t_i$ and $t_j$ are the initial and target temperatures (°C), respectively.

The required heat energy is converted into different fuel types using the conversion coefficients presented in Table 4 [14]. Table 4 shows the required heat energy for asphalt binder (QB), aggregate (QAgg), total aggregate and asphalt binder (QT), and fuels used to heat the rejuvenated asphalt binder and RAP aggregate. The effects of the aggregate type and source on the required heat energy as well as the amount of required fuel are presented in Table 4. Although the specific gravity values of the aggregates from different sources are similar to each other, as shown in Table 2 their specific heat capacities differ widely. A higher specific heat capacity means that more energy is required to raise its temperature. When the material temperature decreases, the stored heat energy is liberated.

Table 4. Parameters for Determination of Energy Consumption

| Parameters                              | Unit       | Value |
|-----------------------------------------|------------|-------|
| Specific heat capacity of binder        | J/kg/°C    | 920   |
| Specific heat capacity of granite aggregate | J/kg/°C | 890   |
| RAP content                            | %          | 30-40 |

2.5 Effects of Mixing Temperatures on Fuel and GHG Emission

The fuel usage at targeted mixing temperatures was estimated. The type of fuel used was diesel. The estimation was done for one ton of asphalt production. For further analysis, the fuel usage was converted to carbon dioxide equivalent emissions based on the conversion factor by types of fuel in volume given by the Department of Environment, Food and Rural Affair, United Kingdom. The conversion factors are listed in Table 5.
Table 5. Conversion factors to Carbon Dioxide Equivalent Emissions

| Fuel Types | Unit | CO₂ | CH   | N₂O   |
|------------|------|-----|------|-------|
|            |      | KgCO₂e/unit | KgCO₂e/unit | KgCO₂e/unit |
| Diesel     | Liter | 2.6413 | 0.0015 | 0.0292 |

3. Result and Discussion

3.1 Mix design

The obtained volumetric properties which are consists of air voids (AV), voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and stability meets the JKR specifications. Increment of compaction temperature from 135°C to 150°C for RAP with biobased rejuvenator decreases the air voids. On the other hand the increment of RAP content decreases the VFA. However, as the temperature increases from 135°C to 150°C the RAP binder start to melt and fill in the voids in the aggregates. The softening effect of biobased rejuvenator on RAP binder can be observed by comparing the VFA of RAP with and without biobased rejuvenator. It can be observed that at same binder content, RAP with biobased rejuvenator exhibit higher VFA. The interaction of compaction temperature, binder content and RAP content on bulk specific gravity are shown in figures above. As it can be seen, RAP with and without biobased rejuvenator exhibit the highest Gmb at 5.5% binder content for all RAPs content.

For the production of the RAP without biobased mixtures, an optimum binder content of 5.2% was used, both RAP content (30% and 40%) show a similar trend of OBC reduction when the compaction temperature increases from 145°C to 160°C. moreover the effect of RAP content on the OBC is minimal with only 0.0% to 0.1% variation of binder content at the same temperature. This is similar to the findings of the studies by al-Qadi et al. (2009) on the effect of RAP content on OBC. This implies that RAP content has no effect on the OBC. On the other hand the effect of biobased rejuvenator on the mixture is noticeable because the biobased rejuvenator aids in making the mixture more workable by melting and rejuvenating the RAP binder which as a result of that the OBC of the RAP mixture with biobased rejuvenator is reduced especially at 40% RAP content.

Marshall Stability and flow are used to indicate the strength properties of the RAP mixtures. Both the marshall and flow result meet the JKR specification. Accordingly, marshall stability test is selected to indicate the strength properties. At the same binder content, increasing the RAP content results in higher Marshall Stability which indicates that RAP content contributes to strength. All mixtures comply with the minimum requirements for strength in JKR specification (Table 6).

Table 6. Summarizes the result of mix design parameters which comply with JKR standard

| Mixtures       | Optimum Binder Content (%) | Compaction Temperature (°C) | Parameters | Volumetric | Strength |
|----------------|---------------------------|----------------------------|------------|------------|----------|
|                |                           |                            |            | Air Voids  | Gmb      | VFA      | Stability | Flow      |
| Virgin         | 5.2                       | 150°C                      | 3.80       | 2.33       | 72.9     | 18.83    | 3.61      |
| 30% RAP        | 5.2                       | 150°C                      | 3.93       | 2.38       | 75.1     | 16.51    | 3.21      |
| 40% RAP        | 5.2                       | 150°C                      | 3.98       | 2.34       | 74.31    | 19.0     | 3.32      |
| 30% RAP-R      | 5.0                       | 135°C                      | 3.58       | 2.38       | 78.7     | 16.67    | 3.50      |
| 40% RAP-R      | 4.9                       | 135°C                      | 4.00       | 2.34       | 71.61    | 18.69    | 3.79      |
3.2 Energy Consumption of RAP with Biobased rejuvenator mixture production

Figure 1 presents the energy requirement for production of RAP containing Biobased rejuvenator for RAP. It is assumed that the mixture is produced for a road construction which is located less than 10 km from the asphalt mixing plant. Hence, the asphalt mixture was mixed at 10°C higher than the compaction temperature. Mixtures that were fabricated at the same RAP content, binder content and mixing temperature show different energy requirement. The difference in energy demand between the sources of RAP is influenced by the stiffness of the binder and the bulk specific gravity of the mixture. The mass of a mixture was calculated based on the bulk specific gravity obtained from an individual specimen fabricated at the specified condition. When the bulk specific gravity is higher, it means that the density is higher and therefore, increases the mass of the mixture. Similarly, the stiffer binder will have a higher specific heat capacity.

![Graph showing energy consumption](image)

**Figure 1.** Energy consumption for producing 1 tonne of RAP with and without bio-based rejuvenator

3.3 Effects of Mixing Temperatures on Fuel and GHG Emission

| mixtures     | Mixing temperature (°C) | Fuel Usage (litre) | CO₂ (kg CO₂e per unit) | CH₄(kg CO₂e per unit) | N₂O(kg CO₂e per unit) | Total GHG(kg CO₂e per unit) |
|--------------|-------------------------|--------------------|------------------------|----------------------|----------------------|-----------------------------|
| Virgin       | 160                     | 9.2                | 24.3000                | 0.0138               | 0.2686               | 24.5824                     |
| 30% RAP      | 160                     | 9.2                | 24.3000                | 0.0138               | 0.2686               | 24.5824                     |
| 40% RAP      | 160                     | 9.2                | 24.3000                | 0.0138               | 0.2686               | 24.5824                     |
| 30% RAP - R  | 145                     | 7.5                | 19.8100                | 0.0113               | 0.2190               | 20.0400                     |
| 40% RAP - R  | 145                     | 7.5                | 19.8100                | 0.0113               | 0.2190               | 20.0400                     |

**Table 1.** Comparison of GHG emissions produced from various mixing temperature with control mixture
Table 7 compares the effect of mixing temperatures on different greenhouse gases. The values give an indication of potential GHG emissions produced by mixtures fabricated at various mixing in comparison with the control mixtures. In context, higher mixing temperature produces higher GHG emissions while lower mixing temperature produces less GHG emissions. For example at 160°C mixing temperature the GHG is 24.5824 but upon addition of the bio-based rejuvenator the mixing temperature reduced to 150°C which emits less GHG compared with the control mixtures. This suggest that to save production cost in terms of mixing temperature, a lower mixing temperature is preferred. From the environmental point of view, lowering the mixing temperature can contribute to environmentally friendly and sustainable mixture.

4. Conclusion
The application of biobased rejuvenator helps to reduce the viscosity of binder at lower temperature and improve coating, mixture workability, and compaction for the asphalt mixes; this has been verified as viable based on the results as presented. With respect to the parameters examined, the application of bio based rejuvenator in asphalt mixtures containing high reclaimed content allows reducing the compaction temperature in the laboratory while maintaining the quality of common hot asphalt mixtures. This, as a consequence, facilitates a more favourable recycling of reclaimed material which would not have to be heated to extremely high temperatures; that, in turn, would prevent the consumption of excess while at same time reduces GHG and costs simultaneously, this opens the option of a more effective use of rejuvenators.

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