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# Comparative study on engineering properties and energy efficiency of asphalt mixes incorporating fly ash and cement

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## HIGHLIGHTS

- The effect of fly ash (FA) as an alternative filler mineral was evaluated.
- Samples were assessed based on workability, structural performance, and its sustainability.
- Synergistic effects of WMA and FA improve the sustainability in asphalt mix productions.
- The Sasobit® and FA show great combination to produce eco-friendly asphalt pavement.
- The use of WMA with FA reduced the total energy requirement and GHG emissions.

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## ABSTRACT

In this study, the effect of fly ash (FA) as an alternative filler mineral was evaluated regarding workability, structural performance, durability, and its sustainability when prepared using hot (HMA) and warm mix asphalt (WMA) technologies. The results revealed that workability of HMA and WMA samples containing FA are comparable to the mixes containing cement powder, yet the WMA mixes containing 4% Sasobit® prepared at 145 °C exhibited the highest workability, regardless of filler type. However, the compaction energy index (CEI) of WMA samples containing FA is more sensitive to the Sasobit® content variations at each mixing temperature. Besides, use of FA as an alternative filler mineral increased the resilient modulus up to 7.5% as compared to HMA and WMA containing cement powder. The tensile strength ratios of asphalt mixtures containing FA are not only satisfied the design criteria, but it is also higher than those of samples with cement filler. Use of WMA technology improves sustainability in the construction phase, while incorporation of FA filler decreases the greenhouse gas emissions during the raw material manufacturing stage. Therefore, synergistic effects of using the WMA technology and FA improve the sustainability of both construction and raw material processing within the cradle to gate phases. In conclusion, a higher workability and resilient modulus test result together with less environmental emission indicate that the WMA technology using Sasobit® and FA as an alternative filler are showing great potential for the production of eco-friendly asphalt pavement.

## 1. Introduction

Although various types of by-product or waste materials being adopted as the modifier in the asphaltic concrete production, compatibility of such materials are one of the leading concerns. In other words, the waste materials should not only improve the functional performance of mixes, yet to increase the durability for various service conditions. Moreover, the waste materials should also be compatible with the new technologies emerge in the asphalt industry, for example, warm-mix asphalt (WMA). The WMA additives can be incorporated either by wet or dry processes to allow the mixing and construction activities to be conducted at a lower temperature via various mechanisms [1]. It is also practical to improve the rheological properties of asphalt binders, and the engineering performance of asphalt mixes [2–5]. The type and additive content of WMA additives can be chosen based on the rheological properties of the virgin binder and the targeted engineering characteristics of mixes to achieve. Among other aspects, the engineering properties of indigenous materials, construction facilities, and cost should also be deliberated [6]. Herewith, reductions in GHG emissions, less carbon tax paying, and lower costs due less energy consumption make the WMA technology as an attractive option for any paving

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projects [7,8]. Both laboratory and field assessments give a promising picture for the application of WMA technology [9,10].

Numerous studies have been carried out on the compatibility of waste materials in WMA, such as reclaimed asphalt pavement (RAP), crumb rubber (CR), and recycled asphalt shingle (RAS). A study performed by Tao and Mallick [11] reported that a higher RAP content is applicable in WMA due to less mix stiffness. Mogawer et al. [12] also specified that WMA samples incorporating 40% RAP had a higher dynamic modulus ($E^*$) and workability than the HMA sample. The result indicated that incorporations of RAP do not adversely affect the mix performance. In another study, Buss et al. [13] found that the dynamic modulus of RAS-WMA is not only comparable with the HMA, yet resulted in a higher resistance to rutting based on the flow number test. The fatigue test results also showed that the interaction between crumb rubber and WMA additive could help to extend the fatigue life of rubberized-WMA mixtures compared to the control HMA [14]. However, the reduced construction temperature by WMA mixes has been compensating for the higher production temperatures due to use of RAP, RAS, and CR. Therefore, one of the stone to the ultimate goal of low-energy pavement using the waste materials has been removed. There are various types of waste material where their interactions with the WMA technology are not yet investigated in great details. One of such materials is coal fly ash (FA), which is a by-product of burning coal in the power plants. The annual global coal production is approximately 600 million tons, and 70%–80% produced ash composed of FA [15–17]. For example, in China, FA is produced approximately 50 million tons per year, which is the most significant source of industrial solid waste material [18]. Therefore, it is necessary to dispose of the FA in the landfills in an appropriate way to avoid undesirable impacts to the surroundings. However, it should be noted that the designated disposal areas are limited. Meanwhile, continuous and constant consumption of the coal will consequently increase the generation of FA. To cope with this problem, FA can be a potential alternative material in the pavement construction. FA is a hydrophilic powder that can be adopted as alternative cement with relatively high hydration potential. Its small size and granule shape make FA as an appropriate material as mix filler and asphalt modifier. A study carried out by Carpenter [19] showed that FA increases the compressive strength of asphalt mixes. Celik [20] reported the best performance based on the highest stability was obtained using 5% FA, which in line with the recommendation by Rosner et al. [21] within the range of 3%–6%. In another study, Ali et al. [22] reported that samples incorporating 50% and 2% FA as the fine and coarse aggregate, respectively, showed superior laboratory and field rutting performance. However, mixes containing FA showed relatively poor performance in fatigue behaviour compared to the control sample (without FA). FA also can be used to modify the asphalt rheological characteristics regarding the shear complex modulus [23], which depends on the FA content and the granular size. Suheibani [24] found that the FA granule size in a range of between 1 μm and 44 μm can be considered as the optimum gradation for asphalt binder upgrading.

However, the performance of FA as an alternative filler material and its synergistic with reduced construction temperature due to the use of WMA technology is unknown. Also, the effect of WMA additive content on the structural response, durability, and the workability of mixes are unclear. This research aims to fill these chasms in the asphalt pavement technology.

## 2. Materials

### 2.1. Asphalt binder

The asphalt binder used for this study was AC 80/100. Table 1 shows the rheological properties of the control asphalt binder (without WMA additives).

### 2.2. WMA additive

Sasobit® was used as an additive to prepare WMA specimen (Fig. 1) and Table 2. In this study, 2% and 4% Sasobit® by mass of binder was added and blended using the mechanical propeller. The rheological properties of the unaged and aged Sasobit® asphalt binders subjected to various ageing conditions as shown in Table 3.

### 2.3. Fly ash

Fig. 2 shows the fly ash powder used in this study. Table 4 presents the chemical components of FA and cement. Whereas, Table 5 shows the sieve analysis result of FA. The specific gravity of the FA was 2.33 g/cm$^3$.

### 2.4. Aggregate grading

Granite was used and blended to the mid-gradation of the Malaysian Public Works Department [26] specifications for the asphaltic concrete mixture type with nominal maximum aggregate size 14 mm (Fig. 3).

## 3. Methodology

### 3.1. Mixing and compaction process

Optimum asphalt binder content was 5% for all mix samples. A mechanical mixer equipped with a temperature control unit using heating oil was employed to blend the aggregate and the binder. Mixing and compaction temperatures for HMA samples are 160 °C and 150 °C, respectively. It should be noted that the mixing and compaction temperatures are varied for different WMA additives. For Sasobit®, the mixing and compaction temperatures are 10 °C–30 °C less than the HMA [27,28]. The chosen temperature ranges for WMA fall within the recommended range as shown in Table 6. The samples were compacted using gyratory Servopac compactor at 75 gyrations.

### 3.2. Analysis of workability

Workability is a property that indicates the ease with which an asphalt mix can be placed and compacted. It depends on many variables including construction temperature, aggregate gradation, aggregate type, and nominal maximum aggregate size of aggregate, asphalt binder type, content, binder modification technology, and waste material content in the asphalt mix. Additionally, external parameters such as method or equipment designed to evaluate workability are also an important factor. There are different technologies and analytical methods to measure the workability. In this study, compaction energy index (CEI) criteria, which was proposed by Bahia et al. [29]. CEI means the area under 8th gyration and to 92% of maximum theoretical density ($G_{mm}$), which schematically illustrated in Fig. 4. CEI is considered as an indication of the work applied by roller to reach the target compaction degree during the construction phase.

**Table 1**
Rheological properties of unaged and aged AC 80/100 binder.

| Aging State | Test Properties | Value |
|---|---|---|
| Unaged (original state) | Viscosity at 135 °C (mPa·s) | 465.0 |
| | $G^*/\sin(\delta)$ at 64 °C (kPa) | 1.23 |
| Short-term-aged | Viscosity at 135 °C (mPa·s) | 627.5 |
| | $G^*/\sin(\delta)$at 64 °C (kPa) | 2.68 |
| Long-term-aged | $G^*\sin(\delta)$ at 25 °C (kPa) | 2959 |