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Case study

Moisture susceptibility and environmental impact of warm mix asphalt containing bottom ash

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ABSTRACT

Warm Mix Asphalt (WMA) is recognised as a sustainable pavement construction technology due to its economic and environmental benefits. However, there are still some major concerns related to its performance properties, like moisture susceptibility. Certain researchers have reported desired performances using waste and by-products as constituent material in the WMA mixture. Therefore, this study was proposed to assess the Bottom Ash (BA) impact on WMA mixtures moisture susceptibility and environmental properties because its potential has widely been reported in HMA. It was limited to 20 % of fine aggregate substitution with BA and granite stone dust as a filler. Evotherm 3G was used as a WMA additive, and the Hot Mix Asphalt (HMA) mixtures were treated with 2 % hydrated lime by replacing stone dust. The Marshall mix design was followed to fabricate asphalt mixtures, where HMA and WMA specimens were mixed at 165 °C and 140 °C, respectively. The indirect tensile strength, tensile strength ratio, toxicity characteristic leaching procedure (TCLP) and pollutant emission of mixtures were investigated through laboratory tests. The mixtures containing BA improved the indirect tensile strength of mixtures, while Evotherm 3G potentially improved the tensile strength ratio of WMA mixtures containing BA. The results showed that BA as a constituent of asphalt mixture coupled with Evotherm 3G produced a compatible blend for WMA. The findings of the TCLP test showed that the compound of heavy elements found in BA does not leach out if introduced in the asphalt mixtures. Heavy elements concentrations were either undetectable or below the minimal level. However, the presence of BA in the asphalt mixture slightly increased the level of Carbon dioxide (CO_2). However, the carbon monoxide (CO) of the WMA mixture containing BA was reduced to approximately 75 %.

1. Introduction

Global warming and environmental concerns are among the most severe issues facing human beings. Hot Mix Asphalt (HMA) production is a contributing factor that implies significant fuel and energy consumption, resulting in pollutant emissions [1]. On the other hand, for the construction of flexible pavements, large quantities of raw mineral are used. Therefore, scientists are looking for innovative techniques to limit construction costs and reduce pollutant emissions in relation to the compatibility of asphalt pavements

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to sustainable construction [2]. As a result, Warm Mix Asphalt (WMA) technology was developed to meet the economic and environmental needs of sustainability.

In the late 1990s, initial WMA technologies were developed. In Germany and Norway, different additives were tested, and as a result, Foamed WMA technology was developed [3]. In 1956, Prof. Ladis Csanyi at Lowa State University investigated the production of foamed WMA technology [4,5]. Currently, several WMA technologies exist to produce asphalt mixtures, and others are in the developing stage [6]. Three accepted techniques are used to produce WMA mixtures: foaming techniques, organic additives, and chemical additives [5].

In general, the enormous benefits of WMA techniques have been reported over HMA, but the particular advantages and their level based on the technique used. The lower production temperature ensures the lower ageing of the WMA binder, which increases the pavement service life. Reduced fuel or energy costs have been reported due to their lower fuel or energy consumption [7]. From the comparison, it has been estimated that WMA technologies reduce fuel prices by up to 40 %. This fuel saving is directly linked to the WMA lower production temperature. However, the type of fuel, WMA technique, and the fuel price may contribute to the savings [5]. A drop in production temperature of 27 °C results in a 35–50 % reduction in fuel consumption. WMA decreases emissions of CO2, SO2, volatile organic compounds, CO, NOx and ash by 30–40 %, 35 %, 50 %, 10–30 %, 60–70 % and 20–25 %, respectively, compared to HMA [8–10]. The reduction in emissions provides a better working environment for the plant and paving crew [7].

Other than the benefits of using WMA, there are some significant concerns related to the long term performance, in-service moisture susceptibility and rutting potential of some specific techniques [6,11]. Generally, it is hypothesised that the reduced production and compaction temperature of WMA technologies increase the susceptibility of moisture-induced damaging of asphalt concretes [12,13]. Anand [14] also reported lower TSR results for WMA mixtures using Evotherm J1, Rediset, and Sasobit at reduced production temperatures. Studies show that Evotherm 3G significantly improves the moisture susceptibility of WMA compared to the foaming technique and other additives [15,16].

On the other hand, for the sake of preserving natural resources that are being utilised to obtain construction material and to overcome the adverse effects of landfills to the subsurface water due to the dumping of industrial waste. Recycled Asphalt Pavement (RAP) and industrial by-products, including steel slag and coal combustion by-products, are in practice as an alternative material for road construction. The residual deposits left behind, mainly in the form of Fly Ash (FA) and Bottom Ash (BA), are the core products that the construction industry can potentially use as raw material. Bottom ash produces in coal power plants during coal combustion when fired at 1100–1400 °C. Bottom ash is composed of large granular particles heavier than fly ash and deposits into the furnace bottom during coal combustion. Depending on the furnace, BA could be in a dry or wet form [17]. Its colour may range from brown to grey and black. Consisting of lime and melted sand with a small percentage of oxides, including sulfur, iron, aluminium, magnesium and other materials. BA is an angular-shaped material consisting of granular to sand-size particles [18].

Regarding the utilisation of BA, various research activities have been conducted and published since 1976 and onwards [19]. Its lower specific gravity and high water absorption require additional binder content with increased BA content [19,20]. Despite this, a high abrasion value of BA indicates a high potential for ravelling [21]. It is found to be less durable in terms of strength compared to the conventional aggregates because its popcorn-like particles tend to crush under heavy loading and compaction [17]. Therefore, it has been mostly recommended for subsequent pavement layers instead of wearing course. However, recent studies revealed that substituting a reliable portion of fine aggregate with BA may present comparable results to conventional HMA for wearing course [18]. Substitution of fine aggregate with 10 and 20 % BA by weight of total aggregate for wearing course and binder course do not degrade tensile strength, lower temperature cracking and rutting resistance of HMA mixtures [20,22,23]. Ksabati et al. [18] reported that HMA mixtures containing 15 % BA substituted with limestone and granite aggregate demonstrated comparable results when treated with hydrated lime. Jian Shiuh et al. [24] reported a linear decrease in TSR with an increase in bottom ash content.

It is apparent that during coal combustion, power plants predominantly release Carbon Dioxide (CO_2), Sulphur Oxides (SOx), Nitrogen Oxides (NOx) and inorganic pollutants, including fly ash and suspended particulate matters [25]. Many countries like Malaysia, producing a considerable amount of coal combustion by-products, lag behind using bottom ash as a construction material just because of its pollutant concerns. However, these concerns are more related to the disposal of BA in landfills [26]. Saha et al. [27] classified the trace elements into three groups according to their percentage present in coal residues. The most volatile elements (As and Se) found to be equally depleted in fly ash and bottom ash, placed in Class I. The semi-volatile elements (Zn, Cu, Ni, Cr, Cd and Pb) increased in fly ash compared to bottom ash categorised as Class II. In comparison, the least volatile elements (Co and Mn) of Class III increased at the same ratio in both fly ash and bottom ash. Through ageing in an open environment and washing of BA significantly reduces the concentration of heavy elements [28]. However, the leaching and toxicity potential of identified volatile elements depend on BA application, either used in unbound, hydraulically bound and bitumen bound pavement layers. Therefore, heavy metals concentration were reported mostly in unbound utilisation of BA in road construction [26].

WMA technology has been applied to different asphalt mixtures including, dense-graded asphalt, open-graded asphalt, stone matrix asphalt, polymer-modified asphalt, crumb rubber modified asphalt and sulfur modified asphalt [29–31]. Studies have been conducted to investigate the compatibility of alternative materials with WMA to enhance its environmental and performance properties. It has widely been investigated to produce WMA mixtures using recycled asphalt pavement (RAP) [32–35]. Literature is also available regarding the use of steel slag as an alternative aggregate for WMA production [1,2,12,36]. However, there is a lack of studies into the use of bottom ash as WMA aggregate.

The study investigates the moisture damage and environmental impact of WMA mixtures containing BA compared to HMA mixtures using a chemical additive Evotherm 3G. This study was limited to 20 % BA substitution in place of fine aggregate to produce WMA mixtures for the AC 28 binder course. As a result, a new asphalt mixture was developed named Bottom Ash Warm Mix Asphalt (BAWMA). To be noted that bottom ash content and its use in the binder course were selected based on recommendations and concerns of previous researchers.

2. Materials and experimental procedures

2.1. Materials and physiochemical characterisation

For the production of asphalt mixtures, un-modified 60/70 penetration grade bitumen and Evotherm 3G was used as a WMA additive and anti-stripping agent instead of hydrated lime. Evotherm 3G is an upgraded version of chemical packages released in 2008 and reported that it also acts as an anti-stripping agent [37]. Initially, it was developed in Europe as an Evotherm ET (Emulsion Technology) by Mead Westvaco and Eurovia in 2003, then upgraded into Evotherm DAT (Dispersed Asphalt Technology) and Evotherm 3G (Third Generation), a water-free chemical additive [38–40].

Crushed granite aggregate as coarse, fine aggregate and mineral filler was used in this study, supplied by Hanson Heidelberg Cement Group, Kulai, Johor Bahru. Bottom ash was collected from Tanjung Bin Power Plant Johor Bahru. BA was used by replacing 20 % of fine aggregate to obtain a homogeneous blend without altering the aggregate gradation, starting from 3.35 mm to 0.075 mm sieve size. In other words, 60 % of each fine aggregate fraction was replaced with BA and purely stone dust obtained from granite was used to avoid any adverse effects of BA on mixtures properties. Only to fabricate HMA mixtures, 2 % of mineral filler was replaced with hydrated lime to overcome the potential of granite aggregate in moisture damage as per recommendations of JKR 2008 specification. However, the WMA mixtures were blended and tested without hydrated lime because Evotherm 3G has specifically been selected as an additive and anti-stripping agent in this study. The proportional combined aggregate gradation for the binder course AC 28 is shown in Table 1.

The basic characteristics of BA are shown in Table 2. Bottom ash exhibited significantly higher abrasion loss and impact value than JKR 2008 standard specification which suggests that the bottom ash particles can easily break under the action of abrasion and impact load. This property discourages the use of BA as coarse aggregate or even as fine aggregate in wearing course because the higher losses indicate the ravelling potential subjected to heavy loading [21]. Comparatively, the lower specific gravity and higher water absorption confirm the higher abrasion losses and impact value of BA. These properties indicate the high carbon contents and the presence of popcorn-like particles that tend to increase the binder content and may disintegrate easily under loading.

The chemical composition of aggregates may affect the moisture susceptibility of mixtures. In this study, the X-Ray Fluorescence (XRF) test was used to analyse BA chemical composition to predict its suitability as a fine aggregate. In general, the main contents of oxides found in granite and bottom ash are Silica (SiO_2), Alumina (Al_2O_3), Ferric Oxide (Fe_2O_3) and Calcium Oxide (CaO), including a small percentage of other oxides as shown in Table 3. According to the ASTM C 618 standard, BA is categorised as F type material if the total proportion of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 70 % [41,42]. The oxides of aggregate, including calcium, aluminum, iron and magnesium, improve the bonding properties, but sodium and potassium degrade the bonding between aggregate and binder due to stripping [43]. Very low oxides of sodium and potassium detected in granite are 3.3 to 1.1 % and 1.3–1.5 % in BA, respectively.

The aggregates exhibit higher silica contents considered to be acidic and therefore known as hydrophilic aggregates. On the other hand, hydrophobic aggregates are basic in nature, generally exhibit lower silica content. In general, hydrophobic aggregates are less susceptible to stripping compared to hydrophilic aggregates [44]. However, the chemical composition of BA is almost similar to granite. Both aggregates are predominantly rich in silicon oxide and probably susceptible to moisture damage. Therefore, hydrated lime or other stripping agents are recommended when granite aggregate is used in asphalt concrete.

2.2. Specimen preparation

Four different asphalt mixtures were blended in this study, and granite aggregate was blended using 20 % BA as fine aggregate and 2 % hydrated lime. The type of mixtures comprising of Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), Bottom Ash Hot Mix Asphalt (BAHMA) and Bottom Ash Warm Mix Asphalt (BAWMA) are shown in Table 4. Before the production of WMA mixtures, virgin bitumen was heated to a temperature of 130 °C, then by weight of the bitumen, 0.4 % Evotherm 3G was added to the blend and mixed approximately for 10 min to achieve a homogeneous binder. The HMA mixtures were produced and compacted at 165 and 155 °C,

Table 1
Aggregate gradation for AC-28.

Sieve Size (mm)	Percent Aggregate Retained by Weight		
	Conventional Mix	Mix with 20 % Bottom Ash	
	Granite	Granite	Bottom Ash
28	0	0	0
20	19	19	0
14	14	14	0
10	11	11	0
5	17.5	17.5	0
3.35	6.5	2.6	3.9
1.18	11	4.4	6.6
0.425	7	2.8	4.2
0.150	7	2.8	4.2
0.075	2	0.8	1.2
Pan	3	3	0
Hydrated Lime	2	2	

Table 2
Characterisation of Bottom Ash.

Test	Standard	Bottom Ash	Specification
Los Angeles Abrasion Value	ASTM C131	49.17	≤ 25 %
Aggregate Impact Value	BS 812: Part 112	38.83	< 25 %
Specific Gravity			
Coarse Aggregate	AASHTO T85	2.062	–
Fine Aggregate	AASHTO T84	2.139	–
Water Absorption			
Coarse Aggregate	AASHTO T85	1.182	≤ 2 %
Fine Aggregate	AASHTO T84	1.668	≤ 2 %

Table 3
Chemical Composition.

Aggregate	Oxide Composition %								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	TiO_2
Granite	59.8	11.4	8.5	7.1	3.5	3.3	1.1	0.2	0.6
Bottom ash	56.9	17.1	10.9	6.5	2.0	1.3	1.5	0.7	1.5

while WMA at the temperature of 140 °C and 130 °C, respectively.

As per the Malaysian Public Works Department (2008) recommendations, Marshall Mix Design was followed to fabricate all the asphalt mixtures to determine optimum bitumen content (OBC) for HMA and BAHMA specimens. The test was carried out in compliance with ASTM D2726/D2726M-14. Based on the average of three replicates, the OBC for HMA and BAHMA was obtained 4.2 and 4.8 %, respectively. Because the chemical additives do not considerably alter the OBC of asphalt mixtures [45], therefore OBCs of 4.2 and 4.8 % were also used in this study to fabricate WMA and BAWMA respectively.

2.3. *Moisture susceptibility test*

The specimens were produced for the moisture susceptibility test following ASTM D4867/D4867M-09 and tested as per ASTM D6931-12 standard procedures. Six cylindrical Marshall specimens were prepared for each type of mixture and compacted according to the specification within the range of 6–7 % air voids. The specimens were further grouped in two subsets of three specimens in each, having the same average air void content. The first group was tested in a dry condition at 25 ± 1 °C. The second group was partially saturated in distilled water by applying a vacuum pressure of 70 kPa for five minutes to achieve a level of saturation within the range of 55–80 %. The specimens were transferred into a water bath to maintain their temperature at 60 °C for 24 h and then loaded at 25 ± 1 °C.

2.4. *Evaluation of environmental effects*

2.4.1. *Toxicity characteristic leaching procedure (TCLP) test*

The United States Environmental Protection Agency (EPA SW 846-1311) has developed a test setup to estimate heavy metals concentration found in hazardous wastes. Therefore, the toxicity characteristic leaching procedure (TCLP) was followed to examine the concentration of heavy metals in the leachates of WMA containing bottom ash. A loose specimen of BAWMA was incorporated and allowed to cool down to room temperature. Three specimens of approximately 100 g were sieved using 9.5 mm sieve size and transferred into polyethene bottles. An extraction liquid (Nitric acid) having a pH equal to 2.88 ± 0.05 was added into the bottle with the ratio of 20:1 liquid to the solid-state by weight. The bottles were allowed for agitation at 30 rpm for 18 h using rotary agitator equipment. The material was then filtered through a 0.45 μm membrane filter to extract the leachate. Finally, the test was performed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) to identify the heavy elements.

2.4.2. *Emission measurement test*

It has already mentioned that BA contains volatile elements that may release when heated. This test's main objective was to evaluate the effect of BA on the release of pollutant emissions at production temperatures. Four types of mixtures (HMA, BAHMA, WMA and BAWMA) with two replicates were investigated, and the test was limited to the conditions of 165 ℃ and 140 ℃ (mixing temperature) and weighing 10,000 g (mixture weight). The emissions were recorded at an interval of 1 min for 5 min to observe the

Table 4
Type of Mixtures with Aggregate Composition.

Mix Type	Aggregate Composition
HMA	Granite (coarse, fine aggregate and mineral filler), 2 % mineral filler replaced with hydrated lime (Control)
WMA	Granite (coarse, fine aggregate and mineral filler)
BAHMA	Granite (coarse, fine aggregate and mineral filler), BA (fine aggregate), 2 % mineral filler replaced with hydrated lime
BAWMA	Granite (coarse, fine aggregate and mineral filler), BA (fine aggregate)

Fig. 1. Asphalt mixer with Testo 350 gas analyser.

emission rate with time, although the aggregates were completely coated within 3 min.

This test was performed using a locally manufactured laboratory asphalt mixer. The mixer was specially modified and designed to confine the emissions release from asphalt mixture to attain a quantitative amount of pollutants and precise results. A portable Testo 350 gas analyser was used to measure the amount of emission from the mixtures while mixing, as demonstrated in Fig. 1. The instrument consists of a control unit and a meas-box can be connected to control the system by plugging through a data bus cable or Bluetooth. The flue gas probe 335 mm (sensor) was used to deduct the emission release from mixtures. The probe connected to the meas-box through thermocouples of 2.2 m long tubes, inserted into the mixer through a slot made from the mixer's top to detect pollutants.

3. Results and discussions

3.1. Moisture susceptibility

Type of aggregate, source of bitumen, properties of asphalt concrete, binder film thickness and the environmental conditions with traffic loading may influence moisture susceptibility of pavements [46]. However, the main influencing factor found to be the WMA lower production temperature [47]. Therefore, the BAHMA and BAWMA mixtures were evaluated for moisture susceptibility compared to their corresponding asphalt mixtures.

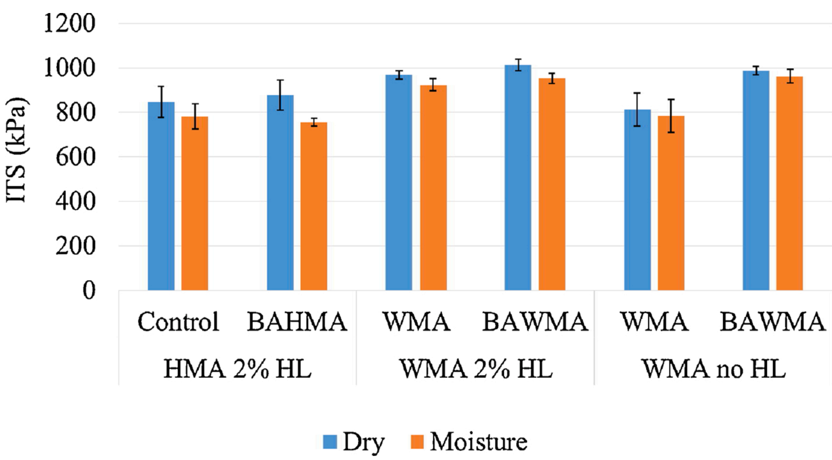

Fig. 2. Indirect Tensile Strength.

3.1.1. Indirect tensile strength test results

As can be observed from the graph shown in Fig. 2, the moisture conditioned specimens demonstrated lower tensile strength values than those unconditioned. This could be attributed to the loss of binder cohesion or the loss of adhesion between mineral aggregates due to moisture present in the specimen. The unconditioned ITS of BAHMA with the addition of 2 % hydrated lime represented good results. However, the moisture conditioned BAHMA showed a slightly lower ITS than conventional HMA. Byung Soo et al. [23] have also reported similar results when evaluating the tensile strength of HMA mixtures containing 10, 20 and 30 % BA.

Two WMA mixture groups were prepared and tested; one group was prepared with 2 % hydrated lime and the other was without hydrated lime. As can be observed from Fig. 2, the WMA mixture with 2 % hydrated lime demonstrated higher ITS values than the WMA mixture without hydrated lime. Despite this, the BAWMA mixture with and without hydrated lime represented almost similar results and improved the overall tensile strength compared to other mixtures. The results achieved eliminates the substitution of hydrated lime for the production of WMA with Evotherm 3G. These observations are in agreement with previously published work by [16], mentioning that there is no need for any other stripping agent if Evotherm 3G is used. In addition, the possible cause of higher ITS value could be the combination of bottom ash providing maximum interlocking due to its highly rough and angular properties. On the other hand, Evotherm 3G facilitated with a stripping agent resists moisture damage and provides a complete coating of aggregates even at a lower temperature.

3.1.2. Tensile strength ratio test results

From Fig. 3, it can be observed that all the WMA mixture groups provide comparable results. Accordingly, the BAHMA mixture satisfied the minimum Tensile Strength Ratio (TSR) limit of 80 % as recommended by AASHTO M323 (2008) but demonstrated a bit lower TSR than the conventional HMA. It can be attributed to the chemical composition of BA that categorises it as a hydrophilic aggregate like granite aggregate or due to the porous and absorptive nature of BA that provides more room for water to penetrate the mixture. Zeng and Ksaibati [48] also reported similar performance of asphalt mixture using 15 % BA in HMA for the production of wearing course.

The results obtained from WMA mixtures with or without hydrated lime showed some variation in the findings. Hydrated lime is considered an effective adhesion promoter; therefore, recommended explicitly by JKR 2008 specification to improve moisture resistance when using granite aggregate to produce HMA. However, in the case of WMA mixtures produced using Evotherm 3G, the addition of 2 % hydrated lime seems to be unnecessary because the WMA and BAWMA specimens prepared without hydrated lime demonstrated the highest TSR values. The reduction in TSR values of WMA mixtures containing hydrated lime may be attributed to the

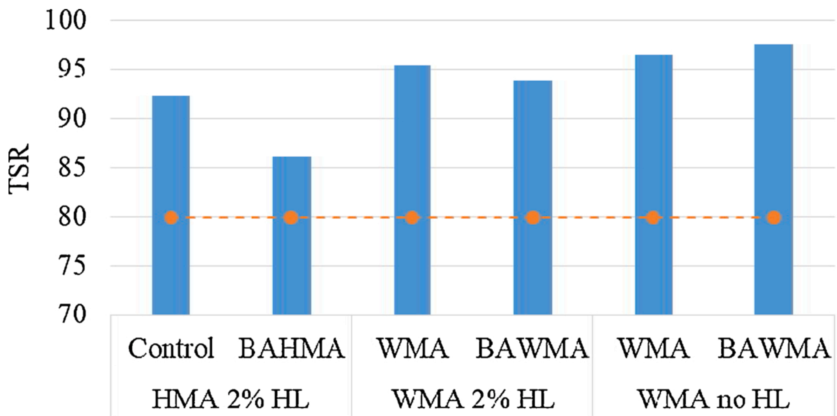

Fig. 3. Tensile Strength Ratio.

Table 5
TCLP Test Results of WMA Mixture Containing 20 % Bottom Ash.

Parameters	Replicates			Avg. Result (mg/L)	Standard Limit
	1	2	3		
Lead (Pb)	0.416321	0.392869	0.360702	0.389964	5.0
Arsenic (As)	0.240552	0.220648	0.218884	0.226694	5.0
Chromium (Cr)	0.187936	0.189165	0.187458	0.188186	5.0
Cadmium (Cd)	ND				1.0
Mercury (Hg)	ND				0.2
Copper (Cu)	ND				25

ND.- Not detected.

reduction in the production temperature or the incompatibility of hydrated lime with Evotherm 3G. TSR values conform that the fabrication of BAWMA mixtures using Evotherm 3G can significantly increase the resistance against moisture-induced damages without any additional agent. The amines facilitated into Evotherm 3G as anti-stripping agent and the compatibility of mixture constituents among each other (i.e., Evotherm 3G, binder, granite and the bottom ash) significantly improved the moisture resistance of specimens. Therefore, the addition of hydrated lime to the WMA mixtures specifically produced using Evotherm 3G could possibly increase the cost.

3.2. Environmental investigation

3.2.1. Toxicity characteristic leaching procedure test results

The obtained concentration of leachates from the listed heavy elements shown in Table 5, was found to be significantly below the minimum threshold imposed by the US EPA standard SW- 846. The results indicate that the concentration of leachates could be minimised to a sufficient extent if BA particles are encapsulated and coated through the asphalt binder. The asphalt binder used is known as a hydrophobic substance that provides a restricting barrier around the particles. Pollutants of such materials can be restricted from leaching out into the water or environment [24]. Hassan's [21] findings are somewhat similar to the results obtained. Therefore, results achieved from this study suggest that BA generates from the Tanjung Bin power plant may be considered as a non-hazardous by-product for asphalt application.

3.2.2. Pollutant emission results

This test involves specifically the evaluation of pollutant emissions discharged from the asphalt mixtures while mixing at production temperatures. During the emission measurement of mixtures, mainly the concentration of Carbon Dioxide (CO_2) and Carbon Monoxide (CO) was detected. A minimal concentration of SO_2 was observed from the control and BAHMA. Similarly, NO_x and NO_2 were observed from the WMA and BAWMA with a minimal concentration. Due to the minimal concentration of SO_2, NO_2 and NO_x emitted during the test. Therefore, CO_2 and CO were considered the leading indicators to assess the impact of mixing temperatures and BA on the concentration of emission generated from the mixtures.

The sampling for CO_2 emission measurement was performed directly from the confined and closed mixer using an Infrared (IR) sensor facilitated into the gas analyser probe. The average concentrations of CO_2 emission were obtained from HMA and WMA mixtures produced at 165 °C and 140 °C and graphically plotted in Fig. 4. The WMA and BAWMA mixtures demonstrated relatively lower emissions compared to HMA mixtures. A reduction of 7 % and 8 % of CO_2 emissions from WMA and BAWMA was recorded compared to the control and BAHMA. Even though different researchers have used different approaches to measure the emission of asphalt mixtures, the percentage of reduction in CO_2 emission is similar to the findings of Alejandra et al. [49] obtained at reduced temperatures in their study. Despite this, a remarkable increase in CO_2 was noticed from the mixtures containing BA. It was observed that BAHMA and BAWMA increased the CO_2 emission by 13 % and 4 % compared to conventional HMA. The results reveal that even at a lower temperature (140 °C), the coal bottom ash releases carbon dioxide. However, the use of WMA seems to reduce the CO_2 emission compared to HMA.

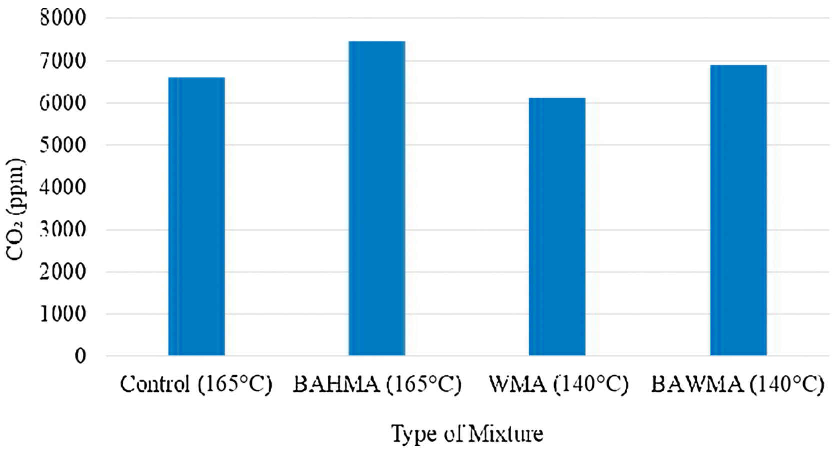

Fig. 4. Accumulated Concentration of Emitted Carbon dioxide.

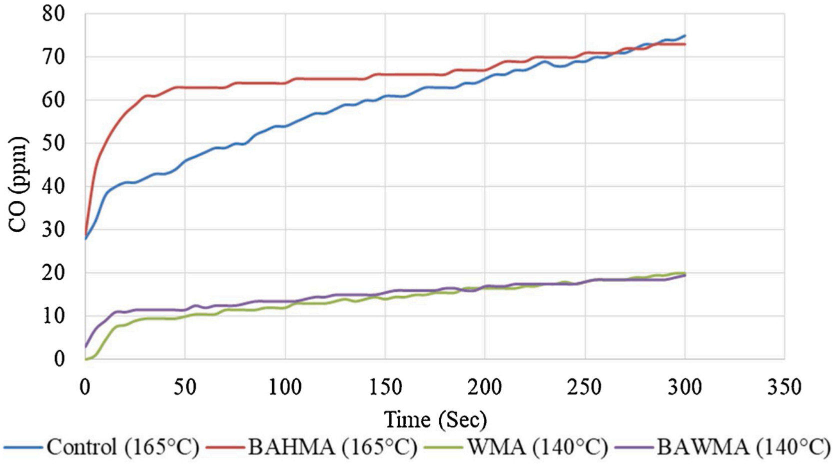

Fig. 5. Cumulative Concentration of Emitted Carbon monoxide.

Simultaneously, the Carbon monoxide (CO) concentrations were recorded at the tested temperatures for HMA and WMA mixtures up to 5 min, as demonstrated in Fig. 5. As can be observed in the figure, at the initial stage of mixing, BAHMA showed a significant increase in the trend line, but after mixing four minutes, a decline in the trend lines can be observed compared to the conventional mixture. A similar trend can also be observed from the trend line of BAWMA but with a small difference, as the WMA mixtures were mixed relatively at a reduced temperature. The small difference in the emission of the mixture containing BA could be attributed to the carbons emitted from the bottom ash. After 3 min of mixing, the concentration of CO emission from the control and BAHMA mixtures was recorded at 63 ppm and 66 ppm, and for WMA and BAWMA, the readings were 16 ppm and 17 ppm. WMA and BAWMA demonstrated a significant reduction of 75 % and 74 % CO emission than conventional HMA. The results can be correlated with the findings of Chaohui Wang et al. [50], where they developed a laboratory testing setup to estimate the emission generated from the mixtures at production temperatures.

4. Conclusions

The aim of this study was to look into the moisture sensitivity of asphalt mixtures incorporating 20 % bottom ash as fine aggregate and Evotherm 3G as WMA additive. Furthermore, the effect of BA asphalt mixtures on the environment was also investigated. Based on the findings, both granite and BA found to be rich in silicon oxide and considered hydrophilic aggregates. BAHMA demonstrated a higher ITS in dry conditions, but it reduced slightly in the presence of moisture compared to the conventional HMA. Bottom ash was observed to be more compatible with Evotherm 3G by demonstrating the highest ITS value compared to all other mixtures. The rough surface and angularity of BA probably improved the interlocking between aggregates, hence increasing the resistance of pavement against loading. BAHMA showed the least TSR with hydrated lime, while BAWMA without hydrated lime represented the highest value among all other mixtures. TSR results reveal that Evotherm 3G eliminates the addition of hydrated lime for WMA mixtures. As a result, good compatibility among the mixture constituents (Evotherm 3G, binder, granite and bottom ash) was achieved for the BAWMA mixture. TCLP results show that BA can be treated as a potential aggregate for the production of asphalt mixture. The reduction of 25 °C significantly reduced pollutant emissions. However, BA found to be an influencing constituent to increase pollutant emissions. An average increase of 13 % and 4 % was observed in carbon dioxide of BAHMA and BAWMA compared to the conventional HMA. Despite this, a different trend was observed from the emission of carbon monoxide. Overall, WMA and BAWMA significantly reduced CO emission by 75 % and 74 % respectively.

In order to confirm the findings of this study, more laboratory or field research may be carried out to measure the carbons emit from BA asphalt mixtures. As a result, if the carbon content of asphalt mixtures containing BA is higher than that of conventional HMA, then the BA content added to the asphalt should be limited or reduced for future studies.

Declaration of Competing Interest

The authors report no declarations of interest.

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References

[1] H.S. Zeinoddin, S.M. Abtahi, S.M. Hejazi, S. Babamohammadi, A. Goli, M. Amuchi, Design and production of steel slag warm mix asphalt (SSWMA) using an amino-based resin, Transp. Infrastruct. Geotechnol. 3 (2016) 91–108, https://doi.org/10.1007/s40515-016-0032-4.
[2] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Constr. Build. Mater. 49 (2013) 611–617, https://doi.org/10.1016/j.conbuildmat.2013.08.034.
[3] R.A. Tarefder, J. Pan, Field and Laboratory Evaluation of Warm Mix Asphalt (WMA)-Phase 1, Report No. NM13MSC-04, Albuquerque, 2014.
[4] M. Zaumanis, Warm Mix Asphalt Investigation, Thesis (Master's), TECHNICAL UNIVERSITY OF DENMARK, 2010.
[5] A. Vaitkus, D. Čygas, A. Laurinavičius, Z. Perveneckas, Analysis and evaluation of possibilities for the use of warm mix asphalt in lithuania, Balt. J. Road Bridg. Eng. 4 (2009) 80–86, https://doi.org/10.3846/1822-427X.2009.4.80-86.
[6] F. Martinho, S.D. Capitão, L.G. Picado-Santos, Sustainable pavements: warm asphalt mixtures made with recycled aggregates from different industrial by-products, Eur. Pavement Asset Manag. – EPAM4 (2012) 12.
[7] J.W. Button, C. Estakhri, A. Wimsatt, A Synthesis of Warm-Mix Asphalt, Report No. FHWA/TX-07/0-5597-1, NTIS, Texas, 2007. http://tti.tamu.edu/documents/0-5597-1.pdf.
[8] H.A. Rondón-Quintana, W.D. Fernández-Gómez, C.A. Zafra-Mejía, Behavior of a warm mix asphalt using a chemical additive to foam the asphalt binder, Rev. Fac. Ing. Univ. Antioquia (2015) 129–138, https://doi.org/10.17533/udea.redin.n78a17.
[9] M.E. Abdullah, K.A. Zamhari, R. Buhari, S.K.A. Bakar, N.H.M. Kamaruddin, N. Nayan, M.R. Hainin, N.A. Hassan, S.A. Hassan, N.I.M. Yusoff, Warm mix asphalt technology: a review, J. Teknol. (Sci. Eng.) 71 (2014) 39–52.
[10] H.M.R.D. Silva, J.R.M. Oliveira, J. Peralta, S.E. Zoorob, Optimisation of warm mix asphalts using different blends of binders and synthetic paraffin wax contents, Constr. Build. Mater. 24 (2010) 1621–1631, https://doi.org/10.1016/j.conbuildmat.2010.02.030.
[11] F. Safari, J. Lee, L.A.H. Do Nascimento, C. Hintz, Y.R. Kim, Implications of Warm-Mix asphalt on long term oxidative aging and fatigue performance of asphalt binders and mixtures. Asph. Paving Technol. Assoc. Asph. Paving Technol. Tech. Sess., 2014, pp. 45–61, https://doi.org/10.1080/14680629.2014.927050.
[12] K. Kanitpong, N. Charoentham, S. Likitlersuang, Investigation on the effects of gradation and aggregate type to moisture damage of warm mix asphalt modified with Sasobit, Int. J. Pavement Eng. Asph. Technol. 13 (2012) 451–458, https://doi.org/10.1080/10298436.2011.565058.
[13] F. Xiao, V.S. Punith, B.J. Putman, Effect of compaction temperature on rutting and moisture resistance of foamed warm-mix-asphalt mixtures, J. Mater. Civ. Eng. 25 (2013) 1344–1352, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000664.
[14] A. Sampath, Comprehensive Evaluation of Four Warm Asphalt Mixture Regarding Viscosity, Tensile Strength, Moisture Sensitivity, Dynamic Modulus and Flow Number, Thesis (Master's), The University of Iowa, 2010, https://doi.org/10.17077/etd.k37qhxba.
[15] R.T. Abd El-Hakim, J. Epps, A. Epps Martin, E. Arámbula-Mercado, Laboratory and field investigation of moisture susceptibility of hot and warm mix asphalts, Int. J. Pavement Eng. Asph. Technol. 0 (2019) 1–10, https://doi.org/10.1080/10298436.2019.1694150.
[16] A.A. Tayebali, D. Ph, N.P. Khosla, D. Ph, H. Malladi, D. Ph, N. Carolina, Impact of WMA Technologies on the Use of RAP Mixtures in North Carolina, FHWA/NC/2013-05, Raleigh, North Carolina, 2015.
[17] C.W. Lovell, T.C. Ke, W.H. Huang, J.E. Lovell, Bottom ash as highway material, Transp. Res. Rec. 1310 (1991) 106–116. http://www.trb.org/Publications/Pages/262.aspx.
[18] K. Ksaibati, S. Rama, K. Sayiri, Utilisation of Wyoming Bottom Ash in Asphalt Mixes, No. MPC Report No. 06-179, Mountain-Plains Consortium, 2006.
[19] R.K.D.O. Ciaran, J. Lynn, Gurmel S. Ghataora, Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements, Int. J. Pavement Res. Technol. 11 (2016) 185–201.
[20] H.F. Hassan, K. Al-Shamsi, Characterisation of asphalt mixes containing MSW ash using the dynamic modulus |E*| test, Int. J. Pavement Eng. 11 (2010) 575–582, https://doi.org/10.1080/10298436.2010.501865.
[21] H.F. Hassan, Recycling of municipal solid waste incinerator ash in hot-mix asphalt concrete, Constr. Build. Mater. 19 (2005) 91–98, https://doi.org/10.1016/j.conbuildmat.2004.05.010.
[22] K. Ksaibati, G.L. Conner, Laboratory Evaluation of Bottom Ash Asphalt Mixes, University of Wyoming, P.O. Box 3295 Laramie, WY 82071-83295, 2004.
[23] B.S. Yoo, D.W. Park, H.V. Vo, Evaluation of asphalt mixture containing coal ash, Transp. Res. Procedia 14 (2016) 797–803, https://doi.org/10.1016/j.trpro.2016.05.027.
[24] J.-S. Chen, P.-Y. Chu, J.-E. Chang, H.-C. Lu, Z.-H. Wu, K.-Y. Lin, Engineering and environmental characterization of municipal solid waste bottom ash as an aggregate substitute utilised for asphalt concrete, J. Mater. Civ. Eng. 20 (2008) 432–439, https://doi.org/10.1061/(ASCE)0899-1561(2008)20:6(432).
[25] S.P. Raghuvanshi, A. Chandra, A.K. Raghav, Carbon dioxide emissions from coal based power generation in India, Energy Convers. Manage. 47 (2006) 427–441, https://doi.org/10.1016/j.enconman.2005.05.007.
[26] C.J. Lynn, G.S. Ghataora, R.K. Dhir, Environmental impacts of MIBA in geotechnics and road applications, Environ. Geotech. 5 (2018) 31–55, https://doi.org/10.1680/jenge.15.00029.
[27] D. Saha, D. Chatterjee, S. Chakravarty, T. Roychowdhury, Investigation of environmental-concern trace elements in coal and their combustion residues from thermal power plants in Eastern India, LREC Int. Conf. Lang. Resour. Eval. 28 (2019) 1505–1520, https://doi.org/10.1007/s11053-019-09451-2.
[28] C.M. Huang, C. Te Chiu, K.C. Li, W.F. Yang, Physical and environmental properties of asphalt mixtures containing incinerator bottom ash, J. Hazard. Mater. 137 (2006) 1742–1749, https://doi.org/10.1016/j.jhazmat.2006.05.016.
[29] H.A. Rondón-Quintana, M.S. Ocampo-Terreros, H.A. Vacca-Gámez, F.A. Reyes-Lizcano, J.P. Nieto-Mora, D.P. Beltrán-Cruz, The mechanical behavior of two warm-mix asphalts, Ing. e Investig. 36 (2016) 29–38, https://doi.org/10.15446/ing.investig.v36n3.54861.
[30] X. Yu, Z. Leng, T. Wei, Investigation of the rheological modification mechanism of warm-mix additives on crumb-rubber-modified asphalt, J. Mater. Civ. Eng. 26 (2014) 312–319, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000808.
[31] Z. Liu, S.M. Asce, X. Yu, M. Asce, Laboratory evaluation of warm-mix open graded friction course mixtures, J. Mater. Civ. Eng. 27 (2013) 1239–1247, https://doi.org/10.1061/(ASCE)MT.
[32] A. Foroutan Mirhosseini, A. Tahami, I. Hoff, S. Dessouky, A. Kavussi, L. Fuentes, L.F. Walubita, Performance characterisation of warm-mix asphalt containing high reclaimed-asphalt pavement with bio-oil rejuvenator, J. Mater. Civ. Eng. 32 (2020) 04020382, https://doi.org/10.1061/(asce)mt.1943-5533.0003481.
[33] S.R. Omranian, M.O. Hamzah, L. Gungat, S.Y. Teh, Evaluation of asphalt mixture behavior incorporating warm mix additives and reclaimed asphalt pavement, J. Traffic Transp. Eng. (English Ed.) 5 (2018) 181–196, https://doi.org/10.1016/j.jtte.2017.08.003.
[34] M.J. Ayazi, A. Moniri, P. Barghabany, Moisture susceptibility of warm mixed-reclaimed asphalt pavement containing Sasobit and Zycotherm additives, Pet. Sci. Technol. 35 (2017) 890–895, https://doi.org/10.1080/10916466.2017.1290655.
[35] H. Behbahani, M.J. Ayazi, A. Moniri, Laboratory investigation of rutting performance of warm mix asphalt containing high content of reclaimed asphalt pavement, Pet. Sci. Technol. 35 (2017) 1556–1561, https://doi.org/10.1080/10916466.2017.1316738.
[36] H. Ziari, A. Moniri, R. Imaninasab, M. Nakhaei, Effect of copper slag on performance of warm mix asphalt, Int. J. Pavement Eng. 20 (2019) 775–781, https://doi.org/10.1080/10298436.2017.1339884.
[37] Y. Kuang, Evaluation of Evotherm as a WMA Technology Compaction and Anti-strip Additive, Thesis (Master's), Iowa State University, Ames, Iowa, 2012. https://lib.dr.iastate.edu/etd.
[38] B. Kheradmand, R. Muniandy, L.T. Hua, R.B. Yunus, A. Solouki, An overview of the emerging warm mix asphalt technology, Int. J. Pavement Eng. 15 (2014) 79–94, https://doi.org/10.1080/10298436.2013.839791.
[39] R.C.W. Ashley Buss, Mohamed Rashwan, Investigation of Warm-Mix Asphalt Using Iowa Aggregates, Report No. IHRB Project TR-599, Ames, 2011.
[40] Z.W.James S. Lai, James Y. Tsai, Evaluating Constructability and Properties of Warm Mix Asphalt, Report No, FHWA-GA-10-0904, Atlanta, Georgia, 2010. https://www.dot.ga.gov/doingbusiness/research/Documents/WMA.pdf.
[41] N.I.R. Ramzi hannan, S. Shahidan, N. Ali, M.Z. Maarof, A comprehensive review on the properties of coal bottom ash in concrete as sound absorption material, MATEC Web Conf. 103 (2017) 1–10, https://doi.org/10.1051/matecconf/201710301005.

[42] M.H. Abdullah, A.S.A. Rashid, U.H.M. Anuar, A. Marto, R. Abuelgasim, Bottom ash utilisation: a review on engineering applications and environmental aspects, IOP Conf. Ser. Mater. Sci. Eng. 527 (2019), https://doi.org/10.1088/1757-899X/527/1/012006.
[43] M. Singh, P. Kumar, M.R. Maurya, Strength characteristics of SBS modified asphalt mixes with various aggregates, Constr. Build. Mater. 41 (2013) 815–823, https://doi.org/10.1016/j.conbuildmat.2012.12.062.
[44] A.R. Tarrer, V. Wagh, The effect of the physical and chemical characteristics of the aggregate on bonding. National Research Council, 1991. No. SHRP-A/UIR-91-507. Washington, DC: Strategic Highway Research Program.
[45] M.O. Hamzah, B. Golchin, C.T. Tye, Determination of the optimum binder content of warm mix asphalt incorporating Rediset using response surface method, Constr. Build. Mater. 47 (2013) 1328–1336, https://doi.org/10.1016/j.conbuildmat.2013.06.023.
[46] B. Sengoz, E. Agar, Effect of asphalt film thickness on the moisture sensitivity characteristics of hot-mix asphalt, Build. Environ. 42 (2007) 3621–3628, https://doi.org/10.1016/j.buildenv.2006.10.006.
[47] Graham C. Hurley, Brian D. Prowell, Evaluation of potential processes for use in warm mix asphalt, Assoc. Asph. Paving Technol. (2006) 41–90, in: https://www.researchgate.net/publication/313092384_Evaluation_of_potential_process_for_use_in_warm_mix_asphalt.
[48] M. Zeng, K. Ksaibati, Evaluation of moisture susceptibility of asphalt mixtures containing bottom ash, Transp. Res. Rec. (2003) 25–33, https://doi.org/10.3141/1832-04.
[49] A.T. Calabi-Floody, G.A. Valdés-Vidal, E. Sanchez-Alonso, L.A. Mardones-Parra, Evaluation of gas emissions, energy consumption and production costs of Warm Mix Asphalt (WMA) involving natural zeolite and Reclaimed Asphalt Pavement (RAP), Sustain 12 (2020), https://doi.org/10.3390/SU12166410.
[50] C. Wang, Q. Li, K.C.P. Wang, X. Sun, X. Wang, Emission reduction performance of modified hot mix asphalt mixtures, Adv. Mater. Sci. Eng. 2017 (2017) 11, https://doi.org/10.1155/2017/2506381.