PERFORMANCE OF WARM MIX ASPHALT CONTAINING COAL BOTTOM ASH AS ALTERNATIVE AGGREGATE

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DEDICATION

This thesis is dedicated to Allah Almighty, my creature, who blessed me with intellectual ability, knowledge, and the capacity to deal with difficult situations. This is also dedicated to my family, particularly my parents, who have always supported me. To my wife and children who have suffered during this journey.

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ABSTRACT

The increase in energy usage, material cost and environmental concerns encourage the need for cheaper and environmentally sustainable asphalt pavements. The development of Warm Mix Asphalt (WMA) technology has brought environmental and economic benefits. However, there are significant concerns related to WMA performance, such as rutting potential and moisture susceptibility. Recent research shows that the recycling of industrial by-products in WMA mixture offers technical benefits for road construction. Therefore, this research aimed to evaluate the compatibility of Bottom Ash (BA) as fine aggregate in WMA production using chemical additives. The research was initiated with the physicochemical and mineralogical characterisation of BA compared to the granite aggregate. Laboratory tests were conducted to investigate the behaviour of binder incorporated with chemical additives (Cecabase RT and Evotherm 3G) at concentrations of 0.3%, 0.4% and 0.5% by the total weight of 60/70 penetration grade bitumen. The compatibility of the additives, optimal dose, and production temperature for WMA was evaluated and compared to the control asphalt mixtures through the mechanical properties. Laboratory tests were also carried out to assess the performance of the asphalt mixtures, including moisture susceptibility, resilient modulus, dynamic creep, rutting resistance, and cooling rate. The mixtures' potential contamination of leachates and pollutant emissions were assessed using a TCLP test and a combustion analyser. The characterisation of BA disclosed that it is porous and rough-edged granular particles with high abrasion loss, which does not favour its use as coarse aggregates but is applicable as fine aggregate for producing asphalt mixtures. The Marshall properties of the mixture containing BA satisfied the minimum requirements for the design of the binder course. The addition of chemical additives did not significantly change the binder properties, and the viscosity remained un-change. BA improved the tensile strength, resilient modulus, and resistance to permanent deformation of WMA mixtures by increasing aggregate interlocking and stiffness. The incorporation of BA into asphalt also did not indicate the presence of heavy metals but slightly increased the carbon dioxide emission compared to the control asphalt. However, the reduction of 25°C in production temperature significantly reduced the concentration of pollutant emissions and energy usage. Evotherm 3G combined with BA and granite aggregate produced a productive WMA mixture by eliminating hydrated lime as an anti-stripping agent. In conclusion, the WMA mixture with bottom ash (BAWMA) demonstrates a stiffer and more durable mixture for the binder course.

ABSTRAK

Peningkatan penggunaan tenaga, kos bahan dan keprihatinan terhadap alam sekitar mendorong kepada keperluan terhadap turapan berasfalt yang lebih murah dan mampan. Pembangunan teknologi Asfalt Campuran Suam (WMA) telah membawa manfaat terhadap alam sekitar dan ekonomi. Walau bagaimanapun, masih terdapat beberapa kebimbangan yang signifikan berkaitan dengan prestasi WMA, seperti potensi aluran dan kerentanan lembapan. Penyelidikan terkini menunjukkan bahawa kitar semula produk sampingan industri dalam campuran WMA menawarkan manfaat teknikal terhadap pembinaan jalan raya. Oleh itu, penyelidikan ini bertujuan untuk menilai keserasian Abu Dasar (BA) sebagai agregat halus dalam penghasilan WMA menggunakan bahan tambah kimia. Penyelidikan telah dimulakan dengan pencirian fizikokimia dan mineralogi BA dibandingkan dengan agregat granit. Ujian makmal telah dijalankan untuk menyiasat tingkah laku pengikat yang digabungkan dengan bahan tambah kimia (Cecabase RT dan Evotherm 3G) pada kepekatan 0.3%, 0.4% dan 0.5% dengan jumlah berat bitumen gred penusukan 60/70. Keserasian bahan tambah, dos optimum dan suhu penghasilan campuran WMA dinilai dan dibandingkan dengan campuran asfalt kawalan melalui ciri-ciri mekanikal. Ujian makmal juga dijalankan untuk menilai prestasi campuran asfalt, termasuk kerentanan lembapan, modulus berdaya tahan, rayapan dinamik, rintangan aluran, dan kadar penyejukan. Potensi pencemaran campuran terhadap bahan larut lesap dan pelepasan bahan cemar dinilai menggunakan ujian TCLP dan penganalisis pembakaran. Pencirian BA mendedahkan bahawa ia adalah zarah berliang dan berbutir kasar dengan kehilangan lelasan yang tinggi, yang mana tidak sesuai digunakan sebagai agregat kasar tetapi boleh digunakan sebagai agregat halus untuk menghasilkan campuran asfalt. Ciri-ciri Marshall bagi campuran yang mengandungi BA memenuhi keperluan minimum untuk reka bentuk lapisan pengikat. Penambahan bahan tambah kimia tidak mengubah sifat pengikat dengan ketara, dan kelikatan kekal tidak berubah. BA meningkatkan kekuatan tegangan, modulus berdaya tahan dan rintangan terhadap ubah bentuk kekal dengan menambah baik agregat saling mengunci dan kekukuhan. Penggabungan BA ke dalam asfalt juga tidak menunjukkan kehadiran logam berat tetapi sedikit peningkatan terhadap pelepasan karbon dioksida berbanding asfalt kawalan. Walau bagaimanapun, pengurangan 25°C dalam suhu pengeluaran telah mengurangkan kepekatan pelepasan bahan pencemar dan penggunaan tenaga dengan ketara. Evotherm 3G digabungkan dengan BA dan agregat granit menghasilkan campuran WMA yang produktif dengan menghapuskan kapur terhidrat sebagai agen anti-pelucutan. Kesimpulannya, campuran WMA dengan abu dasar (BAWMA) menunjukkan campuran yang lebih kukuh dan tahan lama untuk lapisan pengikat.

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LIST OF ABBREVIATIONS

AASHTO	-	American Association of State Highway and Transport Officials
ACAA	-	American Coal Ash Association
AC 28	-	Asphalt concrete binder course with a nominal aggregate size of 20 mm
AIV	-	Aggregate impact value
APA	-	Asphalt Pavement Analyser
ASA	-	Anti-stripping agent
ASTM	-	American Society for Testing Material
BA	-	Bottom ash
BAHMA	-	Bottom ash hot mix asphalt
BAWMA	-	Bottom ash warm mix asphalt
BOF	-	Basic oxygen furnace
CBR	-	California Bearing Ratio
CCP	-	Coal combustion products
CSS	-	Creep strain slope
DAT	-	Dispersed asphalt technology
ET	-	Emulsion technology
FESEM	-	Field Emission Scanning Electron-Microscope
GLWT	-	Georgia Loaded Wheel Test
HMA	-	Hot mix asphalt
ICP-OES	-	Inductively Coupled Plasma Optical Emission Spectrometry
ITS	-	Indirect tensile strength
JKR	-	Jabatan Kerja Raya (Public Works Department)
LAAV	-	Loss Angeles abrasion value
LTOA	-	Long term oven ageing
LVDT	-	Linear Variable Differential Transducer
NAPA	-	National Asphalt Pavement Association
NCHRP	-	National Cooperative Highway Research Program

OBC	-	Optimum binder content
OGFC	-	Open grade friction course
PA	-	Porous asphalt
PG	-	Performance Grade
PI	-	Penetration Index
PSO	-	Particle Swarm Optimization
RAP	-	Reclaimed Asphalt Pavement
RCRA	-	Resource Conservation and Recovery Act
rpm	-	Revolutions per minute
SG	-	Specific gravity
SMA	-	Stone mastic asphalt
SMBA	-	Sulphur Modified Bottom Ash
SSD	-	Saturated surface dry
STOA	-	Short term oven ageing
TAC	-	Time available for compaction
TCLP	-	Toxicity characteristics of leaching procedure
TEPA	-	Taiwan Environmental protection Administration
TMD	-	Theoretical maximum density
TOT	-	Traffic opening time
TSR	-	Tensile strength ratio
USEPA	-	United States Environmental Protection Agency
UTM	-	Universal testing machine
VFB	-	Voids filled with bitumen
VMA	-	Voids in mineral aggregate
VTM	-	Voids in the total mix
WMA	-	Warm mix asphalt
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence

LIST OF SYMBOLS

σ	-	applied stress
Ɛ	-	strain
Ɛ2000	-	Strain at 2000th cycle
Ɛ3600	-	Strain at 3600th cycle
%	-	percentage
ºC	-	Celsius, Centigrade
Cm	-	Centimetre
cP	-	Centipoise
F	-	mass
g	-	Gram
Gas	-	Apparent specific gravity
Gmb	-	Bulk specific gravity
Gmm	-	Maximum theoretical specific gravity
Gsb	-	Bulk specific gravity of aggregate
3G	-	Third generation
h	-	Hour
Hz	-	Hertz
kg	-	Kilogram
kV	-	kilovolt
kN	-	Kilo Newton
mg	-	milligram
min	-	minutes
mm	-	millimetre
ml	-	millilitre
M_R	-	Resilient modulus
µm	-	micrometre
MPa	-	Mega Pascal
N	-	Newton
Pa.s	-	Pascal second
P	-	Pressure

rpm	-	Revolutions per minute
s	-	Second
U	-	Void content
V	-	volume

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

A significant amount of energy and fuel is consumed to produce Hot Mix Asphalt (HMA) and generates greenhouse gas emissions. The rising cost of fuel and material and environmental issues have prompted the introduction of less expensive asphalt paving techniques. Therefore, more study is needed to find constructive solutions in this sector that are technically possible, cost-effective and environment friendly. One of the appropriate approaches could be the application of reusable materials generated in the form of waste material from industrialisation. The utilisation of industrial by-products may resolve two major issues: the problem related to the disposal of industrial by-products and the alternative raw material in place of traditional quarried stone aggregate used for pavement construction. Nowadays, there is a strong demand for alternative materials for road construction by private companies, highway agencies and public administrations [1].

Several issues related to HMA have been addressed by the invention of Warm Mix Asphalt technology. In 1995, this technique was launched in Europe to provide environmental and economic advantages [2, 3]. WMA is produced and compacted at a lower temperature; therefore, less energy is required for its production, resulting in less atmospheric emission than hot mix asphalt [4, 5]. The WMA temperature allows for the production, placement and compacting of asphalt mixtures without affecting their properties [6, 7]. It is broadly classified into water-based or water-bearing, organic or wax additives and chemical additives [4, 7, 8]. Furthermore, numerous advantages of WMA technology have been reported. These include lower production temperature, reduced plant emission, increased paving season, prolonged hauling distance, ensuring earlier traffic opening, reduced binder ageing or oxidative hardening, and less cracking [9–11]. Numerous investigations have been conducted to evaluate the compatibility of alternative materials with WMA to enhance its environmental and performance properties using recycled asphalt pavement (RAP) [12–14]. Despite this, literature is available regarding industrial by-products (steel slag) as an alternative aggregate for WMA production and reported similar or even better performance than HMA [7, 15–17]. Consequently, there is a scope to investigate the performance of other industrial by-products like Bottom Ash (BA) as alternative aggregates in WMA.

Bottom Ash (BA) is one of the major by-products of coal combustion in coal power plants, known as Coal Combustion Products (CCP). Approximately 52.4% of CCPs produced in Europe are utilised in the building sector and as raw material in underground mining, while the remaining 35.9% are utilised to restore open cast mines, quarries and pits [18]. The BA is not a novel ingredient in HMA because, between 1971 and 1976, the state of West Virginia has built rural roads of approximately 200 miles utilising BA in asphalt mixtures, followed by the first scholarly scientific paper on this subject [18]. Due to some unfavourable characteristics of BA, its potential has mostly been studied in unbound subsequent (subgrade, sub-base and base) pavement layers [19, 20]. However, according to recent research, BA may have favourable technical characteristics and would not influence the mechanical properties of asphalt mixtures if it is used to substitute a portion of fine aggregate [21]. Substitution of fine aggregate with 10 and 20% BA by weight of total aggregate for wearing course and binder course does not degrade tensile strength, lower temperature cracking and rutting resistance of HMA mixtures [21–25]. Therefore, a comprehensive investigation is required to determine the effectiveness of using BA in asphalt with further consideration made on WMA for sustainable pavements.

1.2 Problem Statement

The increase in the generation of industrial by-products has become one of today's major issues because a large area of land needs to be acquired to dispose of this raw material. Industrialists are looking for ways to get rid of the wastes generated from their productions. On the other hand, the construction industries are causing depletion of natural resources as they require a considerable amount of construction material for their projects. Hence the construction industry needs to utilise alternative products and advanced procedures to overcome related concerns.

Potentially reusable by-products are generated from the coal power plants of Malaysia in the form of fly ash and bottom ash. Most fly ash is being used to produce cement and concrete structures. However, the bottom ash is still being treated as waste material and dumped into landfills without any potential application. Bottom ash is composed of weak and brittle particles that make it relatively an unfavourable material for the surface course. Despite this, pyrites are volumetrically unstable, expansive and produce a reddish stain when exposed to water over an extended time [26]. Therefore, its potential has widely been investigated for unbound subsurface pavement layers, where material strength, toughness and gradation requirements are not much critical. However, potentially heavy metals and toxic elements that have been detected in the unbound blends containing BA may pollute the surrounding soil and water [27, 28]. Numerous recent studies reported that substituting a small portion of fine aggregate with BA may not degrade the performance of the asphalt pavement layer [18, 23], which encourages its application in asphalt mixtures.

WMA is a revolutionary step towards the design and construction of sustainable pavements. However, still, there are concerns in context with the performance of different techniques of WMA technology perform differently. The literature reveals that the deficiencies found in WMA can be addressed using potentially alternative materials [29–31]. In this perspective, sufficient literature is available on applying RAP and steel slag as alternative aggregate to fabricate WMA mixtures. Despite this, the upgraded versions of chemical additives like Evotherm 3G were very effective in moisture susceptibility, depending on their compatibility with the type of aggregates used. There is sufficient literature on the investigation of HMA containing BA as fine aggregate, but scarce literature is available on its evaluation in WMA. Therefore, the performance of WMA mixtures incorporating bottom ash as fine aggregate for binder course was thoroughly investigated in this study. The compatibility of bottom ash in WMA was critically investigated with two types of chemical additives, and as a result, the suitable additive was used for further performance investigation. Because BA has not been extensively used as a constituent of asphaltic layer in binder course in Malaysia or even globally and WMA technology was considered for its sustainability in this study. In other words, the WMA technology coupled with alternative construction materials is the future of green road construction.

1.3 Aim and Objectives

This research aims to evaluate the performance of WMA containing Bottom Ash as alternative aggregates (fine aggregate). Detailed objectives are as follows:

1. To characterise the physical, chemical, and microstructural properties of bottom ash compared to control aggregate.
2. To investigate the performance properties and cooling rate of binder course WMA mixtures containing bottom ash compared to control asphalt mixtures.
3. To estimate the environmental emission, possible contamination and leachate of WMA mixtures containing bottom ash.

1.4 Scope of the Study

The scope of the study was to investigate the compatibility of bottom ash as fine aggregate in WMA mixtures using chemical additives. Due to the unfavourable engineering properties of BA, this study was limited to Asphalt Concrete Binder Course, AC 28 mixture type, which was selected according to the Malaysian Public Works Department (2008) specification.

Two types of aggregate (granite and bottom ash) were used, and all the design mixtures were incorporated with 60/70 bitumen. Chemical additives (Ceca base RT and Evotherm 3G) were used to design WMA mixtures. The granite was collected from Hanson Heidelberg Cement Group, Kulai, Johor Bahru. The bottom ash was obtained from Tanjung Bin Power Plant, Johor. The aggregates' physical, chemical and microstructural properties were evaluated to predict their influence on the performance of asphalt mixtures. The basic properties of blended bitumen were examined to estimate the impact of chemical additives on the virgin binder.

After validating that the chemical additives do not reduce the binder's viscosity but improve the workability of asphalt mixtures at reduced temperatures. The workability of WMA mixtures with and without BA was evaluated through the basic mechanical properties of the mixtures. The cooling rate test was included in this study to assess the influence of BA on the Time Allowed for Compaction (TAC). Despite this, the pollutant emission measurement test was also included to estimate the influence of BA coupled with lower temperature on the greenhouse gases released from asphalt mixtures during their production. Almost all of the tests, including the characterisation and performance tests, were conducted at the Transportation Laboratory, School of Civil Engineering UTM Skudai, Johor, Malaysia.

1.4.1 Significance and Contribution to the Knowledge

It is evident from the previous literature analysis that various alternative materials in the form of aggregate or binder modifiers were compatible with WMA technology when used to fabricate asphalt mixtures. Except for the strength and brittleness, bottom ash exhibits similar physical characteristics as demonstrated by steel slag and predominantly siliceous like granite aggregate. Hence investigating the compatibility of BA with WMA technology and its influence on the performance of WMA mixtures would be an effective approach.

Studies show that BA's heavy metals and volatile elements may contaminate groundwater and the surrounding soil when used in unbound or water-bound pavement layers. While the bitumen encapsulated mixtures containing BA were found to be nontoxic. However, BA's lower strength and brittleness exhibit higher losses due to abrasion and impact loading due to the direct contact of the vehicles to the surface course. Therefore, instead of wearing course, the application of BA in binder course would be a practical approach and significantly help to counter the related concerns like the durability of pavement structure and the release of heavy metals and toxicity.

It has been reported that industrial wastes (bottom ash) may contain heavy metals and volatile elements. The emission of volatile elements present in BA may pollute the atmosphere upon heating, which may not have been considered in previous studies. Thus, quantifying the pollutant emissions during elevated temperatures at which asphalt mixtures are produced would add to the knowledge to access its potential in terms of environmental concerns.

1.5 Thesis Outline

This thesis is outlined as follows:

Chapter 1 comprises the background of the study, problem statement, aim and objectives, scope and contribution to the knowledge.

Chapter 2 provides detailed literature on HMA, WMA technology, merits and demerits and previous studies on their performance. Simultaneously, the production, basic characterisation, and possible bottom ash application in asphalt mixtures are explained thoroughly.

Chapter 3 describes the methodology in three stages with reference to the objectives of this study, including the description of materials used, specimen preparation and testing procedures for material characterisation, performance evaluation and environmental impact.

Chapter 4 presents the results, data analysis and detailed discussion of the properties evaluated.

Chapter 5 concludes the findings of this study, potential applications and recommendations for future research.

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