PERFORMANCE OF FINE DENSE-GRADED COLD MIX ASPHALT INCORPORATING SPENT GARNET AND PALM OIL FUEL ASH

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DEDICATION

This thesis is dedicated to my parent Alhaji Usman Abubakar and Hajiya Hafsah Usman Bello, who taught me the virtues of being patient, resilient in all my endeavours, and abiding by Allah’s rules, coupled with obedience to constituted authority. Especially to my mother, who first taught me how to read and helped unleash my confidence in achieving set goals in life.

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ABSTRACT

Cold mix asphalt (CMA) is preferable than hot mix asphalt (HMA) or warm-mix asphalt (WMA) due to minimal energy requirement, cost, and fumes emission in road construction. Efforts in mitigating CMA limitations of low early strength, slow curing, and high void content remained significant for further investigation. Moreover, CMA lacks a unified acceptable mix design method. The inclusion of industrial by-products and binder modification are several strategies aimed at solving these problems. However, there is limited research on the addition of spent garnet, palm oil fuel ash (POFA), and fast setting emulsions in CMA. This study adapted the International Slurry Surfacing Association (ISSA A-143) dense gradation with a nominal maximum aggregate size (NMAS) of 4.75 mm. The gradation with 10% fine content passing the 0.075 mm sieve was used to develop fine dense-graded cold mix asphalt (FGCMA-4.75). The study was carried out in three phases. The first phase entails assessing and characterising the constituent material in terms of its microstructural, physio-mechanical, morphological, and rheological properties. A rapid setting conventional emulsion (RS-1K) and a quick setting polymer-modified emulsion (CQS-1h) in addition to 3% of cement were used as the binders. The second phase involved designing eight (8) different mixtures, including the control mix using the Asphalt Institute (AI) modified Marshall design method. A performance-based mix design was then proposed, employing indirect tensile stiffness modulus (ITSM) and Cantabro loss test results. The FGCMA-4.75 mm consists of a 7 – 9% emulsion content range, 1 – 4% POFA and 50% and 100% spent garnet replacement. A final optimised mix (FGCMA-GP) consisting of 3% POFA and 100% spent garnet as fine aggregate and filler replacements, respectively, was selected using grid analysis. The final phase centred on the engineering properties and performance of the FGCMA-GP. The mixtures were tested for ITSM, dynamic creep, moisture damage, indirect tensile strength (ITS), and wheel tracking tests. The result shows that the Marshall stability, flow, void content, and density of all the modified mixtures met Malaysian Public Works Department (JKR) and India's Ministry of Road and Transportation (MoRTH) specifications. The results revealed that the replacement of up to 3% POFA increased the ITS and ITSM but reduced the void content of the mixture. All CMA samples have better rutting resistance than HMA. Emulsion comparison showed that mixtures with CQS-1h emulsion have higher cracking, abrasion and rutting resistance than RS-1K. Meanwhile, FGCMA-GP has good rutting resistance and a 20% higher tensile strength ratio (TSR) than the control sample. Generally, FGCMA-GP with 100% spent garnet and 3% POFA can be used in CMA for restoration works and pavement wearing course.

ABSTRAK

Asfalt campuran sejuk (CMA) lebih menjadi pilihan daripada asfalt campuran panas (HMA) atau asfalt campuran suam (WMA) kerana keperluan tenaga, kos, dan pengeluaran asap yang minimum dalam pembinaan jalanraya. Usaha dalam mengurangkan had CMA dalam kekuatan awal yang rendah, pengawetan yang perlahan, dan kandungan lompang yang tinggi masih signifikan untuk penyelidikan lebih lanjut. Tambahan pula, CMA kekurangan kaedah rekabentuk campuran yang boleh diterima pakai. Kemasukan produk sampingan industri dan pengubahsuaian pengikat adalah antara kajian yang bertujuan untuk menyelesaikan masalah ini. Walau bagaimanapun, terdapat penyelidikan yang terhad dalam mengkaji penambahan garnet terpakai, abu bahan bakar kelapa sawit (POFA) dan emulsi pengerasan cepat dalam CMA. Kajian ini menggunakan pengredan tumpat *International Slurry Surfacing Association* (ISSA- A-143) dengan 4.75 mm saiz nominal maksimum agregat (NMAS). Penggredan terdiri daripada 10% kandungan halus melepasi ayakan 0.075 mm telah digunakan untuk membangunkan asfalt campuran sejuk bergred tumpat halus (FGCMA-4.75). Kajian ini dilaksanakan dalam tiga fasa. Fasa pertama menilai dan memperincikan sifat bahan dari segi ciri-ciri mikrostruktur, fisio-mekanikal, morfologi, dan reologi. Emulsi tetapan cepat konvensional (RS-1K) dan emulsi tetapan cepat polimer-terubahsuai (CQS-1h) di samping 3% simen digunakan sebagai pengikat. Fasa kedua melibatkan reka bentuk lapan (8) campuran yang berbeza termasuk campuran kawalan menggunakan kaedah reka bentuk Marshall terubahsuai *Asphalt Institute* (AI). Reka bentuk campuran CMA berasaskan prestasi telah dicadangkan, menggunakan keputusan ujian modulus kekukuhan tegangan tidak langsung (ITSM) dan ujian kehilangan Cantabro. FGCMA-4.75 mm terdiri daripada 7 – 9% julat kandungan emulsi, 1 – 4% POFA dan penggantian 50% dan 100% garnet terpakai. Campuran optimum akhir (FGCMA-GP) yang terdiri daripada 3% POFA dan 100% garnet terpakai sebagai penggantian agregat halus dan pengisi telah dipilih menggunakan analisis grid. Fasa terakhir memberi fokus pada ciri-ciri kejuruteraan dan prestasi FGCMA-GP. Semua campuran diuji dengan ITSM, rayapan dinamik, kerosakan kelembapan, kekuatan tegangan tidak langsung (ITS), dan ujian penjejakan roda. Keputusan menunjukkan kestabilan Marshall, aliran, kandungan lompang, dan ketumpatan campuran yang diubahsuai menepati spesifikasi Jabatan Kerja Raya Malaysia (JKR) dan Kementerian Jalanraya dan Pengangkutan India (MoRTH). Keputusan menunjukkan bahawa penggantian hingga 3% POFA telah meningkatkan nilai ITS dan ITSM tetapi telah mengurangkan kandungan lompang campuran. Semua sampel CMA mempunyai rintangan terhadap aluran lebih baik daripada HMA. Perbandingan imulsi menunjukkan campuran dengan emulsi CQS-1h mempunyai rintangan terhadap retakan, lelasan dan aluran yang lebih tinggi daripada RS-1K. Sementara itu, FGCMA-GP mempunyai rintangan terhadap aluran yang baik dan nisbah kekuatan tegangan (TSR) 20% lebih tinggi daripada sampel kawalan. Secara amnya, FGCMA-GP dengan 100% garnet terpakai dan 3% POFA boleh digunakan dalam CMA untuk kerja-kerja pemulihan dan lapisan haus turapan.

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AASHTO	-	American Association of State Highway and Transport Officials
AC	-	Asphalt Concrete
ACV	-	Aggregate Crushing Value
AETM	-	Asphalt Emulsions Treated Mixtures
AI	-	Asphalt Institute
AI MS-14	-	Asphalt Institute Manual Series – 14
AIV	-	Aggregate Impact Value
ANOVA	-	Analysis of Variance
ASTM	-	American Society for Testing and Materials
ASTs	-	Asphalt Surface Treatment(s)
BBCF	-	Binary Blended Cementitious Filler
BBF	-	Binary Blended Filler
BF	-	Binary Filler
BS	-	British Standard
CAEM	-	Cold Asphalt Emulsion Mixtures
CAM	-	Cold Asphalt Mixtures
CBEM	-	Cold Bituminous Emulsion Mixes
CBM	-	Cold Bituminous Mixes
CCPR	-	Cold Central Plant Recycling
CDW	-	Construction and Demolition Waste
CIPR	-	Cold In-Place Recycling
CKD	-	Cement Kiln Dust
CKE	-	Centrifuge Kerosene Equivalent
CMA	-	Cold Mix Asphalt
CMT	-	Copper Mine Tailings
CQS-1h	-	Cationic Quick Setting emulsion of medium viscosity
CRME	-	Emulsion Cold Recycled Mixtures
C-S-H	-	Calcium-Silicate-Hydrate

CSM	-	Creep Stiffness Modulus
CSS	-	Creep Strain Slope
CTM	-	Circular Texture Metre
DFT	-	Dynamic Friction Tester
DSR	-	Dynamic Shear Rheometer
EAF	-	Electric Arc Furnace-Slag
EFB	-	Empty Fruit Bunches
EN	-	European Standard
ER	-	Expansion Ratio
FA	-	Fly Ash
FAA	-	Fine Aggregate Angularity
FGCMA		Fine Dense-Graded Cold Mix Asphalt
FGCMA-C	-	Fine Dense-Graded Cold Mix Asphalt Control mix
FGCMA-G	-	Fine Dense-Graded Cold Mix Asphalt with Garnet
FGCMA-GP	-	Fine Dense-Graded Cold Mix Asphalt with Garnet and POFA
FGCMA-P	-	Fine Dense-Graded Cold Mix Asphalt with POFA
FHWA	-	Federal Highway Administration
FTIR	-	Fourier Transform Infrared Spectroscopy
FWD	-	Falling Weight Deflectometer
GC-MS	-	Gas Chromatography Mass-Spectrometry
GGBS	-	Ground Granulated Blast Furnace Slag
HASW	-	High Aluminosilicate Waste Material
HAUC	-	Highway and Utility Committee
HCFA	-	High Calcium Fly Ash
HCPR	-	Hot Central Plant Recycling
HLB	-	Hydrophilic-Lipophilic Balance
HMA	-	Hot Mix Asphalt
HWMA	-	Half warm mix Asphalt
IBEF	-	International Bitumen Emulsion Federation
ICP-MS	-	Inductively Coupled Plasma-Mass Spectrometry
IEC	-	Initial Emulsion Content

ISSA-III	-	International Slurry Surfacing Association Gradation Type III
ITS	-	Indirect Tensile Strength
ITSM	-	Indirect Tensile Stiffness Modulus
JCPDS	-	Joint Committee on Powder Diffraction Standards
JKR	-	Malaysian Public Works Department (Jabatan Kerja Raya)
LAAV	-	Los Angeles Abrasion Value
LL	-	Lower Limit
LRA	-	Limestone Rock Asphalt
LVDT	-	Linear Variable Differential Transducers
LWST	-	Lock Wheel Skid Trailer
MCCT	-	Modified Cyclic Creep Test
MCDM	-	Multi-Criteria Decision Method
MCP	-	Microbial Carbonate Precipitation
MMHE	-	Malaysia Marine and Heavy Engineering
MoRTH	-	Ministry of Road Transport and Highways
MS-14	-	Malaysian Standard-14
MSCR	-	Multi-stress creep recovery
MTD	-	Mean Texture Depth
NCAT	-	National Centre for Asphalt Technology
NMAS	-	Nominal Maximum Aggregate Size
OEC	-	Optimum Emulsion Content
OFT	-	Oil Palm Trunks
OGFC	-	Open-Graded Friction Courses
OPC	-	Ordinary Portland Cement
OPF	-	Oil Palm Fronds
ORAC	-	Optimum Residual Asphalt Content
ORBC	-	Optimum Residual Bitumen Content
OTLC	-	Optimum Total Liquid Content
PCC	-	Portland Cement Concrete
PFA	-	Pulverised Fuel Ash
pH	-	Positive Hydrogen ions
PLA	-	Palm Leaf Ash

PMECMA	-	Polymer Modified Emulsified Cold Mix Asphalt
PMEs	-	Polymer Modified Emulsions
POFA	-	Palm Oil Fuel Ash
PP	-	Parallel-Plates
RAP	-	Recycled Asphalt Pavement
RCA	-	Recycled Concrete Aggregate
RS-1K	-	Rapid setting emulsion of medium viscosity
SBR	-	Styrene-Butadiene Rubber
SBS	-	Styrene Butadiene Styrene
SCB	-	Semi-Circular Bending Test
SCHSC	-	Self-Consolidating High Strength Concrete
SF	-	Silica Fume
SFS	-	Saybolt Furol Seconds
SMA	-	Stone Mastic Asphalt
TBF	-	Ternary Blended Filler
TCLP	-	Toxicity Characteristics Leaching Procedure
TF	-	Ternary Filler
TMD	-	Theoretical Maximum Density
TSR	-	Tensile Strength Ratio
TxDOT	-	Texas Department of Transportation
UCCT	-	Uniaxial Compression Cyclic Loading Test
UCS	-	Unconfined Compression Test
UK	-	United Kingdom
UL	-	Upper Limit
UPV	-	Ultrasonic Pulse Velocity
US-EPA	-	United State Environmental Protection Agency
UTM-5	-	Universal Testing Machine - 5
VFB	-	Voids Filled with Binder
VTM	-	Voids in the Total Mix
WOR	-	Water-Oil Ratio
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence

LIST OF SYMBOLS

θ	-	Angle between the incident beam and the crystallographic reflecting plane
2θ	-	Angle between the transmitted beam and the reflected beam
σ_d	-	Applied maximum stress
G_{sb}	-	Bulk specific gravity of asphalt mix
G^*	-	Complex shear modulus
℃	-	Degree Celsius
S_t	-	Indirect Tensile Strength in
km/h	-	Kilometre per hour
P	-	Maximum Load in Newton
G_{mm}	-	Maximum specific gravity of asphalt mix
μ_m	-	Micro-metre
μ_s	-	Micro-strains
mA	-	Milliampere
δ	-	Phase angle
π	-	Pie
$\boldsymbol{P}$	-	Pressure
rad/s	-	Radian seconds
r	-	Radius
M_r	-	Resilient Modulus
D,d	-	Sample Diameter
t	-	Sample thickness
s	-	seconds
ε_r	-	Strain of the specimen
CuK_α	-	X-ray energy (equivalent to X-ray wavelength of 1.5406Ȧ

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

A significant number of roads out of the total global estimated length of 221 million kilometres are paved with bituminous wearing courses often constructed using hot mix asphalt (HMA) (Meijer, Huijbregts, Schotten, et al., 2018). However, challenges attributable to HMA mixtures, including fume emissions, high energy requirements, the need for a heavy plant for its production, lead to the development of alternative asphalt mixtures (Thives and Ghisi, 2017). These alternative mixtures include cold mix asphalt and its variant - cold stone mastic asphalt (CSMA) and cold-mix cold-laid. Advances in bitumen emulsion modification with polymers have increased CMA application, especially for pavement rehabilitation (Yaacob, Hainin, Aziz, et al., 2013).

Cold mix asphalt (CMA) emerged as a promising alternative to HMA specifically for patching and maintenance works and to a certain extent as part of the pavement structural layers. CMA is desirable for its versatility (easy set-up), ease of application in a remote location, zero fumes emission (especially with cold mix cold-laid mixes), ease to produce with simple plant requirements, and low energy demand. Typical energy consumption and CO_2 mass equivalent emissions per tonne for both HMAs and CMA were estimated at 277 MJ/t with 21 kg CO_2 and 36 MJ/t with 3 kg CO_2 respectively by the international bitumen emulsion federation (IBEF) (McNally, 2011). In Malaysia, mill and pave was reported as the highest CO_2 emitter with 117.94 ton CO_2 - eq/km-lane (Hafifi Che Wahid, Aminudin, Abd Majid, et al., 2019). However, high void content, slow rate of strength development, weak early life mechanical strength (due to water presence) remains an unsolved problem for CMA. Moreover, the absence of a universally acceptable CMA mix design procedure exacerbates the mentioned problems, thus, necessitating a deeper understanding of this mix in devising an acceptable design and improving mechanical performance.

Essential to a good understanding of CMA is developing a robust, economical, and sustainable mixture combining superior compatible constituents and replicative laboratory-to-field results. Consequently, many research was conducted on CMA's performance improvement, though most solutions were highly technical, leading to unrealistic commercial applicability, such as bitumen encapsulation to reduce CMA water content (Alenezi, Norambuena-Contreras, Dawson, et al., 2019). Further efforts have witnessed the inclusion of industrial by-products in cold mix cold-laid mixtures with promising result in terms of improved Marshall volumetric and mechanical performance (Thanaya, Zoorob, and Forth, 2009). Despite the recorded successes, CMA was still intrinsically slow in curing with a high void and perhaps requiring mobile plant for their placement, especially with cold recycled mixtures or when certain additives are used. In Malaysia, spent garnet and POFA are locally abundant cheap industrial by-products needing broader utilisation. Despite promising reported results on the use of spent garnet in HMA, concrete, and soil stabilisation on road shoulder construction, these materials are not used in CMA (Borhan et al., 2010; Aletba et al., 2018; Raja Zulkefli et al., 2018; Noor et al., 2017). Moreover, the successful incorporation of POFA in concrete (Muttashar, Ariffin, et al., 2018; Hamada, Jokhio, Yahaya, et al., 2018; Thomas, Kumar, and Arel, 2017), and binder modification, serve as a precursor to their use in CMA, but no attention was accorded on incorporating these two waste in CMA.

This study focuses on cold-mix cold-laid CMA, as they don't require rolling and are thus easily shovelled into potholes or utility cuts in pavements. These mixtures need to be fine-textured, resistant to moisture damage, yet with high skid resistance to serve a dual purpose of not breaking pipes if laid in trenches while providing a safe riding surface. Those issues mentioned above informed the decision of incorporating spent garnet and palm oil fuel ash (POFA) in a fine dense-graded cold mix cold-laid asphalt mixture. This study explores the possibility of ameliorating the lingering problem of CMA using a fine dense-graded CMA with a nominal maximum aggregate size (NMAS) of 4.75 mm and proposes an alternative CMA mix design procedure based on performance tests. The rapid-setting and quick-setting emulsions used in this study improve the early-strength gain and achieve fast curing. To date, no identifiable study in the literature on the use of fast-curing emulsions with a combination of spent garnet and POFA to improve CMA's performance.

1.2 Statement of the Problem

The desirable features of CMA as a cost-effective, zero-emission, versatile, and low energy requirement mixture triggered keen concern by construction stakeholders for its performance enhancement. Consequently, the development of a better-performing and durable CMA with relatively comparable performance to an HMA utilising cheaply available material is being explored by researchers. This exploration culminates in the need further to investigate superior performing and compatible materials for CMA. CMA is a more complex system than HMA because its constituent materials must have intrinsic features capable of ensuring compatibility. These constituent materials are bitumen emulsion, aggregate, water, or additives (Jain and Singh, 2021). An emulsion is an intricate system whose formulation requires a skilful, tasking, and elaborate yet, special consideration for its targeted end usage (Ronald and Luis, 2016).

In the ideal state, the bitumen emulsion in a CMA sets upon contact with aggregate due to the electric charge difference and coat the aggregate while the water evaporates. The presence of water in CMA mars adequate adhesion of the aggregate to the base binder, thereby causing weak bonding, thus, high voids leading to stripping and water damage. Adhesion failure was identified as the CMA's critical deficiency (Jain and Singh, 2021). In cutback applications, a hydrocarbon solvent, instead of water, aid in workability, ease of spray and evaporates as well, though rather slowly than water. The time it takes to set may range from 24 hours to a few months as in the case of medium to slow setting emulsions (Al Nageim, Al-Busaltan, Atherton, et al., 2012). However, newly rehabilitated roads need to be opened to traffic the soonest after such work, but medium and slow set emulsions cannot guarantee such. Thus, it is one of the most significant challenges confronting the use of CMA, though solutions were sought by introducing quick set emulsions for CMA (Chávez-Valencia, Alonso, Manzano, et al., 2007).

Other critical problems associated with CMA aside from the slow rate of strength development and weak early strength are high void content and the absence of a globally acceptable mix design. CMA lacks a universal mix design like the Superpave, and Marshall designs are adopted for an HMA – because various transport departments tailor CMA design to suit peculiar situations (Suda, Valentin, and Žák, 2016). Many studies targeted efforts in solving these deficiencies. At the same time, advanced material additives like epoxy bitumen, adhesion promoters, polymer-modified emulsions, and improved preparation techniques, including bitumen encapsulation in emulsions, were tried (Alenezi et al., 2019). Also, new CMA mix designs as a modification to the Asphalt Institute (AI) were introduced. Their use is because applying the HMA Marshall design approach for CMA was argued as deficient (Kazal, 2015; Thanaya, 2003). However, most of these solutions are rather costly because CMA is often used as a patching mixture. CMA is used for reinstatement works and wearing surfaces of light-trafficked roads from time immemorial (Waller, 1980) to the present day (Redelius, Östlund, and Soenen, 2016; Jain and Singh, 2021); thus, a cheap solution is desirable. Consequently, the incorporation of waste material or industrial by-products in CMA availed with recorded successes.

Waste materials improve adhesion, enhance mechanical performance, hasten the absorption of trapped water, and provide economic and environmental benefits (Al Nageim et al., 2012; Shanbara, Ruddock, and Atherton, 2018a; Dulaimi, Nageim, Ruddock, et al., 2017; Al-Busaltan, Al Nageim, Atherton, et al., 2012). The desirability achieved in CMA by waste incorporation depends on the type of waste. More so, CMA with added waste material still suffers the typical long curing time, high voids, and weak early life strength (Thanaya et al., 2009; Shanbara et al., 2018a). Nonetheless, waste incorporation in construction should be environmentally safe, thus, non-toxic (Thomas et al., 2017) – this stressed the need for a chemical leaching test coupled with other characterisation tests to assess the safe utilisation of all such waste in CMA. The health and environmental concerns of heavy metal leachates from a waste used for pavement construction potentially associated with toxic impurities must be addressed before its incorporation. Additionally, the individual constituents' morphological, physical, and mechanical testing to ensure compatibility with emulsion and other additives is stressed by the asphalt institute manual series 14.

This study employs Cantabro and indirect tensile stiffness modulus (ITSM) or resilient modulus performance tests as part of the Fine Dense-Graded Cold Mix Asphalt (FGCMA-4.75) design process. A modified Marshall method was employed, and the result compared to the design method mentioned above. The study adopts the international slurry surfacing association (ISSA A-143) type III aggregate gradation for emulsified asphalt cold slurry mixtures, specially designed for reprofiling and rut-filling heavy-trafficked roads. The inherent problem of high void content is hoped to be reduced by the introduction of spent garnet. Besides, the water susceptibility and bonding problems are set to be addressed by the pozzolanic features of POFA.

Moreover, the potential extension for the use of spent garnet and POFA filler in CMA is hoped to align CMA with universal sustainable construction practices. This study's success is expected to make CMA more environmentally friendly by eliminating landfill disposal of POFA and spent garnet, with attendant less energy consumption and non-renewable resource conservation.

1.3 Research Aim and Objectives

The research aim is to design and evaluate the performance of fine dense-graded cold mix asphalt with an NMAS of 4.75 mm (FGCMA-4.75 mm) incorporating spent garnet and POFA as a fine aggregate and filler replacement, respectively. The aim was achieved through the following objectives:

(a) To characterise the spent garnet, POFA, granite, and the two types of emulsified asphalts based on their physical, chemical, rheological, microstructural, and mechanical properties accordingly.

(b) To design the FGCMA-4.75 mm using modified Marshall mix design while proposing a mix design base on a combination of ITSM and Cantabro tests and select the best spent garnet and POFA mix combination as an optimised mix (FGCMA-GP 4.75 mm).

(c) To evaluate the influence of spent garnet and POFA on the performance of the FGCMA-4.75 mm mixture.

1.4 Scope and limitation of the Research

The scope of this research were:

(a) The constituent materials were tested for physio-mechanical, microstructural, physical, morphological, and chemical properties.

(b) FGCMA-4.75 mm was designed by incorporating spent garnet and POFA while their performance evaluated.

(c) The Illinois design method adopting a modified Marshall mix design was utilised as the design methodology. A design based on combined ITSM and Cantabro result was proposed.

(d) One mix gradation with NMAS of 4.75 mm adapted from the ISSA's gradation type III was utilised. Cationic quick set (CQS-1h) and rapid set (RS-1K) emulsions both of medium viscosity served as the primary binders.

(e) Several trial mixes were produced by varying critical CMA parameters, including mixing/compaction temperatures, amount of pre-wetting water, compactive effort, and curing method/type/duration. Finally, samples were compacted 75 blows per face and tested according to ASTM D6927-15 for Marshall Stability and flow (American Society for Testing Materials, 2015e).

(f) The performance of the mixtures was assessed based on the result of the various laboratory experimentation.

The study's limitations entail peculiarities towards achieving the set objectives, including material supply consistency, laboratory equipment accuracy, and mixture variability properties that were not controlled. All experimental testing was conducted either at the transportation laboratory, central testing laboratory of UTM and Anton Paar laboratory in Kuala Lumpur. Material quality variability due to different batches supplied at different time was monitored but not controlled under this study.

1.5 Significance of the Research

There is engineering, environmental, economic, and social significance derived from this study. The overarching problem of slow curing and low strength gain associated with CMA will be minimised, perhaps eliminated by introducing quick and rapid-setting polymer modified emulsified asphalt emulsions. The pozzolanic features of POFA will reduce the high void content attributed to CMA, leading to improved adhesion and moisture damage resistance. POFA was reported to produce a mixture with enhanced resistance to permanent deformation (Borhan et al., 2010). As the addition of bitumen emulsion stands to be the significant difference in terms of constituent materials between CMA and concrete, successful use of POFA in concrete signals its potential incorporation into CMA. Successful addition of POFA in concrete has long been established, and its potential hazards were highlighted (Thomas et al., 2017). It is projected that the proposed performance-based mix design will be adequate to gain universal acceptance in designing CMA, specifically, FGCMA-4.75 mm. Furthermore, the successful application of spent garnet and POFA in CMA will ameliorate their landfill disposal menace, which poses severe risks to humans, underground water, and the habitat.

Economically, there will be value addition in the spent garnet and POFA life cycle by extending their usage in CMA and increasing affordability to construction clients whilst attaining sustainable construction by replacing non-renewable resources with by-products. The durable mixtures produced with cheaply available waste material will create a win-win scenario for construction clients and contractors alike.

1.6 Thesis Organisation

This thesis is structured into five sections, described herein as chapters. Details for each Chapter are elucidated further below.

Chapter 1 presents the background of the study, including historical antecedents and established trends in similar studies. The Chapter states the aim, objectives, and scope for the current research and any possible limitation that may affect the result. Subsequently, the significance of the research and thesis layout is presented at the end of the Chapter.

Detail survey of relevant literature is given in Chapter 2. The development, modification, advances in CMA research also presented. The Chapter presents essential findings from notable researchers and organisations worldwide on CMA and a rationale for adopting specific procedures in the current study.

Chapter 3 expounds on the methodology used in the research. The Chapter describes the relevant procedure adopted - chapter 3 further presents testing details in three (3) phases. The three phases deal with material characterisation, followed by mixture design and mixture performance measurement.

Chapter 4 presents the overall result for the material characterisation, mixture design, and performance testing according to the phased category in Chapter 3. Analysis of the results and possible relationships among and between results was done. Also, the selection of the best performing mixture and analysis of its performance presented.

Chapter 5 makes a recap of the entire research findings. It presents a concluding remark for the whole study, grey areas of concern for knowledge management, and some recommendations for future studies offered.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Usman, K. R.**, Hainin, M. R., Idham, M. K., Warid, M. N. M., Naqibah, S. N. K., and Suleiman, A (2021). Palm oil fuel ash application in cold mix cold-laid dense- graded bituminous emulsion mixture. *Construction and Building Materials*, 287, 123033. (**Q1, IF: 4.419**) (**Published**)

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Indexed Journal

1. **Usman, K. R.**, Hainin, M. R., Idham, M. K., Warid, M. N. M., Usman, A., Al-Safar, Z. H., Bilema, M. A. A comparative assessment of the physical and microstructural properties of waste garnet generated from automated and manual blasting process. *Case Studies in Construction Materials* **(Indexed by SCOPUS) (Published) (DOI: 10.1016/j.cscm.2020.e00474)**

Non-indexed Journal

None

Indexed Conference Proceedings

2. **Usman, K. R.**, Hainin, M. R., Idham, M. K., Warid, M. N. M., Yaacob, H., Hassan, N. A., Puan, O. C. (2019). Performance evaluation of asphalt micro-surfacing – a review. IOP Conference Series: Materials Science and Engineering, 527, 012052. https://doi.org/10.1016/j.jclepro.2017.09.133 **(Indexed by SCOPUS)**

3. **Usman, K. R.**, Hainin, M. R., Satar, M. K. I., M Warid, M. N., and Abdulrahman, S. (2020). Modified Marshall Test assessment for emulsified asphalt cold mixes. IOP Conference Series: Earth and Environmental Science, 498(1), 012023. https://doi.org/10.1088/1755-1315/498/1/012023. **(Indexed by SCOPUS)**

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