PERFORMANCE OF ASPHALT PAVEMENT CONTAINING POTENTIAL COOL PAVING MATERIALS

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DEDICATION

To My Father and My Mother for their kind support, love and patience.

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ABSTRACT

Asphalt pavement absorbs and stores more heat than natural surfaces. The high surface temperature of the conventional asphalt pavement due to high solar energy absorption, subsequently releases heat into the atmosphere and contributes to the urban heat island (UHI) phenomenon. Previous studies attempt to resolve this issue mainly by using coatings (reflective pavement) and porous asphalt (permeable pavement). However, emphasis was not given on the type of materials used in the asphalt pavement composition. This research aims to produce a cool asphalt mixture based on the modification of asphalt materials that focuses on various waste products. Initially, several samples of asphalt mixtures containing different alternative materials were prepared based on their optical and thermal characteristics. A spectroradiometer was used for indoor measurements of solar reflectance, while an infrared camera and thermocouples were used for outdoor measurements of the surface and internal temperature profiles of the asphalt. The potentially cool paving materials were selected based on the most enhanced thermal properties and highest temperatures decrease compared to conventional sample. In the next phase, the selected materials were then used to modify asphalt and evaluated for microstructural, mechanical, and chemical properties under different ageing conditions (unaged, short-term ageing, and long-term ageing). In the final phase, the slab samples of the selected mixtures were prepared and evaluated in an exposed environmental condition for monitoring their thermal performance, temperature profiles, weather data, and thermophysical parameters, including emissivity and albedo. In addition, the parameters of thermal conductivity and heat capacity were also measured in the laboratory. According to the preliminary test results, the modified asphalt mixtures with waste garnet and coal bottom ash were associated with reduced pavement temperatures compared with conventional pavement at an average of 2°C to 3°C. These materials have also shown their validity as fine aggregates in asphalt pavement by conforming to mechanical, physical and chemical specifications. The thermal performance of asphalt samples containing garnet showed a significant cooling effect followed by bottom ash with better resistance against internal heating and thermophysical properties enhancement. Ageing phenomenon was also discovered to reduce the heat impact as well as the asphalt temperature.

ABSTRAK

Turapan asfalt menyerap dan menyimpan lebih banyak haba daripada permukaan semulajadi. Suhu yang tinggi pada permukaan turapan asfalt konvensional adalah disebabkan penyerapan tenaga solar yang tinggi, seterusnya melepaskan haba ke atmosfera dan menyumbang kepada fenomena pulau haba bandar (UHI). Kajian sebelum ini cuba untuk menyelesaikan isu ini terutamanya dengan menggunakan salutan (turapan reflektif) dan asfalt berliang (turapan boleh telap). Walau bagaimanapun, penekanan tidak diberi kepada jenis bahan yang digunakan dalam komposisi turapan asfalt. Kajian ini bertujuan untuk menghasilkan campuran asfalt sejuk berasaskan pengubahsuaian bahan asfalt yang memberi tumpuan kepada pelbagai bahan buangan. Pada awalnya, beberapa sampel campuran asfalt yang mengandungi bahan-bahan alternatif berbeza disediakan berdasarkan kepada ciri-ciri optik dan termanya. Alat spektroradiometer digunakan untuk pengukuran dalaman pantulan solar, sementara kamera inframerah dan termogandingan telah digunakan untuk pengukuran luar profil suhu permukaan dan dalaman asfalt. Bahan-bahan turapan sejuk yang berpotensi dipilih berdasarkan sifat-sifat terma paling baik dan penurunan suhu terbanyak berbanding sampel konvensional. Dalam fasa seterusnya, bahan yang dipilih kemudian digunakan untuk mengubah suai asfalt dan dinilai untuk sifat mikrostruktur, mekanikal dan kimia di bawah keadaan penuaan yang berbeza (tidak menua, penuaan jangka pendek, dan penuaan jangka panjang). Dalam fasa terakhir, sampel papak daripada campuran yang dipilih disediakan dan dinilai dalam keadaan persekitaran terdedah untuk memantau prestasi terma, profil suhu, data cuaca dan parameter termofiziknya, termasuk emisiviti dan albedo. Di samping itu, parameter kekonduksian terma dan kapasiti haba juga diukur di makmal. Menurut hasil ujian awal, campuran asfalt terubah suai dengan sisa garnet dan abu dasar arang batu berkait dengan pengurangan suhu turapan dibandingkan dengan turapan konvensional dengan purata 2°C hingga 3°C. Bahan-bahan ini juga turut menunjukkan kesahihannya sebagai agregat halus dalam turapan asfalt dengan mematuhi spesifikasi mekanikal, fizikal dan kimia. Prestasi terma sampel asfalt yang mengandungi garnet menunjukkan kesan penyejukan ketara diikuti oleh abu dasar dengan rintangan lebih baik terhadap pemanasan dalaman dan peningkatan sifat-sifat termofizikal. Fenomena penuaan juga turut didapati mengurangkan kesan haba serta suhu asfalt.

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LIST OF ABBREVIATIONS

Q	-	Energy
k	-	Thermal conductivity
d	-	Sample depth
A	-	Surface area
T	-	Temperature
α_a/ α’	-	Surface absorptivity/ Albedo
h_c	-	The convection coefficient
C_p	-	Heat capacity
α_{diff}	-	Thermal diffusivity
ε	-	Emissivity
P	-	Power
AC14	-	Asphaltic Concrete of nominal aggregate size 14 mm
CS	-	Conventional Asphalt (control sample)
GFA	-	Asphalt sample contained garnet
BAA	-	Asphalt sample contained bottom ash
Unaged	-	Non-conditioning (unaged) asphalt sample
STA	-	Short-term ageing condition
LTA	-	Long-term ageing condition
ρ	-	Density
ASTM	-	American Society of Testing and Materials
EPA	-	Environment protection agency
BS	-	British Standards
ANOVA	-	Analysis of variance
F	-	Ratio of the mean-square for that source of variation to the residual mean square
F_{crit}	-	Critical values at a confidence level of 0.05

LIST OF SYMBOLS

m	-	Meter
K	-	Kelvin
W	-	Watt
s	-	Seconds
°C	-	Celsius
kg	-	kilogram
J	-	Joule
σ	-	Stefan-Boltzman constant
Pa.s	-	Pascal second
MPa	-	Mega pascal

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CHAPTER 1

INTRODUCTION

1.1 Background

Pavement plays a vital role in urban living, as it covers a large percentage of urban spaces. For instance, in one city in California, USA, pavement covers nearly 39% of the built-up areas, which include streets, parking areas, and sidewalks [1]. Pavement's dry, impermeable surfaces are susceptible to solar radiation, which causes the pavement to heat up. In turn, the temperature of the surrounding area increases, which negatively affects the surrounding environment. The discrepancy in temperature between construction materials and the natural ground creates what is known as Urban Heat Islands (UHIs). UHIs pose a significant problem for humans due to urban industrial development [2,3]. For example, pavement has a substantial influence on UHI that might contribute to as much as 44% of the UHI phenomenon in cities [4], especially those with dark surfaces, such as asphalt pavement [5,6]. During hot seasons, the temperatures of open urban surfaces, such as rooftops and roads, can exceed the ambient temperature by 40–45°C [7].

Asphalt pavement's impact on UHI can be reduced by adequately controlling its physical characteristics and thermophysical properties. Asphalt pavements subjected to intense solar radiation respond in a variety of ways. When sunlight reaches an asphalt pavement surface, some of the incident solar radiation is reflected, and the rest is absorbed, depends on the materials composition, surface colour and design. The substantial amount of ordinary paved materials and the adverse effects of UHI have encouraged researchers to develop cool pavements. According to the Environmental Protection Agency (EPA), the term "cool pavement" can be used to refer to any technology that reduces the amount of heat that conventional pavement absorbs and stores, thus resulting in a lower surface temperature [8]. The cool pavement is also defined as any new paving material or design technology meant to reduce heat transfer [9–14].

The ability of cool pavement to mitigate UHI has promoted its application in high-temperature areas where researchers focused on the studies of cool pavement mechanisms and the effects of UHIs [15–17]. Decreasing the surface temperature of pavement could significantly improve the thermal conditions of cities that are currently experiencing high temperatures [18]. Therefore, studies related to mitigation strategies are significant, and each one must be assessed independently. Besides, thermophysical properties, such as solar reflectance, thermal emissivity, conductivity, and capacity, have been found useful for evaluating various pavement mitigation strategies. In general, the influence of temperature on asphalt pavement performance is significant, especially in tropical regions. The air temperature in these regions is usually high, which can result in high pavement temperatures [19]. Therefore, conventional materials used for asphalt pavement can be improved by using cool paving materials to reduce the heat impact. The present research focused on the development of cool asphalt pavement containing various alternative materials, including recycled materials. The potential cool paving materials were then selected and evaluated for their thermal mechanisms and performance in asphalt pavement.

1.2 Problem Statement

Generally, asphalt pavement consists of a dense structure and dark surfaces which are good at absorbing and storing solar radiation, often leading to high surface temperature. The amount of solar energy that can be absorbed or reflected by pavement depends on the material's thermophysical properties [20]. The amount of absorbed solar energy that is converted into heat inside the pavement's body depends on the material's conductivity. Later, the heat is released into the surroundings as infrared waves through emission and convection. Therefore, in order to better understand the materials' contribution of asphalt pavement towards UHI mitigation, the aforementioned thermal properties should be studied. Much research has studied the cool asphalt pavement as a strategy for mitigating the heat island effect and improving outdoor thermal comfort [1,21,22].

However, most researchers focused on reflective pavement (light colour coating) and permeable pavement (evaporative cooling) in order to increase the solar reflectance and enhance the thermophysical properties of asphalt [10,22]. Relatively little is known about the material composition and asphalt modification regarding heat storage and heat transfer application. Studies on the role of materials in asphalt pavement by substituting the conventional asphalt with alternative materials are minimal. Therefore, this study is an attempt to investigate the thermal behaviour of an asphalt pavement containing potential cool paving materials.

1.3 Aim and Objectives

This study aims to evaluate the performance of potential cool paving materials in asphalt mixtures. The specific objectives are as follows:

(a) To investigate the heat response of various materials in asphalt pavement through aggregate replacement and bitumen modification and to select the potential cool paving materials.

(b) To determine the chemical and physical properties of the selected materials and evaluate the mechanical and chemical properties of asphalt mixtures containing these materials.

(c) To evaluate the thermal performance of conventional and modified asphalt mixtures under laboratory-controlled and field conditions.

1.4 Scope of the Study

The study focused on cool paving materials strategy, particularly on asphalt mixture design and its potential to reduce localized heat island effects. The tests and analysis were conducted according to the specifications outlined by the Malaysian Public Works Department, which symbolised (JKR) and the American Society for Testing and Materials (ASTM). Several modified asphalt mixtures were prepared based on various designs and alternative materials used. The solar reflectivity and temperature profiles of the asphalt mixtures were monitored using a spectroradiometer and infrared cameras, respectively.

The chemical composition (oxides) of the selected materials was determined using X-ray fluorescence subjected to elemental analysis. The conventional and modified asphalts were prepared using the Marshall mix design method. The verified mixtures were tested for Marshall stability, Cantabro loss, resilient modulus, dynamic creep, rutting resistance, and moisture damage under unaged, short-term ageing, and long-term ageing conditions. Furthermore, the mixtures were chemically profiled using dispersive energy X-ray (EDX) analysis and a toxicity characteristic leaching procedure (TCLP) to characterise their hazardous potential. To evaluate the thermal performance, the thermophysical properties, temperature profiles, emissivity and albedo with weather data, thermal conductivity, and heat capacity were measured on slab samples prepared in different ageing conditions (unaged, short-term ageing, and long-term ageing). Based on thermodynamic laws, the thermophysical properties and weather data-related model were developed to evaluate the validity of the present work.

1.5 Significance and Contribution to Knowledge

The modified asphalt mixtures used in this research are significant towards the green highway implementation. This is relevant as the mixtures consist of recycled materials with potential to be used as cool paving materials to minimise the environmental problems related to UHI phenomenon. As green highway could be any technique used pavement to reduce the negative effects on the environment (e.g. cool pavement) or reused materials (e.g. recycled materials) and so on [23]. Besides, the potential use of recycled materials in the mixture has economic benefits. Although different research institutes have conducted some research, there are knowledge gaps pertaining to green asphalt, particularly in terms of the engineering performance of cool pavements and its impact on the environment.

Evaluating pavement solutions for reducing the UHI effect in road construction will improve human health and comfort, decrease energy use, reduce the emissions of air pollutants and greenhouse gases, improve water quality, and prolong pavement life. The importance of this research as it relates to cool asphalt pavement strategies lies in the detailed evaluation of the mechanical and thermal performance of the recycled materials treated as potential cool paving materials in the asphalt pavement. Furthermore, an enhanced application of thermal imaging techniques was applied to evaluate the feasibility of using the technology as an investigation tool.

1.6 Thesis outline

This thesis consists of six chapters, which are outlined as follows:

Chapter 1 provides a broad introduction and background, which includes the problem statement, objectives, scope, and significance of the study.

Chapter 2 presents a review of the published research, encompassing studies performed by leading investigators in the field of asphalt pavement materials and their performance, thermophysical properties, and the impact of UHI. The testing procedures, parameters, and related findings are described.

Chapter 3 provides a detailed research plan and the procedure, which encompasses three stages of work. The tasks involved in each stage are described, including the preparation and testing of raw materials, the design of the various mixtures, and the principal testing phase.

Chapter 4 presents the results of a preliminary investigation that was conducted to select the potential cool paving materials.

Chapter 5 evaluates the selected potential cool paving materials and a detailed investigation of the physical, mechanical, and chemical properties of the selected materials and asphalt mixtures.

Chapter 6 provides a detailed investigation and the results of the asphalt pavement's thermal response with its surroundings (laboratory and field conditions) and the validation of the result obtained.

Chapter 7 concludes the research and provides recommendations for subsequent work.

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