UNIVERSITI PUTRA MALAYSIA

PERFORMANCE OF STONE MASTIC ASPHALT MIXTURE REINFORCED WITH NEWLY DEVELOPED INTERLOCKING CHAINED PLASTI-BEADS

NADZROL FADZILAH BINTI AHMAD

PERFORMANCE OF STONE MASTIC ASPHALT MIXTURE REINFORCED WITH NEWLY DEVELOPED INTERLOCKING CHAINED PLASTI-BEADS

By

NADZROL FADZILAH BINTI AHMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requrement for the degree of Doctor of Philosophy

February 2014

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

PERFORMANCE OF STONE MASTIC ASPHALT MIXTURE REINFORCED WITH NEWLY DEVELOPED INTERLOCKING CHAINED PLASTI-BEADS

By

NADZROL FADZILAH BINTI AHMAD

February 2014

Chair : **Ratnasamy Muniandy, PhD**
Faculty: **Engineering**

Stone Mastic Asphalt (SMA) is a gap-graded hot mixture consisting of a coarse aggregate skeleton and high binder content. Typical standard and specification of void in mineral aggregate (VMA) for this type of mixture range between 16 to 18%. Aggregate with 3 to 8mm diameter size found to be the largest portion that form a matrix skeletal in SMA mixture. The objective of this study is to develop and design Chained Plasti-beads (CPB) that utilize the VMA existence in SMA mixture as an interlocking mechanism and to evaluate their potential in resisting fatigue failure of Stone Mastic Asphalt.

The research was undertaken in four stages. The first stage of the study was carried out on develop Chained plasti-beads (CPB); this includes designing the shape configuration and dimensions (bead size, shape, chained spacing and thickness) to suit the void spaces in asphalt mixture. The second stage was to evaluate and analysis the CPB physical and mechanical properties. The third stage was to determine and justify the suitable quantity of CPB to be replaced for some portion of aggregate in mixture on volume bases, while the fourth stage devoted to fabrication and testing of fatigue beam specimens using Repeated Flexural Beam Fatigue in accordance with AASHTO TP8-94 321 to investigate the potential prospects to enhance asphalt mixture fatigue cracking properties by means of flexural beam fatigue test.

In this study, CPB of 4mm and 6mm diameter diamond shaped beads with 0.5mm and 1.0mm thick chained beads link (M4/0.5, M4/1.0 and M6/0.5, 6M/1.0) with spacing between beads set at 20mm interval was developed and designed mainly to act as reinforcement to increase the tensile strength when pavement subjected to traffic loading. The interlocking mechanism through VMA concept was adopted using replacement strategy of some portion of aggregate sizes (2.3 – 4.75mm) by CPB on volume bases as

such three different contents (0.5%, 1.0% and 1.5%) of CPB were selected and used throughout the study.

SMA beam specimens were prepared with the above CPB sizes and proportions and tested to simulated loading and temperature conditions in accordance with ASTM and AASHTO Standards. Laboratory repeated flexural fatigue bending beam tests were conducted at five different strain levels (350 to 650μm) represents low, medium, and high traffic loading to evaluate the incorporation of CPB in SMA to assess mixture fatigue cracking performance. Two new concepts of analysis; Stress Loss Ratio (SLR) and Fatigue Resistance Ratio (FRR) along with stiffness reduction and energy ratio concepts were used to determine the significant CPB combinations that serve as an interlocking mechanism through VMA concept and to evaluate fatigue cracking potential.

At 350 micro-strain (με) loading; CPB M4/0.5, M4/1.0 and M6/0.5 specimens showed significant improvement in terms of fatigue resistance and stiffness compare to control specimens. In general, most analyses approaches used in this study revealed, as the strain level increased, the fatigue resistance trend of CPB mixture decreased gradually and the performance showed almost the same trend at higher strain level of 650με. M6/1.0 specimens performed the worst compared to the other CPB specimens.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PRESTASI CAMPURAN BATUAN ASFALT MASTIK YANG DIPERKUATKAN DENGAN PEMBANGUNAN BARU RANTAIAN KEKUNCI MANIK-PLASTI

Oleh

NADZROL FADZILAH BINTI AHMAD

Februari 2014

Pengerusi : Ratnasamy Muniandy, PhD
Fakulti : Kejuruteraan

Batuan Asfalt Mastik (SMA) adalah campuran panas bahan turapan yang mempunyai jurang juzuk gradasi terdiri daripada skeletal batu kasar dengan kadar kandungan asfalt yang tinggi. Menurut tipikal standard dan spesifikasi bagi keperluan ruang dalam campuran batuan kasar dan halus (VMA) untuk campuran bahan turapan jenis ini adalah diantara 16 hingga 18%. Batuan dengan diameter bersaiz 3 hingga 8mm adalah diantara kelompok saiz yang paling besar membentuk skeletal didalam campuran SMA. Lanjutan daripada itu, objektif utama kajian ini adalah untuk merekabentuk dan membangunkan rantaian manik plastic (CPB) yang akan mengunapakai konsep VMA sebagai mekanisma kekunci seterusnya menilai potensi CPB terhadap kebolehupayaan dalam mengurangkan kadar kegagalan rintangan keletihan didalam campuran SMA.

Kajian ini dilaksanakan dalam empat peringkat. Peringkat pertama adalah menjalankan kerja-kerja pembangunan CPB termasuk kerja-kerja merekabentuk rupabentuk, konfigurasi dan dimensi CPB (saiz manik, rupabentuk, jarak dan ketebalan rantaian CPB) yang sesuai dengan keadaan VMA didalam campuran bahan turapan sediada. Peringkat kedua pula adalah untuk menilai dan menganalisis sifat fizikal dan mekanikal CPB. Peringkat ketiga adalah untuk mengenalpasti dan justifikasi kuantiti yang paling sesuai bagi CPB untuk menggantikan sebahagian daripada jumalah batuan dalam basis isipadu yang setara manakala peringkat keempat menumpukan fabrikasi dan ujian rintangan keletihan spesimen rasuk dengan menggunakan kaedah Ulangan Rintangan Keletihan Lenturan Rasuk berdasarkan standard AASHTO TP8-94 321 untuk menyiasat prospek dan potensi bagi sifat kebolehrintangan keretakan didalam campuran bahan turapan SMA oleh CPB.

Dalam kajian ini CPB bersaiz 4mm dan 6mm diameter berupabentuk berlian dengan ketebalan rantaian 0.5mm dan 1.0mm (M4/0.5, M4/1.0 and M6/0.5, 6M/1.0) pada jarak 20mm diantara manik telah dibangun dan direkebentuk untuk bertindak sebagai mekanisme kekunci mengunapakai konsep VMA dengan strategi penggantian CPB kepada sebahagian daripada saiz batuan (2.3 – 4.75mm) dalam basis isipadu setara dengan memilih tiga kandungan berbeza (0.5%, 1.0% dan 1.5%).

Spesimen rasuk SMA mengikut saiz dan kadar CPB seperti diatas telah disediakan dan diuji menurut simulasi bebanan dan kondisi suhu berdasarkan standard ASTM dan AASHTO. Ujian makmal ulangan lenturan rasuk terhadap rintangan keletihan telah dijalankan pada lima kadar regangan yang berbeza (350 to 650µm) mewakili keadaan trafik rendah, sederhana dan tinggi bagi SMA yang mengandungi CPB bagi menilai kebolehupayaan bahan turapan terhadap keretakan keletihan. Dua konsep baharu telah diperkenalkan bagi tujuan analisis; Kadar Kehilangan Stres (SLR) dan Kadar Rintangan Keletihan (FRR) dengan mengambilkira konsep pengurangan kekuatan dan kadar tenaga telah digunapakai untuk mengenalpasti signifikan kombinasi CPB yang menyumbang sebagai mekanisme kekunci menerusi konsep VMA sekaligus berpotensi mengurangkan keretakan.

Pada kadar 350µε, campuran SMA CPB M4/0.5, M4/1.0 dan M6/0.5 telah menunjukkan prestasi yang signifikan yang mempengaruhi tren rintangan keletihan dan kekuatan berbanding dengan campuran SMA konvensional. Secara amnya, keseluruhan pendekatan analisis yang dilakukan dalam kajian ini menunjukkan bahawa, sekirannya kadar regangan ditingkatkan maka tren kadar rintangan keletihan campuan bahan turapan CPB berkurangan secara berkadaran dan pada kadar regangan tinggi 650µε, prestasinya menunjukkan tren yang sama bagi kesemua campuran CPB mahupun tanpa CPB.

Akhirnya, berdasarkan kepada analisis statistik, M4/1.0 didapati campuran CPB yang paling bagus berbanding campuran CPB yang lain. Campuran CPB menunjukkan pengaruh yang hebat terhadap rintangan keletihan dan seterusnya meningkatkan kitaran hidup keletihan melebihi 100% berbanding dengan SMA konvensional pada kadar 350µε.

ACKNOWLEDGEMENTS

Praise and Glory be to Almighty ALLAH S.W.T. for bestowing me with strength, patience and health to complete my study.

I would like to express my deep thanks and gratitude to my great supervisor, Prof. Dr. Ratnasamy Muniandy for his supervision and valuable guidance, constructive comments and encouragement. I am honored to carry out this research study under his direct supervision and look forward to future endeavors. His support and enthusiasm are greatly appreciated. Many thanks also due to Assoc. Prof Ir Salihudin Hasim and Dr Hussain Hamid for serving as committee members and for their valuable input to this work.

I would also like to thank the Malaysian Highway Authority (MHA) for giving me this opportunity and providing the necessary sponsorship to complete my study. In addition, I would like to acknowledge to technician En Azry Tamber and my colleagues Taher, Azurah, Yong and many others who studied and working together in Highway and Pavement Laboratory during sample preparation and testing. Finally, I wish to express my sincere respect to my parents for their understanding and blessings that helped me to be what I am today. I would like to express my special thanks to my husband, Yaakob Salim, for being in my life, thank you so much for your love, patience and support and to all my children Zharfan Dzakirin, Zafry Nabil and Zarith Laila Aqila, you all are my inspiration.

I certify that a Thesis Examination Committee has met on 13 February 2014 to conduct the final examination of Nadzrol Fadzilah binti Ahmad on her thesis entitled "Performance of Stone Mastic Asphalt Mixture Reinforced with Newly Developed Interlocking Chained Plastic Beads" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohd Saleh bin Jaafar, PhD
Professor Dato Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abdul Halim bin Ghazali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Thamer Ahmad Mohammad Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Vernon Ray Schaefer, PhD
Professor
Iowa State University
United States
(External Examiner)

NORITAH OMAR, PhD
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 April 2014

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Ratnasamy Muniandy, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Salihudin bin Hassim, M. Sc., P.Eng
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hussain bin Hamid, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate
Universiti Putra Malaysia

Date :

Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully - owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice - Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, lear ning modules or any other materials as stated in the Universiti PutraMalaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012 - 2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergon e plagiarism detection software.

Signature : ____________________ Date : ____________

Name and Matric No.: Nadzrol Fadzilah Binti Ahmad (GS 22393)

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature :	____________________	Signature :	____________________
Name of Chairman of Supervisory Committee :	**Prof. Dr. Ratnasamy Muniandy**	Name of Member of Supervisory Committee :	**Assoc. Prof. Ir. Salihudin bin Hassim**

Signature :	____________________
Name of Member of Supervisory Committee :	**Dr. Hussain bin Hamid**

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

VMA	Void in Mineral Aggregate
VTM	Void in Total Mix
G_{sb}	Bulk Specific Gravity
G_{mb}	Bulk Specific Gravity of Compacted
G_{se}	Effective Specific Gravity of Asphalt mix
G_{mm}	Theoretical Specific Gravity
P_b	Percentage of Asphalt
W_{dry}	Weight of Specimen in Air
W_{sub}	Weight of Specimen Submerged in Water
W_{SSD}	Weight of Saturated Dry Specimen
Pb	Percent of Asphalt
SSD	Saturated Surface Dry weight
TMD	Theoretical Maximum Density
MQ	Marshall Quotient
Mpa	Megapascal
HDPE	High Density Polyethelene
LDPE	Low Density Polyethelene
PP	Polyproplene
N_f	Number of Load Cycles to Failure
N_1	Failure Point
N_{50}	Number of Cycles to Failure at 50% Stiffness Reduction
R_n	Energy Ratio
SLR	Stress Loss Ratio
FRR	Fatigue Resistance Ratio
σN_f	Stress at Number of Cycles to Failure
σ_i	Initial Stress
ε_0	Initial Strain
S_0	Initial Stiffness

CHAPTER 1

INTRODUCTION

1.1 Background

Plastic has been well recognized by its versatile usage. Despite their tremendous success story on their versatile usage, plastics were also created a negative story on their waste management. This is mainly because of their non-biodegradable properties. Plastic wastes have been viewed as a serious solid waste problem to many municipal authority all over the world as its demand to provide more landfill area. In addition, the most concerned being raised up recently is on their contribution to global warming issues. Many countries encourage researchers to explore innovative way to recycle or reuse plastics.

World statistics of 2010, clearly shown that waste plastic recycling rate was still very minimal as out of 24.7 million tones plastics waste being generated, only 6 million tones or equivalent to 24% of total waste being recycled (Plastics Europe Market Research Group, 2010). Malaysia was not excluded from this scenario. It was reported that plastic industry growth at 20% of Malaysian economy. On the other hand it was also reported that 7 to 12% by weight or 18 to 30% by volume of solid waste generated daily is a plastic waste (Sapan Agarwal, 2007). The concern goes to municipal authority when less than 5% being recycled and this will definitely create a landfill problems. Malaysia has been introduced a policy to ban a plastic bag uses at every Saturday in the week. This is mainly to retain a green environment as plastics are non-biodegradable which is believed partly as contribution factors to global warming issues.

Virgin or recycled plastics that are being used currently in highway industry were also not a new discovery. Various types of plastic were used in roads furniture manufacturing. However, the most popular was on its' usage as an additives in asphalt binder from a group of polymers. Styrene-butadiene-styrene (SBS), Ethylene Vinyl Acetate (EVA), polyethylene (PE) is among the famous plastic or polymer group being used as asphalt modifier. As for example, Mustafa T. et al., (2003) used discarded plastic grocery bags, dry cleaning and household plastics in single size as a modifier that significantly increased the softening point and decreased the penetration and ductility of asphalt cement. In addition, plastics were also being used in pallet formed to replace a quantity of aggregates been studied by Zoorob (2000). The details of plastics usage in highway industry will be discussed in review of literature in Chapter 2.

To further utilize on the versatility of plastic usage, this study will execute a research to develop a special plastics product purposely to be incorporated in asphalt mixture composition as an interlocking mechanism namely Chained Plasti-beads (CPB). Chained plasti-beads were design and fabricate such a way to be an interlocking mechanism between aggregate specific sizes through void in mineral aggregate (VMA) approach. Stone Mastic Asphalt (SMA) with 9.5mm Nominal Maximum Aggregate size (NMAS) in accordance to

Malaysian Public Work Department (JKR) specifications was adapted throughout the entire analyses.

Voids in Mineral Aggregate (VMA) is defined as the volume of intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percentage of the total volume of the compacted paving mixture (Asphalt Institute Manual Series MS-4 2007). Incorporation of CPB in SMA is expected to provide better aggregate interlock and increasing the tensile strain through its chained interlocking mechanism. The chained of CPB has a tendency to increase pavement tensile strength especially for fatigue resistance while resist the repeated traffic load. CPB interlocking mechanism concept can be illustrated in Figure 1.1.

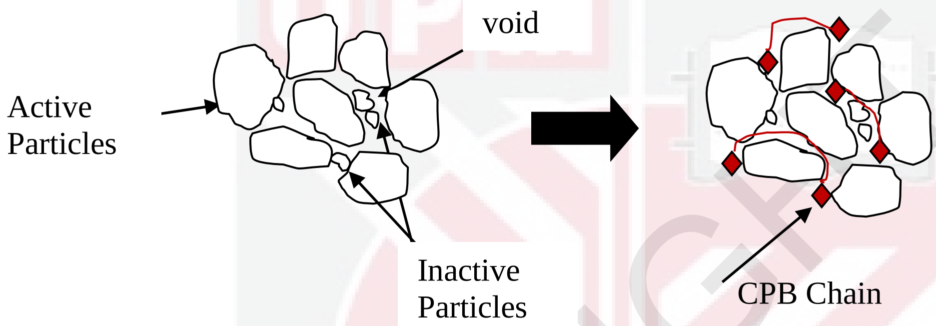

Figure 1.1 SMA Aggregate Skeleton Interlock with CPB through VMA concept

The material, size, dimensions and shape configuration of CPB was determined with rationale and justification to meet the compatibility requirement in asphalt mixture. Nylon 66 Mapex AT0110GN was chosen to fabricate the CPB as this type of plastic met the melting point temperature of 200 ^{0}C. This is very important criteria to be considered as CPB was developed with intention to be permanently and physically functioning as interlocking mechanism during pavement service life.

Based on SMA 9.5mm NMAS, aggregate with size between 3mm to 8mm formed the largest portion of typical matrix aggregate to aggregate skeleton. Therefore, the size of CPB will also be recommended in this range. Another concern is on the determination of CPB's shape and texture that should be rough and angular to provide better interlock condition. Aggregate interlock was highly depends on rough and angular particles which are desired for providing the rut resistance (Kandhal and Mallick, 2001; Sousa et al., 1991; Brown and Bassett, 1990; Button et al., 1990). Diamond shape found to be the most suitable in the current study in order to fulfill the aggregate angularity criteria as well as for convenience of fabrication works.

Since the density of plastic is much lower than the aggregate, a strategy of replacement of certain portion of aggregates by CPB based on volume rather than weight was adopted for further assessment.

1.2 Problem Statement

It becomes worst and bad experience when sometimes the occurrence of surface-initiated cracking in new asphalt surface and overlays are widely reported just after a few months of opening to traffic. With respect to these circumstances, researchers or roads engineers were continuously making attempts to enhance pavement performance. Material variability was favorite area that getting much attention and interest among researchers which directly influenced the pavement performance. Over the years and all over the world, researchers performed extensive research on materials through new technologies and innovation to produce a pavement that could perform double durability with desired performance. A wide variety of additives and modifiers have been used for asphalt modification properties including the study on types and grading of aggregates, angularity and surface texture which were among effort that been carried out to improve the existing asphalt mixtures.

One of the prominent enhancements made was to modify the asphalt properties by adding various types of polymer, fibers and other additives. All these efforts purposely being carried out to increase the tensile strength on asphalt properties. However, according to X. Lu et al., (2001), despite increased interest, modified bitumen will probably never be able to replace conventional bitumen to any great extent due to economic reasons. Reliable statistics showing the present volumes of modified bituminous binders are difficult to obtain. In most countries, only a small proportion of the total bitumen volume used is modified in one way or another. The main reason for the low fraction of modified bitumen is most probably the price, which may exceed twice that of conventional bitumen (D'Angelo, J). Instead of that, the evidence of the effect of using additives or modifier is not often obvious. There are several reasons for this situation. In addition, laboratory test methods do not always simulate behavior on the road and field tests are generally time-consuming and too expensive. In this connection, it is also worth mentioning that the mechanisms of action for most of the additives are insufficiently understood. Besides, the possible problems with modified bitumen are mainly in the storage of the bitumen, mixing temperatures and the length of time the material is held at elevated temperatures before laid on.

Fibers have gotten much attention of their excellent improvements effect. A multitude of fibers materials were continuously being introduce in the market as new applications such as from a group of polyester, polypropylene, asbestos, glass, carbon, cellulose and many others (Serfass et al., 1996). However, past researched reported that fiber reinforced bituminous mixtures has shown mixed results. Consequently, fiber reinforcement is considered as a coin with two sides. One side includes the randomly direct inclusion of fibers into the matrix, i.e. asphalt concrete and/or Portland Cement Concrete slabs. Another side comprises the oriented fibrous materials, e.g. Geo-synthetics family. It is emphasized that the former concept is not as well-known as the second, not only in optimizing fiber properties, fiber diameter, length, surface texture etc., but also in reinforcing mechanism. Obviously, if the fibers are too long, it may create the so called ‘‘balling” problem, i.e. some of the fibers may lump together, and the fibers may not blend well with the asphalt. In the same way, too short fibers may not provide any reinforcing effect. They may just serve as expensive filler in the mix (Mahrez A. et al., 2005). In conclusion, only fiber that have high tensile strength relative to bituminous mixtures, showed the potential to improve the cohesive and tensile strength of bituminous mixes.

Another area that always been studied in research and development of pavement activities was on the main component of asphalt mixture; an aggregate. Instead of aggregate types, grading and physical properties such as surface texture and angularity, sources of aggregate were also play an important role in order to ensure asphalt concrete performance. Besides, based on exploration of aggregate gradation, varieties of new mix design were proposed. Superpave, Stone Mastic Asphalt (SMA) and porous asphalt were typical example being introduced towards this finding. In addition, a lot of studies by using recycled materials such as plastic, glass, steel slag, ceramic and etc. being used to replace a portion of aggregate quantity. This effort was mainly to utilize waste material that created landfill problem and one way to overcome the shortage of natural materials in the future.

Both asphalt and aggregate that been studied for improvement reported various stories of their successfulness. However not many of the findings can be proceeded to improve the asphalt pavement. Therefore, until to-date researchers had never been stopped from looking forward to find the loop hole in this area. In general, most of the efforts go to single improvement either on asphalt or aggregate. However, some can be done but incurred a higher capital cost and totally in-economic to be considered.

Moreover, beside many kind of asphalt mixture design that have been established such as Hot Mix Asphalt (HMA), Porous Asphalt and etc., SMA mixture design was selected since this mixture is design for rut resistance. Most of the reports by the researchers highlighted the mixtures great potential in resisting permanent deformation or rutting, but ignored any potential fatigue resistance of the SMA (Ratnasamy M. and Bujang BK., 2006).Therefore, incorporated of CPB in SMA mix design is aimed to act as a reinforcement agent through interlocking mechanism. CPB was developed as a mix composite to increase a tensile strength in asphalt mixtures through interlocking mechanism between specific aggregate sizes by using void in mineral aggregate (VMA) approach. This attempt is purposely made to enhance the performance of both in asphalt and aggregate composition of asphalt mixture. Moreover, the availability of various type of plastic material is very encouraging towards producing the innovative material to be used in highway pavement industry.

1.3 Objectives

This study was mainly emphasized on investigating the effectiveness of the newly developed of chained plasti-beads (CPB) as an interlocking mechanism which is incorporated in Stone Mastic Asphalt (SMA) mixtures by using void in mineral aggregate (VMA) approach. The comparison between SMA with and without CPB mixtures was evaluated for further assessment on their performance in resisting of tensile strain. Hence, the research objectives of an effect of CPB existence in SMA mixture were structured up as follows:

a) To develop appropriate interlocking chained plasti-beads configuration using the VMA concept.

b) To characterize the physical and mechanical properties of CPB and determine the optimum chained plasti-beads for SMA mixture design.

c) To establish a relationship between interlocking chained plasti-beads system and fatigue life of SMA mixture.

1.4 Scope of Study

The scope of this study was divided into four main work activities. The first activity was to develop Chained plasti-beads (CPB) that are compatible to be incorporated in asphalt mix composition. This includes on designing the shape configuration and dimensions which is to suit with the void spaces in asphalt mixture. Therefore, determination of void in mineral aggregate (VMA) of intended mixes was initially analyzed for the selection of appropriate bead size, chained spacing and thickness in order to get ultimate strength for mixes to resist fatigue and deformation. The fabricated CPB then will be evaluated and analyzed on its physical and mechanical properties at different condition especially in tensile strain test by using Universal Instron Machine in the second activity. In this activity, the aggregate and asphalt was also being tested on their physical and mechanical properties for its suitability to meet the specifications.

The satisfactory CPB properties that met the requirement of melting point more than 200 ^{0}C were used in mix design in the third activity. The main challenge in this stage was to justify the suitable or reasonable quantity of CPB to be replaced for some portion of aggregate in mixture as both CPB and aggregate has obvious differences in density range. Replacement by volume strategy found to be more suitable and realistic to overcome the density differences. The ultimate objective for the mix design analysis was to obtain an optimum asphalt content for each matrix mixes with and without CPB. The ranking system was employed to find the best performing mixture based on CPB matrix combinations for preparation of beam specimens in the next activity.

The fourth or final activity covers a preparation of slab fabrication in order to obtain adequate number of beam specimens in accordance with AASHTO TP8-94 321 Repeated Flexural Beam Fatigue Test requirement. The four point bending beam test was carried out as to compare the performance between the mixture with and without CPB. Further analysis on fatigue resistance was conducted as to find out the significant of CPB employment in SMA mixtures. Overall results, analyses and discussions will be the ultimate scope of this study and will be presented comprehensively.

1.5 Limitation of Study

The evaluation and investigation of this study has their limitation in terms of:-

i) Performance of new invention CPB in SMA mixture to be analyzed in laboratory test only with no further evaluation on actual field condition.

ii) CPB are developed in single diamond shape and single spacing between the beads. As shape was one of criteria that determined the performance in terms of contact area, no comparison could be made for other geometric shape. The single spacing between the beads may also influence and limit the chances aggregate particles to interlock each other.

iii) In addition, the limited of two different diameters of 4mm and 6mm beads size and two different thickness of chain size might not be sufficient to evaluate the overall significant of CPB incorporated in mix composition.

1.6 Significance of Study

As mentioned earlier, in the recent past, investigators and researchers attempted to enhance the mechanical properties of asphalt mixture through single improvement either on asphalt or aggregate. Most of mechanical properties enhancement such as stiffness and modulus of elasticity that may increased the fatigue resistance was done through asphalt modifying or by adding various types of fibers or polymers to increase tensile strength. Various types of polymers and fibers are believed to be a reinforcing agent in asphalt pavement.

New develop and manufactured of chained plasti-beads (CPB) was totally a new invention to be part of asphalt mixture composition by tapping on aggregate skeletal matrix through void in mineral aggregates (VMA) approach. Suitable shape and configuration with appropriate dimensions could be developed once VMA of the selected gradation is determined. VMA matched with the right CPB size and configuration results in optimum strength in terms of fatigue or stability. Therefore, a replacement strategy by volume approach between some portion of aggregate and CPB of 4mm and 6mm diameter size was adopted. These two sizes is expected to be formed partly of 3mm to 8mm aggregate size which was found to be a large portion of the skeletal matrix for SMA 9.5mm NMAS gradation.

Hence, by proving that CPB is workable as a reinforcement agent through interlocking mechanism that increase tensile strength in asphalt mixtures can be considerable interest in the future study. In addition, the new develop CPB will provide significant data and information to be diversified on the plastics waste usage as an alternative to CPB manufacturing in future. On the other hand, it will be part of the mitigation measures to environmental problem where the creation of non-decaying waste materials, combined with a growing consumer population led to be utilized and benefited in highway industry.

1.7 Research Hypothesis

The hypothesis for this study was that, within the practical ranges, incorporating of chained plasti-beads (CPB) as an interlocking mechanism in Stone Mastic Asphalt mixture through void in mineral aggregate concept may increase the tensile strength as well as to enhance the Stone Mastic Asphalt fatigue resistance.

1.8 Thesis Outline

The goal of this report is to answer the research objectives. This report is organized into six chapters as follows:

Chapter 1 : This chapter consists of the introduction of study field, the research problem statement, research objectives, research hypothesis and significance of the research.

Chapter 2 : Literature review covers the previous research conducted with correspond to VMA concept and many kind of improvement been done to asphalt mixture. The exploration of fatigue analyses behavior in many kind of approach adopted by other researchers was also presented.

Chapter 3 : This chapter explains the research methodology involved in this research inclusive discussions of materials characterization and type of testing that being carried out for physical and mechanical properties assessment. Addition to that, preparations of specimens and selection of performance test with justify parameter and variables also discuss in this chapter.

Chapter 4 : The new develop and manufactured of Chained plasti-beads (CPB) was discussed in details in this chapter. This chapter briefed regarding the determination of appropriate shape, size and configuration of entire CPB interlocking system. An assessment on the compatibility of CPB to be included in asphalt mixture was also presented in this chapter.

Chapter 5 : This chapter presents the experimental results, analyses and discussions of the compatibility and its performance of chained plasti-beads under various stage from mix design to performance test. Results and discussions of physical and mechanical properties for aggregate and asphalt as well as mix design analysis were also included in this chapter.

Chapter 6 : This chapter presents a comprehensive conclusions and proposes some recommendations on the possible research opportunities that could carried out in the future on chained plasti-beads as a reinforcement through an interlocking mechanism. In addition, the contribution to knowledge was also included in this chapter.

References

AASHTO. Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix sphalt Sub-jected to Repeated Flexural Bending. AASHTO TP 8-94.

Abdullah WS, Obaidat MT, Abu-Sa'da NM. Influence of Aggregate type and Gradation on Voids of Asphalt Concrete Pavements. ASCE J Mater Eng Div 1998;10(2):76 –85.

Abtahi SM, Ameri M, Sheikhzadeh M, Hejazi SM, Rahnama E. A comparative study on the use of sbs polymers and poly propylene fibers modifying asphalt concrete structures. In: 8th international conference sustainable aggregates, asphalt technology and pavement engineering, Liverpool, UK; 2009.

Abtahi SM, Sheikhzadeh M, Hejazi SM. Fiber-reinforced asphalt-concrete – a review. Construct Build Mater 2010;24:871–7.

Al-Abdul-Wahhab, H. & Al-Amri, G. (1991) Laboratory evaluation of reclaimed rubber asphaltic concrete mixes. J. of Materials in Civil Engineering, ASCE, 3(3), pp. 189–203.

Al-Ghannam KAA. Study on the rheological properties of asphalt, effect of modification process on the homogeneity of the system. Ph.D. Thesis, College of Education, Chemistry Department, University of Mosul, Mosul-Iraq; 1996.

Al-Hadidy AI, Tan Yi-qiu. Effect of polyethylene on life of flexible pavements. J Construct Build Mater 2009;23:1456–64.

Alvarado, C., Mahmoud, E., Abdullah, I., Masad, E., Nazarian, S., Tandon, J., and Button, J. 2006. Feasibility of Quantifying the Role of Coarse Aggregate Strength on Resistance to Load in HMA. Center for Transportation Infrastructure Systems, University of Texas at El Paso, *Research Report 0-5268-2*, October.

Anderson, R. Michael, and Hussain U. Bahia, *Evaluation and Selection of Aggregate Gradations for Asphalt Mixtures Using Superpave*, Transportation Research Record 1583, TRB, National Research Council, Washington, D.C.1997, pp. 91-97.

Asphalt Institute, the asphalt handbook, MS-4 7th edition, 2007.

Asphalt forum responses. Asphalt Technology News2002;14(1):12–13. Available from: http://www.eng.auburn.edu/center/ncat/newsl/newssprng_02.pdf.

Asphalt Institute. Individual asphalt binder tests. Lexington, KY. 2003. Available from: http://www.asphaltinstitute.org/ai_pages/Lab_Services/Lab_Services_Indiv_Binder_Tests_List.asp.

ASTM D4123. Indirect tension test for resilient modulus of bituminous mixtures. ASTM Book of Standards, vol. 04.03, USA; 2003.

ASTM D 1559. Standard test method for marshal Ttest. Annual book of ASTM standards, vol. 04.03. West Conshohocken: American Society for Testing and Materials; 2002.

ASTM D2172 Standard test methods for quantitative extraction of bitumen from bituminous paving mixtures.

Australian Asphalt Pavement Association. National asphalt specification, 2nd ed. Kew, Australia, 2004.

Barksdale, R. D., Pollard C. O., Siegel, T., and Moeller, S. (1992). "Evaluation of the effect of aggregate on rutting and fatigue of asphalt." Technical Report FHWAAG- 92-8812. Georgia Department of Transportation, Atlanta, GA.

Bates R, Worch R. (1987) Engineering Brief No. 39, Styrene–butadiene rubber latex modified asphalt. Federal Aviation Administration, Washington, DC.

Becker Y, Me´ndez MP, Rodrı´guez Y. (2001) Polymer modified asphalt. Vis Technol;9(1):39–50.

Benson FJ. Effects of aggregate size, shape, and surface texture on the properties of bituminous mixtures – a literature review. Highway research board special report 109; 1970. p. 12–21.

Blankenship P et al. Are All PG 70-22_s the same? Lab test on KY I-64 field samples. J Assoc Asphalt Paving Technol (AAPT) 1998;67:493–552

Brian J. Coree and Walter P. Hislop. (1998). The Difficult Nature of Minimum VMA: A Historical Perspective.

Brown, R.R., and Bassett, C.E. (1990). Effects of Maximum Aggregate Size on Rutting Potential and Other Properties of Asphalt –Aggregate Mixtures. Transportation Research Record 1259, pp. 107-119.

Brown, E. R., McRea, J. L., and Crawley A. B. (1989). "Effect of aggregates on performance of bituminous concrete." *American Society for Testing and Materials ASTM STP*, 1016, 34-63.

Brown, E. M, and M. S. Buchanan (2001), "Literature Review: Verification of Gyration Levels in the Superpave Ndesign Table," NCHRP Web Document 34, Transportation Research Board, National Research Council, Washington, DC

BS 812: Part 112. Methods for determination of aggregate impact value (AIV). London, United Kingdom: British Standards Institution; 1990.

BS 812: Part 105.1. Flakiness index. London, United Kingdom: British Standards Institution; 1989.
BS 812: Part 105.2. Elongation index of coarase aggregate. London, United Kingdom: British Standards Institution;
1989.

Bushing H, Antrim D. (1968) Fiber reinforcement of bituminous mixtures. Proc Assoc Asphalt Pav Technol;37:629–59.

Button JW, Lytton RL. (1987) Evaluation of fabrics, fibers and grids in overlays. Sixth international conference on the structural design of asphalt pavements. Ann Arbor, M.

Button, J. W., Perdomo, D., and Lytton, R. L. (1990). “Influence of aggregate on rutting in asphalt concrete pavements.” *Transportation Research Record 1259,* Transportation Research Board, National Research Council, Washington D.C., 141-152.

Campen W. H., and Smith, J. R. (1948). “A Study of the role of angular aggregate in the development of stability in bituminous mixtures.” *Association of Asphalt Paving Technologists Proceedings,* 17, 114-143.

Carpenter, S. H., Khalid A. Ghuzlan, and Shihui Shen. (2003). "A Fatigue Endurance Limit for Highway and Airport Pavement." *Journal of Transportation Research Record (TRR),* No. 1832, pp. 131-138.

General Properties of Plastics. Plastics Engineering Book Third Edition by R. J. Crawford Publisher: Oxford; Boston : Butterworth-Heinemann, 1998.

Chen WF (1995). The civil engineering handbook. Florida: CRC Press.

Chen H, Xu Q, Chen Sh, Zhang Z. (2009) Evaluation and design of fiber-reinforced asphalt mixtures. Material Design;30:2595–603.

Chesner, W. and Petrarca, R. (1987). Report on Glass Aggregate Pavement for the Browning Ferris Industries' Merrick Transfer Station Located in Hempstead, New York, August 1987.

Chowdhury A., and Button, J. W. (2001). “Fine aggregate angularity: Conventional and unconventional approach, aggregate contribution to hot-mix asphalt HMA performance.” *American Society for Testing and Materials ASTM, Special Technical* Publication, 1412, 144-159.

Chowdhury, A., Button, J. W., Kohale, V., and Jahn, D. (2001). “Evaluation of superpave fine aggregate angularity specification.” *International Center for Aggregates Research ICAR Report 201-1*, Texas Transportation Institute, Texas A&M University, College Station, TX.

Chung D. (1994) Carbon fiber composites. Newton (USA): Butterworth-Heinemann Publishing.

Cominsky, R. J., R. B. Leahy, and E. T. Harrigan (1994). Level 1 Mix Design: Materials Selection, Compaction, and Conditioning, Report SHRP A-408. Strategic Highway Research Program, National Research Council.

Designing and constructing SMA mixture. State –of-the-Practice. National Asphalt Pavment Association(NAPA). Quality Improvement Series 122.

D_Angelo J. Modified binders and Superpave Plus specifications.Federal Highway Administration. No date. Available from: http://www.asphaltinstitute.org/upload/Modified_Binders_SP_Plus_Specification.pdf.

Esmaeil A., Majid Z, Karim M., Mahrez A., Payam S. (2011) Using waste plastic bottles as additive for stone mastic asphalt Materials and Design 32; 4844–4849

Fakhri, M. (1997). "Characterisation of Asphalt Pavement Materials," Ph.D. Thesis, The University of New South Wales, Sydney, Australia.

Federal Highway Administration (FHWA). (1993). Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities. Symposium Proceedings, Sponsored by Federal Highway Administration and Environmental Protection Agency, Denver, Colorado.

Federal Highway Administration (FHWA). (1998, April). User Guidelines for Waste and By-Product Materials in Pavement Construction. Report No: FHWA A-RD- 97-148.

Fitzgerald RL (2000). Novel applications of carbon fiber for hot mix asphalt reinforcement and carbon–carbon pre-forms. MSc Thesis, Department of Chemical Engineering, Michigan Technological University.

Fletcher, T. (2002). “Aggregate imaging system for characterizing fine and coarse aggregate shape.” Master’s Thesis, Dept. of Civil and Environmental Engineering, Washington State University, Pullman, WA.

Fletcher, T., Chandan, C., Masad, E., and Sivakumar, K. (2002). “Measurement of aggregate texture and its influence on HMA permanent deformation.”

Flynn, L. (1993) Recycled plastic finds home in asphalt binder. Roads & Bridges, pp. 41–48.

Freddy LR, Kandhal PS, Brown ER, Lee D-Y, Kennedy TW (1996). Hot mix asphalt materials, mixture design, and construction. 2nd ed. National asphalt pavement association research and education foundation. Lanham, MD.

Gerald A. Huber, J. Chris Jones, Paul E. Messersmith, N. Mike Jackson (1998) Contribution of Fine Aggregate Angularity and Particle Shape to Superpave Mixture Performance Transportation Research Record 1609; 98-0928

Ghadieh FWT (1993). Optimization of concrete aggregates grading in Jordan. MS. thesis. Irbid, Jordan: Department of Civil Engineering, Jordan University of Science and Technology.

Ghuzlan, K., and S. Carpenter, (2000). Energy-derived, damage-based failure criterion for fatigue testing. In Transportation Research Record 1723. Transportation Research Board. National Research Council (US) Washington, D.C. pp 141-149.

Ghuzlan, K. (2001). "Fatigue Damage Analysis in Asphalt Concrete Mixtures Based Upon Dissipated Energy Concepts," Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.

G. M. Rowe and M. G. Bouldin, (2000). “Improved Techniques to Evaluate the Fatigue Resistance of Asphaltic Mixtures”, Proceedings of 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain.

Hand, A., and Epps. A. (2001). “Impact of Gradation Related to Superpave Restricted Zone on
Hot Mix Asphalt Performance.” *Transportation Research Record: Journal of the Transportation Research Board*, n 1767, Transportation Research Board of the National Academics, Washington, D.C., p 158-166.

Hand, A.J., J.L. Stiady, T.D. White, A.S. Noureldin, and K. Galal (2002),“Gradation Effects on Hot-Mix Asphalt Performance,” Association of Asphalt Paving Technologists, Vol. 70, pp. 132-175.

Haydar R. Hmoud (2011). *Evaluation of VMA and Film Thickness Requirements in Hot-Mix Asphalt.* Modern Applied Science Vol. 5, No. 4; *ISSN 1913-1844 E-ISSN 1913-1852 pg 166-176*

Hinrichsen, John A., and John Heggen, (1996). *Minimum Voids in Mineral Aggregate in Hot-Mix Asphalt Based on Gradation and Volumetric Properties*, Transportation Research Record 1545, TRB, National Research Council, Washington, D.C., pp. 75-79.

Hopman, P.; Kunst, P. & Pronk, A. (1989). A Renewed Interpretation Model for Fatigue Measurement. Verification of Miner’s Rule, *4th Eurobitume Symposium, 4-6 October 1989*, Vol. 1, pp. 557-561. Madrid.

Huang H, White TD. (1996) Dynamic properties of fiber-modified overlay mixture. Trans Res Rec;1545:98–104.

Huang Y, Bird RN and Heidrich O (2007) A review of the use of recycled solid waste materials in asphalt pavements. Resources Conservation & Recycling 52: 58–73.

Isacsson. U. and Lu, X. (1995): Testing and appraisal of polymer modified road bitumen. Material structure Volume 28, pp. 139–159.

Hveem, F. N. (1940). *Gradation of Mineral Aggregates for Dense-graded Bituminous Mixtures*, Proceedings, Association of Asphalt Paving Technologists, Vol. 11.

Hveem, F. N. (1942). *Use of the Centrifuge Kerosene Equivalent as Applied to Determine the Required Oil Content for Dense-graded Bituminous Mixtures, Proceedings*, Association of Asphalt Paving Technologists, Vol. 13.

Huber, G. A., and G. H. Heiman (1987). *Effect of Asphalt Concrete Parameters on Rutting Performance: A Field Investigation*, Proceedings of the Association of Asphalt Paving Technologists, Vol. 56.

Ishai, I., and Gellber, H. (1982). “Effect of geometric irregularity of aggregates on the properties and behavior of asphalt concrete.” *Association of Asphalt Paving Technologists*, 51, 494-521.

Jacobs, M. M. J., Hopman, P. C., and Molenaar, A. A. A. (1996). "Application of Fracture Mechanics Principles to Analyze Cracking in Asphalt Concrete." *Journal of the Association of Asphalt Paving Technologists (AAPT)*, Vol.65, pp.1-39.

Jahromi S, Khodaii A.(2008) Carbon fiber reinforced asphalt concrete. Arab J Sci Eng;33:355–64.

JKR (2008), Standard Specification for Road Work, Jabatan Kerja Raya Malaysia, Kuala Lumpur

Joon S, Rust, Jon P, Hamouda, Hechmi, Kim Y, et al. (2005) Fatigue cracking resistance of fiber-reinforced asphalt concrete. Tex Res J;75(2):123–8.

Kandhal, S. P. and Mallick R.B., (2001). “Effects of Mix Gradation on Rutting Potential of Dense-Graded Asphalt Mixtures”, Transportation Research Board, National Research Council, Transportation Research Record No. 1767, Washington, D.C., pp. 146-151.

Kandhal, P. S., Motter, J. B., and Khatri, M. A. (1991). “Evaluation of particle shape and texture: manufactured versus natural sands.” *Transportation Research Record 1301*, Transportation Research Board, National Research Council, Washington D.C., 48-67.

Kandhal P.S., and Wenger M.E. (1973). “Effect of crushed gravel coarse aggregate on properties of bituminous concrete.” *Pennsylvania Department of Transportation. Research Report,* 70-82, Harrisburg, PA.

Kandhal, P. S., and Parker, F. Jr. (1998). “Aggregate tests related to asphalt concrete performance in pavements.” *National Cooperative Highway Research Program Report 405*, Transportation Research Board, National Research Council, Washington, D.C.

Kandhal, Prithvi S., Kee Y. Foo, and Rajib B. Mallick, (1998) *A Critical Review of VMA Requirements in Superpave*, NCAT Report No. 98-1, National Center for Asphalt Technology.

Kandhal, Prithvi S., and Sanjoy Chakraborty, (1996) *Evaluation of Voids in the Mineral Aggregate for HMA Paving Mixtures*, NCAT Report No. 96-4, National Center for Asphalt Technology, March.

Khalid and Artamendi “Characterizations of fatigue damage for paving asphalt materials”, Fatigue & Fracture of engineering Materials and Structures, 28, 1113-1118.

Kietzman J. (1960) The effect of short asbestos fibers on basic physical properties of asphalt pavement mixes. High Res B;270:1–19.

Kim, R. Y., Lee, H.-J., and Little, D. N. (1998). "Fundamental Properties of Asphalts and Modified Asphalts." Texas A&M University, Volume 4, final report.

Kim, Y. R., Lee, H.-J., and Little, D. N. (1997). "Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory." *Journal of the Association of Asphalt Paving Technologists (AAPT)*, Vol.66, pp.520-569.

Kim, Y.R., Yim, N., and Khosla, N.P. (1992) Effect of aggregate type and gradation on fatigue and permanent deformation of asphalt concrete. ASTM STP 1147, Philadelphia, 310-328.

King G et al. (1999) Additives in asphalt. J Assoc Asphalt Paving Technol A;68:32–69.

Kuo, C. -Y. (2002). "Correlating Permanent Deformation Characteristics of Hot Mix Asphalt with Aggregate Geometric Irregularities." Journal of Testing and Evaluation, 30(2), 136-144.

Lees G. (1970) The rational design of aggregate gradings for dense asphaltic compositions. Proceedings of Asphalt Paving Technologies. Kansas City, USA;39:60 – 90.

Lee, H.-J. (1996). "Uniaxial Constitutive Modeling of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory," Ph.D. Thesis, North Carolina State University, Raleigh, NC.

Little, D. N., Lytton, R. L., Devon, W., and Chen, C. W. (2001). "Microdamage Healing in Asphalt and Asphalt Concrete, Volume I: Microdamage and Microdamage Healing, Project Summary Report." *FHWA-RD-98-141*, Texas Transportation Institute, The Texas A&M University System, College Station.

Liu, Y. and You, Z. (2011). ”Discrete-Element Modeling: Impacts of Aggregate Sphericity, Orientation, and Angularity on Creep Stiffness of Idealized Asphalt Mixtures.” *J. Eng. Mech.*, 137(4), 294–303.

Lu X, Isacsson U. Modification of road bitumens with thermoplastic polymers. Polym Test 2001;20(1):77–86.

Lu X, Isacsson U, Ekblad J. (1999) Phase separation of SBS polymer modified bitumens. J Mater Civil Eng;11(1):51–7.

Lu X, Isacsson U, Ekblad J. (1998) Low-temperature properties of styrene–butadiene–styrene polymer modified bitumens. Constr Build Mater;12(8): 405–14.

Mahabir Panda, Mayajit Mazumdar (2002). Utilization of reclaimed polyethylene in bituminous paving mixes. Journal of Materials Civil Engineering;14(6):527–30.
Mahrez A, Karim M, Katman H. (2005) Fatigue and deformation properties of glass fiber reinforced bituminous mixes. J East Asia Soc Trans Studies;6:997–1007.

Mahrez A, Karim M, Katman H. (2003) Prospect of using glass fiber reinforced bituminous mixes. J East Asia Soc Trans Studies;5:794–807.

Majizadeh, K., Bokowski, G. and El-Mitiny, R. (1979). Material Characteristics of Power Plant Bottom Ashes and Their Performance in Bituminous Mixtures: A Laboratory Investigation.

Monismith, C. L., and Salam, Y. M. (1973). "Distress Characteristics of Asphalt Concrete Mixes." *Proceedings of Asphalt Paving Technology (AAPT)*, Vol. 42.

Marais C. (1979) The Use of Asbestos in trial sections of cap-graded asphalt and slurry seals. In: Proceedings of the third conference on asphalt pavements for South Africa. Durban. p. 172–5.

Masad, E. (2001). “Review of imaging techniques for characterizing the shape of aggregates used in asphalt mixes.” *Proceedings of the 9th Annual Symposium of the International Center for Aggregate Research (ICAR)*, Austin, TX.

Masad, E., Olcott, D., White, T., and Tashman, L. (2001). “Correlation of fine aggregate imaging shape indices with asphalt mixture performance.” *Transportation Research Record 1757*. Transportation Research Board, National Research Council, Washington, D.C., 148–156.

Masad E, Zollinger C, Bulut R, Little D, Lytton R. (2006) Characterization of HMA moisture damage using surface energy and fracture properties. J Assoc Asphalt Paving Technol;75

Majidzadeh, K., Kaufmann, E. M., and Ramsamooj, D. V. (1971). "Application of Fracture Mechanics in the Analysis of Pavement Fatigue." *Journal of the Association of Asphalt Paving Technology (AAPT)*, Vol.40, pp.227-246.

Milkowski W. (1985) Catalytic modification of road asphalt by polyethylene. J Transport Eng;11(1).

Mills William H. (1983). Evaluation of surface treatment and slurry seal. In: Asphalt paving technology: association of asphalt paving technologists – proceedings of the technical;. p. 198–223.

Mohamed-Asem U. Abdul-Malak, David W. Fowler, Cesar A. Constantino (1996) Aggregate Charateristic Governing Performance of Seal Coat Highway Overlays Transportation Research Record Journal of the Transportation Research Board Volume 1547.

Monismith, C. L. (1970). "Influence of shape, size, and surface texture on the stiffness and fatigue response of asphalt mixtures." *Highway Research Board 109 Special Report*, Transportation Research Board, National Research Council, Washington, D.C., 4–11.

Mustafa T, Ahmet T, Altan C (2003) The use of waste materials in asphalt concrete mixtures. Waste Management & Research; 21:83-92

___, *Mix Design Methods for Asphalt Concrete and other Hot-Mix Types (MS-2)*, The Asphalt Institute, Sixth Edition, March 1995

McFadden, Gayle, and Walter G. Ricketts (1948). *Design and Field Control of Asphalt Pavements for Military Installations*, Proceedings of the Association of Asphalt Paving Technologists, Vol. 17.

McLeod, N. W., (1959) *Void Requirements for Dense-graded Bituminous Paving Mixtures*, American Society of Testing and Materials, STP-252.

Molisch, W. R., Day, D. E., Wixson, B. G. (1975). Use of Domestic Waste Glass for Urban Paving. Summary Report. EPA/670/2-75-053 Final Rpt. Missouri University, Rolla, 1975.

Muniandy R, Ishak SB, Radin URS (2001). Study on the use of oil palm fiber in rubberized stone mastic asphalt. road safety research center. REAAA J;7(1):19–24.

Mulheron, M and O'Mahony, M. M. (1990). Properties and Performance of Recycled Aggregates. Highways and Transportation, v 37, n 2, p 35-37.

Mohammed LN et al (2003). Investigation of the use of recycled polymer modified asphalt binder in asphalt concrete pavements (With discussion and closure). J Assoc Asphalt Paving Technol;72:551–94.

Mohammad F, Martin H. Performance improvement of open-graded asphalt mixes. Department of Mechanical Engineering & Applied Mechanics, University of Rhode Island. Report no. URITC 00-44.

Munn D. (1989). Fiber reinforced hot mix promises improved stability. High Health Constr;132(10):54–6.

National Asphalt Pavement Association. Guidelines for materials. Production, and placement of stone matrix asphalt (SMA). Technical Working Group (TWG); 1994 [Publication No. IS 118].

NCHRP APPENDIX II-1. Calibration of fatigue cracking models for flexible pavements; 2004.

Nolan KL, Geoffry RM, Simon AMH (1995). Low temperature fracture of polyethylene modified asphalt binder and asphalt concrete mixes. AAPT:534–71.

Nukunya B, Roque R, Tia M, Metha YA (2002). Effect of aggregate structure on rutting potential of dense-graded asphalt mixtures. In: Transportation Research Record 1789. TRB, National Research Council, Washington, DC; p. 136–45.

T. Paul Teng. (2001). Superpave Mixture Design Guide. *WesTrack Forensic Team Consensus Report,*Washington, DC.

Pan T, Tutumluer E, Carpenter SH. (2006) Effect of coarse aggregate morphology on permanent deformation behavior of hot mix asphalt. ASCE J Trans Eng;132(7):580–9.

P. F. McCarthy,(1960) "Factors Affecting the Fatigue Characteristics of Bitumen Sand Mixtures", Ph. D. Thesis, University of Nottingham, UK,.

Proceedings of the Fifth International Ash Utilization Symposium, U.S. Department of Energy (1979), Report No. METC/SP-79/10, Part 2, Morgantown, West Virginia.

Pronk, A. and C. Hopman, 1991. Energy Dissipation: the Leading factor of fatigue. Proc., SHRP Conference Highway Research: Sharing the benefits, London, United Kingdom, pp. 255-267.

Prowell, B.D., J. Zhang., and E.R. Brown (2005), "Aggregate Properties and the Performance of Superpave Designed Hot Mix Asphalt," NCHRP Report 539, Transportation Research Board, National Research Council, Washington, DC.

Punith VS, Veeraragavan A. (2007) Behavior of asphalt concrete mixtures with reclaimed polyethylene as additive. J Mater Civil Eng;19(6):500–7.

Putman BJ, Amirkhanian SN. Utilization of waste fibers in stone matrix asphalt mixtures, resources. Conserv Recycle 2004;42:265–74.

Rahnama E (2009). A comparison on the performance of styrene–butadiene–styrene (SBS) polymer and textile fibers modifying asphalt concrete (AC). MSc Thesis, Department of Civil Engineering, Iran University of Science and Technology, Iran.

Ramsamooj DV (2001). An innovative technique for using polymer composites in airport pavement rehabilitation. Composites: Part B;32(1):57–66.

Ratnasamy M, Bujang BK. (2006) Laboratory diameteral fatigue performance of SMA with cellulose oil palm fiber. Am J Appl Sci;3(9).

Roberts, F.L., Kandhal, P. S., Brown, E. R., Lee, D., and Kennedy, T. W. (1996). *Hot-Mix Asphalt Materials, Mix Design, and Construction*, NAPA Education Foundation, Lanham, Maryland.

Roque R, Birgisson B, Tia M, Kim B, Cui Z (2004). Guidelines for the use of modifiers in Superpave mixtures: Executive summary and volume 1 of 3 volumes: Evaluation of SBS modifier. State Job 99052793. Florida Department of Transportation, Tallahassee, FL.

Rowe, G. M., (1993) 'Performance of asphalt mixtures in the trapezoidal fatigue test', *Proceedings of the Association of Asphalt Paving Technologists* 62; 344-

Sanders, C. A., and Dukatz, E. L. (1992). "Evaluation of percent fracture of hot-mix asphalt gravels in Indiana." *Effect of Aggregate and Mineral Filler on Asphalt Mixture Performance,* R. C. Meininger, ed., American Society for Testing and Materials, STP 1147.

Sargand SM, Kim SS (2001). Performance evaluation of polymer modified and unmodified Superpave mixes. In: Second International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control, Auburn, AL.

Sebaaly PE, Bazi GM, Vivekanathan Y. (2003). *Evaluation of new pavement technologies in Nevada*, University of Nevada.

Selim, Ali A, Taha R, Bayomy F. (1994) Laboratory performance of quartzite based Stone Matrix Asphalt Mixtures (SMAM). In: Proceedings of the third materials engineering conference; ASCE p. 635–42.

Serfass J, Samanos J. (1996) Fiber-modified asphalt concrete characteristics, applications and behavior. J Assoc Asph Pav Tech;65:193–230.

Shaopeng W, Qunshan Y, Ning L.(2008) Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. Constr Build Mater;22(10):2111–5.

Shen, S., and Carpenter, S. H. (2006). "Application of Dissipated Energy Concept in Fatigue Endurance Limit Testing." *Journal of Transportation Research Record:Transportation Research Board*, No. 1929, pp. 165-173.

Sherwood, P. (1995). Alternate Materials in Road Construction: A Guide to the Use of Recycled and Secondary Aggregates.

Shiuh J, Kuei-Yi L (2005). Mechanism and behavior of bitumen strength reinforcement using fibers. J Mater Sci;40:87–95.

SHRP A-404, (1994). "Fatigue Response of Asphalt-Aggregate Mixes." Asphalt Research Program, Institute of Transportation Studies, University of California, Berkeley. Strategic Highway Research Program, National Research Council.

Shukla RS, Singh VKP, Bhanwala RS. (2003) Polymer modified bitumen for construction of heavy traffic density corridors. Indian Highways;31(4):55–66.

Shukla RS, Singh VKP, Bhanwala RS. Polymer modified bitumen for construction of heavy traffic density corridors. Indian Highways 2003;31(4):55–66.

Simpson, Amy L, Mahboub C. Case study of modified bituminous mixtures: somerset, kentucky. In: Proceedings of the third materials engineering conference, ASCE; 1994. p. 88–96.

Sinan Hınıslıoglu, Emine Agar (2004). Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. J Mater Lett;58:267–71.

Sapan Agarwal (2007). Solid Waste Recycling – The Malaysian Perspective, *Consulting and Business Research Manager, Building Technologies Group APAC, Frost & Sullivan.*

Sousa, J.B., Craus J., Monismith, C.L. (1991). Summary Report on Permanent Deformation in Asphalt Concrete. Strategic Highways Research Program IR-91-104.

Stuart, Kevin D, Malmquist P. (1994) Evaluation of using different stabilizers in US route 15 (Maryland) stone matrix asphalt. Trans Res Rec;1454:48–57.

Tapkın S. (2008) The effect of polypropylene fibers on asphalt performance. Build Environ;43:1065–71.

Tapkın S, Us_ar U, Tuncan A, Tuncan M. (2009) Repeated creep behavior of polypropylene fiber-reinforced bituminous mixtures. J Trans Eng;135(4):240–9.

Tayebali, A. A., Rowe, G. M. and Sousa, J. B., (1992) 'Fatigue response of asphalt-aggregate mixtures', *Proceedings of the Association of Asphalt Paving Technologists 61;* 333-360.

Tayebali, A. A., Rowe, G.M., and Sousa, J.B. (1992). "Fatigue Response of Asphalt Aggregate Mixtures." *Proceedings of Asphalt Paving Technologists*, Vol.62, pp.385-421.

Tayebali, A. A., Coplantz, J. S., Harvey, J. T., and Monismith, C. L. (1992). "Interim Report on Fatigue Response of Asphalt-Aggregate Mixtures." *SHRP project A-003A, TM-UCB-A-003A-92-1*,

Tons, E., and Goetz, W. H. (1968). "Packing volume concepts for aggregates." Asphalt research program, Institute of *Highway Research Record* 236, Transportation Research Board, National Research Council, Washington D.C., 79-96.

Tayebali, A. A., Deacon, J.A., Coplantz, J.S., and Monismith, C.L. (1993). "Modeling Fatigue Response of Asphalt-Aggregate Mixtures." *Proceedings of Associations of Asphalt Paving Technologists*, Vol.62, pp. 385-421.

The Superpave Mix Design System Manual of Specifications, Test Methods, and Practices," SHRP-A-379, (1994).

Tang Y, Haddock E. Investigation of the performance of neat and modified asphalt binders, joint transportation research program. Project number C-36-56L. <http://docs.lib.purdue.edu/jtrp/258>.

The Marshall Method for the Design and Control of Bituminous Paving Mixtures, 3rd rev., Marshall Consulting and Testing Laboratory, Jackson, MS 1949.

Thompson DC. Hoiberg AJ, editor. Bituminous materials:Asphalt tars and pitches. Robert Krieger Publishing Co.; 1979.

Terrel R, Walter J. Modified asphalt pavement materials: The European experience. J Assoc Asphalt Paving Technol 1986;55:482.

Tons, E. and Krokosky, E. M. (1960). A study of welded wire fabric strip reinforcement in bituminous concrete resurfacing. In *Proc. AAPT., 29, 43-76*

Used Tyre Working Group. Recycling and recovery. No date. Available from: http://www.tyredisposal.co.uk/ disposal_routes. asp.

UNI EN 12697-24. Bituminous mixtures - Test methods for hot mix asphalt – Part 24. Wegan V, Nielsen BC. Microstructure of polymer modified binders in bituminous mixtures. Report Number 87-90145-85-8. Danish Road Directorate, Roskilde, Denmark, 2001.

Van Dijk, W. (1975). "Practical Fatigue Characterization of Bituminous Mixes." *Proceedings of the Association of Asphalt Paving Technologists (AAPT)*, Vol. 44, p. 38.

Van Dijk, W., and Visser, W. (1977). "The Energy Approach to Fatigue for Pavement Design." *Proceedings of Annual meeting of the Association of Asphalt Paving Technologists (AAPT)*, Vol.46, pp.1-40.

Vavrik, W.R, S.H. Carpenter (1998), "Calculating Air Voids at Specified Number of Gyrations in Superpave Gyratory Compactor," Transportation Research Record 1630, Transportation Record Board, National Research Council, Washington, D.C., 1998, pp. 117-125.

Vavrik, W. R., Huber, G., Pine, W. J., Carpenter, S. H., and Bailey, R. (2002). "Bailey Method for Gradation Selection in Hot-Mix Asphalt Mixture Design." *Transportation Research E-Circular, Report No: E-C044*.

Walter P. Hislop And Brian J. Coree. (2000). VMA As A Design Parameter In Hot-Mix Asphalt. Proceedings Mid-continent transportation symposium.

Walter P. Hislop And Brian J. Coree (2000). VMA as a Design Parameter in Hot-Mix Asphalt *Mid-Content Transportation Symposium Proceedings*

W. D. Park, and S. H. Lee (2002). "Test Methods for Fine Aggregate Angularity Considering Resistance of Rutting", KSCE Journal of Civil Engineering, Vol. 6, pp. 421-427.

Wen Hafiang (2001). Fatigue performance evaluation of Westrack asphalt mixtures based on viscoelastic analysis of indirect tensile test. North Carolina State University, Department of Civil Engineering.

West, R.C., and R. S. James (2005), "Determining Ndesign for SMA Mixtures in Alabama," NCAT Report No. 05-xx, Alabama Department of Transportation, Auburn University, AL.

Witczak MW, Hafez I, Qi X. (1995). Laboratory characterization of Elvaloy_ modified asphalt mixtures: vol. I – Technical report. College Park, Maryland: University of Maryland.

Won, M. C. (1999). Use of Crushed Concrete as Aggregate for Pavement Concrete. Conference Proceedings, Annual Meeting of Transportation Research Board, Transportation Research Council, Washington, DC.

Wu S, Ye Q, Li N, Yue H. Effects of fibers on the dynamic properties of asphalt mixtures. J Wuhan Univ Technol – Mater Sci Ed 2007;22:733–6.

Wu S, Ye Q, Li N. (2008) Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. Constr Build Mater;22(10):2111–5.

*www.**plasticseurope**.org/.../20110304140734-**plasticseurope**,*

Yahia A. Abdel-Jawad, Waddah Salman Abdullah, (2002) Design of maximum density aggregate grading Construction and Building Materials 16 ;495–508

Yeggoni, M.; Button, J. W. ;Zollinger, D. G. (1996). "Fracta ls of Aggregates Correlated With Creep in Asphalt Concrete" J. Transp . Engrg. ASCE ,122 (1), p.p.22-28.

Yetkin Yildirim (2007). Polymer modified asphalt binders. Construct Build Mater;21:66–72.

Yildirim Y, Hazlett D, Davio R. (2004) Toner-modified asphalt demonstration projects. Resources, conservation and recycling, vol. 42. Amsterdam: Elsevier; pp. 39–50.

Yildirim, Y., Smit, A. F., and Korkmaz, A. (2005). "Development of a Laboratory Test Procedure to Evaluate Tack Coat Performance." *Turkish Journal of Engineering & Environmental Science*, n 29, p 195-205.

Yi J, McDaniel S. (1993) Application of cracking and seating and use of fibers to control reflection cracking. Trans Res Rec;1388:150–9.

Yue Huang, Roger N. Bird, Oliver Heidrich (2007) A review of the use of recycled solid waste materials in asphalt pavements Resources, Conservation and Recycling 52; 58–73

Zoorob SE, Suparma LB. (2000). Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). J Cem Concr Compos;22:233–42.

Zanariah Bt Abd Rahman. (2006). Evaluation On Properties Of Tender Mixes. A project report submitted in partial fulfillment of the requirements for the award of the degree of Master of Engineering (Civil – Transportation and Highway), Faculty of Civil Engineering, University Teknology Malaysia.