

**PERFORMANCE OF RECYCLED PAPER MILL
SLUDGE AS A MODIFIER IN ASPHALT
MIXTURES THROUGH DRY PROCESS**

CHEW J-WEI

UNIVERSITI SAINS MALAYSIA

2018

**PERFORMANCE OF RECYCLED PAPER MILL SLUDGE AS A MODIFIER
IN ASPHALT MIXTURES THROUGH DRY PROCESS**

by

CHEW J-WEI

**Thesis submitted in fulfilment of the
requirements for the Degree of
Master of Science**

August 2018

There is nothing impossible
To him who will try

ACKNOWLEDGEMENT

I would like to express my gratitude to my supervisor, Dr. Mohd Rosli Mohd Hasan for his continuous patience, motivation, expertise and constructive recommendations. My appreciation to the guidance and insight offered, which expedited my progress in completing this thesis on time. To respective staffs from School of Civil Engineering and School of Materials and Mineral Resources, my gratefulness to their supervision in facilitating this research effort.

I gratefully acknowledge the financial support from the Malaysian Ministry of Higher Education through Fundamental Research Grant Scheme under Grant No: 203.PAWAM.6071358 received as a graduate research assistant. This research is made possible with the support from Kuad Sdn.Bhd. and PENS Industries Sdn. Bhd for providing granite and limestone respectively. I express my gratitude also to the paper mill company which requested for confidentiality in providing raw recycled paper mill sludge which is crucial to this research initiative.

My deepest appreciation to my father, Assoc. Prof. Dr. Chew Cheng Meng, my mother, Pung Chen Choy, and my sister, Chew J-Yin, for their perpetual encouragement both morally and spiritually. Last but not least, my sense of gratitude to all whom had directly or indirectly lent their hand in this endeavor.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF PLATES	xiii
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xvi
ABSTRAK	xviii
ABSTRACT	xx
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	2
1.3 Research Hypotheses	4
1.4 Objectives	4
1.5 Scope of Research Work	5
1.6 Justification of Research	7
1.7 Organization of Thesis	7
CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction	9
2.2 Emerging Interest and Options to Incorporate Solid Waste	11
2.3 Prerequisite Test of Solid Waste to Address Engineering Limitations	16
2.3.1 Prerequisite Test of Solid Waste to be Incorporated as Aggregate	17

2.3.2	Prerequisite Test of Solid Waste	18
2.4	Addressing Environmental Concerns of Solid Waste	21
2.4.1	Implementation of TCLP Test to Determine Heavy Metal Leaching	22
2.4.2	Methodology of TCLP Test with Modifications	23
2.4.3	Regulation of TCLP Test	24
2.5	Pre-treatment of Solid Waste prior to Incorporation into Asphalt Mixture	25
2.6	Mechanical Performance of Asphalt Mixture Incorporating Solid Waste	26
2.6.1	Mechanical Performance of Solid Waste In Form of Aggregate	28
2.6.2	Mechanical Performance of Solid Waste In Powder and Ash Form	29
2.6.3	Mechanical Performance of Solid Waste In form of Fiber	30
2.6.4	Mechanical Performance of Solid Waste from Paper Mill Industry	31
2.7	Surface Morphology of Solid Waste - SEM	33
2.8	Mineralogical Composition of Solid Waste – XRD	37
2.9	Chemical Composition of Solid Waste - XRF	38
2.9	Gap of Knowledge	41
2.10	Summary	41

CHAPTER THREE: METHODOLOGY

3.1	Introduction	42
3.2	Preparation of Raw Materials	46
3.2.1	Aggregates	46
3.2.1(a)	Aggregates Sieving Process	47
3.2.1(b)	Physical Properties of Aggregates	48
3.2.1(b)(i)	Aggregate Crushing Value (ACV)	48
3.2.1(b)(ii)	Los Angeles Abrasion Test	48

	3.2.1(b)(iii)	Flakiness and Elongated Index	49
	3.2.1(b)(iv)	Aggregate Specific Gravity and Water Absorption	50
3.2.2	Asphalt Binder		50
3.2.3	Recycled Paper Mill Sludge (RPMS)		51
	3.2.3(a)	Physical Properties of RPMS	51
	3.2.3(a)(i)	Determination of Moisture Content in RPMS	52
	3.2.3(a)(ii)	Time Taken to Eliminate Moisture Content in RPMS	52
	3.2.3(a)(iii)	Combustion Test of RPMS	53
	3.2.3(a)(iv)	Specific Gravity and Water Absorption of RPMS	53
	3.2.3(b)	Pre-requisite Treatment of RPMS	53
	3.2.3(b)(i)	Size Reduction of RPMS	55
	3.2.3(b)(ii)	Sieving Analysis of RPMS	55
3.3	Surface Morphology – Scanning Electron Microscope (SEM)		56
3.4	Chemical Composition – X-Ray Fluorescence (XRF)		58
	3.4.1.	Loss on Ignition Test (LOI)	58
3.5	Mineralogical Composition – X-Ray Diffraction (XRD)		59
3.6	Toxicity Characterization Leaching Test (TCLP)		60
	3.6.1	Progressive Leaching	61
3.7	Preparation of Asphalt Mixture Specimen		62
	3.7.1	Compaction of Asphalt Mixture Specimens	63
	3.7.2	Pre-Marshall Test to Determine Optimum RPMS Content	64
3.8	Marshall Mix Design		65
	3.8.1	Theoretical Maximum Specific Gravity	66

3.8.2	Bulk Specific Gravity	67
3.8.3	Number of Gyration at 4% and 7% Air Voids	67
3.9	Service Characteristics of Asphalt Mixture	68
3.9.1	Workability of Asphalt Mixture	68
3.10	Mechanical Performance of Asphalt Mixture	70
3.10.1	Indirect Tensile Strength Test	71
3.10.2	Moisture Sensitivity	71
3.10.2	Resilient Modulus	72
3.10.4	Leutner Shear Test	73
3.10.5	Dynamic Creep	73
3.11	Summary	74

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1	Introduction	75
4.2	Physical Properties of Raw Materials	75
4.2.1	Physical Properties of Aggregates	76
4.2.2	Physical Properties of RPMS	77
4.3	Combined Aggregate Specific Gravity and Water Absorption	79
4.4	Pre-Requisite Treatment of RPMS	80
4.5	Scanning Electron Microscope (SEM)	81
4.6	X-Ray Fluorescence (XRF)	84
4.7	X-Ray Diffraction (XRD)	87
4.8	Pre-Marshall Mix Design to Determine Optimum RPMS Content	88
4.9.	Marshall Mix Design Parameters	91
4.9.1	Determination of Number of Gyration at 4% and 7% Air Voids	90

4.10	Service Characteristic of Asphalt Mixture	91
4.10.1	Workability Index	91
4.10.2	Compaction Energy Index	92
4.11	Mechanical Performance of Asphalt Mixture	95
4.11.1	Indirect Tensile Strength (ITS)	95
4.11.2	Moisture Sensitivity – Indirect Tensile Strength Ratio (ITSR)	98
4.11.2(a)	Two-Way Analysis of Variance (ANOVA) on Indirect Tensile Strength Ratio (ITSR)	99
4.11.3	Resilient Modulus (M_r)	101
4.11.3(a)	Two-Way Analysis of Variance (ANOVA) on Resilient Modulus	103
4.11.4	Leutner Shear Test	103
4.11.4(a)	Two-Way Analysis of Variance (ANOVA) on Leutner Shear	105
4.11.5	Dynamic Creep	106
4.11.5(a)	Two-Way Analysis of Variance (ANOVA) on Dynamic Creep	110
4.12	Toxicity Characterization Leaching Procedure (TCLP)	110
4.13	Summary	114

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1	Conclusions	116
5.2	Recommendations for Future Research	118

REFERENCES	139
-------------------	-----

APPENDICES

Appendix A: Physical Properties of Aggregates

Appendix B: Physical Properties of RPMS

Appendix C: Marshall Mix Design Parameters

Appendix D: Service Characteristic

Appendix E: Mechanical Performance

Appendix F: Two-Way Analysis of Variance (ANOVA)

LIST OF TABLES

	Page	
Table 2.1	Interest to Incorporate Solid Waste into Asphalt Binder	12
Table 2.2	Interest to Incorporate Solid Waste into Asphalt Mixture	12
Table 2.3	Prerequisite Test Prior Incorporating Solid Waste	20
Table 2.4	Regulatory Standards for Heavy Metals Leaching Concentration	25
Table 2.5	Rheological Performance of Solid Waste Incorporated Asphalt Binder	26
Table 2.6	Performance of Solid Waste Incorporated Asphalt Mixture	26
Table 2.7	Intrest to Incorporate Solid Waste from Paper Mill Industry	31
Table 2.8	Surface Morphology of Solid Waste Incorporated Mixture	34
Table 2.9	Mineralogical Composition of Solid Waste Incorporated Asphalt Mixture	38
Table 2.10	Chemical Composition of Solid Waste Incorporated Asphalt Mixture	39
Table 3.1	Physical Properties of Aggregates	48
Table 3.2	Physical Properties of 60/70 Asphalt Binder	50
Table 3.3	Composition of RPMS	52
Table 3.4	Selected Mineralogical Compound	60
Table 3.5	Type of Asphalt Mixture	63
Table 3.8	Aggregate Gradation for Control Asphalt Mixture	65
Table 3.9	Aggregate Gradation for 0.5% RPMS Incorporated Asphalt Mixture	65
Table 3.10	Aggregate Gradation for 0.5% RPMS Incorporated Asphalt Mixture	66
Table 4.1	Mechanical Properties of Aggregates	76
Table 4.2	Specific Gravity and Water Absorption of Aggregates	77
Table 4.3.	Physical Properties of RPMS	77

Table 4.4.	Observations of Oven Dried RPMS at 200°C	78
Table 4.5	Combined Specific Gravity and Water Absorption %	79
Table 4.6	Surface Morphology of Fillers	83
Table 4.7	Relationship of Fillers to OBC and Water Absorption	83
Table 4.8	Loss On Ignition Test (LOI)	86
Table 4.9	X-Ray Fluorescence (XRF) Analysis	86
Table 4.10	X-Ray Diffraction (XRD) Analysis – Mineralogical Compound	87
Table 4.11	X-Ray Diffraction (XRD) Analysis – Intensity Peak	88
Table 4.12	Determination of Optimum RPMS Content	88
Table 4.13	Marshall Mix Design Parameters	90
Table 4.14	Number of Gyration at Air Voids at 4% and 7%	90
Table 4.15	Number of Gyration at Air Voids at 4% and 7%	98
Table 4.16	Two-Way ANOVA Analysis of ITR	100
Table 4.17	Post Hoc Analysis of ITR	101
Table 4.18	Two-Way ANOVA Analysis of Resilient Modulus	103
Table 4.19	Two-Way ANOVA Analysis of Leutner Shear	106
Table 4.20	Post Hoc Analysis of Leutner Shear	106
Table 4.21	Two-Way ANOVA of Dynamic Creep	110
Table 4.22	Comparison of RPMS Chemical Content	111
Table 4.23	Heavy Metal Element after Initial and Progressive Leaching	112
Table 4.24	Non-heavy Metal Element after Initial and Progressive Leaching	113

LIST OF FIGURES

	Page	
Figure 1.1	The Framework of Task in this Research	6
Figure 2.1	The Framework of Discussion in this Systematic Review	10
Figure 2.2	Solid Waste from Agriculture Industry	14
Figure 2.3	Solid Waste from Construction and Demolition Industry	14
Figure 2.4	Solid Waste from Plastic Industry	15
Figure 2.5	Solid Waste from Paper Industry	15
Figure 2.6	Solid Waste from Steel Industry	15
Figure 2.7	Solid Waste from Rubber Industry	16
Figure 2.8	Solid Waste from Glass Industry	16
Figure 2.9	SEM Images of Solid Waste from Agriculture Industry	35
Figure 2.10	SEM Images of Solid Waste from Plastic Industry	35
Figure 2.11	SEM Images of Solid Waste from Paper Industry	35
Figure 2.12	SEM Images of Solid Waste from Construction Industry	36
Figure 2.13	SEM Images of Solid Waste from Steel Industry	36
Figure 2.14	SEM Images of Commercial Fillers	36
Figure 3.1	The Methodology Framework of Stage 1	43
Figure 3.2	The Methodology Framework of Stage 2	44
Figure 3.3	The Methodology Framework of Stage 3	44
Figure 3.4	The Methodology Framework of Stage 4	45
Figure 3.5	The Methodology Framework of Stage 5	46
Figure 3.1	Compaction Energy Index (CEI)	72
Figure 4.1	Time Taken to Eliminate Moisture from RPMS	78
Figure 4.2	Sieve Analysis of Milled RPMS after 5 Cycles	81
Figure 4.3	Sieve Analysis of Milled RPMS after 10 Cycles	81

Figure 4.4	Workability Index of Asphalt Mixtures	91
Figure 4.5	Compaction Energy Index of Asphalt Mixture	93
Figure 4.6	Indirect Tensile Strength (ITS) of Asphalt Mixture	95
Figure 4.7	Indirect Tensile Strength Ratio (ITSR) of Asphalt Mixture	98
Figure 4.8	Resilient Modulus of Asphalt Mixture	101
Figure 4.9	Leutner Shear of Asphalt Mixture	104
Figure 4.10	Accumulative Microstrain (UE) of Asphalt Mixture	107
Figure 4.11	Creep Modulus of Asphalt Mixture	107

LIST OF PLATES

		Page
Plate 3.1	RPMS in Recycled Paper Mill Factory	51
Plate 3.2	Oven Dried Clumps of RPMS	54
Plate 3.3	Size reduction of RPMS	55
Plate 3.4	Sieving of RPMS	56
Plate 3.5	Scanning Electron Microscope (SEM)	57
Plate 3.6	X-Ray Fluorescence (XRF) Spectrometer Rigaku Rix 3000	58
Plate 3.7	Combustion at 1200°C for six Hours within incinerator	59
Plate 3.8	X-Ray Diffraction (XRD) D2 Phase	60
Plate 3.9	Toxicity Characterization Leaching Procedure (TCLP) Test	62
Plate 3.10	Vacuum saturator used for the assessment of G_{mm}	66
Plate 3.11	Corelok system used to measure G_{mb}	67
Plate 4.1	Surface Morphology of Granite at 500x Magnification	82
Plate 4.2	Surface Morphology of Limestone at 500x Magnification	82
Plate 4.3	Surface Morphology of RPMS at 500x and 700x Magnification	82

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ABS-PC	Acrylonitrile Butadiene Styrene-Polycarbonate
ACV	Aggregate Crushing Value
ALVS	Accelerated Laboratory Vacuum Saturator
ASLP	Australian Standard Leaching Procedure
AV	Air Voids
CAM	Cold Asphalt Mixture
CEI	Compaction Energy Index
EPA Victoria	Environmental Protection Agency of Victoria
ESAL	Equivalent Single Axle Load
HIPS	High Impact Polystyrene
HMA	Hot Mix Asphalt
HOKLAS	Hong Kong Laboratory Accreditation Scheme
ICE	Initial Change Equilibrium
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometer
ITS	Indirect Tensile Strength
LAAB	Los Angeles Abrasion Value
LOI	Loss on Ignition
RAP	Recycled Asphalt Pavement
ROI	Return of Investment
RPMS	Recycled Paper Mill Sludge
SEM	Scanning Electron Microscope

SFE	Surface Free Energy
SGC	Servopac Gyrotory Compactor
SMA	Stone Mastic Asphalt
SMA	Stone Matrix Asphalt
SSA	Specific Surface Area
SSD	Saturated Surface Dry
SST	Total Surface Area of Mix Design Combined Aggregates
TCLP	Toxicity characterization leaching procedure
USEPA	United State Environmental Protection Agency
UTM	Universal Testing Machine
VFA	Voids Filled by Asphalt
VMA	Voids in Mineral Aggregate
WI	Workability Index
WMA	Warm Mix Asphalt
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

LIST OF SYMBOLS

$\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$	Anorthite
Al_2O_3	Aluminium Oxide
As	Arsenic
Ca	Calcium
$\text{Ca}(\text{SO}_4)$	Calcium Sulfate
CaCO_3	Calcium carbonate
CaCO_3	Calcite
CaO	Calcium Oxide
Cd	Cadmium
CO	Carbon monoxide
Cr	Chromium
Cu	Copper
CuO	Copper Oxide
$\text{CaMg}(\text{CO}_3)_2$	Dolomite
Fe	Iron
Fe_2O_3	Ferric Oxide
Ga_2O_3	Gallium Oxide
Hg	Mercury
K_2O	Potassium Oxide
Mg	Magnesium
MgO	Magnesium Oxide
Mn	Manganese

MnO	Manganese (II) Oxide
Na ₂ O	Sodium Oxide
NaCl	Halite
Nb ₂ O ₅	Niobium Oxide
Ni	Nickel
NiO	Nickel (II) Oxide
P ₂ O ₅	Phosphorus pentoxide
Pb	Lead
PbO	Lead (II) Oxide
MgO	Periclase
Ca(OH) ₂	Portlandite
SiO ₂	Quartz
Rb ₂ O	Rubidium Oxide
Se	Selenium
SiO ₂	Silicon Dioxide
SO ₃	Sulphur Trioxide
Sr	Strontium
KCl	Sylvite
ThO ₂	Thorium Dioxide
TiO ₂	Titanium Oxide
Zn	Zinc
ZnO	Zinc Oxide
ZrO ₂	Zirconium Dioxide

**PRESTASI SISA KILANG KERTAS KITAR SEMULA SEBAGAI
PENGUBAHSUAI DALAM CAMPURAN ASFALT MELALUI PROSES
KERING**

ABSTRAK

Pengumpulan sisa pepejal yang semakin meningkat memerlukan usaha global dalam pengurusan sisa yang efisien dan rawatan ekologi. Industri turapan asfalt yang menggunakan sumber semula jadi di samping menyumbang kepada gas rumah hijau, dilihat sebagai industri yang berpotensi tinggi bagi penggunaan sisa pepejal. Usaha penyelidikan ini memaparkan penggunaan sisa kilang kertas kitar semula (RPMS) sebagai bahan tambah baru ke dalam campuran asfalt. Rawatan prasyarat RPMS memerlukan 6 jam oven kering, 10 pusingan penggilingan dan semburan retak 0.075mm manakala didapati tidak mudah terbakar. Lebih 60% RPMS digunakan, manakala baki 40% boleh digunakan sebagai pindaan tanah. RPMS dimasukkan ke dalam campuran aspal pada 0.5% dan 1% berat campuran asfalt. Bahan pengikat asfalt bergred penusukan 60/70 dan dua jenis agregat iaitu batu kapur dan granit digunakan. Campuran asfalt disediakan pada suhu 160°C, dan dipadatkan menggunakan pemadat legar pada suhu 150°C. Ciri-ciri perkhidmatan gabungan campuran RPMS asfalt menyebabkan indeks keboleherjaan (WI) yang lebih tinggi dan indeks tenaga pemadatan (CEI) yang lebih rendah berbanding kawalan. Campuran kering asfalt 0.5% RPMS menyebabkan kekuatan tegangan tidak langsung (ITS) yang setanding dengan kawalan, namun mempunyai rintangan kelembapan yang lemah dengan nisbah kekuatan tegangan tidak langsung (ITSR) yang rendah. RPMS mengakibatkan modulus kebingkasan & ricih Leutner yang

lebih tinggi, sementara mempunyai prestasi rayapan dinamik berbanding kawalan campuran asphalt.

mikroskop elektron imbasan (SEM) menggambarkan morfologi permukaan berserat dan berliang RPMS. pembelauan sinar-X (XRD) menunjukkan komposisi mineralogik RPMS yang mengandungi kalsit, mempromosikan lekatan bitumen-agregat yang baik. Walau bagaimanapun, RPMS mengandungi sebatian kelarutan larut air yang tinggi iaitu anhydrite, halite, sylvine, quart dan periclase. Komposisi kimia ditentukan melalui pendarflour sinar-X (XRF) yang menunjukkan RPMS mengandungi komposit simen Portland yang sama iaitu SiO_2 , Al_2O_3 , K_2O dan CaO walaupun selepas kerugian penyalaan (LOI) sebanyak 52.52%. Prosedur larut lesap pencirian ketoksikan (TCLP) membuktikan hanya logam berat Arsenik dikesan jauh bawah had pengawalseliaan atas RPMS mentah. Sementara RPMS yang dimasukkan pengikat asphalt menunjukkan pengurangan Arsenik membuktikan integrasi pengikat asphalt yang baik. Unsur-unsur logam berat yang mempunyai aplikasi agronomik iaitu kalsium, besi & magnesium dikesan. Oleh itu membuktikan RPMS tidak berbahaya kepada alam sekitar. Kajian ini bertindak sebagai rangsangan untuk menggabungkan RPMS dalam penghasilan turapan asphalt eco di samping menyediakan industri kaedah pelupusan alternatif yang lebih hijau.

PERFORMANCE OF RECYCLED PAPER MILL SLUDGE AS A MODIFIER IN ASPHALT MIXTURES THROUGH DRY PROCESS

ABSTRACT

The escalating accretion of solid waste requires a global notion to strive for efficient waste management and ecological treatments. The asphalt pavement industry which consumes natural resources while contributing to greenhouse emissions, is viewed as a potential alternative for the incorporation of solid waste. This research effort incorporates Recycled Paper Mill Sludge (RPMS) as a solid waste additive into asphalt mixture. Pre-requisite treatment of RPMS required 6 hours oven dried, 10 cycles milling and sieved retaining 0.075mm while found to be not combustible. Over 60% RPMS is utilized, while remaining 40% can be utilized as soil amendments. RPMS is incorporated into asphalt mixture at 0.5% and 1% asphalt mixture weight. Asphalt binder with penetration grade 60/70 and two types of aggregates namely limestone and granite is utilized. Asphalt mixture is mixed at temperature of 160°C and compacted at 150°C. Service characteristics of RPMS incorporated asphalt mixture resulted higher Workability Index (WI) and lower Compactability Energy Index (CEI) than control. Unconditional 0.5% RPMS asphalt mixture led to comparable Indirect Tensile Strength (ITS) with control, yet having poor moisture resistance with low Indirect Tensile Strength Ratio (ITSR). RPMS resulted in higher resilient modulus and Leutner shear, while having comparable dynamic creep performance than control asphalt mixture. Scanning Electron Microscope (SEM) illustrated the fibrous and porous surface morphology of RPMS. X-Ray Diffraction (XRD) shown RPMS mineralogical composition which contains calcite, promoting good bitumen-aggregate adhesion. However, RPMS contained

high water solubility mineralogical compounds namely anhydrite, halite, sylvine, quartz and periclase. Chemical composition are determined via X-Ray Fluorescence (XRF) indicating RPMS contained similar Portland cement composition namely SiO_2 , Al_2O_3 , K_2O and CaO even after Loss On Ignition (LOI) of 52.5%. Toxicity Characterization Leaching Procedure (TCLP) proved only Arsenic heavy metal is detected with levels far below regulatory limits on raw RPMS. While RPMS incorporated asphalt binder indicated a reduction in Arsenic proving good asphalt binder integration. Non heavy metal elements which have agronomic application namely calcium, iron & magnesium are detected. Thus proving RPMS is not harmful to the environment. This research acts as a stimulus to incorporate RPMS in eco and sustainable asphalt pavement development while providing industries with a greener disposal alternative.

CHAPTER ONE

INTRODUCTION

1.1 Background

Solid waste is accumulating on an escalating pace, snowballing into clusters of environmental and economic issues at an alarming rate [1-4]. Spanning over a decade from 2004 to 2014, the amount of household and industrial waste generated from the European Union (a collective of 28 countries), amounted to a staggering cumulative sum of approximately 12.5 billion tons [5]. In Malaysia, the generation of RPMS increased from 16,200 tons per day in 2001 to 19,100 tons in 2005 translating an average of 0.8 kilograms per capita per day, and the amount is escalating by about 4% annually [5]. Rapid population growth coupled with the increase in consumption rate are looming us towards a dire state of solid waste management which is dependent on landfilling as the main disposal method. As the amount of land available gets scarce for new landfill construction, illegal dumping or incineration alternatives are implemented despite the dominance of recyclable materials in the waste composition [3, 4]. The upsurge of a global movement consisting of diverse institutions including governments, universities and private sectors are facilitating solid waste recycling and reusing in a wide array of applications, to not jeopardize the resources of future generation [6, 7, 8].

Riding on this stimulus, the asphalt pavement industry which spans a production of more than 550 million tons of asphalt pavement annually in the United States alone [9] is viewed as a highly potential alternative for solid waste application. The emergence of asphalt pavement industry revolve around conventional Hot Mix