University of Illinois at Chicago

DEPARTMENT OF CIVIL & MATERIAL ENGINEERING

IAPA Asphalt Pavement Association

Sustainable Pavement System and Materials

Name: Moutz Slim
MS Candidate in Civil Engineering

I certify that this work is ***entirely*** mine

Table of Contents

List of Tables

List of Figures

Background and Introduction

Sustainability of roadways is becoming a major topic nowadays; many studies are being made on enhancing and making use of different sustainable materials which are recyclable or renewable due to high costs of fuel and high environmental impacts as a result of traditional techniques usage. This Paper focuses on studying the use of Plastic Wastes, Crumb Rubber, Warm Mix Asphalt, Reclaimed Asphalt Pavements, Solar Roadways and Electric Roads. The paper compares the application of these techniques, performance of the techniques and feasibility along with benefits and disadvantages of each technique. A case study is made for choosing the best sustainable pavement material on a 42 Km Strip of Maliha road in Sharjah, United Arab Emirates using AHP which considers the cost, durability, feasibility in the UAE, Weather in UAE, and worldwide deployment as the criteria of comparison. The weather in UAE is consider as same as the weather in some places in the south of the USA.

Sustainable Pavement Materials and Additives

Plastic wastes

Sustainable road construction is driven largely by the demand to build green infrastructure, preserve natural resources, and reduce carbon footprint. An innovative approach in road construction industry is the recycling of plastic wastes in pavements. According to the World Economic Forum (WEF) report, plastic can make roads more durable against extreme weather — floods and extreme heat [1]. Littered plastic is rich in polymers. It can be used either as a stabilizing agent in soil and subgrade applications or as an additive to blends of aggregates in hot mix asphalt (HMA) pavement. Plastic is added in two ways; to the binder as pellets in the rate of 0.25-0.5% of binder weight in the wet approach, or to the aggregates in the dry approach. Adding plastic up to 25% resulted in enhanced HMA performance in terms of skidding, stability, fatigue, and deformation resistance [2] [3] [4].

Plastic wastes recycled in pavement construction include polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC), foamed polystyrene (FP), low-density polyethylene (LDPE), high-density polyethylene (HDPE) [5]. Based on desktop research the addition of recycled plastic wastes results in variations of asphalt properties, as presented in Table 1 below. Some of these reviewed articles managed to reach an optimum plastic content (OPC) and optimum binder content (OBC) for each mix design experimented.

Table 1: different recycled plastics and other materials in bituminous compositions

Ref. No.	Materials	OBC/OPC	Remarks
[6]	PET plastics bottle wastes post-mixing with SMA	OPC=4–6% by wt. of OBC	Higher resilient modulus, improved rutting resistance, reduction in tensile strength and tensile strength ratio
[7]	PET plastic bottle wastes in SMA	OPC=6% by wt. of bitumen	Improved resistance against permanent deformation due to increased Marshall quotient (MQ), increased VIM, decreased specific gravity, and reduction in compatibility
[8]	HDPE/SBS + LLDPE g-MAH (modification of asphalt)	NO OBC NO OPC	Improvement in low-temperature performance. no effect on high-temperature property, increased susceptibility to rutting
[9]	HDPE and LDPE (Grinded and Ungrinded)	OBC= 5.4%	Grinded HDPE performed better than LDPE. Grinded HDPE had the max. stability. The plastic contents reduced the density and slightly increased the air voids and voids of mineral aggregates which will increase rutting resistance of asphalt mixture and provide better adhesion between asphalt and aggregates.
[10]	Plastic wastes [Polypropylene (PP)]	OBC=4% by wt. of total mix	Reduction in aggregate impact value (AIV) and crushing values and increase in specific gravity. Plastic coating can be used to improve performance of poor quality aggregate

Use of waste plastic materials for road construction in Ghana

A case study was reviewed for using plastic materials (recycling) in road construction in Ghana. The study provided scientific data that form a basis for plastics recycling in road construction. The properties of the binder used displayed in Table 2 were all in accordance with the Ghana Highway Authority Specifications for unmodified bitumen (AC-20 Grade) [11].

Table 2: Physical Properties of Unmodified Binder [11]

Physical Properties of Unmodified Bin	**ler**	**Ghana Highway Authority Specifications for Unmodified Bitumen**
Penetration (dmm) at 25 C, 100 g,5 s	140	-
Softening Point,C	53	48-53
Kinematic Viscosity at 135 C, cSt.	360	300
Viscosity at 60 C, cP	2,300	2,000 ± 400
Specific Gravity	1.01	1.01 – 1.06

The wet process was employed to modify the binder. Using melt-blending technique, 400 g samples of bitumen were heated in the oven, and the polymers were slowly added. The mixer rotational speed was maintained at 120 rpm, and the temperature varied between 160 and 170^{o}C. Two thermoplastic modifiers were added to the binder; HDPE and Polypropylene (PP). The concentration of HDPE and PP, ranged from 0.5% to 0.3% by weight of blend, to produce the Polymer-Modified Binder (PMB). It was observed that these polymer modifiers improved the viscoelastic behavior of the bitumen and changed its rheological properties at different levels of influence; increasing the softening point, decreasing penetration value whilst enhancing the overall dynamic and absolute viscosities of the binder. Results of laboratory testing are shown in Figure 1 to Figure 4 [11].

The results obtained confirmed that for stable PMB suitable for road making purposes in Ghana Polypropylene (PP) provides better performance. Despite the great environmental and economic impact to plastic waste recycling for waste management in Ghana, further investigation should be done to study the long-term performance of the PMB road sections to evaluate the effect on storage, rutting, cracking resistance under different traffic conditions [11].

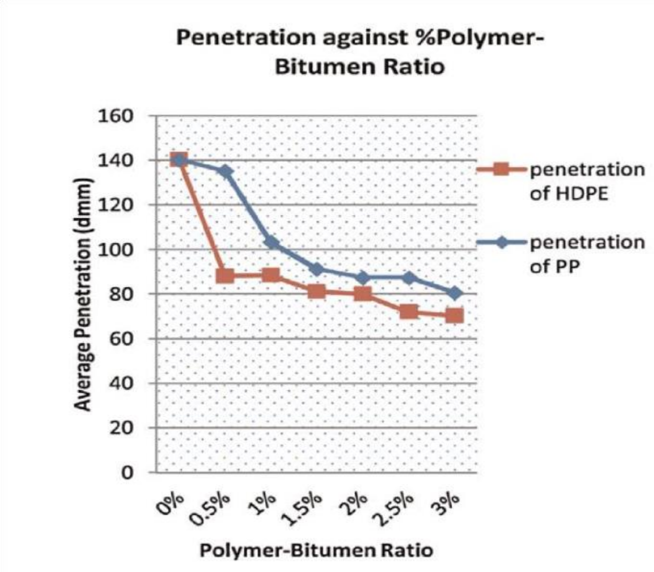


Figure 1: Penetration Graph of HDPE vs PP [11]

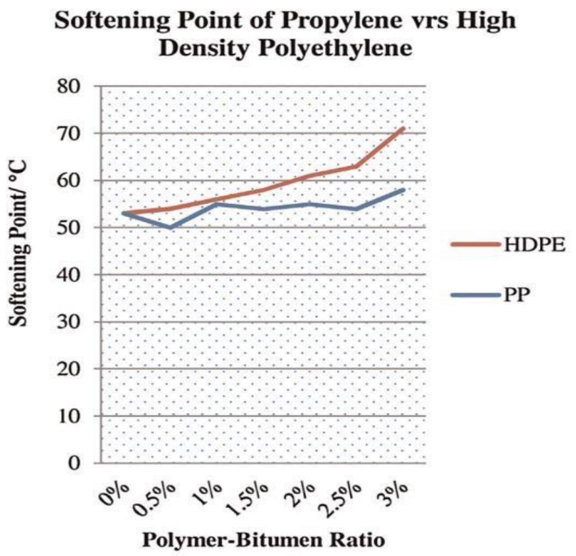
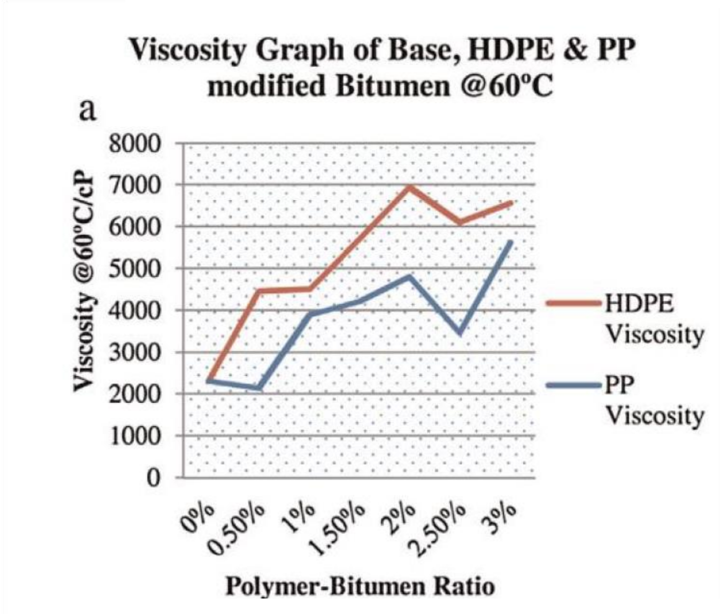


Figure 1: Softening Point of Propylene vs High Density Polyethylene [11]



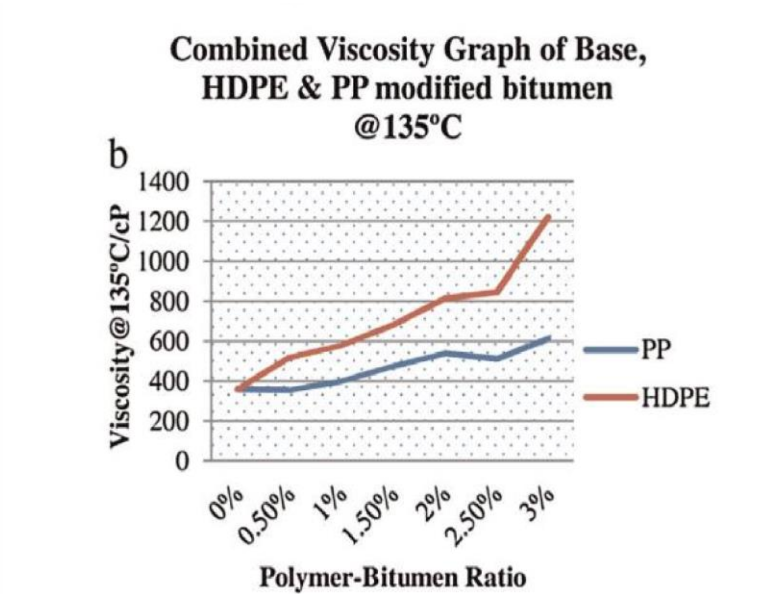


Figure 4: Combined Viscosity, HDPE & PP modified bitumen @135 c [11]

Figure 3: Combined Viscosity graph of base, HDPE & PP modified bitumen @60 c [11]

Crumb Rubber

Crumb rubber is formed using Recycled Tyre Rubber RTR, under two different procedures: cryogenic grinding and ambient grinding. Crumb rubber was generalized in 1975 and later by 1988 was included in the American Society for Testing and Materials (ASTM) D8 and later specified in ASTM D6114-97 [12]. Crumb rubber was combined with asphalt mixes in envisions to alter and improve the resultant properties of the bitumen binder.

Regardless of the used method to manufacture crumb rubbers the resulting products are fairly the same (particle size) with a principal difference in the surface texture of the particles. Using Cryogenic grinding forms crumb rubbers with an impartially smooth surface in correspondence to ambient grinding, which generates irregular shaped particles with a texturized surface formed due the nature of the process action of shredding rubber particles. It should be noted that the originated crumb rubber particle surface structure resulted from ambient grinding, result in a higher surface area with respect to cryogenic processing [13].

Crumb rubber exerted benefits are highly dependent on the effectiveness of the interaction between the asphalt binder and the produced crumb rubber particles. Several researches have been carried to identify the exhibited benefits of crumb rubber practice on the asphalt mix binder.

Viscosity characteristics

Viscosity of the binder at high temperatures is an imperative property, since it defines it’s pumping capability in the plant, in addition to coherently covering the aggregates in the asphalt mix to properly form a pavement surface. In an investigated research carried by S.-J. Lee et al. to identify the optimum mix design, effects of CRM were experimented using 3 unmodified asphalt binder mixes with 4 varying CRM percentages ranging from [5-20] %, and different crumb rubber particle surface structures [14]. As depicted in Figure 5, viscosity of binder A is shown to exhibit a higher initial viscosity with respect to the other mixes, prior to the adjustment of crumb rubber additions. Moreover, it is illustrated that CRM binders exhibits an improved viscosity with the increased percentage of CRM. Lastly, it is established that the process method of manufacturing crumb rubber presented an effect with respect to the binder viscosity; the mix formed through ambient process resulted in a higher viscos mix than cryogenic process.

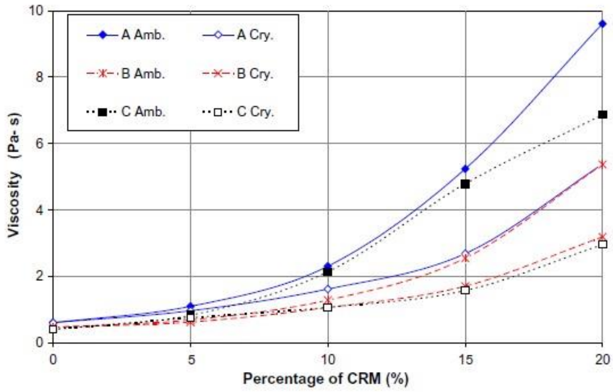


Figure 5: Viscosity of Experimented CRM Binders % [14]

Temperature effects

According to the Asphalt Institute, to reduce the chance of low temperature cracking, creep stiffness should be restricted to 300 MPa [15]. The limit in stiffness correspondingly diminishes the formed tensile stresses in the binder and prevents thermal cracking. As presented in Figure 6, CRM application presents a lower chance of temperature cracking with reduced stiffness results with respect to the increase of CRM percentages, regardless of the crumb rubber particle surface or the binder type. Nevertheless, it should be noted that similar to the viscosity results; ambient CRM process presented lower stiffness values. Although binder A presents lower initial stiffness values, with the increase of CRM percentages, stiffness values inclined to be almost similar. This suggests that lower temperature effects are experienced with respect to different binder mixes, with CRM percentage increase.

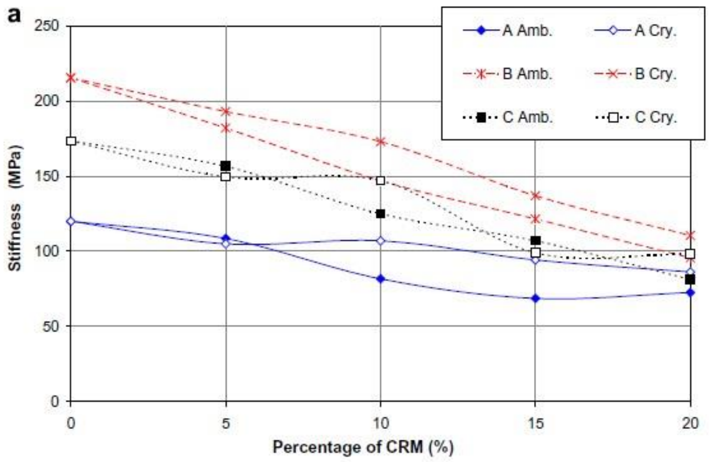


Figure 6: Stiffness of Experimented CRM Binders % [14]

<u>KSA Application: Performance Evaluation of Asphalt Modified with Municipal Wastes for Sustainable Pavement Construction</u>

In Saudi Arabia, due to severe hot temperature and high traffic loadings due to rapid urbanization, flexible pavements are failing prematurely during the initial period of service. Bitumen extracted from local oil refineries (PG 64-10) does not conform with the requirements of the SuperPave performance grade for KSA regions. This called for an alternative modified HMA pavement mix design. A study in 2016 undertaken by Amin, Muhammad, et al. investigated the potential impacts of incorporating different percentages of municipal and industrial wastes (plastic and crumb rubber "CR") as bitumen additives. HDPE, LPDE and CR with 5%, 10%, and 15% by weight of bitumen, were mixed with the base bitumen (PG 64-10) [16].

The HDPE, LDPE, and CR additives were procured from local recycling factories (size range from 1–4 mm). Using a mechanical grinder, the waste was converted into powder form (between 0.15 mm to 0.75 mm) to obtain fine material. The constituents are then all mixed together at a temperature of 165°C [16].

Rotational viscometer (RV), dynamic shear rheometer (DSR), and bending beam rheometer (BBR) were used to evaluate the viscosity, rutting, fatigue, and low temperature behaviour of base and modified binders. Modified binder showed significant improvement of viscosity. Careful consideration for workability however is needed when adding CR as the viscosity exceeds the SuperPave specifications at 15%. The test results also indicated that the rutting (permanent deformation) and fatigue resistance were significantly improved in modified binders. Binder modified with 15% HPDE and LDPE conformed with the SuperPave rutting criteria at the highest temperature (82 ◦C), and the performance grade increased to PG 82-10. Consequently, bitumen modified with 15% HDPE, LDPE, and CR could satisfactorily be implemented in road construction throughout KSA. An inverse relationship was noted between creep stiffness and the binder resistance against low temperature cracks. This results in an increased resistance to low-temperature cracks with the higher dosage of modifiers. However, it is slightly irrelevant to the case of KSA regions due to its hot climatic conditions. Laboratory test Results are graphically presented in Figure 7 to Figure 12 [23].

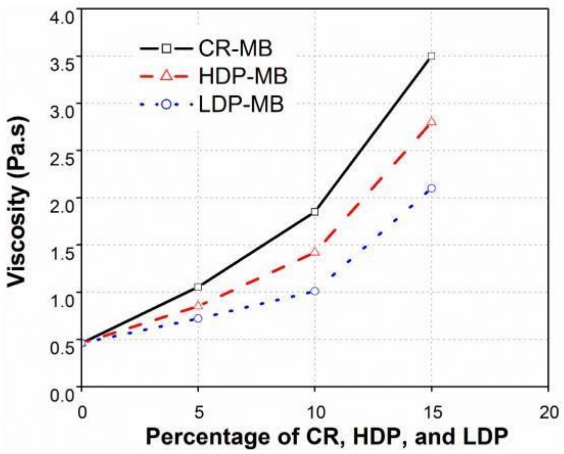


Figure 7: Viscosity of controlled and CR, HDPE, and LDPE modified binders at 135°C [16]

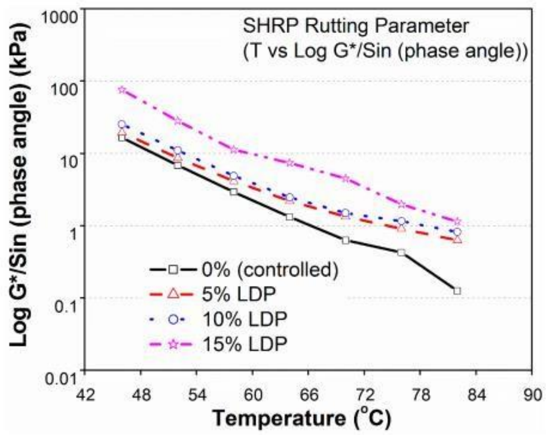


Figure 8: Effect of temperature and percentage of LDPE on rutting parameter of LDPE-MB [16]

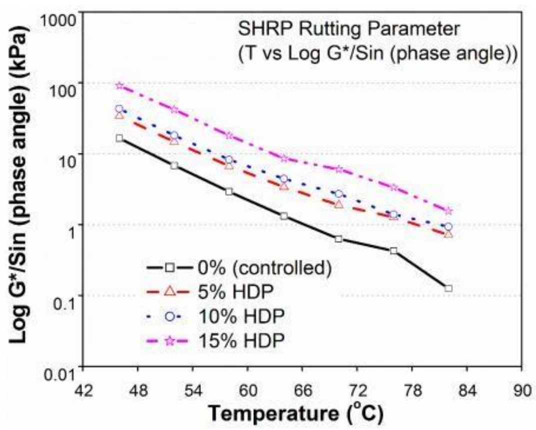


Figure 9: Effect of temperature and percentage of HDPE on rutting parameter of HDPE-MB [16]

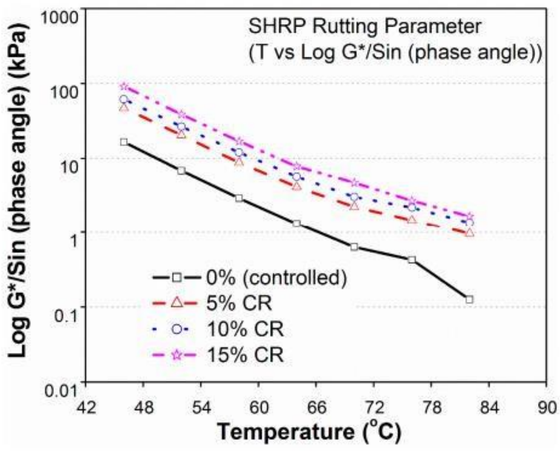


Figure 10: Effect of temperature and percentage of CR on rutting parameter of CR-MB [16]

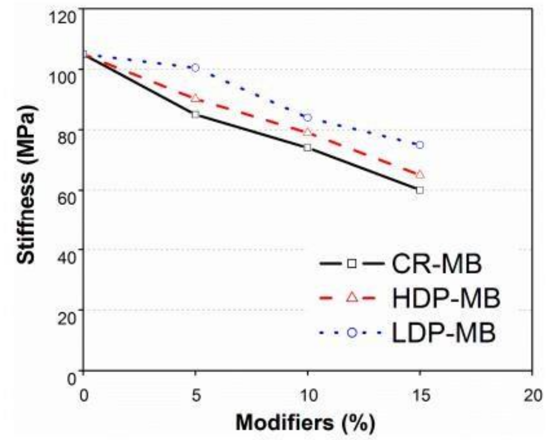


Figure 11: Stiffness of CR, HDPE, and LDPE modified binders at -10 °C [16]

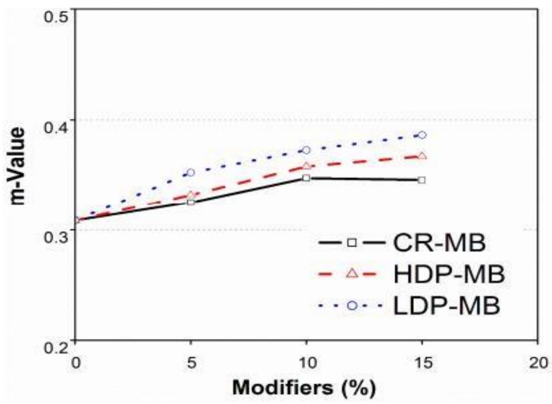


Figure 12: Rate of change in creep stiffness (m-value) at -10 °C for CR, HDPE, and LDPE modified binders [16]

Warm Mix asphalt (WMA)

Efforts by the federal highway authority are constantly made to reduce the temperatures required to produce and place hot mix asphalt. To assess the warm mix asphalt technology a team of material experts from United States visited Belgium, France, Germany and Norway. The development of WMA was driven by its environmental aspects, improvement in field compaction and welfare of workers. Types of warm mix asphalt vary between warm mix asphalt with reduced temperatures of 30 to 50 degrees Celsius to temperatures above 100 degrees Celsius less than HMA temperatures. Another way to classify WMA is the classification by technologies using water, organic additives or wax to reduce temperature. Warm Mix Asphalt technologies reduce the viscosity of asphalt and provide complete aggregate coating at lower temperatures. WMA not only act to improve workability of the pavement but also improve compaction to reduce permeability and binder hardening due to aging tending to improve performance in terms of cracking resistance and moisture susceptibility.WMA also have the potential to be beneficial in cold weather paving and long-distance hauling and the small difference between the mix temperature and ambient temperature result in a slow rate of cooling and provide more time for compaction. WMA is also used to reduce the fuel consumption of heating and drying the aggregates by up to 11% whereas WMA with temperatures reduced less than 100 degrees indicated more than 50% reduction in fuel consumption required to heat and dry aggregates. Reduction of CO2 emissions is one of the major factors of sustainable development and the use of HMA resulted in 31.5% of emissions in Norway, 23% in France, 3040 % in Italy and 15-30% in Netherlands. Paving benefits are also present in the use of WMA which include the ability to pave in cool temperatures and obtain density, ability to haul the mix longer distance while having workability to place and compact, ability to compact the mix with less effort in normal conditions, ability to include higher percentages of RAP and the ability to complete the work in shorter time periods. In Germany, a case study was made with ambient temperatures between -3 and -4 degrees, a base, binder and a Stone mastic asphalt (SMA) surface was applied, the base course contained 45% RAP. The ambient temperature of the

WMA while placing was -1 to -3 degrees and the mix temperatures for WMA were between 102 and 139 degrees. Better density results were obtained with WMA compared to HMA, compacting the mix at lower temperatures was achieved due to the reduced viscosity of the binder. WMA technologies are useful with high proportions of RAP in 2 ways by reducing the viscosity which aids in compaction and the decreased aging of the binder as lower temperature is used compensates for the aged RAP binder. Worker exposure to fumes and hydrocarbons indicate significant reductions compared to HMA while providing more comfortable working environment. WMA technologies that use small amounts of water to hot water asphalt by a foaming nozzle or a hydrophilic material resulting in steam, expand the binder phase and reduce the viscosity of the mix. The temperature of organic additives or wax is to be higher than the inservice temperature for WMA using organic additives to avoid permanent deformations and to minimize embrittlement of asphalt at low. temperature. Fischer-Tropsch wax are hydrocarbon waxes with melting point of 98 degrees and have a high viscosity at low temperatures and low viscosity at high temperature, they are used to solidify in asphalt at a temperature between 65- and 115-degree ds Celsius and are used to modify the binder, modifying the mixture. Foaming processes use Aspha-min which is a synthetic material composed of aluminum silicates of alkalimetals containing 20% water of crystallization released by increase temperature. The zeolite releases small amounts of water creating a foaming effect used to increase binder volume and viscosity of the binder while improving the workability of the asphalt mix. [17] Another study on WMA was made in rehabilitation of a pavement on Interstate 90 highway between Colombia river and town of George, the project has a steep grade of 5% where the roadway climbs out of the Columbia river Gorge. The steep slope continues for 1.5 miles and moderates toward the end of the project, the project was made of 2 lanes with paved shoulder and Average Daily Traffic(ADT) between 6448 and 7327 with 27% trucks. Paving was made on the right outside lane of the interstate, distress in it consisted of low severity alligator and transverse cracking, the high level of distress was due to high pavement stress which is a result of slow trucks going up to steep grade. The existing pavement was grinded to a depth of 0.25 ft and inlaying it with HMA or

WMA. The inlay consisted of HMA from the west end of the point and WMA for the remaining part. Control sections consisted of WMA and HMA on the flat rolling portion of the project, it was felt that WMA by WSDOT should not be placed on the steep grade where its exposed to severe load conditions of slow-moving uphill truck traffic. The price of WMA was 6$ more than the price of HMA per ton resulting in a cost increase about 28,344 dollars for about 4724 tons of WMA. Same aggregate types and binder were used for the mix along with the same design mix criteria used for both mixes. Placement was made using the same equipment and methods with haul times of between 30 to 45 minutes for HMA and 25 to 35 minutes for WMA. Trucks dumped the material on site to form a windrow and then a windrow elevator picked them up. Compaction of the mixes consisted of three double drum vibratory rollers, the only problem faced was clumps of mix sticking together in WMA and they were due to excessive cooling of the WMA during approximately 40 minutes hauls. The lumps may be due to the temperature not being high enough to break chunks of RAP. Sieve analysis showed that no aggregates remain on ¾ inch sieve, hence only small sized aggregates were used. The temperature of mixing averaged 286 Fahrenheit's which is 131 Celsius and is about -1 to 10 degrees less than HMA. Gradation ranges were similar for both HMA and WMA as well as density results. Moisture resistance was between 1.66% to 4% which is lower than the required by WSDOT. The stiffness, Flow number which indicates stiffness of WMA was higher than that of HMA. The Hamburg testing which tests for rutting resistance and stripping resistance did not find a significant difference in rut depth between HMA and WMA. After use of pavements for 5 years it was found that the friction resistance is higher for WMA compared to HMA. Rutting values ranged between -0.3 differences to 0.5 mm for WMA compared to HMA.HMA was better in Ride characteristics. It was concluded that HMA is slightly better in performance compared to WMA [18]. Challenges in WMA include insuring that the overall performance of WMA is better than HMA in further studies, another challenge is ensuring that coarse aggregates are dry [17].According to National Asphalt Pavement

Association(NAPA) about 39% of Asphalt pavements are produced as Warm Mix Asphalt in the States.[19]

Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement is another way to provide sustainable pavements and is used as a valuable component in HMA due to the increased demand and limited aggregate and binder supply. The two primary factors that influence RAP selection are economic savings and environmental benefits. RMA is considered an alternative to virgin materials such as aggregates and binders and reduces their use while conserving energy, lowering transportation costs and decreasing amount of construction debris placed in landfills and optimizes the use of natural resources while sustaining the asphalt pavement industry. RAP is a result of removed materials during resurfacing, rehabilitation or reconstruction operations. Over 80% of asphalt material is recycled yearly making it the most recyclable material. Asphalt binder is the most expensive material in asphalt pavements and to reduce costs of asphalt pavements, using RAP in intermediate and surface layers of the pavement to resist distortion, protect the asphalt pavement from moisture and provide smooth skid resistant riding surface withstanding wear from traffic. The usage rate of RAP was surveyed in all 50 states along with Ontario in Canada and it was found that the average usage rate was 12% which indicated that a potential to increase the usage percent in the intermediate and surface layers as shown in Figures 13 and 14 below.

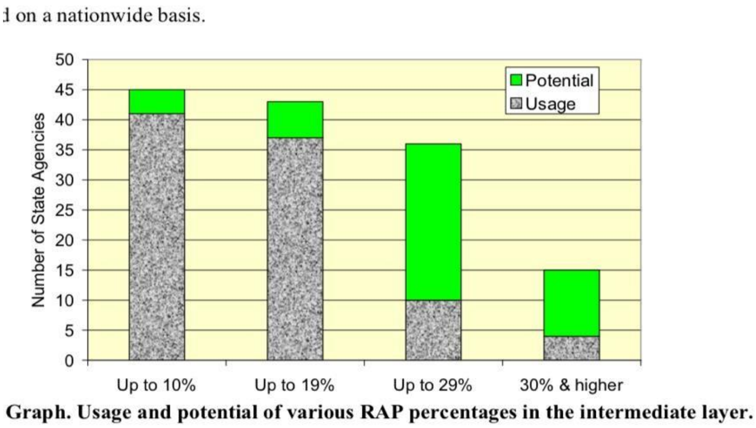


Figure 13: Usage and potential of usage of Various RAP percentages in Intermediate layer [20]

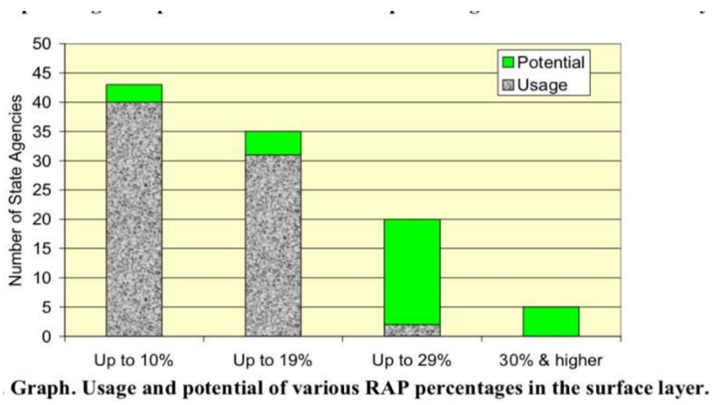


Figure 14: Usage and Potential usage of various RAP percentages in Surface layer [20]

RAP collected from several sources over time is usually generated from milling, full- depth pavement removal, and waste HMA materials generated at plant. A major consideration in RAP lies in determining whether to use RAP from 1 source or combine RAP from different sources. Milling is a major part of pavement rehabilitation as all distressed upper layers of existing pavement to a certain depth are removed. In order to obtain a uniform and consistent RAP which does not require further processing, the mill speed at the site should be controlled and kept uniform. Another form of producing RAP is in the form of slabs which are a result of heavy equipment breaking the pavement structure. After the slabs are taken from field they are transported, crushed and processed to a manageable recycling size. One precaution to consider in using the RAP material is ensuring that that the material is free from contamination, hence an inspection is necessary to avoid soil dumping, construction debris or any unnecessary material in the stockpile. Processing of RAP involves screening to separate sizes of materials, removing of oversized particles and separation between fine and coarse stockpiles to maximize the amount of RAP used in a particular mix and to increase control and reduce variability. RAP from pavement slabs requires crushing the material to produce RAP with a suitable size for use in new asphalt mixes and improve the consistency of the RAP material if multiple sources of RAP are used. A limit on the maximum of variability in the RAP material needs to be set by agencies to improve consistency and improve the quality of RAP. Percentage of RAP to be included in the mix depends on the contribution of RAP in the total mix by weight or by determining the contribution of RAP binder on the total binder in the mix by weight while maintaining the volumetric properties requirements. If RAP contribution weight of the total weight percent is less than 15% then no change in binder selection is required, in case of having RAP percent by weight between 15 and 25, then a grade softer than the normal grade of binder is required due to the stiffening effect of aged binders. In the case of having RAP percentages of more than 25% then AASHTO blending charts are to be used. Another way to determine the RAP percent is to use a formulation depending on the RAP percent binder content, RAP Percent in mixture and the total percent binder content in mixtures. In the case of having a high RAP, a method is required to select the appropriate grade of the virgin binder as a softer binder is required to balance the stiffer aged asphalt binder. Solvent extraction and recovery processing is necessary to recover the RAP binder for testing, Physical properties and critical temperatures of recovered RAP binder are also to be determined. After obtaining the temperatures and properties blending of the mix can be done in two methods which are blending at a known RAP percent or blending with a known virgin binder grade. In 1990's two reports were published to evaluate the field performance of RAP with varying percentages of RAP, an evaluation on virgin and recycled asphalt pavements containing 10-25% RAP was made by Kandhal et al. and it was found that after 1-2.5 years of service, no signs of deformations such as cracking or rutting was seen in any of the study sections which indicates an equal well performance on both types of pavements. After expanding the study on sections with 10-40% RAP it was found that there was no difference in the performance or recycled or virgin pavements. Moreover, in Louisana, Paul evaluated field performance of conventional and recycled asphalt pavements containing 2050% RAP and found no difference between their performance after 6-9 years. RAP is considered a high-quality material that can replace more expensive virgin aggregates and binders. The use of RAP is driven by the cost of virgin materials and transportation, economic and environmental benefits of allowing higher percentages of RAP is being studied by state transportation departments. The most common challenges to increase the use of RAP are state transportation department specification limits, lack of processing, lack of RAP availability and past experiences, moreover, the most common concerns in terms of performance for the of the blended virgin and RAP binders specially for High RAP mixes is the quality of them as well as stiffening of the mix from high RAP quantities and resulting cracking performance. Some considerations and recommendations include ensuring that proper techniques are used for obtaining, stockpiling and processing RAP to maintain its quality. Sampling and testing of RAP is to be made and random samples are to be taken to identify the variability of the RAP material properties. In the case of RAP with more than 25%, careful considerations are to be made for the selection of the grade of asphalt binder added to the recycled asphalt binder [20].

Solar Road Systems

Solar Roads are roads which include solar panels interlinking together under the road to drive on and include photovoltaic effect, LED's and microprocessor chips. Solar roads are used to replace petroleum-based asphalt highway infrastructure with an intelligent road generating electricity. Solar panels in the road are divided into three basic layers which are Road surface layer, Electronics Layer and Base Plate Layer. The road surface layer is the top layer which is used to capture solar rays and move them to photovoltaic cells, the layer should be translucent and high in strength and the same time it should provide enough friction to avoid skidding of vehicles and should be waterproofed to protect electronics under it. The electronic layer is the layer which includes the circuits and microprocessors to sense loads on the surface and control the heating element which results in no snow/ ice removal expenditures, moreover, the microprocessors control lighting, communication and monitoring. Energy moves from the surface layer to electronics layer which then moves it to the base plate layer to distribute power and data signals and the base layer is waterproof as well to protect the electronics layer from water coming from the bottom. Solar roads can also be used as illuminated roads which can help drivers see the road lines at night and reduce accidents at night. LED's on the road can also move with the drivers and produce warnings to drivers when they exceed the speed limits, moreover, they can be used to issue warnings when an animal is on the road or an accident is ahead. Solar roadways can also promote the use of electric vehicles as the electrical vehicles will be charging their own without the need of drivers waiting to charge their cars and hence more people will be motivated to use them. Advantages of solar roads include them utilizing a renewable source of energy to produce electricity. Another advantage is that the roadway does not require development of unused and potentially environment sensitive lands. Disadvantages of them include the initial costs of construction and maintenance of such roads being high, the efficiency of solar panels is still a concern and further research is required on it, another disadvantage includes the difficulty of providing sunlight to the system when the roadway gets sand accumulated on and in rainy seasons and hence such roads require a lot of cleaning and maintenance [21].Solar roadways replace the need of burning fossil fuels which reduces the greenhouse gas emissions by half. Although the cost of solar roads may be three times the cost of asphalt, they are more durable and easily replaced and pay for themselves by generating more electricity than what our economy consumes. A solar roadway with just below 15% efficiency can produce three times the electric demand. More advantages of solar roads include having major new investments and economic benefits as a result of global leadership in the world most advanced clean energy infrastructure, every dollar invested in renewable energies generates great retures as the resource is not wasted. The structural design requirement for solar road panels include the structure's ability to support cyclic distribution from vehicle tires without failing, ie. 480 KPA of stress. The structure also needs to be corrosion resistant [22]. In the end, Solar roadways can be a major source of clean energy which can impact the climate in a positive way while optimizing traffic in terms of work productivity, fuel consumption and prevention of accidents.

Electric Road Systems

An electric road (ER) system aims to continually provides the vehicle with electricity as the vehicle runs on the track. The technology is said to be compatible with existing road infrastructure, and conventional vehicles propelled by other fuels. However, electric roads have no active deployment worldwide, and the system is still being studied for performance indicators. The system is environmentally friendly and consumes unrenewable sources of energy. In Sweden, the first electrified road in the world is currently under construction. The system is to be installed over a stretch of 2-kilometer using a pair of electric rails to transfer energy from the road to an Electric Vehicle above it via a mechanical arm. ERs charge vehicles as they run on the track, which eliminates the need for EV charging stations in the future. As a further benefit, smaller batteries will be required for EVs. On the other hand, the technology is still emerging, and there is very limited deployment worldwide. Moreover, the system implementation is disruptive and expensive as the full road scheme needs to be reformed. Lastly, the ER systems themselves are costly, requiring a continuous line of electromagnets along the length of the road. As a result, the infrastructure would be unlikely to extend beyond a few high traffic routes throughout the city [23].

Case Study: UAE Application

Project Identification

The case study investigated in this project is for Al Maliha road in the emirate of Sharjah shown in Figure 15. Sharjah Al Maliha road extends from Sharjah Kalba road and connects at the Al Badee Interchange and Sheikh Khalifa Interchange to Emirates Road and Sheikh Mohammed Bin Zayed Road, respectively. The road serves mainly Sharjah Industrial Area and provides a direct connectivity to the University City. Some of the surrounding areas and neighborhoods served by Al Maliha Road include; Al Naof, Al Khawaneej, and the American University of Sharjah, as shown in Figure 16.

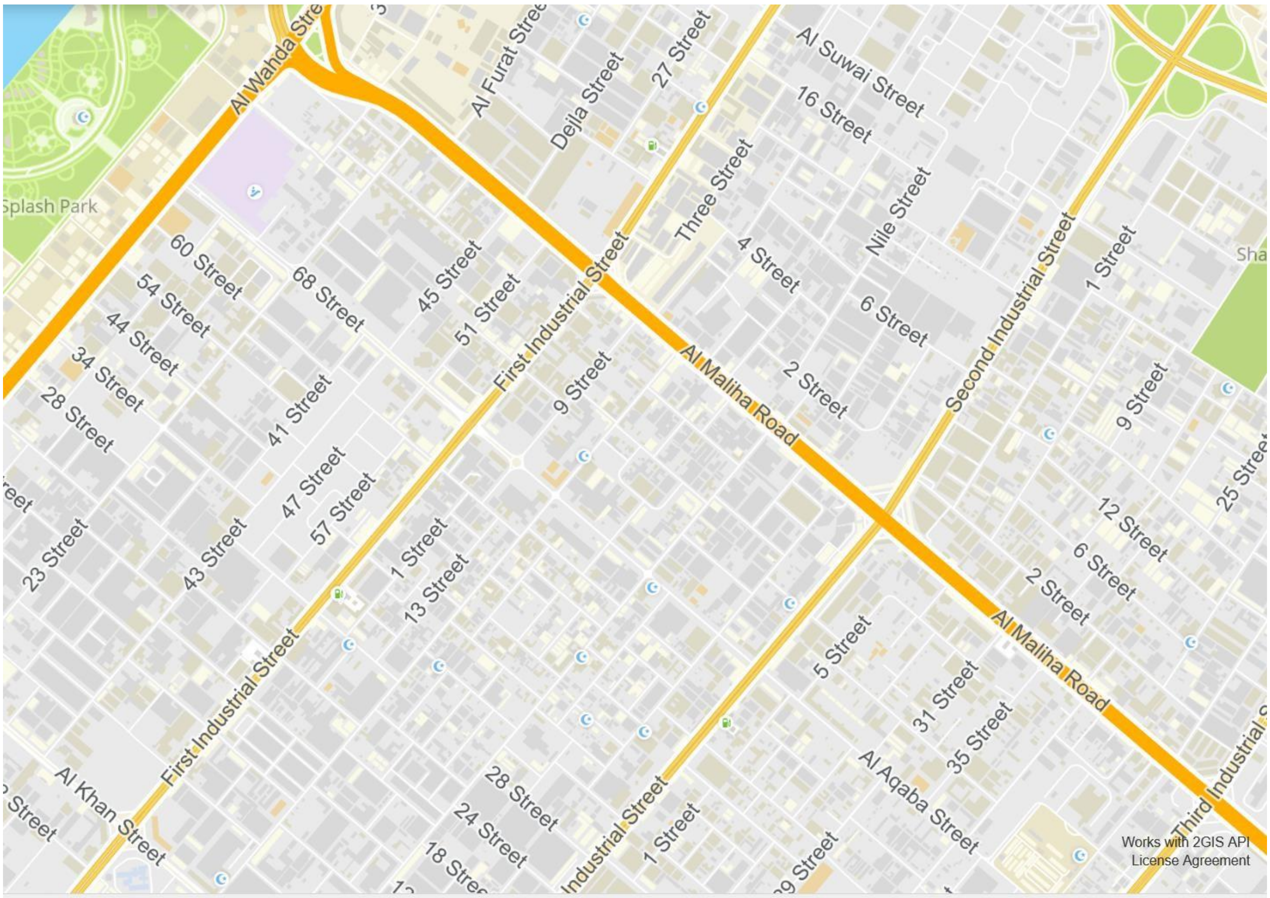


Figure 15: Al Maliha Road in Sharjah

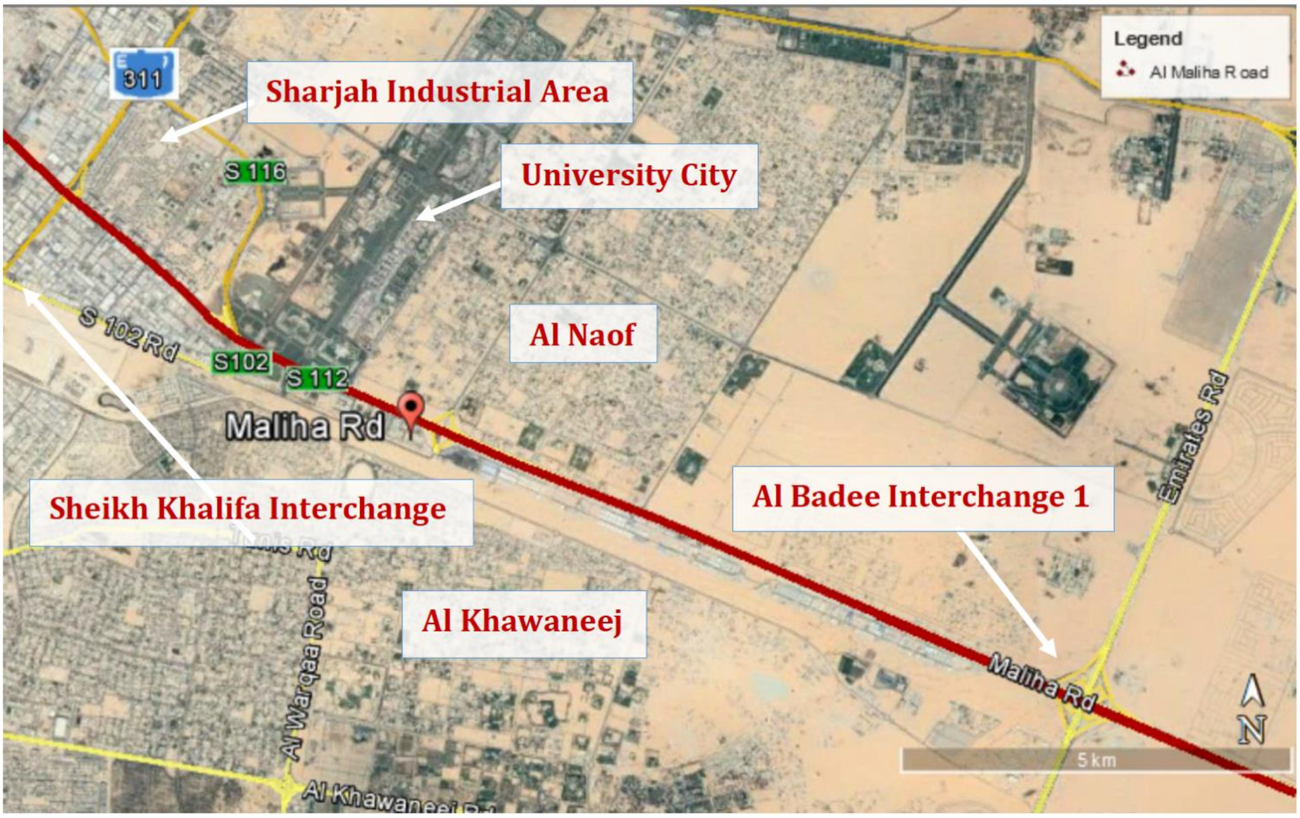


Figure 16: Al Maliha Road and Surrounding Areas

Project Requirements

The 42-km Al Maliha Road was recently launched for public operation, upon the rehabilitation of the pavement system. The road development scheme spans the maintenance of the existing road and adding a third lane in both directions. Al Maliha road encounters heavy traffic almost all week long, due to its connectivity to Sharjah University City, and Industrial Area. The traffic loading reported at Sheikh Khalifa Interchange reaches approximately 17,000 vehicle/hour/direction, in the morning peak. The UAE has adapted a sustainable approach to rehabilitate the pavement in Al Maliha Road by incorporating recycled crumb rubber in the mix design.

In this case study, the main objective is to evaluate the different sustainable pavement systems and materials reviewed and investigated in this report, to select the most appropriate technique for deployment in Al Maliha Road. This will confirm and validate the chosen material of recycled rubber [24]. The Analytical Hierarchy Process (AHP) as a decision analysis tool was used to evaluate the different alternatives, based on some defined evaluation criteria.

AHP Model

The Analytical Hierarchy Process (AHP) is a decision analysis tool that ranks several alternatives using a multi-attribute comparison. In an AHP, the criteria for selection of the best alternative is established, and different options are evaluated relatively. The result is the identification of the alternatives hierarchy to identify the significance for each alternative comparatively.

Evaluation Criteria

The AHP Model built for this case study was to evaluate six different sustainable pavement systems using five different attributes as presented in Table 3 and Table 4, respectively.

Table 3: Sustainable Pavement Systems

Sustainable Pavement System
Plastic Wastes
Crumb Rubber
Warm Mix Asphalt (WMA)
Reclaimed Asphalt Pavement (RAP)
Solar Roads
Electric Roads

Table 4: Attributes of Evaluation

Attribute
Cost (Short-term)
Durability
Feasibility in the UAE
Weather
Worldwide Deployment

A qualitative assessment for the systems alternatives based on the information collected using the desktop research is shown in Table 5. This will aid in the comparative analysis and grading of the systems.

The decision matrix for mathematical representation of attributes priority is built using pairwise comparison based on the 9-point scale of Saaty, presented in Table 6, and shown in Table 7. The decision matrix for Al Maliha Road Rehabilitation Project is shown in Table 8.

Table 5: Qualitative Assessment of Sustainable Pavement Systems

Attribute	Plastic Wastes	Crumb Rubber	WMA	RAP	Solar Roads	Electric Roads
Cost (short-term)	LOW	LOW	MEDIUM	LOW	HIGH	HIGH
Durability	**HIGH**	**HIGH**	**MEDIUM**	**LOW**	**MEDIUM**	**MEDIUM**
Feasibility in the UAE	**HIGH**	**HIGH**	**MEDIUM**	**HIGH**	**LOW**	**LOW**
Weather	**MEDIUM**	**MEDIUM**	**MEDIUM**	**MEDIUM**	**HIGH**	**LOW**
Worldwide Deployment	**MEDIUM**	**HIGH**	**HIGH**	**MEDIUM**	**LOW**	**LOW**

Table 6: Saaty 9-point Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

Table 7: Pairwise Comparison for Sustainable Pavement Systems

	A - Importance - or B?		Equal	How much more?
1	○ Cost (shortterm)	or ◉ Durability	○ 1	◉ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
2	◉ Cost (shortterm)	or ○ Feasibility in UAE	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
3	◉ Cost (shortterm)	or ○ Weather	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
4	○ Cost (shortterm)	or ◉ World-Wide Deployment	○ 1	○ 2 ◉ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
5	◉ Durability	or ○ Feasibility in UAE	○ 1	○ 2 ○ 3 ◉ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
6	◉ Durability	or ○ Weather	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9
7	◉ Durability	or ○ World-Wide Deployment	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
8	◉ Feasibility in UAE	or ○ Weather	◉ 1	○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9
9	○ Feasibility in UAE	or ◉ World-Wide Deployment	○ 1	○ 2 ○ 3 ○ 4 ○ 5 ◉ 6 ○ 7 ○ 8 ○ 9
10	○ Weather	or ◉ World-Wide Deployment	○ 1	○ 2 ○ 3 ○ 4 ◉ 5 ○ 6 ○ 7 ○ 8 ○ 9

Table 8: Decision Matrix for Al Maliha Road Project

	1	2	3	4	5
1	1	0.50	5.00	3.00	0.33
2	2.00	1	4.00	5.00	1.00
3	0.20	0.25	1	1.00	0.17
4	0.33	0.20	1.00	1	0.20
5	3.00	1.00	6.00	5.00	1

The resulting global weights for the evaluation criteria based on the pairwise comparisons are shown in Table 9.

Table 9: Evaluation Criteria Weights

Category		Priority	Rank
1	Cost (short-term)	18.6%	3
2	Durability	31.6%	2
3	Feasibility in UAE	5.9%	5
4	Weather	6.3%	4
5	World-Wide Deployment	37.6%	1

<u>Options Assessment & Final Selection</u>

The different alternatives were assessed using a scoring system out of (100%). Depending on the number of alternatives, the lowest score is 16.7% and the highest is 100% (of the global score of the attribute). The score for each alternative highly depended on the applicability of a short-term UAE deployment. Depending on each the systems performance illustrated earlier, the scores are given as shown in Table 10.

Table 10: Sustainable Pavement Systems Assessment Results

Category	Global Weights	Plastic Wastes	Crumb Rubber	WMA	RAP	Solar Roads	Electric Roads
Cost (short-term)	18.60%	18.60%	18.60%	6.20%	18.60%	3.10%	3.10%
Durability	31.60%	31.60%	31.60%	10.53%	5.27%	10.53%	10.53%
Feasibility in UAE	5.90%	5.90%	5.90%	1.97%	5.90%	0.98%	0.98%
Weather	6.30%	2.10%	2.10%	2.10%	2.10%	6.30%	1.05%
World-Wide Deployment	37.60%	12.53%	37.60%	37.60%	12.53%	6.27%	6.27%
Total (%)		**70.73%**	**95.80%**	**58.40%**	**44.40%**	**27.18%**	**21.93%**

The results of the assessment qualify the use of Crumb rubber which yielded in the highest score out of all other alternatives to serve and fulfil the project main requirement of using a sustainable pavement material satisfying the conditions of Maliha road.

Limitations of the Study

Limitations of the study include quality variations in recycled materials and inadequate information about the properties of products produced with recycled wastes along with lack of standards to support design using such materials along with lack of awareness on the use of recycled materials as elements in design. Lack of government awareness and support on the use of recycling materials along with lack of much real-life applications using such materials to evaluate their performance can be considered as a limitation in this study. More limitations in the study lie in the lack of development of techniques such as the electric roadways and solar road ways. Challenges are also present in the use of Warm Mix asphalt and Reclaimed Asphalt pavement include ensuring that WMA may be able to provide higher quality characteristics which may be developed to be better than HMA, moreover, Reclaimed Asphalt Pavement challenges lie in determining the appropriate binder grades in case of having more than 25% RAP content and hence this is yet to be developed.

Conclusion and Recommendations

Different pavement sustainability was assessed and studied in this paper which include, Plastic Pavements, Rubber Pavements, Electric Pavements, Warm Mix Asphalt Pavements, Reclaimed Asphalt pavements and Solar Pavements. Performance of the different types of pavements was studied and techniques of applying those sustainable pavement materials was studied. Advantages and disadvantages of the materials was described in the paper. A case study considering the different materials was made in the end using AHP to help in deciding which material would be best for Maliha road in Sharjah determined that crumb rubber yielded the highest score and confirmed that the actual solution used in the project was the most optimum. Recommendations of the study include further studies and assessment of long-term performance of all materials along with their feasibility under different weather and loading conditions.

References

[1] M. Tuncan, A. Tuncan, & A. Cetin, “The use of waste materials in asphalt concrete mixtures,” *Waste management & research*, vol. 21, no. 2, pp. 83-92, 2003.

[2] S. Karmakar & T. K. Roy, “Effect of Waste Plastic and Waste Tires Ash on Mechanical Behavior of Bitumen,” *Journal of Materials in Civil Engineering*, pp. 04016006, 2016.

[3] Y. Huang, R. N. Bird, & O. Heidrich, “A review of the use of recycled solid waste materials in asphalt pavements,” Resources, Conservation and Recycling, vol. 52, no. 1, pp. 58-73, 2007

[4] R. Vasudevan, A. R. C. Sekar, B. Sundarakannan, & R. Velkennedy, “A technique to dispose waste plastics in an ecofriendly way–Application in construction of flexible pavements,” *Construction and Building Materials*, vol. 28, no. 1, pp. 311- 320, 2012.

[5] Sojobi, Adebayo Olatunbosun, et al. “Recycling of Polyethylene Terephthalate (PET) Plastic Bottle Wastes in Bituminous Asphaltic Concrete.” *Cogent Engineering*, vol. 3, no. 1, 2016, doi:10.1080/23311916.2015.1133480.

[6] Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Ahmadinia, E. (2012). “Performance evaluation of utilization of waste polyethylene terephthalate (PET) in stone mastic asphalt.” *Construction and Building Materials, 36*, 984–989. http://dx.doi.org/10.1016/j.conbuildmat.2012.06.015

[7] Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Shafgh, P. (2011). “Using waste plastic bottles as additive for stone mastic asphalt.” Materials & Design, 32, 4844– 4849. http://dx.doi.org/10.1016/j.matdes.2011.06.016

[8] Zhang, H., Wu, X., Cao, D., Zhang, Y., & He, M. (2013). “Effect of linear low density-polyethylene grafted with maleic anhydride (LLDPE-g-MAH) on properties of high density polyethylene/styrene–butadiene–styrene (HDPE/SBS) modifed asphalt.” *Construction and Building Materials, 47*, 192–198. http://dx.doi.org/10.1016/j.conbuildmat.2013.04.047

[9] Awwad, M. T., & Shbeeb, L. (2007). “The use of polyethylene in hot asphalt mixtures.” *American Journal of Applied Sciences, 4*, 390–396.

[10] Chavan, A. J. (2013). “Use of plastic waste in flexible pavements.” *International Journal of Application or Innovation in Engineering and Management, 2*, 540–552.

[11] Appiah, Johnson Kwabena, et al. “Use of Waste Plastic Materials for Road Construction in Ghana.” *Case Studies in Construction Materials*, vol. 6, 2017, pp. 1–7., doi:10.1016/j.cscm.2016.11.001.

[12] Putman BJ. Quantification of the effects of crumb rubber in CRM binders. Dissertation in

partial fulfilment of the requirements for PhD in Civil Engineering, Clemson, SC: Clemson University; 2005.

[13] Presti, Davide Lo. "Recycled Tyre Rubber Modified Bitumens for Road Asphalt Mixtures: A Literature Review." *Construction and Building Materials*, vol. 49, 2013, pp. 863– 881., doi:10.1016/j.conbuildmat.2013.09.007.

[14] Lee, Soon-Jae, et al. "The Effect of Crumb Rubber Modifier (CRM) on the Performance Properties of Rubberized Binders in HMA Pavements." *Construction and Building Materials*, vol. 22, no. 7, 2008, pp. 1368–1376. doi:10.1016/j.conbuildmat.2007.04.010.

[15] The Asphalt Institute. Performance Graded Asphalt Binder Specification and Testing, SP- 1. Lexington, KY: The Asphalt Institute; 2003.

[16] Amin, Muhammad, et al. "Performance Evaluation of Asphalt Modified with Municipal Wastes for Sustainable Pavement Construction." *Sustainability*, vol. 8, no. 10, 2016, p. 949., doi:10.3390/su8100949.

[17] D,Angelo, John. Warm Mix Asphalt: European Practice. Federal Highway Administration, Office of Policy, Office of International Programs, 2008, international.fhwa.dot.gov/pubs/pl08007/pl08007.pdf.

[18] Anderson, Keith, et al. Warm Mix Asphalt Final Report. 2014, Warm Mix Asphalt Final Report, www.wsdot.wa.gov/research/reports/fullreports/723.2.pdf.

[19] Ross, T. Carter. Asphalt for Performance www.asphaltpavement.org /index.php?option =com_content& view=article &id= 1169:2017 -survey-results- warm-mixasphalt-use-grows-recycled-materials-hold-steady&catid=24:napanews4&Itemid=767.

[20] Copeland, Audrey. Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice. 2011, Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice, www.fhwa.dot.gov/publications/research/infrastructure/pavements/ 11021 /11021.pdf.

[21] Katdare, Amey, et al. "A Study On Roads Using Solar Energy." International Journal for Research in Applied Science & Engineering Technology (IJRASET), Dec. 2016, www.ijraset.com/fileserve.php?FID=6010.

[22] Shingate, Varsha, et al. "Study on Solar Roadway." International Journal of Advance Research,Ideas and Innovations in Technology, 2017, pp. 345–348., www.ijraset.com/fileserve.php?FID=6010.

[23] Condliffe, Jamie. "Do You Really Need Wireless Charging Roads?" *MIT Technology Review*, MIT Technology Review, 18 May 2017, www.technologyreview.com /s/607902/ the-case-for-building-roads-that-can-charge-electric-cars-on-thego/.

[24] Shaaban, Ahmed. "Used Rubber Tyres, Organic Materials Pave UAE Roads." Khaleej Times , www.khaleejtimes.com/news/general/used-rubber-tyres-organicmaterials-pave-uae-roads.