Integrated Sustainability Assessment of Asphalt Rubber Pavement Based on Life Cycle Analysis

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ABSTRACT: This study aims to quantify and compare the life-cycle environmental, economic and social impacts of two pavement materials: namely 10mm Asphalt Rubber Stone Matrix Asphalt (ARSMA10) and 10mm Polymer Modified Stone Matrix Asphalt (PMSMA10). To achieve this objective, a comparative sustainability framework was developed by: 1) combining the Life Cycle Assessment (LCA) with pavement maintenance plan developed based on the pavement conditions predicted by the Mechanistic-Empirical Pavement Design Guide (MEPDG) software; 2) examining the additional fuel consumption and emissions based on predicted pavement condition; 3) and integrating the cost-benefit analysis (CBA) to estimate the environmental damage cost and noise reduction benefit. The major findings of this study include: 1) in the 56-year analysis period, the dominant contributions to environmental impact are made by the extra vehicle greenhouse gas (GHG) emission and fuel consumption caused by pavement roughness change; 2) PMSMA10 has better environmental performance than ARSMA10 in terms of energy consumption and GHG emissions; 3) the long-term accumulated tire-road noise impact is considerable, which can almost offset its higher economic cost and environmental damage cost assuming ARSMA10 is able to decrease noise by 4%,.

1 INTRODUCTION

Pavement, as one of the major components of the infrastructure system, plays an important role in the development of civilization and economic prosperity. Currently, the booming transportation and the increasing awareness of sustainable development have attracted significant research interest in reducing the negative environmental and social impacts of pavement during its construction and service. In 2005, the greenhouse gas (GHG) emissions from road transportation accounted for 12.5% to 13.0% of global total emissions (ASTAE, 2009), while pavement condition heavily affects vehicle emissions and fuel consumption. For instance, rough pavement surface has been reported to negatively affect vehicle fuel economy (Chatti and Zaabar 2012). Though the environmental impact variables in a pavement life-cycle are complicated, some sustained efforts have been made to minimize the environmental burdens from pavement projects, for example, many recycled materials, such as reclaimed asphalt pavement (RAP) and waste tire rubber, are now being used in pavement construction to conserve raw material resources without compromising pavement performance.

Asphalt rubber (AR), which is composed of raw asphalt and at least of 15% of waste tire rubber as modifier, is one good example of using waste materials in pavement. However, AR has received different popularities in different areas around the world, because on one hand it provides various benefits, such as recycling waste tires (Caltrans, 2013), enhancing pavement performance, and reducing tire-road noise (Lo Presti, 2013; SCDER & ABB. Inc., 1999; RPA, 1999), while on the other hand, it requires higher construction temperature and cost. To achieve a comprehensive sustainability assessment of AR, this study quantified the economic, environmental, and social impacts of 10mm Asphalt Rubber Stone Matrix Asphalt (ARSMA10) through an extended life cycle assessment (LCA) approach, using 10mm Polymer Modified Stone Matrix Asphalt (PMSAM10) as a reference.

LCA provides a systematic procedure to quantify the environmental performance of products throughout their life cycles. The report of FHWA (2014) divided the life cycle of pavement into five phases: production, construction, use, maintenance, and disposal. The pavement LCA studies have been documented in many literatures since 1996 (Häkkinen & Mäkelä, 1996), but the research focuses and results differ in various studies. Recent studies have combined LCA with other analysis methods to achieve results that are more comprehensive. Yu et al. (2013) integrated LCA and Life Cycle Costing Analysis (LCCA) to estimate the evidential damage cost to optimize the pavement maintenance plan. Yang et al. (2015) developed an international roughness index (IRI) progression model in the LCA to compute the GHG emissions and energy consumption of vehicles. Chong and Wang (2016) developed an LCA framework based on the pavement design and management decisions.

However, noise, on which AR pavement can provide significant benefit, is often considered as one of the social-economic impacts, and has not been included and defined in the staple life cycle inventories (LCI). European Commission (2014) has assessed the noise impact by computing the corresponding noise cost introduced by the Cost-Benefit Analysis (CBA) method. In this study, the comparative sustainability framework extended the use of LCA by: 1) combining the Mechanistic-Empirical Pavement Design Guide (MEPDG) software to predict pavement conditions and determine the maintenance plan; 2) integrating the pavement conditions to examine the additional fuel consumption and emissions; and 3) integrating the CBA to examine the environmental damage cost and noise reduction benefit.

2 METHODOLOGY

The methodology adopted in this study incorporated the MEPDG software, LCA, and the calculation of Environmental Damage Cost (EDC) and Noise Reduction Benefit (NRB). For the two compared pavement materials, i.e., ARSMA10 and PMSMA10, all calculations were conducted under the same traffic, project and climate condition. The calculation process can be further divided into five steps:

1) determine the maintenance plans for the two comparison materials according to the modeling results of the MEPDG;
2) perform LCA according to ISO 14044 (2006a) and ISO 14040 (2006b) to acquire the environmental impacts;
3) estimate the investment costs involved in the initial construction and life cycle maintenance;
4) convert the GHG emission and noise reduction to the Environmental Damage Cost (EDC) and Noise Reduction Benefit (NRB) following the method described in the Cost Benefit Guidelines (European Commission, 2014) and the Handbook on Estimation of External Costs in the transport sector (Maibach et al., 2008); and
5) calculate the overall cost based on the results of the former four steps.

2.1 *Goal and Scope Definition*

The goal of this study is to express the life-cycle environmental, economic and social impacts of two pavement materials (ARSMA10 and PMSMA10) into monetary values, and compare the overall sustainabilities of the two mixtures based on their estimated performance in the life cycle view. The performances of the two materials were predicted by the MEPDG software using the experimental data of the material properties as input. The only variable in this comparison study is the asphalt mixture and other parameters (i.e., traffic loading, climate, construction and maintenance methods) were fixed and assumed same.

2.2 *Functional Unit and System Boundaries*

The functional unit of this study is the square meter (m^2) of 40mm wearing course throughout the 56-year analysis period.

The system boundary determination will have significant influence on the results when considering the environmental impacts. In this study, four life-cycle phases were considered, including: material production, construction, usage and end-of-life (EOL). The examining processes of ARSMA10 in each phase are illustrated in Figure 1. The processes of the two asphalt mixtures are almost same except for the difference in the material production phase, where ARSMA10 includes an additional process of producing crumb rubber modifier from EOL tires.

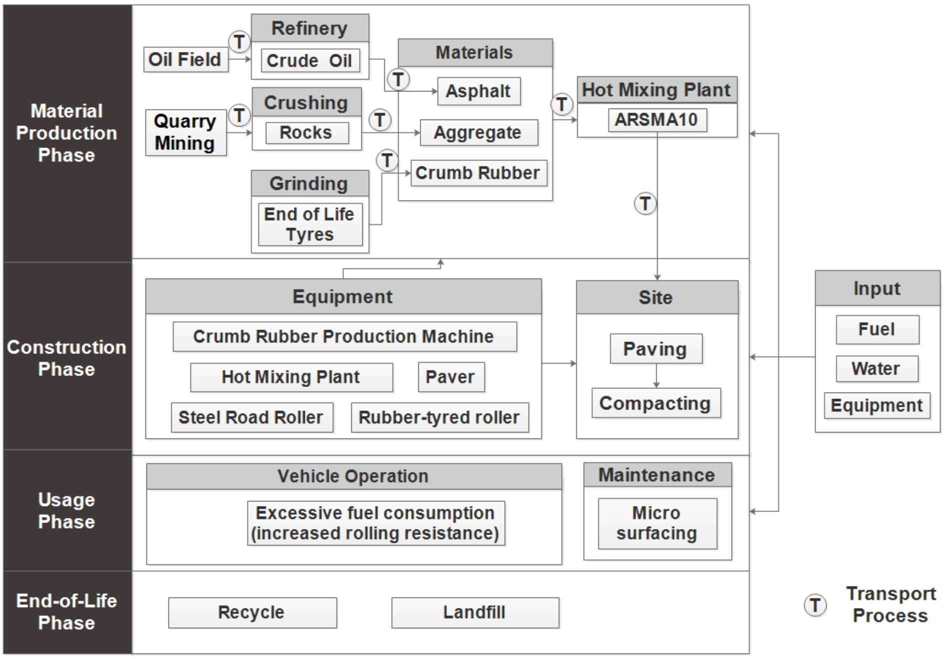


Figure 1. Life cycle phase and system boundary of ARSMA10

2.3 *Maintenance Strategies Determination Based on the MEPDG*

The MEPDG methodology was adopted to predict the pavement performance based on the traffic loading, material properties, and environmental data. The responses were used to predict incremental damage over designed life time (Baus & Stires, 2010). The MEPDG software applied in this study was AASHTOWare Pavement ME Design (Version 2.2, 2015), and its design methodology is documented in the Mechanistic-Empirical Pavement Design Guide, Manual of Practice, Interim Edition (AASHTO, 2008). There were two objectives of employing MEPDG: to make sure the pavement designs of the two materials can meet the performance criterion, and to predict the distress development of pavement material.

To predict the accumulated deterioration of the two materials, the laboratory measured material properties were used as the input variables. Specifically, the property inputs of ARSMA10 and PMSMA10 included unit weight, effective binder content, dynamic modulus of mixture, and Superpave performance grade of asphalt. Table 1 summarizes the general pavement design information, which was assumed according to the common practice in Hong Kong.

Table 1. The summary of pavement design information

General Information	
Pavement type	Flexible Pavement
Design life (years)	20
Layer Thickness (mm)	40
Length (m)	1000
Lane width (m)	3.5
Number of Lanes	4
Discount Rate	4%
Traffic Information	
AADT	10000

Growth Rate	3%	
Growth Function	Linear	
Vehicle Distribution	37.3%	Passenger car
	23.2%	Single-unit, short-haul truck
	37.2%	Single-unit, long-haul truck
	1.8%	Combination short-haul truck
	0.5%	Combination long-haul truck,
Operation Speed (km/h)	90	
Climate Information *		
Climate Station	Hongkong, HK (99998)	
Mean annual Wind speed (kph)	9.31	
Mean annual Air temperature (deg C)	23.41	
Mean annual sun radiation	80.91%	
Mean annual precipitation (mm)	100.8	
Annual depth to water table (m)	6	

*The climate data is time-related and dynamic, the values of climate information in the table were calculated based on the hourly climate data from Jan/2000 - Jan/2010 to reflect the average level.

The IRI and rut depth were selected as the two measurement indexes in this study. The first index represents a standardized pavement unevenness (Sayers et al., 1986), while the second one refers to the accumulated pavement deformation (Simpson, 2003). Based on these two indexes, an effective pavement maintenance strategy was developed accordingly.

Previous studies have shown that preventive maintenance may prevent a pavement from requiring corrective maintenance, and can be six to ten times more cost-effective than a “do nothing” maintenance strategy (Johnson, 2000). Hence, preventive maintenance strategy was selected in this study. Furthermore, among various candidates for the preventive maintenance treatments, microsurfacing was selected in this study, considering that it is documented to be appropriate for most of the common distress types, such as roughness, rutting, cracking and raveling (Wilde et al., 2014). The maintenance intervals of the two asphalt mixtures were determined based on the accumulated deterioration predicted by the MEPDG software.

2.4 *Life Cycle Inventory Analysis*

LCI analysis is the second step of LCA method (ISO, 2006). This step is dedicated to present the major unit processes and relative calculation procedures within the considered life-cycle phase.

The material production phase included the extraction and initial processing of aggregates, asphalt, and other supplementary materials such as crumb rubber (Wang et al., 2012). The unit processes considered in this study included asphalt refinery, aggregate production, and mixture hot mixing. For ARSMA10, the rubber powder production was also considered. The data with respect to the energy consumption factor and GHG emission factor of aggregate were obtained from the Chinese Life Cycle Database (CLCD) Database (CLCD, 2010), and the relative factors of polymer modified asphalt were provided by the European Bitumen Association (Eurobitume, 2011). Besides, the process of processing asphalt rubber included crumb rubber production and asphalt rubber production. The data for energy consumption and GHG emissions were calculated according to the survey results of Zhu et al. (2014). The reference data of material production phase employed in this study are summarized in Table 2.

The construction phase consisted of two parts: transportation of material and on-site construction. The 30t diesel truck was selected in the transportations of raw materials and hot mixtures, and the corresponding energy consumption and emissions were calculated according to CLCD (2010). The construction schedule and equipment activities of ARSMA10 were formulated following the Asphalt Rubber Design and Construction Guidelines (Hicks, 2002), by only considering the paving and compacting. Furthermore, the construction activities of PMSAM10 were assumed to be the same as ARSMA10. The emission factors of the paving and compacting processes of the two materials were calculated according to the power of machines and production efficiency (Zhu et al., 2014).

The usage phase primarily focused on the roughness effect on the additional fuel consumption and GHG emissions. The relationship between pavement smoothness and extra fuel consumption of vehicles has been studied in various literatures. It was reported that from 60 to 123.4 in/mi (0.95 to 1.95 m/km), a 63.4 in./mi (1m/km) incremental change of IRI would increase the energy consumption by 3.7% for passenger cars, 1.2% for small trucks, 1.3% for medium trucks, and 0.9% for large trucks (Yang et al., 2015). According to Kalembo et al. (2011), the GHG emissions can increase 35,010 kg annually for the traffic volume of 1,000 vehicles per hour when the IRI changes from the good (<95 in./mi) to poor condition (>150 in./mi). The IRI changes of ARSMA10 and PMSAM10 were predicted by the MEPDG, so the calculation of the GHG emissions and energy consumption in the functional unit (Table 2) should be consistent with the AADT, growth rate and the vehicle distribution used in the MEPDG. Furthermore, the pavement maintenance work is necessary during the operation of the pavement system, and the corresponding emissions and energy required were also counted into the usage phase in this study.

When a road pavement reaches its service life, it can remain in place serving as support for a new pavement structure or be removed. By adopting a "cut-off" allocation method, no environmental impacts were assigned to the EOL phase in this study.

Table 2. GHG emission and energy consumption of pavement life cycle inventory

Life Cycle Inventory			Mixture Type		Data Reference
			ARSMA10	PMSMA10	
Material Production	Asphalt	Energy consumption (MJ/t)	189.33	311.20	CLCD (2010), Eurobitume (2011) and Zhu et al. (2014)
		Emissions (CO_2-e kg/t)	21.42	18.57	
	Aggregate	Energy consumption (MJ/t)	29.99	29.99	
		Emissions (CO_2-e kg/t)	2.29	2.99	
Transportation of Raw Materials (50km)		Energy consumption (MJ/t)	40.20		
		Emissions (CO_2-e kg/t)	3.74		
Asphalt Mixture Hot Mixing		Energy consumption (MJ/t)	353.50	336.67	
		Emissions (CO_2-e kg/t)	29.67	28.26	
Transportation of Hot Mixture (20km)		Energy consumption (MJ/t)	16.08		
		Emissions (CO_2-e kg/t)	1.50		
Pavement Construction	Paving	Energy consumption (MJ/t)	15.86		
		Emissions (CO_2-e kg/t)	1.18		
	Compaction	Energy consumption (MJ/t)	18.60		
		Emissions (CO_2-e kg/t)	1.38		
Pavement Usage	Preservation (Micro Surfacing)	Energy consumption (MJ/m^2)	6.5		Chehovits & Galehouse et al. (2010)
		Emissions (CO_2-e kg/m^2)	0.3		
	Additional energy consumption and GHG emissions caused by IRI changes	Energy consumption* (MJ/vehicle mile)	Passenger car	0.15	Yang et al. (2015) & Kang et al. (2014)
			Single-unit, short-haul truck Single-unit, long-haul truck	0.12	
			Combination short-haul truck Combination long-haul	0.25	

	truck		
	GHG Emissions** (CO$_2$-e kg/vehicle hour)	0.004	Kalembo et al. (2011)

*Under the condition that per 63.4 in/mi (1m/km) increase of IRI

**Under the conditions that IRI increases from Good condition (<95 in/mi) to poor condition (>150 in/mi).

2.5 *Total Cost and Benefit Accounting*

The final step was to convert all the impacts into monetary value for the purpose of more accessible comparison of the two pavement materials. The report by the World Conservation Union (2006) suggests that the three dimensions of sustainability: environmental, social and economic, are the mainstream sustainability thinking, which needs to be balanced and better integrated. In this study, all three dimensions were considered and expressed as the cost and benefit. The economic impacts were represented by the agency investment cost; the environmental impacts computed from LCA were converted to the environmental damage cost; and the social impacts of pavement materials mainly focused on the noise impact to people, which were presented as the noise reduction benefits.

The agency investment costs consisted of the material cost, construction cost and the maintenance cost, which were investigated according to the Asphalt Rubber Usage Guide (State of California Department of Transportation, 2003), Rubber Asphalt Industrialization Feasibility Report in Guangdong Province (Guangzhou Municipal Industries Ltd., 2011), and Handbook on Asphalt Pavement Maintenance (Johnson, 2000).

The Environmental Damage Costs (EDC) are the costs for unit of air pollutants that people need to pay to offset the effects on environment (Yu et al., 2013). A statistical analysis was conducted by Yu et al. (2013) to find the mean values (50$/t in 2010) of the EDC for CO$_2$ among the wide range from 5$/t to 1667$/t.

The value of noise was calculated as the unit marginal cost per person exposed to a certain noise level (European Commission, 2014), which are provided in the Handbook on Estimation of External Costs in the Transport Sector (Maibach et al., 2008). The noise reduction benefit of asphalt mixtures is the difference between the noise costs of ARSMA10 and PMSAM10. According to various global rubberized asohalt studies, the avergar noise reduction of asphalt rubber would be 2-3 dB and the noise of asphalt rubber overlay is measured and documented as 73.7dB. Consequently, 3dB was selected as the noise reduction when employing ARSMA10 in this evaluation, and 200 persons were assumed to be directly exposed to the highway every year.

The details of the life cycle costs are listed in Table 3.

Table 3. Summary of life cycle cost

Life Cycle Cost*		ARSMA10	PMSMA10	Data Reference
Construction Cost**	Material ($\$/\mathrm{t}$)	87	68	State of California Department of Transportation (2003)
	Equipment ($\$/\mathrm{m}^2$)	0.17		Guangzhou Municipal Industries Ltd. (2011)
	Fuel($\$/\mathrm{m}^2$)	1.37		
	Labor($\$/\mathrm{m}^2$)	0.07		
	Management($\$/\mathrm{m}^2$)	0.04		
Maintenance Cost*** ($\$/\mathrm{m}^2$)		3.92		Johnson (2000)
Environmental Damage Costs**** ($\$/\mathrm{t}$)		63.27		Yu et al. (2013)
Noise Costs ($\$$/person year)		510.86 (>73dB)	593.97 (>76dB)	Maibach et al. (2008), RPA (2003) and Sacramento County Department of Environmental Review and Assessment (1999)

*The costs have been converted to the present value (PV) according to the cost in the reference, and 4% was selected as the discount rate.

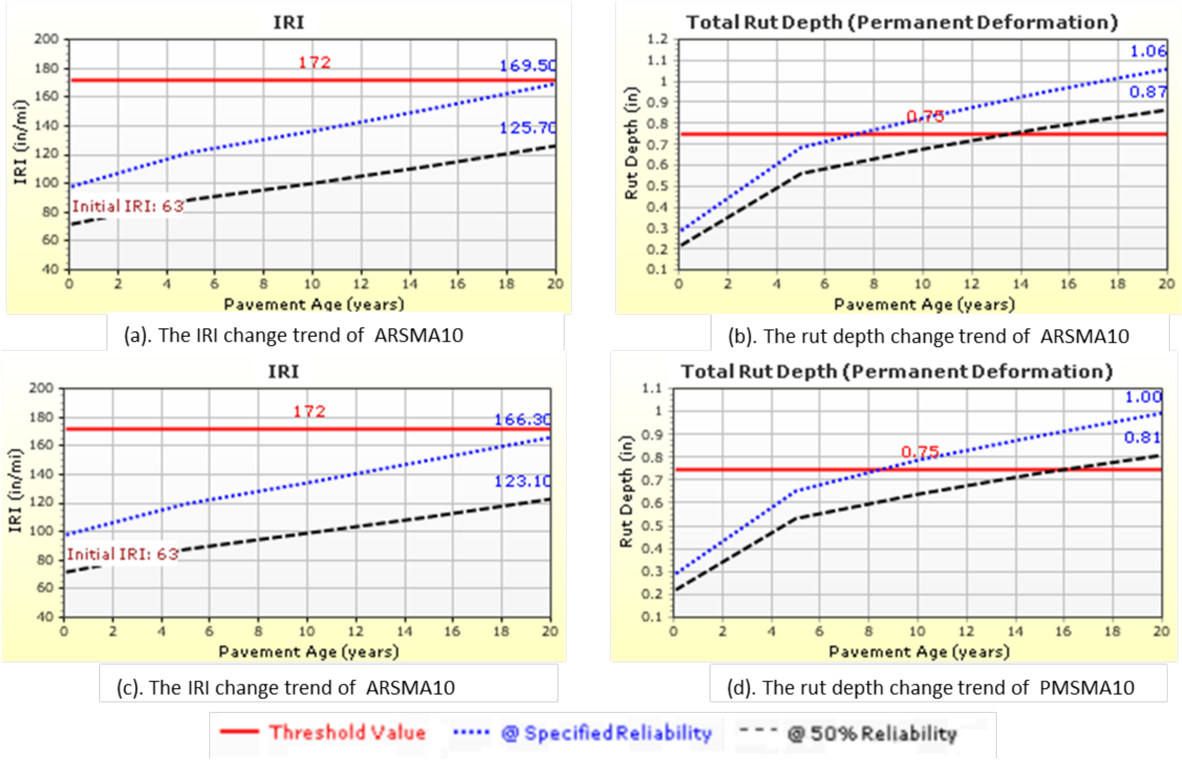
** The thickness of pavement is 40mm

*** The maintenance refers to the pavement preservation treatment, microsurfacing.
****The air pollutant item considered is the mass of CO_2 in the whole life cycle.

3 RESULTS AND DISCUSSION

3.1 *Maintenance Plan Determination from MEPDG*

The results of the accumulated change of IRI and rut depth in 20-year design life predicted by the MEPDG software are illustrated in Figure 2.



(a). The IRI change trend of ARSMA10

(b). The rut depth change trend of ARSMA10

(c). The IRI change trend of ARSMA10

(d). The rut depth change trend of PMSMA10

Figure 2. Performances of the two materials predicted by the MEPDG software

It is evident that the IRI values for the two materials stay within the permissible range of MEPDG during the design life.

For ARSMA10, when it reaches approximate seven years, the predicted rut depth exceeds the threshold value, while for PMSAM10, it takes eight years. This indicates that the rut-resistance of the selected polymer modified asphalt mixture is better than that of the asphalt rubber mixture in this study. The maintenance strategies were then determined according to the estimated development of rut depth. The analysis period (56 years) is determined as the least common multiple (LCM) of maintenance intervals (7 & 8 years) for the two materials based on the rut depth prediction. As illustrated in Figure 3, in the 56-year analysis period, the preservative maintenance (microsurfacing) would be conducted every eight years for PMSMA10, and every seven years for ARSMA10.

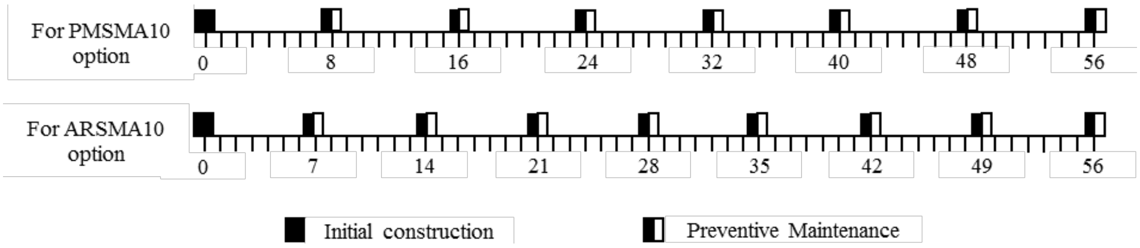


Figure 3. Maintenance plans for the two pavement material designs

3.2 *Environmental Performance*

The breakdowns of GHG emissions and energy consumption for the four major phases of the life cycle of the two mixes are shown in Figure 4 and Figure 5, respectively. In the 56-year analysis period, the dominant contributions were made by the extra impacts caused by the pavement IRI change. In general, PMSMA10 has better environmental performance than ARSMA10 with regarding to both emissions and energy consumption.

As in Figure 4 shows, the percent distribution of the extra GHG emissions due to roughness change in the usage phase is especially overwhelming, approximately 242 and 214 kg/m^2 for the two mixes, respectively, since the sum of emissions in the other life-cycle phases of ARSMA10 and PMSAM10 (3.37 and 3.35 kg/m^2) are negligible in comparison.

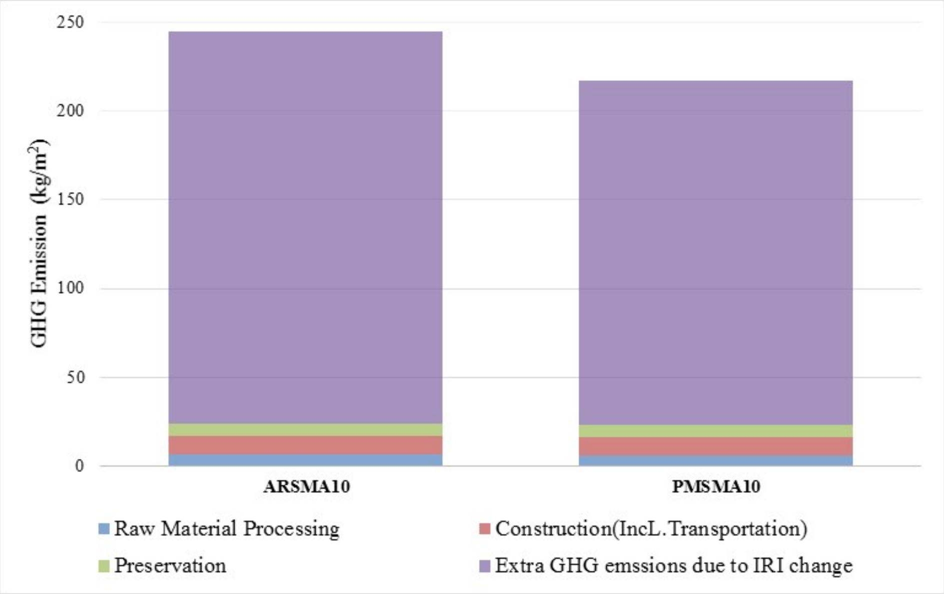


Figure 4. GHG emissions breakdown of the two pavement materials

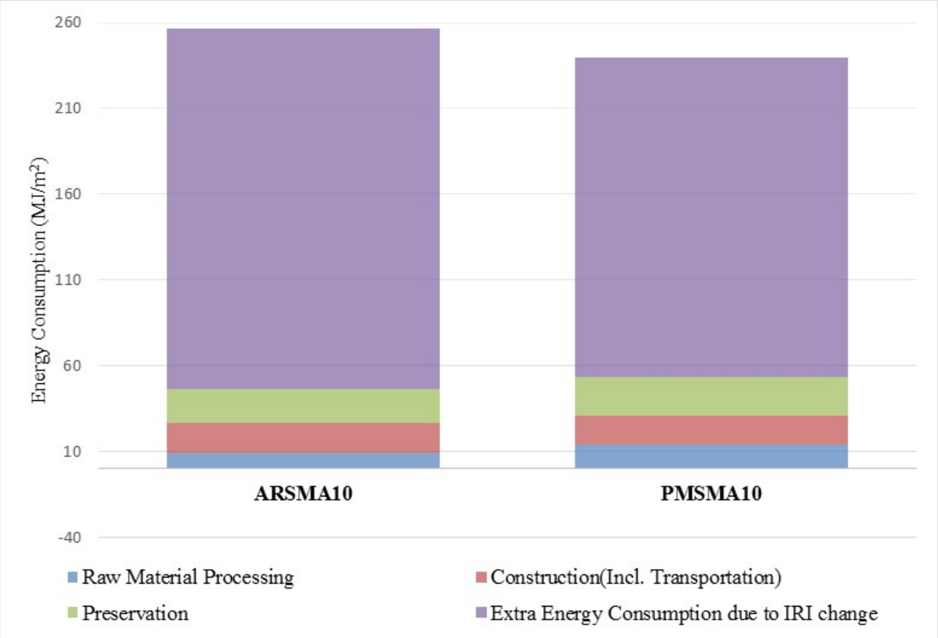


Figure 5. Energy consumption breakdown of the two pavement materials

As Figure 5 illustrates, when the impact of IRI in the usage phase is ignored, the energy consumption by the function unit of ARSMA10 (46.5 MJ/m^2) is less than that of PMSMA10 (53.5 MJ/m^2). Because of the better serviceability performance of PMSAM10 predicted by MEPDG, the extra energy consumed by vehicles on ARSMA10 pavement (209.8 MJ/m^2) is estimated to be more than that by vehicles on PMSMA10 (185.7 MJ/m^2), which leads to more overall life-cycle energy consumption of ARSMA10.

3.3 *Overall Sustainability Performance*

When the environmental impact is considered as the only performance measurement, PMSAM10 is estimated to perform better because of its lower EDC (13.5 \$/m^2). In addition, the investment cost of ARSMA10 (17.2 \$/m^2) is slightly higher than that of PMSAM10 (16.2 \$/m^2), as the asphalt rubber material had higher price than the polymer modified asphalt.

Nevertheless, when assuming that the ARSMA10 can contribute 3dB noise reduction from 76dB noise of PMSMA10, the noise reduction benefit (29.1 \$/m^2) of ARSAM10 in the 56-year analysis period is estimated to be able to offset the other cost expenditure (32.7 \$/m^2) in economic and environmental dimensions.

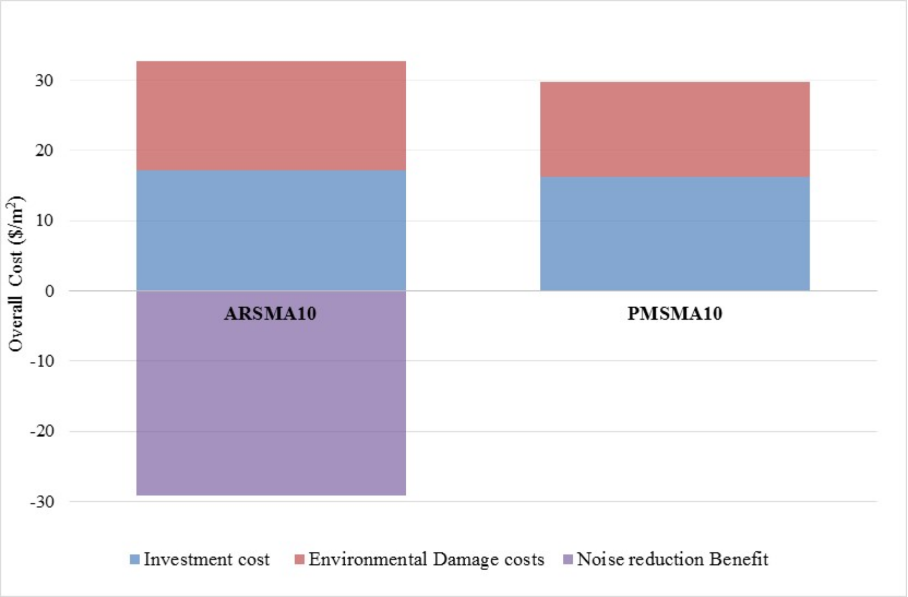


Figure 6. Overall cost breakdown of the two pavement materials

4 CONCLUSIONS

In this study, a comparative sustainability assessment was conducted on two asphalt mixtures: ARSMA10 and PMSAM10, by converting their corresponding economic, environmental and social impacts to the monetary values. The following points summarize the main findings of this study:

- In the 56-year analysis period, the dominating contributing factor for environmental impact is the extra GHG emissions and energy consumption of vehicles due to the pavement roughness change. Overall, PMSMA10 has better environmental performance than ARSMA10, in terms of both emissions and energy.
- When the noise impact is ignored, the overall long-term performance of PMSMA10 is better with lower agency investment cost and environmental damage cost.
- The long-term accumulated noise impact is considerable assuming that ARSMA10 is able to decrease the noise by 4%, which can almost offset its higher agency investment cost and environmental damage cost.

Based on the findings of this study, further research is recommended on the cost and benefit analysis of installing noise barrier to PMSMA10 pavement to achieve the same amount of noise reduction as the ARSMA10 pavement. It is also worth to mention the land use saving due to the recycling of EOL by ARSMA10 was not considered in this study, which is a factor that will further improve the environmental performance of ARMSA10.

Furthermore, this research followed many standards: the cost benefit calculation technique was adopted from European standards; Pavement material design information and performance prediction based on Hong Kong traffic and climate data; and the data references were accessed from California and China. For simplicity, the potential effects from this multi-standard employment would be stated through compare Hong Kong with other regions (e.g. China, U.S., and Europe). For the life cycle assessment part, assuming the same decisions in the selection of construction equipment and techniques, the emission factors would largely rely on the energy source and distribution. According to Hong Kong Energy Statistics (2015), Hong Kong derives its energy supplies almost entirely from external sources. Energy is either imported directly, or produced through some intermediate transformation processes using imported fuel inputs. In the contrary, both China and U.S. can self-supply to satisfy the domestic energy demands (China Energy Group, 2014; Ratner & Glover, 2014). In this sense, when the energy demands are same, the energy costs and environmental impacts in Hong Kong would evidently larger than the other two regions. In terms of the monetary transformation of noise impacts, the cost factors are the investigated willing-to-pay (WTP) for reducing annoyance based on stated preference studies and quantifiable costs of health effects in Europe. It is hard to say that the WTP in Hong Kong would be higher than Europe. Nonetheless, the uniqueness of Hong Kong (e.g. hot climate, topography, dense population, high-rise buildings and intensive bus traffic) is most likely to create more serious noise impacts in Hong Kong. In general, the usage variety of standard would indeed cause some effects on the overall impacts, however, from the perspective of comparison, simultaneous increase or decrease would not greatly affect the relative results from the two comparative objects.

Finally, this study only investigated these two materials as a case study, sensitivity analysis is recommended in the future study to take into consideration of the effects of uncertainties in various variables, such as the material composition and performance, time period, system boundaries, transportation distance, and treatment of refinery allocation.

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