https://dx.doi.org/10.1016/j.jclepro.2022.130405

Environmental and Economic Assessment of Collective Recycling Waste Plastic and Reclaimed Asphalt Pavement into Pavement Construction: A Case Study in Hong Kong

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Abstract

The use of waste plastic and reclaimed asphalt pavement (RAP) in roadway construction has been considered as sustainable paving practice due to its potential environmental and economic benefits. For cities with scarce land and mineral resource, such as Hong Kong, these benefits are expected to be greater. However, no study has yet attempted to quantitively assess the benefits of simultaneously recycling waste plastic and RAP into road. To fill this gap, this study investigated the technical, environmental, and economic feasibility of using Polyethylene Terephthalate (PET) modified asphalt containing RAP in pavement maintenance and rehabilitation (M&R) from a life cycle perspective. The technical feasibility was demonstrated by laboratory test results. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) were performed to quantify the environmental and economic impact. This was followed by a sensitivity analysis, which was conducted to identify the critical variables, determine the tolerable variable variations, and estimate the potential loss under the pessimistic scenario. The results show that incorporating waste PET and RAP into pavement could reduce the life cycle costs and greenhouse gas (GHG) emissions by up to 26.2% and 29.0%, respectively. The durability was the key factor in maintaining their advantages throughout the pavement life cycle. It was also found that the benefits of using PET modified asphalt were significantly greater than the potential losses. The outcomes of this study are expected to help the practitioners to enhance the sustainability of roadway infrastructure and improve waste management in metropolitan cities like Hong Kong.

Keywords: Asphalt pavement; Waste PET modified asphalt; RAP; Life cycle assessment; Life cycle cost analysis; sensitivity analysis.

1 Introduction

Transportation sector contributes a large percent of greenhouse gas (GHG) emissions. According to Hong Kong Environmental Protection Department (HK EPD, 2020a), the total GHG emissions in Hong Kong is 40.4 million metric tons of carbon dioxide equivalent (CO_2e) in the year of 2017, of which the transportation sector is the second largest source of emissions, accounting for 18.2% of the total GHG emissions. As a major contributor in this sector, roadway construction requires significant energy consumption due to the rapid deterioration of pavement infrastructure and the considerable volume of raw materials consumed every year. Meanwhile, the construction, maintenance and rehabilitation of roadways require a large amount of budgetary investment. It was estimated that the annual shortfall of pavement maintenance funds in the U.S. was around $89 billion after a scheduled budget of $91billion (Yu et al., 2013). These facts have motivated the transport agencies to seek for more environmentally friendly and cost-effective paving materials and technologies.

One common sustainable practice is the incorporation of reclaimed asphalt pavement (RAP) into virgin hot mix asphalt (HMA) materials (Lee et al.,2010; Bressi et al., 2021). Many studies have reported the economic and environmental benefits of using RAP in asphalt mixtures due to its partial replacement of virgin aggregates and asphalt binder (Aurangzeb et al., 2014; Cao et al., 2019). Moreover, for cities like Hong Kong where local mineral and land resource are very scarce, recycling of RAP may even generate more energy and budget savings due to the reduced dependency on imported materials and less construction and demolition

(C&D) materials that need to be transported to other regions (Hossain et al., 2016). However, the main concern arising from this substitution is that the aged binder in RAP would make the modified mixtures more susceptible to thermal and fatigue cracking than virgin mixtures (Zhou et al., 2019). As a consequence, the benefits derived from using fewer raw materials may be offset by the need for more maintenance and rehabilitation (M&R) cycles. To improve the performance of RAP mixtures, the current practice is to add bitumen modifiers or rejuvenators to the RAP binder (Ma et al., 2020; Sreeram et al., 2018; Jiang et al., 2020). While this could be a solution, the production and transportation of modifiers or rejuvenators may cause additional burdens.

On the other hand, the inundation of waste plastic bottles has posed significant environmental and economic burdens. In Hong Kong, the generation of waste plastic was 923.9 thousand tonnes in 2019, of which 846.8 thousand tonnes (91.7%) were disposed of at landfills and 77.1 thousand tonnes (8.3%) were recovered for recycling (HK EPD, 2020b). This low recovery rate contrasts with that of 13% in 2017 owing to China's waste import ban, which in some ways also promoted the development of local recycling facilities. However, the plastic recovery rate in Hong Kong is still very low with the vast majority ending up in landfills, which would not only occupy scarce land resources but also cause serious pollution concern (Environment Bureau, 2021). Thus, appropriate management of post-consumer and post-industrial plastic waste becomes increasingly important.

To address the waste plastic problem, one of the attempts is the utilization of waste plastic as polymeric additives in asphalt binder. Previous studies have demonstrated the potential technical benefits of recycling waste plastic as an asphalt modifier (Leng et al., 2018; Sreeram et al., 2018). Types of waste plastics that have been investigated in the literature as potential asphalt additives include polyethylene (PE) (Ma et al., 2021a, 2021b; Hınıslıoğlu and Ağar, 2004; Ho et al., 2006), polyethylene terephthalate (PET) (Ahmadinia et al., 2011; Li et al., 2021), polypropylene (PP) (Al-Hadidy and Tan, 2009), and so on. Among them, PET, which is commonly used for beverage bottles, has been widely studied. Some frequently highlighted merits of PET modified asphalt include the better resistance to permanent deformation, reduced temperature susceptibility, improved fatigue resistance, greater Marshall Stability and stripping resistance (Ahmadinia et al., 2011; Moghaddam et al., 2014; Gürü et al., 2014; Ahmad et al., 2017). Recently, some researchers started to look into the possibility of using waste PET-based additives to improve the performance of RAP mixtures while simultaneously recovering two waste materials (Leng et al., 2018; Sreeram et al., 2018). It was found that the incorporation of PET-derived additives to mixtures containing RAP improves the rutting and fatigue cracking resistance and reduces the aging effect. Therefore, it can be expected that PET additives derived from waste plastic bottles may potentially replace commercial polymers such as styrene-butadiene-styrene (SBS) at a lower cost and reduced energy demand.

Although the potential advantages of waste plastic modified asphalt were frequently reported in recent studies, there is little knowledge regarding the quantitative evaluation of the economic and environmental effects of using such materials in road pavement applications. To the best of authors' knowledge, only five published studies have quantitively investigated the environmental impact of waste plastic modified asphalt (Guðmundsdóttir, 2018; Gulotta rt al., 2019; Praticò et al., 2020; Santos et al., 2021; Oreto et al., 2021). However, they differ from the present study in three ways. First, none of them simultaneously dealt with the technical, economic, and environmental performance of waste plastic modified asphalt. Second, the modification methods and the geographical scopes of those studies were different from this study. Third, none of these studies considered the simultaneous recovery of waste plastic and RAP in one mixture.

Hence, this study aims to quantitively evaluate the economic and environmental performance of PET modified asphalt containing RAP from a life cycle perspective. By incorporating life cycle assessment (LCA), life cycle cost analysis (LCCA) and sensitivity analysis (SA), this study is expected to ultimately shed some light on whether and to what extent the simultaneous recycling of waste PET and RAP in road may exert positive influence under different scenarios.

2 Materials and method

2.1 Goal and scope definition

LCA was performed in this study to assess the environmental impact associated with the various pavement life cycle phases following the ISO 14040/44 guidelines (ISO, 2006a; ISO, 2006b) and the pavement LCA framework established by Federal Highway Administration (FHWA) (Harvey et al., 2016). Meanwhile, LCCA was conducted to evaluate the long-term economic efficiency of the competing alternatives in accordance with the FHWA report of Life-Cycle Cost Analysis in Pavement Design (Walls and Smith, 1998).

It is worth repeating that the goal of this study is to quantify the environmental and economic benefits resulting from the application of PET modified asphalt with RAP. The waste plastic was recycled through the so-called wet method, which means it was used as an additive for binder rather than a substitute for aggregate. The geographic scope of the study is Hong Kong SAR, China. Hence, the polymer modified stone matrix asphalt with 10 mm maximized aggregate size (PMSMA10), a widely used asphalt mixture in Hong Kong, was selected as the benchmark material. Four mixtures containing 2% of PET-derived additives by weight of virgin binder and different RAP contents (0%, 15%, 25% and 40%) were considered as the alternative materials, which are labelled as 2%PETSMA10, 15%RAP-2%PETSMA10, 25%RAP-2%PETSMA10 and 40%RAP-2%PETSMA10. By comparing the different materials, five sub-goals, as listed below, could be further achieved.

1) To investigate the potential impact of using PET-derived additives as a substitute for the most commonly used commercial polymer modifier for asphalt binder, i.e., SBS.
2) To estimate the benefits of simultaneously recycling waste PET and RAP into asphaltic paving materials.
3) To determine whether PET modified asphalt containing higher RAP content is more sustainable.
4) To calculate the minimum service life that can guarantee the sustainability performance of PET modified asphalt.
5) To identify the critical variables that may eliminate the advantages of PET modified asphalt and estimate the corresponding risk levels.

The functional unit (FU) considered in this study was the 4cm wearing course of a one lane-km pavement section. The analysis period was set to be 50 years to allow multiple M&R cycles in the pavement life cycle. Based on a thorough investigation of the highway construction industry and the municipal solid waste (MSW) management practice in Hong Kong, the system boundary of the LCA and LCCA model was established as Fig. 1 illustrates. The following four pavement life cycle phases were covered: material production, construction, maintenance and end-of-life (EOL).

The use phase was not considered in this study due to the lack of reliable and consistent field data of these innovative materials. The material production phase can be further broken down into several sub-stages. To produce the PET-derived additive, the waste PET bottles were first collected and transported from the collection sites to the recycling plant. They were then cleaned and shredded into small flakes. After that, an aminolysis process as reported by (Leng et al., 2018) was employed to chemically recycle the PET. Triethylenetetramine (TETA) was used as the amine and the ratio of it with PET flakes is 2:1. The reaction mixture was heated at 140°C to reflux for 2 h. Following the completion of the PET degradation process, the final product can be acquired by filtration and drying. More information on the manufacture of PET-derived additives could be found in Leng et al. (2018). In addition, the production of TETA and the wastewater treatment were also included in the system boundary. The production of PET-derived additives was a multi-output situation. The co-product was ethylene glycol which can be recycled after appropriate processing. Thus, the physical (i.e., mass) allocation method was employed to allocate the environmental burden between the products. The transport of waste PET bottles to landfill sites as well as the environmental impact associated with the landfilling were considered as the avoided impact. The corresponding avoided cost was estimated with reference to the MSW charging scheme (HK EPD, 2018). As for the end-of-life phase, a salvage value was considered for the LCCA model, while the cut-off method was used in the LCA model.

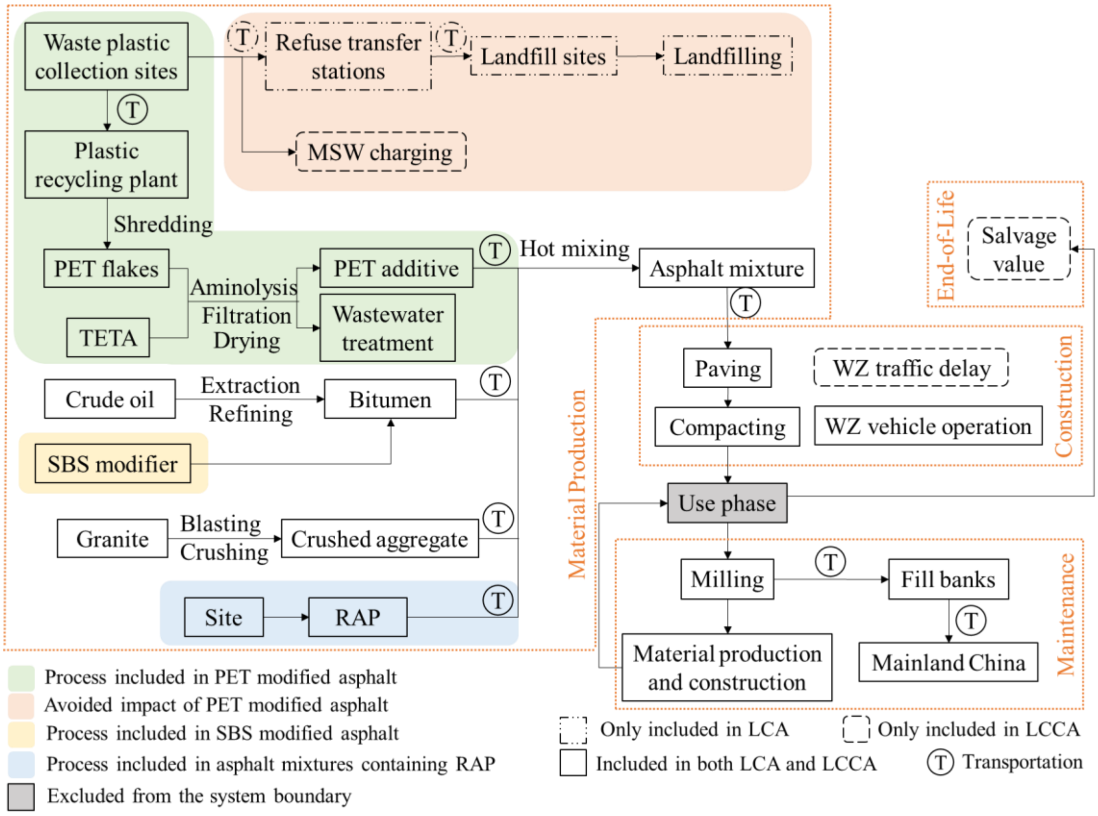


Fig. 1. System boundary.

2.2 Technical feasibility

To demonstrate the technical feasibility of PET modified asphalt, the laboratory test results presented in the authors' previous research papers were reviewed and summarized (Leng et al., 2018; Sreeram et al., 2018; Padhan et al., 2020). Meanwhile, a method was developed to estimate the service lives of the four alternative materials. Firstly, the service life of the benchmark material PMSMA10 was assumed to be 12 years (Cao et al., 2019). Secondly, the fatigue resistance performance of the different asphalt binders characterized by the fatigue index (G*sinδ) from the Dynamic Shear Rheometer (DSR) test was compared. The percentage change of this indicator relative to the benchmark binder (i.e., SBS modified binder) was then calculated. Finally, the percentage change with the same magnitude but opposite sign as that of G*sinδ was adopted to estimate the service lives of the alternative materials. Although such a method might not be accurate, it can still provide useful and reasonable information especially for comparison purpose. The studies conducted by Landi et al. (2020) and Guðmundsdóttir (2018) also adopted similar approaches.

2.3 Environmental and economic sustainability

2.3.1 Life cycle inventory analysis

The life cycle inventory (LCI) analysis is to collect the primary and secondary data for quantifying all the physical inputs to and outputs from the processes within the system boundary. In this study, the process-based LCI data were collected from a combination of governmental reports, specifications, public/ commercial databases, open-source software tools, literature, and a survey of equipment information. The LCI would be compiled using local data whenever and wherever possible. Table 1 and Table 2 present the transport information of the concerned materials and the detailed data sources for the LCA/LCCA model.

The fuel consumption (FC), emission factor (EF) and unit cost of diesel were obtained from Hong Kong Electrical and Mechanical Services Department (HK EMSD, 2020), Environmental Protection Department (HK EPD, 2010) and Census and Statistics Department (HK C&SD, 2021a), respectively. The EF and unit cost of marine transport were collected from the literature with the same geographic scope (Zhang et al., 2014) and the online resource (GlobalPetroPrice, 2021). This information would be used to calculate the GHG emissions and cost due to the use of fuels throughout the pavement life cycle.

Table 1

Transport data of raw materials.

Materials	Locations	Distance (km)	Transport type	Fuel type	FC/EF	Unit
Bitumen	Dongguan Taihe Asphalt Co. Ltd., China to mixing plant	100[*]	24t truck	Diesel	0.322[b]	L/km
Aggregates	Hui Dong Quarry, Guangdong, China to Huizhou Port	30[*]	24t truck	Diesel	0.322[b]	L/km
	Huizhou Port to Hong Kong Port	84[*]	Marine Transport	Heavy fuel oil	33.3[c]	g CO_2e/tkm
	Hong Kong Port to mixing plant	30[*]	24t truck	Diesel	0.322[b]	L/km
RAP	Site to mixing plant	30[*]	24t truck	Diesel	0.322 [b]	L/km
Milled asphalt materials	Site to fill banks	30[*]	24t truck	Diesel	0.322[b]	L/km
	Fill banks to reclamation site in Taishan of mainland China	200[a]	Marine Transport	Heavy fuel oil	33.3[c]	g CO_2e/tkm
Recycled PET	Waste plastic collection sites to plastic recycling plant	30[*]	18t truck	Diesel	0.262[b]	L/km
	Plastic recycling plant to mixing plant	11[*]	18t truck	Diesel	0.262[b]	L/km
Waste PET (landfill)	Waste plastic collection sites to refuse transfer stations	6[a]	6t truck	Diesel	0.201[b]	L/km
	Refuse transfer stations to landfill sites	35[a]	24t truck	Diesel	0.322[b]	L/km
Asphalt mixture	Mixing plant to construction site	30[*]	24t truck	Diesel	0.322[b]	L/km

[*] Estimated based on the geographic locations (average distance)

[a] Hossain et al., 2016

[b] HK EMSD, 2020

[c] Zhang et al., 2014

Table 2

Process-based data source for the LCA/LCCA model.

Life cycle phases	Materials/ processes	Data source (LCA)	Data source (LCCA)
Material production	Bitumen	Eurobitume (2011)	HK C&SD (2021a)
	Aggregate	Stripple (2001)	HK C&SD (2021a)
	TETA	Ecoinvent 3 (2016)	Supplier quotation
	PET-derived additive	Measured, CLP (2020)	Supplier quotation, GlobalPetroPrice (2021)

	preparation		
	Wastewater treatment	HK DSD (2020a)	HK DSD (2020b)
	Hot mixing	Santos et al. (2017), Engineering ToolBox (2003)	GlobalPetroPrice (2021)
	Avoided landfilling of PET	/	ELCD (2016)
	Avoided MSW charging	HK EPD (2018)	/
Construction / Maintenance	Milling, paving, compacting	JTG/T 3832-2018, JTG/T 3833-2018	
		HK EPD (2010)	HK C&SD (2021a), GlobalPetroPrice (2021), Ship&Bunker (2021)
	Labor	/	HK C&SD (2020)
	Work zone traffic delay	/	HK TD (2020), RealCost 2.5 (FHWA, 2011)
	Work zone vehicle operation	HK TD (2020), RealCost 2.5 (FHWA, 2011), MOVES (EPA, 2014)	
End-of-life	Salvage value	/	Walls and Smith (1998)

2.3.1.1 Material production phase

2.3.1.1.1 Bitumen and aggregate

In Hong Kong, a distinguishing region-specific characteristic is the local resource scarcity. According to HK HyD (2021), more than half of the local bituminous material suppliers imported bitumen and aggregates from mainland China. Meanwhile, the only active local quarry is also scheduled to cease operations in 2022. Thus, it can be expected that the dependency on imported aggregates is more likely to be heavier in the future. The transportation of imported materials significantly increases the carbon footprint of the locally used pavement materials. Therefore, promoting the wider use of RAP in bituminous pavement construction is always one of the environmental objectives and targets in Hong Kong (HK HyD, 2020). As shown in Table 1, the bitumen used in this study was imported from Dongguan Taihe Asphalt Co. Ltd., China with an average transport distance of about 100 km. Natural aggregates were sourced from Hui Dong Quarry in Guangdong, China and transported to Hong Kong by ocean ship and truck. The total transport distance was 144 km which was estimated based on the geographic locations. The emission factors of bitumen and aggregate production were taken from the two public reports (Eurobitume, 2011; Stripple, 2001) due to the lack of local data while their unit costs were retrieved from the website of Hong Kong Census and Statistics Department (HK C&SD, 2021a).

2.3.1.1.2 RAP

RAP was assumed to be milled and transported directly from the site to the mixing plant. In contrast, the unused milled asphalt materials were delivered to and temporarily stored in fill banks, pending an opportunity for reuse as public fill in reclamation, site formation and other earth filling works (HK CEDD, 2019a). However, in recent years, the amount of generated public fill was much larger than that in demand. As a result, a great deal of surplus public fill was delivered to Taishan in mainland China since 2007, which is about 200 km away from Hong Kong (HK CEDD, 2019b; Hossain et al., 2016). Such long-distance transport requires a large fleet of vessels, resulting in enormous costs and high carbon emissions. Hence, the local recycling of RAP plays an important role in reducing these impacts.

2.3.1.1.3 PET-derived additive preparation

Waste PET bottles are assumed to be collected from the designated recycling bins and transported to the local plastic recycling plant in Tuen Mun to produce PET-derived additives. Since both TETA and ethanolamine (EA) are amines and can be used for PET-derived additive preparation (Xu et al., 2020), the LCI data of EA production in the ecoinvent database were utilized to represent the environmental burden of TETA production (Ecoinvent 3, 2016). The energy consumption during the preparation of PET-derived additives was mainly associated with the shredding, aminolysis, filtration and drying process. The specific information of the machines, including the power, productivity, operation hours, and input/output materials, was collected first and then combined with the EF of electricity generation to calculate the GHG emissions. There are currently two electricity suppliers in Hong Kong. The EF provided in the sustainability report of CLP Power Hong Kong Limited (CLP, 2020) who supplies electricity to Kowloon was used in the base case scenario while the other would also be considered in the scenario analysis. As for the cost of PET-derived additives, it includes the cost of TETA, PET fakes, electricity consumed during preparation, and diesel fuel consumed in transportation. The unit costs of TETA and PET flakes were provided by the suppliers, with the former ranging from 26 to 35 HKD/kg and the latter being 3.5 HKD/kg. It is worth noting that the economic value of PET flakes must have included the costs for transporting and shredding the PET bottles, which turns waste PET bottles into PET flakes. Thus, the diesel fuel consumption of transporting waste PET bottles from collection sites to recycling plant and the electricity consumption during the shredding process was not considered in the cost calculation to avoid double counting.

In addition, the preparation of PET-derived additives could produce a certain amount of wastewater which mainly contains some chemical substances. Therefore, the environmental and cost burden of wastewater treatment was also covered in this study. Both the energy consumption and unit cost of wastewater treatment were obtained from the statistical data of Hong Kong Drainage Services Department (HK DSD, 2020a, b). In accordance with the sewage services charging scheme in Hong Kong, the surcharge for trade effluent containing basic industrial chemicals was used in this study.

2.3.1.1.4 The avoided impact

The avoided impact of transporting and disposing equivalent waste PET bottles to landfill sites was also considered. The transport distances from collection sites to refuse transfer stations (RTS) and then to landfill sites were obtained from the study conducted by Hossain et al. (2016). The avoided environmental impact of disposing waste plastic was calculated using the ELCD database (ELCD, 2016). Meanwhile, the MSW charging scheme (HK EPD, 2018), although not yet implemented, was used to estimate the potential economic loss resulting from the disposal of waste plastic, which is considered as the avoided cost in the present study.

2.3.1.1.5 Mixture production

The thermodynamics-based approach was employed to estimate the heat energy required for the production of asphalt mixtures, as shown in Eq. (1):

$$Q = {\left(\sum_i c_i \cdot m_i \cdot \Delta T + L_v \cdot m_{water}\right)} \Big/ f \qquad (1)$$

where Q is the total heat energy (J), c_i is the specific heat value of material i: $c_{granite}$=790 J/(kg·°C), $c_{waster,liquid}$=4182 J/(kg·°C), $c_{waster,vapor}$=1864 J/(kg·°C) (Engineering ToolBox, 2003), m_i is the mass of material i, ΔT is the temperature increase (°C), L_v is the latent heat required to evaporate water which is equal to 2256 J/kg, and f is a correction factor that accounts for the casing loss (Santos et al., 2017). Asphalt binder was assumed to be stored at 160 °C in heated tanks at the asphalt plant. The energy required to maintain the tank temperature against heat loss was obtained from the literature (Santos et al., 2017). A natural gas-fired drum-mix plant was assumed to produce the asphalt mixtures in this study. Thus, the GHG emission and cost of hot mixing can be roughly estimated by combining the required heat energy with the emission factor and unit cost of natural gas, respectively (US EIA, 2016; GlobalPetroPrice, 2021).

Moreover, based on the survey of the geographic locations of asphalt plants and construction sites in Hong Kong, an average distance of 30 km was considered for transporting the asphalt mixtures.

2.3.1.2 Construction and M&R phase

In the construction phase, the environmental burdens were caused by the combustion-related emissions from the usage of construction equipment while the economic impact was due to the fuel consumption and labor use. Information regarding the fuel type, machine productivity, fuel consumption, and labor use of each equipment were collected from the Chinese specifications (JTG/T 3832-2018, JTG/T 3833-2018). They were then combined with the fuel emission factor, fuel cost and labor cost in Hong Kong to calculate the GHG emissions and cost.

Additionally, the impact of work zone (WZ) traffic speed changes and delays was also considered. WZ user cost is the additional costs incurred by the reduced capacity in WZ areas. It generally includes the vehicle operation costs (VOC), time delay costs (TDC), and crash costs. In this study, crash costs were excluded due to the lack of data. The RealCost software (FHWA, 2011) was applied to estimate the WZ user cost. It was assumed that one of the four lanes in one direction of the highway was closed during WZ operations. The annual average daily traffic (AADT) and hourly traffic distribution of a counting station listed in the annual traffic census 2019 of Hong Kong Transport Department (HK TD, 2020) were used in this case study. The speed limit was assumed to be reduced from 90km/h to 60km/h in the WZ. Regarding the environmental impact of WZ operations, a two-step method was adopted. First, the outputs from RealCost software such as the number of vehicles traversing WZ, the number of vehicles traversing queue, queue length and queue speed in each hour were stored. Second, the inputs of MOVES software (EPA, 2014) were prepared using these outputs. For example, several links with different vehicle speeds (normal speed, WZ speed and queue speed) were established. The software then run to calculate the additional GHG emissions arising from the WZ operations.

2.3.1.3 End-of-life phase

A cut-off method was used for the EOL phase in the LCA model. Thus, no environmental burden was assigned to this phase. In the LCCA model, a salvage value was considered for the EOL phase, which is defined as the remaining value of the investment at the end of the analysis period, as shown in Eq. (2):

$$SV = C_{last\ M\&R\ activity} \cdot \frac{RSL}{SL} \tag{2}$$

where SV is the salvage value, $C_{last\ M\&R\ activity}$ is the cost of the last M&R activity, RSL is the remaining service life of the last M&R activity at the end of the analysis period, and SL is the service life of the last M&R activity.

2.3.2 Life cycle impact assessment

Life cycle impact assessment (LCIA) estimates the human or environmental impact of the system by translating the LCI results into various impact categories. A large variety of metrics could be used to measure such impact from different aspects. In this study, the global warming potential (GWP) measured in CO_2e, which is a mid-point indicator for evaluating the climate change effect was used since the carbon emission data is more reliable and easy to localize. The 100-year GWP for each greenhouse gas described in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013) was employed as the characterization factor.

2.3.3 Life cycle cost (LCC) computation

LCCA evaluates the economic performance of competing alternatives by incorporating the initial and discounted future cost over the entire life cycle into the calculation. The cost items generally include agency cost (i.e. material, machinery and labor cost), user cost (i.e. VOC, TDC and crash costs) and other relevant costs, which have been explicitly introduced in the previous sections. To obtain the LCC, the expenses occurred at different time points of the life cycle were converted to the present values using a discount rate of 4% and then summed up (Walls et al., 1998).

2.4 Sensitivity analysis

Although this study has endeavored to adopt primary data and location specific secondary data, there remains considerable uncertainty in input parameters in the absence of long-term field performance data of these innovative materials. Therefore, a sensitivity analysis was conducted in accordance with European Commission guidelines (European Commission, 2014) to identify the critical variables and estimate the risk levels. Based on this approach, all the costs including the monetization of intangible items (i.e. GHG emissions) were integrated into the economic appraisal. Thus, the previously quantified GHG emissions were first converted to monetary value by multiplying by the unit cost of CO_2e. Economic Net Present Value (ENPV), which is defined as the difference between the discounted total benefits and costs (European Commission, 2014), was then employed to evaluate the economic performance of each alternative, as shown below (Landi et al., 2018):

$$ENPV = PV(B) - PV(C) \tag{3}$$

where PV(B) refers to the present value of total benefits and PV(C) is the present value of total costs. Table 3 presents the benefit and cost items related to the replacement of PMSMA10 with PET modified asphalt.

Table 3

Benefits and costs of replacing PMSMA10 with the four PET modified asphalt mixtures.

Benefits	Costs
• Cost savings due to the reduced price of virgin binder than SBS modified binder • Cost and GWP savings due to the reduced amount of new binder and raw aggregates (not applicable for 2%PETSMA10) • Cost and GWP savings due to the reduced amount of RAP that needs to be transported long distances for reuse (not applicable for 2%PETSMA10) • Cost and GWP savings due to the prolonged service life (only applicable for 2%PETSMA10) • Avoided GHG emissions of transporting and disposing waste PET bottles to landfill sites • Avoided cost of MSW charging	• Costs of TETA and PET fakes • GHG emissions of TETA production • Costs and GHG emissions of the electricity consumed during the preparation of PET-derived additives • Costs and GHG emissions of the diesel fuel consumed in transporting recycled PET • Labour costs of preparing PET-derived additives • Costs and GHG emissions of wastewater treatment • Cost and GWP burdens due to the shortened service life (not applicable for 2%PETSMA10)

Intuitively, this is equivalent to the life cycle cost and GWP savings of the alternative material relative to the benchmark material, as given in Eq. (4):

$$\begin{aligned} ENPV = {} & LCC_{benchmark} + GWP_{benchmark} \cdot Cost_{CO_2e} \\ & - (LCC_{alternative} + GWP_{alternative} \cdot Cost_{CO_2e}) \end{aligned} \tag{4}$$

With this indicator, three sub-methods were used to perform the sensitivity analysis. The first one is to identify the critical variables that may eliminate the advantages of the alternative materials. This was done by changing the range of a potentially relevant variable by ±1% each time while keeping the other variables fixed. If this resulted in a variation of ENPV greater than 1%, then this variable was deemed as a critical variable (European Commission, 2014). The second one is to calculate the switching value of a variable which could make the ENPV become zero (European Commission, 2014). The switching value was usually expressed as the percentage change of the variable. Its magnitude and direction could provide useful information on the risk level of the project. The last one is the so-called scenario analysis, which could examine the joint effects of different variables (European Commission, 2014). Through this method, the ENPVs under optimistic and pessimistic scenarios were calculated based on the variable ranges obtained from the governmental reports, literature, etc.

3 Results and discussion

3.1 Technical feasibility

The technical feasibility of PET modified asphalt has been investigated through laboratory tests in previous studies (Leng et al., 2018; Sreeram et al., 2018; Padhan et al., 2020). The fatigue factor ($G^*\sin\delta$) and rutting factor ($G/\sin\delta$) obtained from the DSR test demonstrated that incorporating PET-derived additives and RAP improved the rutting and fatigue performance of virgin binder (Leng et al., 2018). The PET modified asphalt binder even outperformed the SBS polymer modified bitumen (PMB) in terms of fatigue resistance, but the addition of RAP compromised this advantage (Leng et al., 2018; Padhan et al., 2020). Meanwhile, although the rutting resistance of PET modified asphalt binder was inferior to PMB, adding RAP could significantly increase the rutting performance and make it comparable to PMB (Leng et al., 2018; Padhan et al., 2020). Besides, according to the hot water stripping test, the addition of PET-derived additives would significantly improve the stripping performance of RAP binder (Leng et al., 2018). It was also found from the results of the bending beam rheometer (BBR) test that the PET modified asphalt binder has better low temperature performance than PMB. It also enhanced the low temperature performance of RAP binder, making them equivalent to PMB (Leng et al., 2018; Padhan et al., 2020). The Fourier Transform infrared spectroscopy (FTIR) spectroscopy studies indicated that the PET-derived additives may also provide the rejuvenating function (Leng et al., 2018).

This study estimated the service lives of asphalt mixtures based on the fatigue performance of the asphalt binder, given that fatigue resistance is a key property affecting the durability of RAP mixtures. Table 4 shows the fatigue factor values derived from the DSR test for various asphalt binders. Based on this, the service lives of the four PET modified asphalt mixtures were roughly estimated. It is noteworthy that while assuming the same percentage change for the laboratory test result and field service life may not be accurate, it is believed to provide reasonable estimations for comparative study. Meanwhile, the application of heatmap visualization technique and the idea of breakeven service life in the following sections will offer a complete comparison between different mixes under various service life assumptions. The sensitivity analysis may also aid in understanding the potential risk levels resulting from the service life estimation.

Table 4

Binder fatigue performance and estimated service lives of different mixtures.

Binder Type	$G^*\cdot\sin\delta$ (kPa)	Percentage change relative to 4%SBS (%)	Estimated service life (years)
4%SBS	2391[a]	/	12.00
2%PET	2130[b]	-10.92	13.31
15%RAP-2%PET	2457[b]	2.76	11.67
25%RAP-2%PET	2522[b]	5.48	11.34
40%RAP-2%PET	2848[b]	19.11	9.71

[a] Padhan et al., 2020

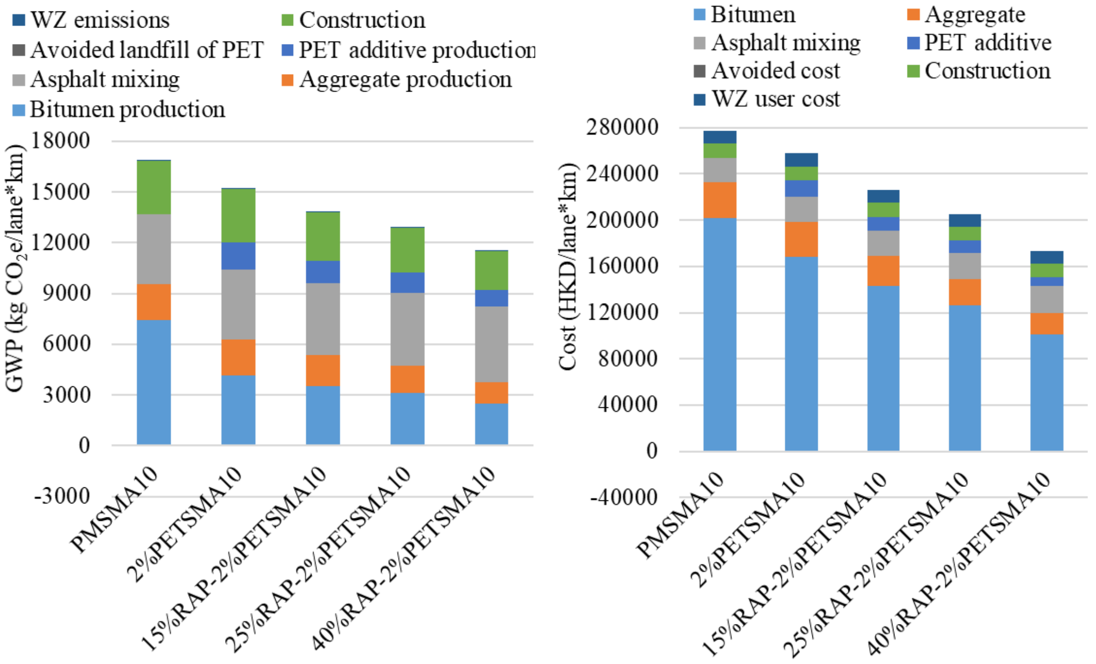
[b] Leng et al., 2018

3.2 Environmental and economic sustainability

3.2.1 GWP and cost breakdowns of surface mill & fill (M&F)

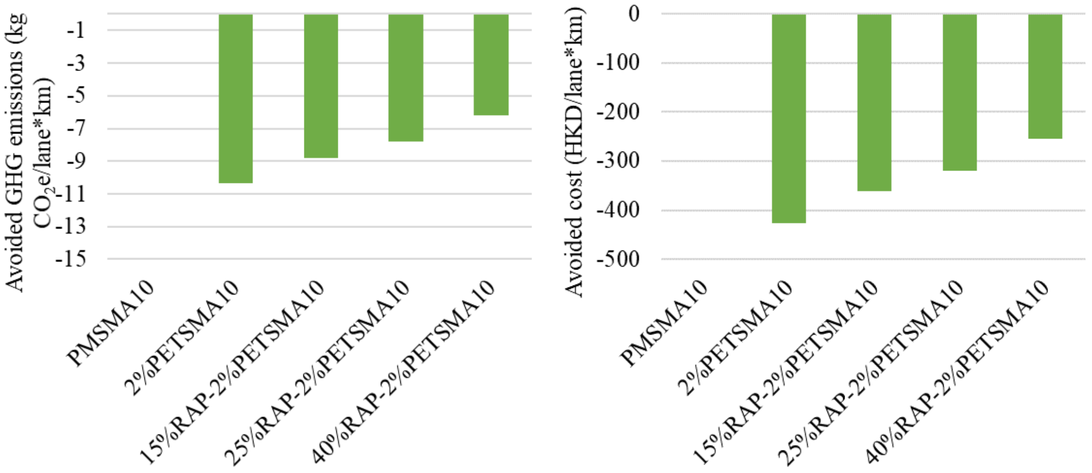
The GWP and cost breakdowns of surface M&F with different mixtures were illustrated in Fig. 2. The avoided impact due to avoiding the disposal of waste plastic was shown in Fig. 2 (c) and (d) separately because of the relatively small values. Fig. 2 indicates that the use of SBS modified binder resulted in the highest environmental and economic burdens. In other words, the replacement of commercial SBS polymer with waste plastic derived additives could yield significant benefits. It was estimated that only considering the material production and construction phases, the cost and GWP reduction brought by the application of 2%PETSMA10 in M&F activities were about 10.1% and 7.3%, respectively. When incorporating different contents of RAP (i.e., 15%, 25% and 40%) into the PET modified asphalt, the cost and GWP could be further reduced by as much as 31.8% and 37.6%, respectively.

In Fig. 2(a), it is obvious that the bitumen production, asphalt mixing, and construction stages were the main contributors to GWP. The GWP in the bitumen production stage of PMSMA10 was remarkably higher than the other materials, mainly due to the use of SBS polymers. The slightly different GHG emissions in the construction stage were caused by the different amount of milled materials that need to be transported to the mainland. Increasing the RAP content not only decreased the GHG emissions in virgin aggregate production but also reduced the environmental burdens associated with the transportation of milled materials. Besides, although the preparation of PET-derived additives could generate additional GHG emissions, the amount was far from offsetting the benefits from other stages. As for the cost part, the bitumen cost dominated the cost of the mixtures. The cost difference between PMSMA10 and 2%PETSMA10 was mainly attributed to the higher price of SBS modified binder than the virgin binder. For the PET modified asphalt containing various contents of RAP, the difference in the amount of virgin binder was the main reason for the cost difference.



(a) GWP

(b) Costs



(c) Avoided GWP (d) Avoided costs

In both environmental and economic dimensions, the avoided impact of disposing equivalent waste PET bottles at landfills was not as significant as the impact from other stages. This is because the amount of waste plastic that can be recycled through the wet method is limited, only about 2% by weight of the bitumen in this case study. However, assuming that the more than 6000 lane-km roadways in Hong Kong are all resurfaced using these sustainable paving materials, such avoided GWP and cost would be up to 62 tonnes of CO_2e and 2.55 million HKD, respectively. If further considering the benefits received from other stages, the corresponding GHG emission and cost savings of replacing PMSAM10 with PET modified asphalt to resurface the existing roadway wearing course in Hong Kong could be up to 32.3 thousand tonnes of CO_2e and 626.6 million HKD.

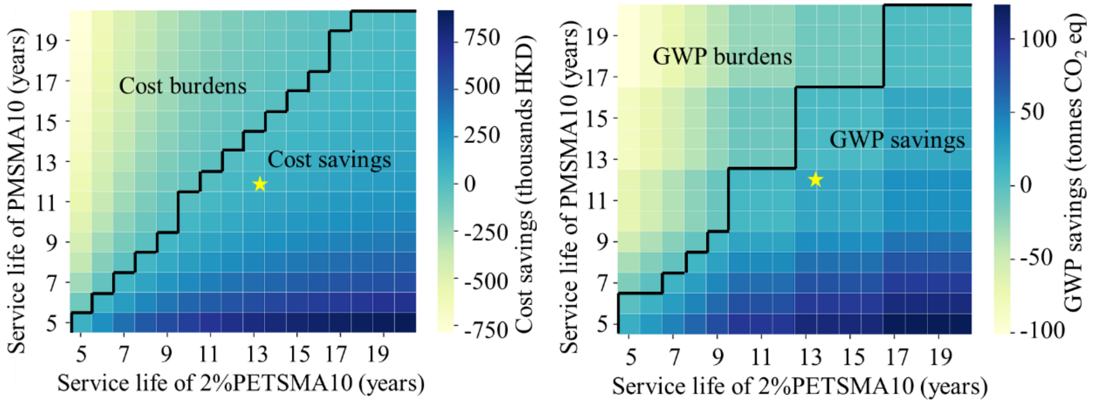
Fig. 2. GWP and cost breakdown of surface M&F with different asphalt mixtures

3.2.2 Life cycle GWP and cost savings or burdens

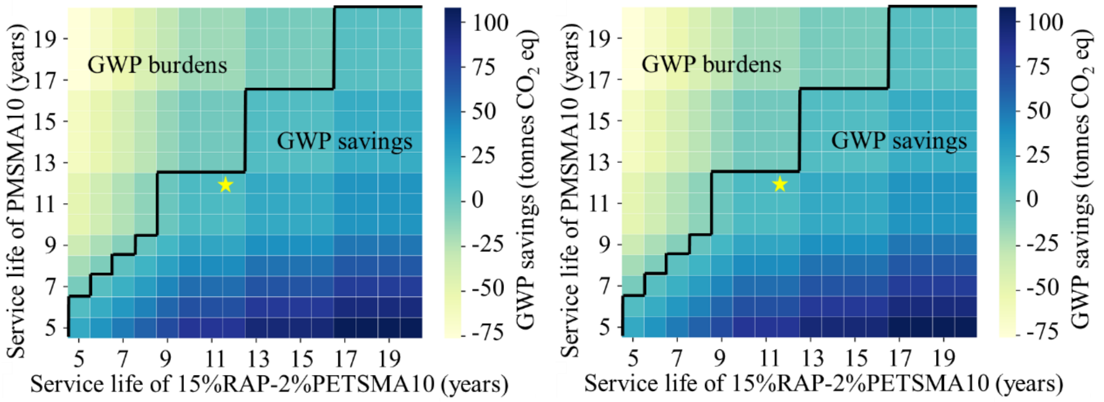
In addition, it has been demonstrated from the previous section that the service lives of these mixtures vary a lot. Shorter service life increases the number of M&R activities or decreases the salvage value, which may offset the benefits obtained from the material production and construction phases. Conversely, longer service life could further enhance the benefits. Hence, it is necessary to investigate the environmental and economic impact from a life cycle perspective. In this study, M&F the wearing course was considered as the only M&R treatment. It was assumed that during the analysis period, whenever the treatment reached the end of its service life, M&F with the same mixture would be implemented.

The difference in life cycle costs and GHG emissions between PMSMA10 and the four PET modified asphalt mixtures under various service life combinations were visualized through heatmaps, as shown in Fig. 3. The x-axis and y-axis represent the service life of the alternative and benchmark material, respectively. The dark blue color denotes the greatest cost or GWP savings while the light-yellow color corresponds to the greatest burdens. A step curve was drawn in each heatmap to divide the saving and burden area. On this curve, the benefits derived from the material production and construction were balanced by the burdens arising from the shorter service life, which was defined as the breakeven service life (Yang et al., 2015). It is clear from Fig. 3 that the breakeven service lives of 2%PETSMA10, 15%RAP-2%PETSMA10, 25%RAP-2%PETSMA10 and 40%RAP-2%PETSMA10 were around 10.5, 8.5, 8.5 and 6.5 from the economic aspect and 9.5, 8.5, 8.5, and 7.5 from the environmental aspect. In other words, the four PET modified asphalt mixtures were both environmentally and economically preferable as long as their service lives were longer than 10.5, 8.5, 8.5 and 7.5 years, respectively. The star marks in Fig. 3 indicate the service lives considered in this study. In all subgraphs, the star marks are located in the "saving" area. This reveals that under current assumptions, the continuous application of M&F with PET modified asphalt in the pavement life cycle was expected to reduce the cost and GHG emissions at the same time. The corresponding life cycle cost and GWP savings were in the range of 14.5~26.2% and

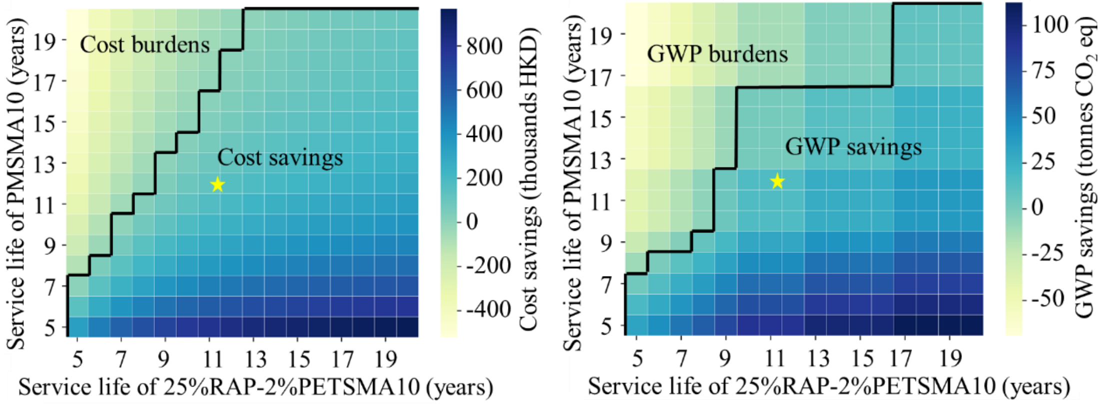
17.7%~29.0%, respectively. The 40%RAP-2%PETSMA10 achieved the greatest cost savings while the 2%PETSMA10 generated the most considerable GWP savings. The horizontal distance between the star mark and the step curve measures the degree of tolerable reduction in the service life of PET modified asphalt mixture, i.e. such a reduction will not impose environmental or economic burdens. Therefore, based on the current estimation, the tolerable reductions in the service life of the four PET modified asphalt mixtures were approximately 2.8, 3.2, 2.8, and 2.2, respectively.



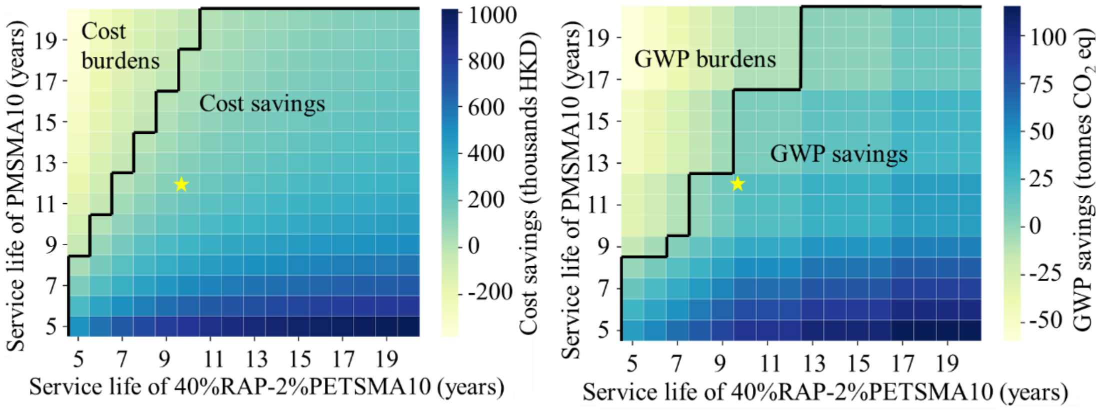
(a) LCC (2%PETSMA10) (b) GWP (2%PETSMA10)



(c) LCC (15%RAP-2%PETSMA10) (d) GWP (15%RAP-2%PETSMA10)



(e) LCC (25%RAP-2%PETSMA10) (f) GWP (25%RAP-2%PETSMA10)



(g) LCC (40%RAP-2%PETSMA10) (h) GWP (40%RAP-2%PETSMA10)

Fig. 3. Life cycle GWP and cost savings/burdens compared to PMSMA10.

In summary, Fig. 3 can serve as a useful tool for assessing the sustainability performance and risk level of using PET modified asphalt mixtures in M&R activities. It also allows the agencies to make judgements on the possible consequences of using PET modified asphalt mixture to replace the conventional asphalt mixture based on their own estimates of the mixture service life.

3.3 Sensitivity analysis

3.3.1 Identification of critical variables

Fig. 4 shows the variation of ENPV due to the 1% variation of the variables. In Fig. 4, the cost difference between PMB and virgin bitumen (VB) could be considered as a proxy indicator of the unit cost of SBS polymer. The service life refers to the service life of the alternative materials, whereas the service life of the benchmark material was fixed at 12 years. The energy consumption of PET additive preparation denotes the electrical energy demand for preparing 1 tonne of PET-derived additives. It can be concluded from Fig. 4 that the service life is the only variable whose 1% change will cause a change in ENPV by more than 1%, so it was deemed as the potential critical variable. Regarding the other variables, their variations have a very low impact on the economic performance (i.e., ENPV) of the PET modified asphalt mixtures.

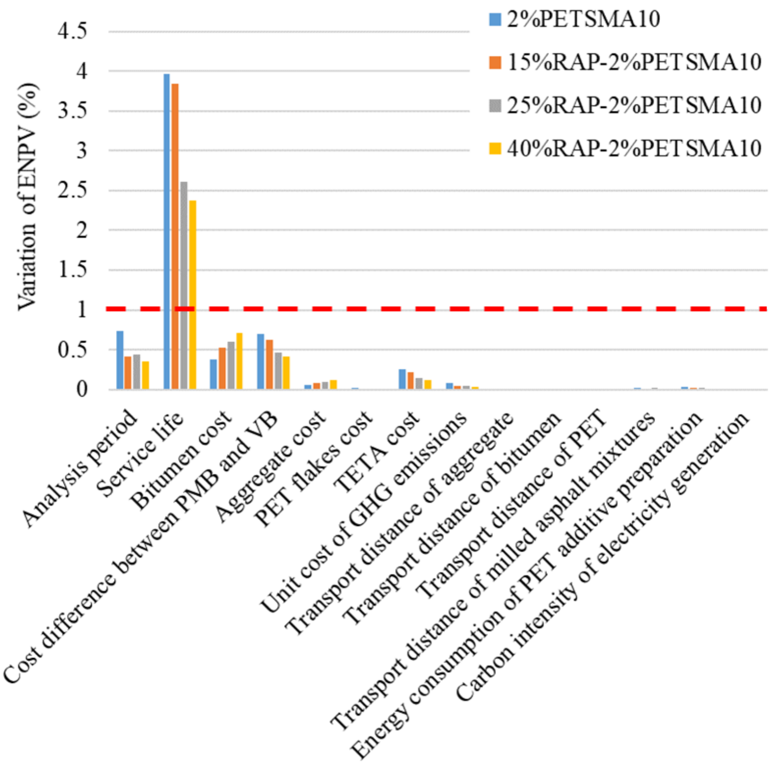


Fig. 4. Identification of critical variables

3.3.2 Switching values

The switching values that made the ENPV zero were determined by varying the value of each variable from 0 to 501 times its base value. Since the switching value was expressed as a percentage change, this search range was equivalent to changing the value of each variable from a decrease of 100% to an increase of 50,000%.

Table 5 lists the variables whose switching values can be found in this search range and the corresponding switching values. The variable was more likely to be a risky factor if its switching value was closer to zero. The use of switching values in sensitivity analysis allows the agencies to estimate the risk level of the project and identify the key factors that may make the project risky. It also provides some insight into the ways to mitigate the risks.

For example, an 18% reduction in service life would completely eliminate the advantages of 2%PETSMA10. It implied certain risks in replacing PMSMA10 with 2% PETSMA10 completely during the pavement life cycle, especially when the service life of 2%PETSMA10 cannot be guaranteed. The durability of the alternative materials was always the determining factor in maintaining their environmental and economic advantages in the entire pavement life cycle. In addition, the switching value of the service life was farther away from zero with the increase of RAP content, indicating that improving the RAP content in PET modified asphalt from 0% to 40% can reduce the risk of being overtaken by PMSMA10. Other methods to reduce such risks include further improving the long-term performance of PET modified asphalt, alternating the use of innovative and conventional paving materials, and so on. As for other variables, they had to be varied considerably to make the ENPV zero, so they were not considered as the key factors to evaluate the risk of the project.

Table 5
Switching values.

Mixtures Variables	2%PETSMA10	15%RAP-2%PETSMA10	25%RAP-2%PETSMA10	40%RAP-2%PETSMA10

Service life	-18%	-20%	-25%	-29%
PET flakes cost	6851%	8181%	12234%	15195%
TETA cost	395%	470%	704%	875%
Energy consumption of PET-derived additive preparation	3670%	4383%	6556%	8144%
Carbon intensity of electricity generation	11383%	12032%	18416%	21566%

3.3.3 *Scenario analysis*

The scenario analysis was carried out starting from the investigation of variable impacts and the collection of variable ranges. As shown in Table 6, the upward and downward arrows indicate the positive and negative correlation between the variable and ENPV, respectively. This information was used to distinguish the optimistic and pessimistic values of the variable. For example, the ENPV decreased with the increase of TETA cost. Therefore, the lower and upper limits of TETA cost were regarded as its optimistic and pessimistic values, respectively. In other words, the optimistic and pessimistic scenarios in this study referred to the most and least favorable conditions for the PET modified asphalt.

The variable ranges were collected from different sources, as shown in Table 6. The cost ranges of bitumen and aggregates were estimated based on their cost indexes (HK C&SD, 2021b) while the cost ranges of TETA and PET flakes were provided by the suppliers. The pessimistic value of the transport distance of aggregate and asphalt was determined under the assumption that these materials were provided by local suppliers (HK HyD, 2021). The waste PET bottles were assumed to be collected from the nearest and farthest RTS or landfills in the optimistic and pessimistic scenarios. The locations of RTS and landfills were obtained from HK EPD (2021). It was assumed that in the pessimistic scenario, the milled asphalt mixtures were stored in local fill banks and did not need to be delivered to mainland China. CLP's carbon intensity target for the year 2030 (CLP, 2020) and HK Electric's current carbon intensity (HK Electric, 2020) were used in the optimistic and pessimistic scenarios, respectively. For variables whose ranges cannot be reasonably estimated based on the available information, a ±20% variation was assumed for them.

Table 6
Variable ranges for scenario analysis.

	Trend	Base case scenario	Optimistic scenario	Pessimistic scenario	Data source
Service life (year)	↑	13.31/ 11.67/ 11.34/ 9.71	15.97/ 14.00/ 13.61/ 11.65	10.65/ 9.34/ 9.07/ 7.77	a
Bitumen cost (HKD/tonne)	↑	7900	7900	7096.57	HK C&SD (2021b)
Cost difference between PMB and VB (HKD/tonne)	↑	1400	1400	1257.62	b
Aggregate cost (HKD/tonne)	↑	92	96.968	76.1944	HK C&SD (2021b)
PET flakes cost (rmb/kg)	↓	3	2.7	3.5	Supplier quotation
TETA cost (rmb/kg)	↓	26	22	30	Supplier quotation

Unit cost of GHG emissions (Euro/t)	↑	36	1386.2786	4.158	Cao (2020)
Transport distance of aggregate (km)	↑	144	144	0.5	Material sources: HK HyD (2021)
Transport distance of bitumen (km)	↑	100	100	23	Material sources: HK HyD (2021)
Transport distance of Recycled PET	↓	30	8.8	50.1	HK EPD (2021)
Transport distance of milled asphalt mixtures	↑	230	230	30	c
Energy consumption of PET-derived additive preparation (kWh/t)	↓	2630.78	2104.62	3156.93	a
Carbon emission from electricity generation (kg CO_2e/kWh)	↓	0.57	0.5	0.71	CLP (2020), HK Electric (2020)

[a] calculated by assuming a ±20% variation.

[b] estimated using the same cost index as bitumen.

[c] the milled materials were assumed to be stored in local fill banks and did not need to be delivered to mainland China.

Table 7 shows the results of the scenario analysis. Although under the pessimistic scenario, completely replacing PMSMA10 with 2%PETSMA10 or 15%RAP-2%PETSMA10 may cause loss, the magnitude of the loss was much lower than the ENPV in the base case scenario or optimistic scenario. This indicated that the use of PET modified asphalt can obtain greater benefits with less risk. Hence, it could be concluded that the application of waste plastic modified asphalt in pavement maintenance is not very risky and thus worth trying. Decision-makers could decide whether to use these innovative paving materials to gain possible benefits based on their tolerance for risks.

Table 7

Results of scenario analysis.

	Base case scenario	Optimistic scenario	Pessimistic scenario
ENPV of 2%PETSMA10 (HKD)	99218.97	474166.57	-18709.028
ENPV of 15%RAP-2%PETSMA10 (HKD)	111444.17	553557.42	-7349.99
ENPV of 25%RAP-2%PETSMA10 (HKD)	150503.99	630534.77	31967.03
ENPV of 40%RAP-2%PETSMA10 (HKD)	169194.32	567671.65	48098.16

4 Conclusions

Even though extensive research work is ongoing to investigate the feasibility of incorporating waste plastic into asphalt pavement, the quantitative evaluation of its potential environmental and economic benefits from a life cycle perspective is still very limited. Thus, the present study aims to examine the potential effect of applying PET modified asphalt containing RAP in pavement M&R activities to improve the sustainability of roadway construction based on comparative analysis and life cycle modeling approaches.

The technical feasibility of the PET modified asphalt mixture was verified by the authors' previous studies. It was found that PET modified asphalt binder outperformed the PMB in terms of fatigue resistance. The addition of RAP in PET modified asphalt provided comparable rutting performance as PMB. Moreover, adding PET-derived additives significantly improve the stripping performance and low temperature performance of RAP binder. All these demonstrated that PET-derived additive could be a promising substitute to the commonly used SBS polymer in pavement construction.

LCA and LCCA were performed to assess the environmental and economic sustainability of the waste plastic modified asphalt materials. It was found that the replacement of SBS modified asphalt with PET modified asphalt in M&F could save about 10.1% of the cost and 7.3% of the GHG emissions. If further incorporating the RAP into the PET modified asphalt mixture, such savings would be up to 31.8% and 37.6%, respectively. Furthermore, a heatmap-based visualization was performed to illustrate the LCC and GWP savings by replacing PMSMA10 with the four PET modified asphalt mixtures under various service life combinations. The results showed that under current assumptions, the continuous application of M&F with PET modified asphalt mixture is expected to be both environmentally and economically beneficial. During the 50-year analysis period, costs and GHG emissions can be reduced by approximately 14.5%-26.2% and 17.7%-29.0%, respectively. The largest cost and GWP savings were achieved by 40%RAP-2%PETSMA10 and 2%PETSMA10, respectively. Given the assumed 12-year service life of PMSAM10, the minimum service life for PET modified asphalt mixtures containing 0%, 15%, 25%, and 40% RAP to maintain their advantages was 10.5, 8.5, 8.5, and 7.5 years, respectively.

The sensitivity analysis demonstrated that the durability of the alternative materials was the key factor in maintaining their environmental and economic advantages in the entire pavement life cycle. An 18%, 20%, 25% and 29% reduction in the service life of the PET modified asphalt mixtures with RAP content of 0%, 15%, 25% and 40% would eliminate their advantages over the benchmark mixture PMSMA10. Potential mitigation strategies for reducing this risk were revealed, including improving the long-term performance of PET modified asphalt, alternating the use of innovative and conventional paving materials, etc. The joint effect of different variables was also investigated by scenario analysis. Although the complete replacement of PMSMA10 may cause loss under the pessimistic scenario, such loss was much smaller compared with the benefits under the base case or the optimistic scenario, which indicated that the use of PET modified asphalt mixture could obtain greater benefits with less risks.

Moreover, although this study has carefully evaluated the mechanical, environmental, and economic benefits of simultaneously recycling waste PET and RAP into the road, there are still opportunities to further extend this research. Firstly, the use phase should also be included in the system boundary once reliable field performance data or modelling approaches are available. Secondly, more practical M&R schedules could be considered in addition to the continuous use of the same M&R activity. Finally, other waste PET recycling technologies such as the dry method (i.e. replacing part of the natural aggregates in the asphalt mixture with the waste plastic), or using physically treated instead of chemically treated waste PET to modified asphalt binder, should also be investigated and compared in future research.

Acknowledgement

This study was conducted under the support of the Research Institute for Sustainable Urban Development (RISUD) at the Hong Kong Polytechnic University.

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