Innovative Approaches to Bitumen Modification: Comparison of Rice Husk Ash, Pyrolysis Carbon Black, and Waste Face Mask Polymers

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Abstract. Passengers expect a smooth and safe transition along the roads. Bitumen is mainly used in flexible pavement construction. However, inherent shortcomings of bituminous pavement such as rutting, fatigue, thermal cracking and water submergence cause issues related to the pavement performance and its durability. To overcome these shortcomings, modifiers are added to the bitumen to improve its properties. With the advent of sustainable concepts, addition of waste-based material into construction materials to improve their performance while addressing the waste management issue is an emerging area of research. Many researches have utilized waste-based materials as bitumen modifiers. Out of them, Pyrolysis Carbon Black (PCB), Rice Husk Ash (RHA) and Waste Face Mask (FM) have been selected for this study by considering the availability on a local basis. Although there are many waste-based modifiers, a critical comparison has not been carried out among them and it is essential to compare these alternatives in multiple aspects to have a better understanding before selecting the most suitable option. Therefore, this study aims to conduct a comprehensive comparison among three alternatives under performance, environmental and, economic impacts. To evaluate the performance, mechanical and rheological properties are assessed under the suitability to Sri Lankan context. The environmental and economic impacts are evaluated by calculating embodied GHG emission (ECO2-e), embodied energy (EE) and cost values to prepare 1kg of binder. The results indicate PCB is the best modifier for the Sri Lankan practice. PCB-modified binder has 13% decreased EE value and 5% decreased ECO2-e values. Further, the study reveals that PCB is the best cost-effective option by having 13% cost reduction compared to conventional binder. Pavement performance also has improved while adhering to the Sri Lankan Specifications. RHA can be recommended as the second-best alternative.

Keywords: *bitumen modification, rice husk ash (RHA), waste face masks, carbon black, economical solutions, greenhouse gas (GHG) emission*

3. Introduction

The traffic volume, tyre pressure and environmental conditions cause the depletion of road pavement performance levels such as propagating low thermal cracks, rutting and fatigue of the pavements (Feng et al., 2021). But to enhance the road quality, enhancing pavement performance is vital. Further, the characteristics of asphalt binder can influence the service life of the road and the maintenance cost of the pavement (Arabani & Tahami, 2017). From the beginning of asphalt technology, researchers have put effort into bitumen modification using several materials to enhance the overall performance of the road pavement. Polymer modifiers are the frequently used modifier types in current practice (F. Wang et al., 2022). However, with the emerging trend towards low carbon emission materials, usually waste based materials are investigated on their ability to modify conventional construction materials.

Polymer modifiers such as styrene butadiene styrene (SBS) are the commonly used modifier type, under the Sri Lankan contest (Sitinamaluwa & Mampearachchi, 2014). Therefore, diving

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more into the locally available greener options is essential. Under this study, three greener modifier options such as Pyrolysis Carbon Black (PCB), Rice Husk Ash (RHA) and waste surgical face masks (FM) have been selected for further analysis. PCB is derived as a by-product of the waste tyre manufacturing process, which is an industrial waste. RHA is an agricultural waste, which is derived after the burning of rice husks (RH). FM is a waste polymer option that comes as a disposal of the medical field.

The disposal of waste tyres is a major issue in the world, where traditional disposal practices such as dumping into bare lands or incineration are no longer applicable. Pyrolysis process has been recognised as the best available option to address this increasing waste tyre issue (Zerin et al., 2023). The resulting gas phase and liquid phase of waste tyre pyrolysis are successfully capable of being used as a fuel source (Xiao et al., 2022). But the solid phase or the char which contains carbon black (CB) in higher percentage, is difficult to directly replace with commercial carbon black (CCB) (Cardona et al., 2018; Hoang et al., 2020). Therefore, innovative methods to reuse PCB are highly needed under this scenario (Arabiourrutia et al., 2020). Ability to modify bitumen using PCB for better pavement performance has been explored in several studies (Chaala et al., 1996; Feng et al., 2021).

Along with the increasing world population, demand for rice has increased, especially in Asian countries as Rice is their staple food (Zou & Yang, 2019). Sri Lanka, which is a South Asian country having rice as the staple food, shows exponential increase in annual paddy production within the past 40 years according to the data collected by the Department of Census and Statistics, Sri Lanka. Rice Husk (RH) is a by-product which comes out in milling process of rice grain. 20% weight of rice husk generation occurs for each total rice weight while milling (Nagrale et al., 2012). The usual disposal method of RH in Sri Lanka is dumping into bare lands or open-air burn. But with the high siliceous component within RH causes several environmental issues such as soil and water contamination and greenhouse gas emission (Bhattacharyya, 2014). However, many researchers have put efforts on utilizing the high silicon content by mixing with construction materials (Mistry et al., 2023; Xue et al., 2014). Hence, RHA have become an evolving modifier for enhancing the bitumen performance.

With the ability to decrease cracking and rutting in asphalt concrete, polymer plays a vital role in the pavement industry by increasing the durability of the pavement (Porto et al., 2019). However, it can increase the initial construction cost as polymers are expensive and their recycling process is complex (Duarte & Faxina, 2021). Especially due to polymers being difficult to degrade, reusing is the best option to manage polymer waste issues. With the Covid-19 pandemic, waste medical face mask generation was increased. According to the literature, 12 million face masks are disposed of in Sri Lanka daily (Kankanamge et al., 2022, 2023). But the main disposal method of them in Sri Lanka is open-air burning or dumping into bare lands with other waste while leading the county into severe environmental issues. However, used facemasks (FM) which consist of polypropylene majorly, can be used as a replacement to polymer in asphalt concrete construction technology in both economical and environmentally beneficial ways (Chen et al., 2023).

The objective of the study is to conduct a comparative analysis among these three modifiers based on performance, environmental and economic aspects. To analyse the performance, some numerical data was taken from literature while some data was derived by conducting the tests in order to maintain the consistency in testing parameters. In the first section the background and the research significance are discussed while the second section delivers a detailed literature review. Subsequently, the material properties and the methodology carried out is explained. In the results and discussion section, the performance of three bitumen is evaluated. Further, cost comparison and environmental impact assessment is done by estimating the cost and equivalent carbon dioxide emission (ECO_{2-e}) and embodied energy (EE).

4. Literature review

2.1 Carbon Black

There are several attempts recorded on bitumen modification with both PCB and CCB. Wang et al. (2019) (H. Wang et al., 2019) have investigated the behaviour of PCB modified bitumen. They have observed an effective improvement in both electrothermal properties and rheological properties in modified bitumen. Further, high-temperature rutting resistance, and aging resistance has improved in bitumen by associating with PCB. Moreover, the storage stability of bitumen has reduced while viscosity is increasing in the mixture. Gan et al. (2023) (Gan et al., 2023) have studied the properties of co-pyrolytic carbon black (CPCB) and low-temperature vacuum pyrolytic carbon black (VPCB) modified bitumen mixtures where PCB comes from two sources. They also have noticed these improvements and efforts have been made to further develop the mixture by associating with SBS. Geckil et al. (2018) (Geckil et al., 2018) has done a series of experiments to have clear understandings on the behaviour of PG 58-28 bitumen modified by adding FEF N-550 graded CB (0, 5, 10, and 15 wt%). The experiments revealed the mixture turns more elastic and less susceptible to temperature changers. Guo et al. (2023) (Guo et al., 2023) has explored on the UV-Resistant properties of N330 CB modified bitumen.

According to the current studies, it is obvious that PCB or CB has the potential to improve pavement properties. However, the major drawback of this alternative is that PCB elemental composition changes with the tyre types (such as car or truck tyres) and their proportions for the pyrolysis process. Table 1 clearly figures out the difference in elemental percentage along with the resource (Nkosi & Muzenda, 2014; Rikmann et al., 2024; Sugatri et al., 2018). It can be observed that carbon percentage in PCB varies between 70-85% by weight. Moreover, elements such as oxygen, sulphur, zinc, calcium and silicon are the abundant impurities which contribute around 15-25% of the total mass. In this study, the chemical composition of the PCB which is available in Sri Lankan context has been evaluated and PCB-modified bitumen characteristics were further analysed.

Table 1. The chemical composition of the PCB from different resources

Element	**Weight by percentage in Past studies**		
	Nkosi et al. (2014) (Nkosi & Muzenda, 2014)	Rikmann et al. (2024) (Rikmann et al., 2024)	Sugatri et al. (2018) (Sugatri et al., 2018)
C	83	74.2	84.10
O	6	-	10.34
S	2.6	6.0	0.49
Zn	4.2	5.3	5.04
Ca	2.4	1.7	-
Si	1.6	4.3	0.02

Fe	-	1.0	-
K	-	0.1	-
Co	-	0.05	-
Sr	-	0.026	-
Hg	-	0.018	-
Pb	-	0.0016	-

2.2 Husk Ash (RHA)

Several studies have assessed the rheological properties of RHA modified bitumen and the mechanical properties of asphalt concrete. They illustrate that the rheological characteristics which are evaluated using many tests like penetration, ductility, viscosity, softening point and dynamic shear rheometer (DSR), have improved in RHA modified binders (Arabani & Tahami, 2017). The mechanical properties of asphalt concrete such as marshall stability, stiffness modulus, rutting resistance and fatigue performance are also have improved according to the literature (Arabani & Tahami, 2017). Further, aging resistance and high temperature performance also have enhanced in RHA based asphalt concrete (Cai et al., 2013). However, Xue et al. (2014) (Xue et al., 2014) have compared the performance of RHA based asphalt binder and wood sawdust ash (WSA) based asphalt binder, they have revealed that there is no any chemical reaction between bitumen and RHA using the FTIR test results. Moreover, in a study conducted to compare the performance in between coal waste ash (CWA) modified binder and RHA based binder, they have mentioned that RHA based binder have enhanced the moisture resistance and tensile strength of asphalt concrete mixtures (Ameli et al., 2020). Most of the recent studies have tried to couple RHA with another substituent for modifying the bitumen. Addition of crumb rubber with RHA shows better result more than the bitumen which have modified using RHA only (Abdelmagid & Pei Feng, 2019). Mistry et al. (2019) (Mistry et al., 2019) have obtained better economical results while having improved properties by using RHA and Fly ash mixture to modify. Bio oil (BO) has used as a viscosity reducer in RHA based binder (Han et al., 2017). They have improved the low-temperature and fatigue resistance properties while improving the uniformity within the modified bitumen. The modified asphalt binder using SBS and RHA also have derived better high-temperature performance (Lu et al., 2020). Therefore, RHA based asphalt have enhance performance of conventional asphalt, especially in high-temperature conditions. Further, it is good economical and greener option which provides solutions for waste management issues too.

However, the chemical composition of the RHA also varies with respect to the source. Table 2 shows chemical composition of RHA in several literature (Ameli et al., 2020; Arabani & Tahami, 2017; Mistry et al., 2019). RHA contains SiO_2 in highest percentages between 85-95% which inherits the pozzolanic behaviours to RHA. Further several metal oxides such as CaO, Al_2O_3 and Fe_2O_3 contains by nearly 1%. However, the chemical composition related to each resource need to be assessed for better application.

Table 2. The chemical composition of the RHA from different resources

Compositions	**Weight by percentage in Past studies**		
	Mistry et al. (2019) (Mistry et al., 2019)	Ameli et al. (2020) (Ameli et al., 2020)	Arabani et al, (2017) (Arabani & Tahami, 2017)
SiO_2	86.67	87.8	91.42
CaO	1.88	1.04	1.03
Al_2O_3	1.62	0.12	0.114
Fe_2O_3	1.06	-	0.197
MgO	0.97	0.81	0.821
K_2O	0.42	2.61	2.596
SO_3	0.12	-	0.572
Na_2O	-	1.15	1.12
ZnO	-	0.38	0.016
SrO	-	-	0.005
LOI	6.11	2.17	2.109

2.3 Waste Surgical Masks

With the increasing consumption of plastics, the world has faced a critical issue on environmental pollution. Therefore, researchers have taken attempts to find waste plastics reusing methods (Naghawi et al., 2018). Incorporating waste plastics with construction materials is such an emerging solution for this issue (Pandey et al., 2023). Polypropylene (PP) is one of plastic forms which is highly used in bitumen modification. PP has the potential to increase the rutting and fatigue resistance of pavements (Nizamuddin et al., 2021). There are several studies done on reusing PP based waste to modify bitumen. Vargas et al. (2024) (Vargas & Hanandeh, 2024) has used recycled polypropylene for bitumen modification and derived improved performances. Hu et al. (2024) (Hu et al., 2024) have proposed a mechano-chemical method for waste PP to recycle and reuse as a bitumen modifier in large-scale application. They have addressed the issues on PP bitumen modification such as high blending temperatures and asphalt smoke emissions by adding phthalic anhydride.

Moreover, with the Covid-19 pandemic mass collection of one-time-used face masks has become a huge environmental issue (Selvaranjan, Navaratnam, et al., 2021). It is recognized as a better way to recycle FM by associating with bitumen for modification as they are abundant with PP (Goli & Sadeghi, 2023). Goli et al. (2023) (Goli & Sadeghi, 2023) have observed that the pavement performance has improved in asphalt mixtures after adding FM. Ayyadurai et al. (2023) (Ayyadurai et al., 2023) have modified bitumen by adding both shredded face masks and saline tubes. They state that mixing 1.25% shredded FM and 1% waste saline tubes is the ideal proportion to derive optimum performance and stability. Wang et al. (2020) (G. Wang et al., 2020) has noticed that FM becomes semi-liquid at hot mix asphalt (HMA) mixing temperature range. Therefore, FM can glue the aggregates together which helps to increase pavement stability and stiffness after cooling down. Furthermore, Yalcin et al. (2022) (Yalcin et al., 2022) have compared the performance of binders modified with SBS and FM. They have discovered that 2% FM has more potential than 3% SBS to improve physical and rheological properties of binder.

There are three layers in FM which has two types of polymer layers (Figure 1). PP Spunbond non-woven fabric has used for both outer layers while the middle layer contains PP meltblown non-woven fabric (Goli & Sadeghi, 2023). Occasi et al. (2022) (Occasi et al., 2022) reveal that FM consists of 92.3 wt% high grade PP. That PP in FM can not be reused as virgin PP because it has been subjected to a non-woven manufacturing process and as a result has a higher melt volume index. Therefore, utilizing waste FM to modify bitumen is a mutually beneficial solution as waste recycling option and low-cost polymer modifier option.

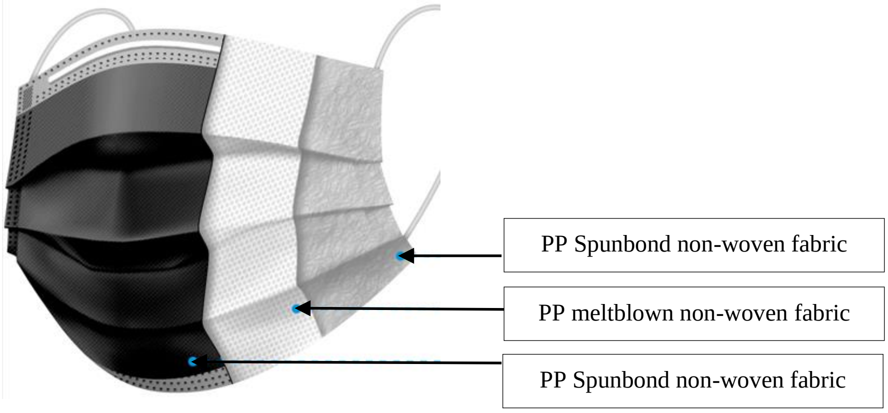

Fig.1. Layers of surgical facemask (FM)

According to the above information, PCB, RHA and FM display their applicability to modify bitumen. Further, all three waste materials are locally abandoned and searching for reusing or recycling options. However, it is important to have a comparative knowledge in selecting the best option in Sri Lankan context. But there are no any attempts have recorded on comparative studies between waste-based modifiers (PCB, RHA and FM) ether in locally or globally. Therefore, this comparison can help to make better decisions in selecting relevant modifier types and to understand further required knowledge gaps.

5. Methodology

The overview of the methodology is presented in Figure 2 where two phases are carried out such as finding optimum modifier percentages and environmental impact assessment

3.1 Materials

PCB

The PCB sample was obtained from Rivoga Pvt Ltd which is located in Puttalam district, Sri Lanka. The tyre composition which put into a pyrolysis batch is presented in Table 3. As the elemental composition in PCB sample is not a constant, scanning electron micrograph SEM analysis was for the respective sample. Figure 3 presents the branched and rough surface morphology of PCB present in SEM analysis. Table 4 presents the elemental composition by percentage of weight, where carbon is the main constituent.

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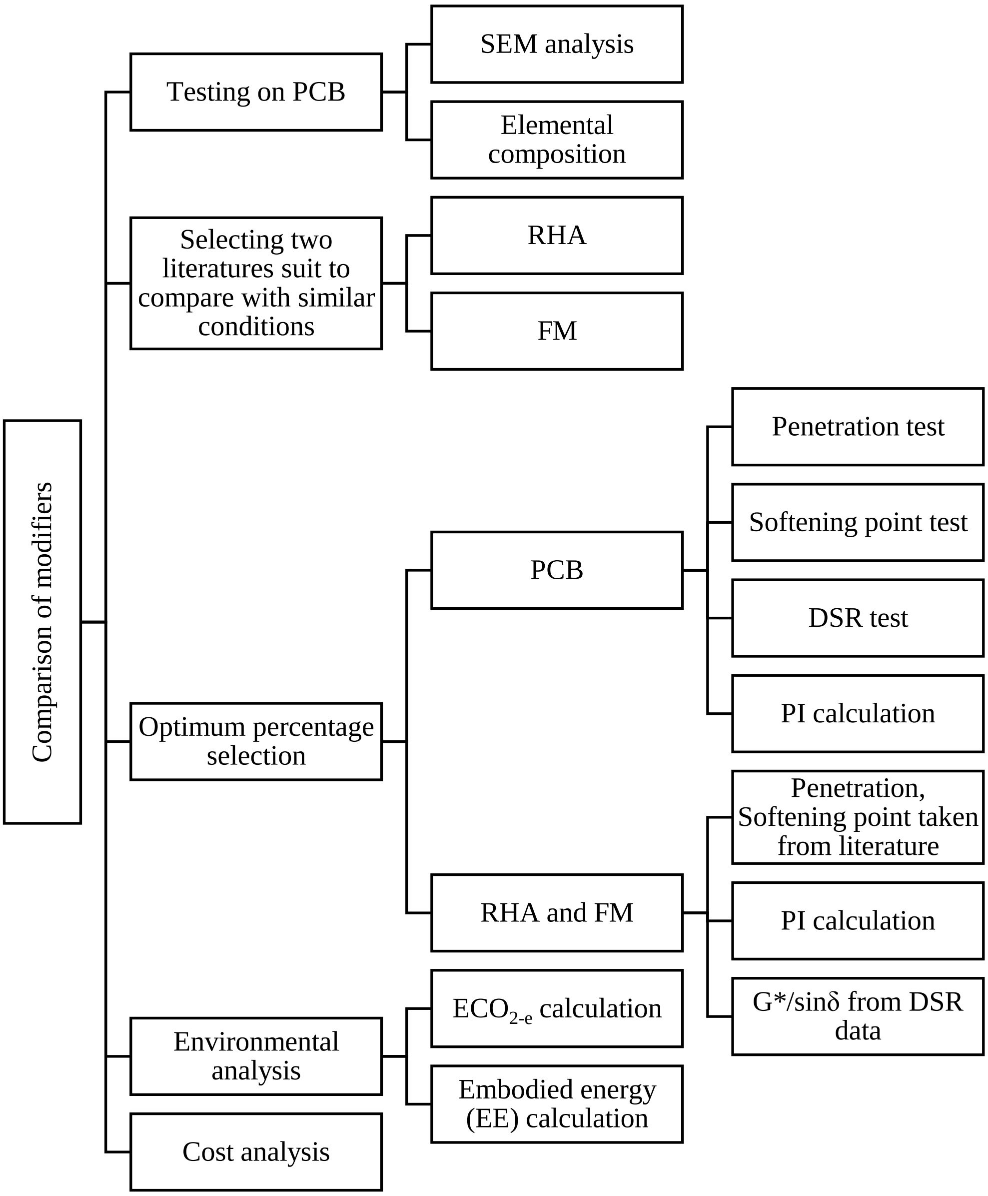

Fig.2. Overview of the process

Table 3. Tyre composition

Tyre material type	**Percentage by weight**
Lumps	28.2
1000/20 (truck and bus tires)	28.5
Waste rubber	5.6
750/16 (tyres from light trucks/ SUV /off-road vehicles)	10.1
Three Wheel/ bike bundles	9
Gantry and Tractor tyres	5.6
Car/Van bundles	12.9

Table 4. Elemental composition of PCB by percentage of weight

Element	Weight %
C	78.62
O	3.91
Al	0.38
Si	3.79
S	5.25
Ca	1.44
Ti	0.32
Fe	0.54
Zn	5.73

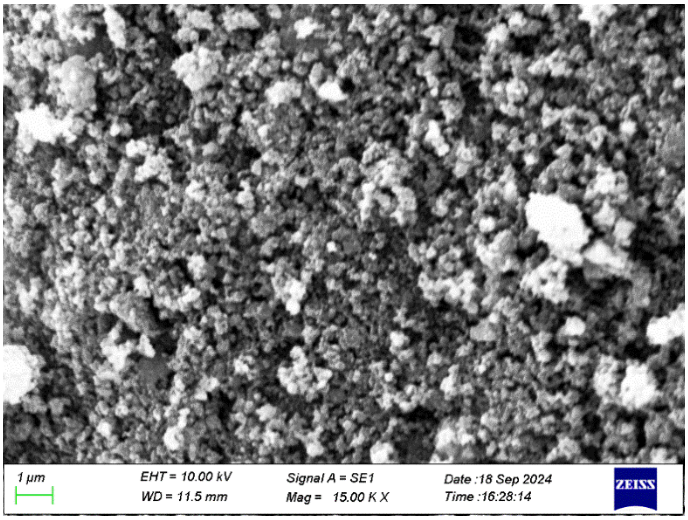

Fig. 3. SEM image of PCB sample (150,000x)

Rice Husk Ash (RHA) and Waste Surgical Face Masks

For the analysis on RHA and FM performances, the two literature; Arabani et al. (2017) (Arabani & Tahami, 2017) for RHA, Putra et al. (2024) (Putra et al., 2024) for FM, are selected by considering compatibility in used testing conditions between three modifier types (PCB, RHA, FM).

Arabani et al. (2017) (Arabani & Tahami, 2017) has obtained RHA after subjecting RH to an incineration for 2 hours at 650°C. Then it was put into a ball mill for 15 minutes and particles passing from 0.075 mm sieve were taken for testing. The chemical composition of the sample is present in the last column of Table 2 where it predominantly contains SiO_2.

At first, Putra et al. (2024) (Putra et al., 2024) have put waste FM into an oven for an hour at 70 °C by considering health and safety during handling of the FM. Then, the metal strip and the ear loops have been removed. Subsequently, the masks broke down into smaller pieces using a shredder machine.

3. 2 Bitumen

The 60/70 penetration-graded bitumen were, used for the experiments. Moreover, the literature on RHA (Arabani & Tahami, 2017) and FM (Putra et al., 2024) based modifications have used 60/70 and 50/70 penetration graded bitumen respectively. Table 5 presents the properties of bitumen used for PCB modification and the properties of bitumen used in RHA and FM modification literature (Arabani & Tahami, 2017; Yalcin et al., 2022).

Table 5. Properties of base asphalt binder used for modification

Test	Results			Specification
	PCB	RHA	FM	
Penetration (25°C; 0.1 mm)	63	63	56	ASTM D5 (ASTM_International, 2006a)
Softening point (°C)	51	51	53.3	ASTM D36 (ASTM_International, 2006b)
Ductility (25°C; cm)	>100	>100	>100	ASTM D113 (ASTM D 113, 2007)
Specific gravity (25°C; g/cm^3)	1.022	1.022	1.015	ASTM D70 (ASTM_International, 2009)

3. 3 Testing Procedures

Modification Process and Performance Tests

The mixing percentages and mixing conditions were selected for PCB by considering the respective parameters used in the literature (Jerin et al., 2020; Tanzadeh & Shafabakhsh, 2020; F. Wang et al., 2022). The selected mixing percentages for PCB are 5%, 10%, and 15%. For mixing high shear mixture was used at 3000rpm for 1 hour. The mixing temperature was maintained between 155-160°C. The penetration values were derived according to ASTM-D5 (ASTM_International, 2006a) and softening point was determined according to ASTM-D36 (ASTM_International, 2006b). The penetration values used to observe the stiffness of the binder after adding PCB. Then using penetration and softening point values Penetration Index (PI) was calculated using Equation 1 (Geckil et al., 2018) to evaluate the temperature susceptibility of bitumen.

$$PI = \frac{1952-500\times log(P_{25})-20\times SP}{50\times log(P_{25})-SP-120} \quad (1)$$

Where,

P_{25}= penetration at 25°C

SP = Softening point

Then Dynamic Shear Rheometer (DSR) Test was performed on PCB-modified samples to evaluate the rutting resistance using the G*/sinδ parameter. Complex shear modulus (G*) reveals deformation resistance when torsion is applied on the binder for a defined period. Phase angle (δ) is the time lag between the applied shear stress and the resulting shear strain in a material during oscillation. The higher the δ, the binder is more viscous. Rutting parameter (G*/sinδ) which is derived using complex modules and phase angle assesses the permanent deformation by restricting it to 1.0kPa for unaged binder (Airey et al., 2002). The rutting parameter was used to figure out the high-temperature performance. When selecting the optimum binder, it is required to consider the intended application. As these decisions are based on the Sri Lankan context, this study has focused on a hot climate with heavy traffic conditions, by prioritizing rutting resistance (G*/sinδ) and softening point.

3. 4 Environmental and Economic Impact Assessment

To provide a proper comparison as sustainable industrial alternatives, both environmental impact and the cost is needed to further assess. To evaluate the environmental impact, the embodied GHG Emissions ($ECO_{2\text{-}e}$) and embodied energy (EE) parameters are calculated.
Equation 2 is used to calculate the cost, embodied GHG Emissions ($ECO_{2\text{-}e}$), and embodied energy (EE) for 1 kg of binder mix (Selvaranjan, Gamage, et al., 2021), (Liew et al., 2024) .

$$\text{EE};\ ECO_{2-e};\ \text{Cost} = \sum_{i=1}^{n} g_i \text{ x } m_i \tag{2}$$

where,

g_i is the GHGE, embodied energy or cost per unit mass of component i,
m_i corresponds to the mass of ingredient i per kg of a binder.

Table 6 represents the cost, embodied GHGE ($ECO_{2\text{-}e}$) and embodied energy (EE) values relevant unit mass of material. The values for bitumen are taken from the study done by Blaauw et al. (2020) (Blaauw et al., 2020). The cost value for bitumen is taken from Bitumix (pvt) Ltd from where the virgin bitumen was bought for tests.

Dissanayake et al. (2017) (Dissanayake et al., 2017) who have done a comparative embodied energy analysis for a building with recycled EPS based foam concrete wall panels, have considered EE as zero for waste-based materials under the process analysis method. In this study, for all three modifiers EE value is taken as zero as all of them are waste material. But according to the ICE database (Geoff Hammond, 2008) 0.1MJ/kg is considered for handling purposes for each waste material. As these entire modifier materials are wastes, they are freely available and zero cost is considered.

The EE and $ECO_{2\text{-}e}$ values for the oven are taken by referring to Oreto et al. (2021) (Oreto et al., 2021) considering industrial electric ovens. The cost is calculated considering the expense of electricity according to the current price rates in the Ceylon Electricity Board (CEB).

The EE and ECO_2 values are derived from Santos et al. (2021) (Santos et al., 2021) and cost calculated considering the electricity energy rate in Sri Lanka. The values for processing to prepare modified binders were obtained from the study done by Salehi et al. (2022) (Salehi et al., 2022). The cost value was calculated by considering CEB electricity rates and labour costs in Sri Lanka.

Table 6. The environmental and cost factors of raw materials.

Material	Embodied Energy (EE) (MJ/kg)	ECO_{2-e} (kg CO_{2e}/kg)	Cost (LRK/kg)
bitumen	2.201	0.222	189.00
PCB	-	0.100	-
RHA	-	0.100	-
FM	-	0.100	-
Oven for FM	12.410	1.639	172.00
Shredding of FM	0.011	0.428	0.16
Processing	0.300	0.150	35.50

6. Results and Discussion

4.1 Results of Conventional Performance Tests

Table 7 displays the results of the afore-mentioned performance tests for PCB-modified binders. Further, Table 8 and Table 9 have been developed according to the Table 7 values by referring to two pieces of literature on RHA (Arabani & Tahami, 2017) and FM (Putra et al., 2024).

Table 7. Properties of PCB modified binder.

Test	Specification/ Reference	PCB % by weight			
		0	5	10	15
Penetration (25°C; 0.1 mm)	ASTM D5 [46]	63	64	63	60
Softening point (°C)	ASTM D36 [47]	51.5	52	53	56
Penetration Index (PI)	Geckil et al. (2018) (Geckil et al., 2018)	-0.3	-0.1	0.1	0.7
rutting resistance (G*/sinδ) = 1 kPa temperature (°C)	ASTM D7175 (ASTM_International, 2024)	64	68	70	74

Table 8. Properties of FM modified binder.

Test	Specification/ Reference	RHA % by weight				
		0	5	10	15	20
Penetration (25°C; 0.1 mm)	ASTM D5 [46]	63	61.2	59.1	58.2	57.3
Softening point (°C)	ASTM D36 [47]	51	53.1	57.7	60.1	61.5
Penetration Index (PI)	Geckil et al. (2018)	-0.4	0.0	1.0	1.4	1.7
Temperature(°C) when rutting resistance (G*/sinδ) = 1 kPa	ASTM D7175 (ASTM_International, 2024)	70.9	73.1	74.8	76.4	78.4

4.2 Optimization Approach

When penetration value decreases, the binder becomes stiff and reduces the risk of rutting under high temperatures. When the softening point increases, the binder can withstand elevated temperatures without deforming. Therefore, with the increasing modifier percentage, both penetration and softening points show a positive trend. However, according to the Standard specification for construction and maintenance of roads and bridges ("Standard Specification for Construction and Maintenance of Roads and Bridges," n.d.), the recommended softening point range is in between 48°C-56°C and 47°C-55°C for 60/70 and 80/100 penetration graded bitumen respectively. However, the recent study done by Sitinamaluwa et al. (2014) (Sitinamaluwa & Mampearachchi, 2014) have observed that the maximum pavement temperature varies from 48°C to 62°C in Sri Lanka. By considering both existing limits in specifications and practical aspects they have recommended upper limits for the softening point temperature 65°C to 70°C for heavy and very heavy traffic conditions. Therefore, when selecting the best modifier percentage for Sri Lankan context, 47°C-65°C softening point range is considered in this study. Further, according to Meegahage (2015) (Meegahage, 2015) who had reviewed the penetration grading system in Sri Lanka, has used Penetration Index (PI) between -1 and +1 as the best range for the local context. Therefore, modifier percentages which are not within between -1 and +1 range, are not selected.

Sitinamaluwa et al. (2014) (Sitinamaluwa & Mampearachchi, 2014) has recommended the PG 58-16 binder grade for all areas in Sri Lanka by considering the maximum and minimum temperature variations in the country. Therefore, for the rutting parameter, 58°C is considered as the boundary minimum temperature in this study. This means the binder which has a rutting parameter of at least 1.0 kPa at 58°C should have enough stiffness and elasticity at this temperature to resist deformation under traffic load. Moreover, all three modifiers display an increasing trend in $G^*/\sin\delta$ value, which reflects the strong rutting resistance and suitability for Sri Lanka's climate.

Table 10 conveys the selected modifier percentages by considering the above criteria as the most appropriate binders to the Sri Lankan context.

Table 9. Optimum percentages for modifiers.

Modifier type	Percentage by weight
PCB	15%
RHA	10%
FM	3%

6.3 Environmental and Economic Impact Assessment

According to the above derived optimum modifier percentages, the mass required from each ingredient to create 1kg of binder is calculated in Table 11. Using the data from both Tables 6 and 11, EE, $ECO_{2\text{-}e,}$ and cost values for modified binders are calculated. (Refer Table 12)

Table 10. The mass of mixing for 1kg binder.

Modified binder	**Modifier (g)**	**Bitumen (g)**
Conventional binder	-	1000
PCB	150	850
RHA	100	900
FM	30	970

Table 11. Calculated EE, ECO2-e and Cost values for modified binders

	Embodied Energy (EE) (MJ/kg)	ECO2-e (kg CO2e/kg)	Cost (LRK/kg)
Conventional binder	2.501	0.372	224.50
PCB	2.171	0.354	196.15
RHA	2.281	0.360	205.60
FM	2.808	0.430	223.99

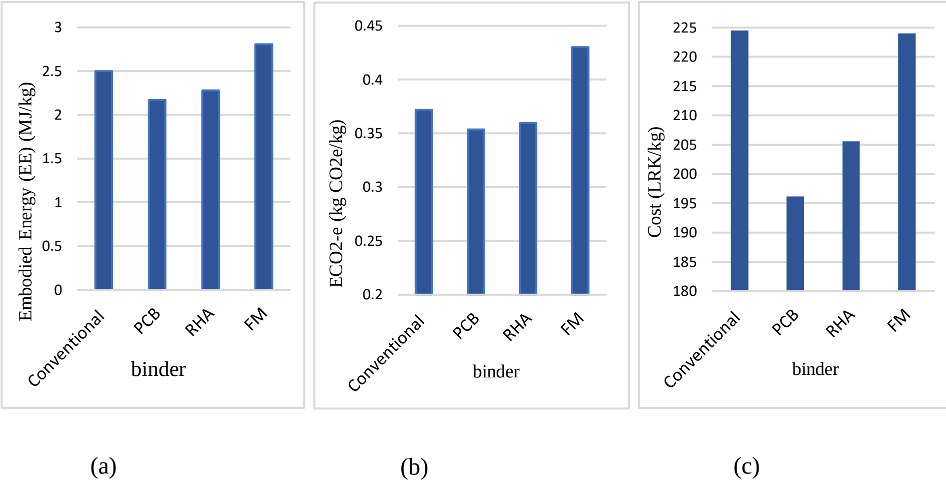

Fig. 4. Estimated (a) Embodied Energy (EE), (b) Equivalent CO_2 emission, and (c) cost values for binders

Figure 8 shows the lowest EE, ECO_{2-e} and cost values belong to PCB modified binder. However, RHA modified binder shows similar values to PCB modified binder for EE and ECO_{2-e}. But the cost values have a considerable difference. The critical point indicated in the graphs is that the FM-modified binder has higher EE and ECO_{2-e} than the conventional binder. Although it has a lower cost value, due to the higher environmental impact, FM-modified bitumen is unable to be considered as a sustainable option. In the study on reprocessed plastics and commercial polymer-modified asphalts by Salehi et al. (2022) (Salehi et al., 2022), they have mentioned that reprocessed plastics can be introduced as an environmentally friendly substitute for commercial polymers. Therefore, FM binder which is also a recycled polymer, may have the potential to replace commercial polymers, as polymer modifiers are the frequently used modifier type in Sri Lanka (Sitinamaluwa & Mampearachchi, 2014).

7. Conclusion and Recommendations

This study investigated the performance of three waste-based modifiers; PCB, RHA and FM and evaluated their applicability under Sri Lankan context. Two literature sources were used to collect data on RHA and FM modifiers. In order to be compatible with testing conditions of all three modifiers, laboratory experiments were carried out for PCB modifier while maintaining similar conditions. As performance is not the only governing parameter when selecting a bitumen modifier option for a construction project, environmental and economic impact was evaluated further. To analyse environmental impact, embodied GHG Emissions (ECO2-e) and embodied energy (EE) parameters are calculated. Moreover, the total expenses are an important concern for large-scale construction projects such as highways. Therefore, by adding a locally available waste material would be an attractive cost reducing option for a project. A cost comparison has been carried out by considering the market price of ingredients, labour and electricity in 2024. Based on the analysis of three aspects; pavement performance, environmental impact and economic impact, following conclusions and recommendations are drawn.

From the results obtained from both experimental and calculated data, PCB can be recommended as the most sustainable modifier option for Sri Lanka, with regard to performance, environmental, and economic impact. PCB-modified binder decreased the EE value by 13% and the ECO2-e value by 5% compared to conventional binder. Additionally, PCB reduced costs by 13%, making it the most cost-effective option.

Adding 15% PCB by total weight for bitumen modification is recommended as the optimal percentage for use in Sri Lanka.

RHA is identified as the second-best sustainable option, offering improvements over conventional binder properties in all three aspects. It decreased the EE value by 9%, the ECO2-e value by 3%, and costs by 8% compared to conventional binder.

Although the FM-based binder showed negative impacts in terms of both environmental and economic factors, it exhibited improvements in pavement performance. Therefore, further investigation into the environmental impact of FM is recommended. Since Sri Lanka commonly uses SBS as a modifier, it is advisable to compare the environmental and cost impacts of SBS and FM modifiers. Additional research on FM to streamline the preparation process is encouraged to reduce both environmental and cost impact values.

A major limitation of these waste-based modifiers is the inconsistency in their chemical composition depending on the source. However, the variation in impurity percentages in PCB samples can be minimized by maintaining constant proportions of the respective tyre types and controlling parameters during the pyrolysis process.

Additionally, there is limited literature on the environmental impact of highway construction materials specific to the Sri Lankan context. Therefore, further research into the environmental impact of highway construction materials is encouraged

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