INVESTIGATION OF THE PROPERTIES OF CARBON BLACK MODIFIED BITUMEN AND HOT MIX ASPHALT MIXTURES

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Degree of Master of Science

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Thesis submitted in partial fulfillment of the requirements for the degree

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DECLARATION

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The above candidate has carried out research for the Masters thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. Chamod Hettiarachchi

Signature of the Supervisor: Date:28/05/2025

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Sudharshi Jayasinghe

ABSTRACT

The traffic volume, tyre pressure, and environmental conditions cause the depletion of road pavement performance levels. However, to enhance road quality, improving pavement performance is vital. Researchers have been studying ways to improve the performance of pavements by modifying the asphalt using various materials. With the emerging trend towards low carbon emission materials, waste-based materials are usually investigated on their ability to modify conventional construction materials. Pyrolysis Carbon Black (PCB) is a by-product of the waste tyre recycling process, which can potentially improve pavement performance. This study aims to investigate the properties of PCB modified bitumen and its performance impact factors. Further to evaluate the manufacturing process of PCB-modified asphalt concrete by comparing the effects of wet and dry mixing methods on pavement performance when PCB is incorporated with asphalt. Penetration, softening point and Dynamic Shear Rheometer (DSR) test was conducted to investigate the Rheological and Physical properties. Marshall Stability and flow tests are used to evaluate the volumetric properties. The bitumen properties provide the evidence of ability to improve the rutting resistance and high temperature performance of the asphalt by adding PCB. Further volumetric properties show that both methods have improved the asphalt properties where the flow has increased in wet and dry mixing mixtures, compared to the conventional mixture. Moreover, PCB modified road section was evaluated and calculated Pavement Condition Index (PCI). For better insight, another section from the same road prepared with conventional asphalt at the same period was evaluated. The calculated PCI values are 85% and 88% for conventional and PCB-modified pavements, respectively demonstrating the potential for long-term performance in PCB-modified pavements. PCB can be recommended as a promising modifier option to develop pavement performance while adhering to sustainability guidelines. Furthermore, additional investigations into low-temperature performance and wet mixing manufacturing process of PCB-modified asphalt are encouraged.

Keywords: Pyrolysis Carbon Black (PCB), Bitumen modification, Asphalt concrete, wet mixing, dry mixing, Pavement Condition Rating

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LIST OF ABBREVIATIONS

Abbreviation	Description
AHO	Aromatic hydrocarbon oil
BET	Brunauer-Emmett-Teller
BR	Butyl Rubber
CB	Carbon black
CCB	Commercial carbon black
CDV	Corrected Deduct Value
CEB	Ceylon Electricity Board
CPCB	Co-pyrolytic carbon black
DBP	Dibutyl phthalate
DSR	Dynamic Shear Rheometer
DV	Deduct Value
EDS	Energy-dispersive X-ray spectroscopy
EE	Embodied energy
$ECO_{2\text{-}e}$	Embodied GHG Emissions
FTIR	Fourier transform infrared spectroscopy
GHG	Greenhouse gas
HMA	Hot mix asphalt
HSE	Health and Safety Executive
NPCB	Nano-carbon black
OBC	Optimum Bitumen Content
OSHA	Occupational Safety and Health Administration
PAH	Polynuclear aromatic hydrocarbons
PAV	Pressure Age Vessel

PCB	Pyrolysis Carbon Black
PCI	Pavement Condition Index
PE	Polyethylene
PET	Polyethylene Terephthalate
PI	Penetration Index
RPM	Rounds Per Minutes
RTFO	Rolling Thin Film Oven
SBS	Styrene butadiene styrene
SBR	Styrene-butadiene copolymer
SEM	Scanning electron micrograph
SFE	Surface free energy
SSCM 05	Standard Specification for Construction and Maintenance of Roads and Bridges
TDV	Total deducts value
UV	Ultra-violet
VMA	Voids in Mineral Aggregate
VPCB	Vacuum pyrolysis carbon black
XRD	X-ray diffraction

LIST OF APPENDICES

CHAPTER 1

1. INTRODUCTION

1.1 General Overview

Bitumen, derived from crude oil, plays a crucial role in asphalt concrete, which is a widely used material for road construction (Provatorova & Vikhrev, 2020). It binds aggregates such as sand, gravel, and crushed stone, ensuring a stable and durable road surface (Nizamuddin et al., 2021). However, conventional bitumen has limitations, especially in regions with extreme climates and heavy traffic (Arabani & Tahami, 2017). It can soften at high temperatures, leading to rutting, and become brittle in cold conditions, leading to cracking and premature pavement failure (Z. Feng et al., 2021).

From the beginning of asphalt technology, researchers have put effort into bitumen modification using several materials to enhance the overall performance of road pavement (Nizamuddin et al., 2021). In response to the shortcomings of unmodified bitumen, various modifiers are used to enhance its properties (Malinowski et al., 2022). These modifications improve flexibility, resistance to deformation, and overall durability (Rohayzi et al., 2023). This is particularly important in regions with extreme weather conditions, where the performance of unmodified bitumen is compromised. Their aim is to create a more resilient material that can withstand high temperatures, heavy traffic loads, and the natural ageing process. 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, waste-based materials are usually investigated for their ability to modify conventional construction materials.

Polymer modifiers such as styrene butadiene styrene (SBS) are the commonly used modifier type, in the Sri Lankan context (Sitinamaluwa & Mampearachchi, 2014). Therefore, diving more into the locally available greener options is essential. Under this study, the greener modifier option - Pyrolysis Carbon Black (PCB)- has been selected for further analysis. PCB is derived as a by-product of the waste tyre manufacturing process, which is an industrial waste. Especially, the potential of PCB to improve bitumen performance and simultaneously address environmental concerns related to end-of-life tyre waste makes it an attractive option for road construction (H. Wang et al., 2019).

1.2 Background

Unmodified bitumen exhibits several performance issues, such as rutting, cracking, and ageing (Penki & Rout, 2021). These issues are particularly pronounced in regions with high temperatures, where bitumen softens, and in high-traffic areas, where the road is subjected to repeated stresses. Additionally, over time, bitumen undergoes oxidation, which results in a loss of flexibility and increased brittleness (Ameli et al., 2020). As a result, pavements constructed with conventional bitumen often require frequent maintenance and repairs, leading to higher costs and shorter service life (Y. Li et al., 2022). That can be overcome by improving adhesive and flexibility properties (Y. Li et al., 2022). Polymer modifiers are the frequently used modifier types to address these issues regarding the pavements. However, researchers have paid attention to waste polymers to address the sustainability criteria by polymer modifiers (Emtiaz et al., 2023). Developing waste-based modifiers has become an emerging research area along with the emerging sustainability concept (Casado-Barrasa et al., 2019). Waste-based Bitumen modifiers, such as PCB, have been developed to enhance the performance of bitumen and mitigate its weaknesses while achieving sustainable goals.

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. The 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 a higher percentage, is difficult to replace with commercial carbon black (CCB) directly (Cardona et al., 2018; Hoang et al., 2020). Therefore, innovative methods to reuse PCB are highly needed under this scenario (Arabiourrutia et al., 2020). The ability to modify bitumen using PCB for better pavement performance has been explored in several studies (Chaala et al., 1996; Z. Feng et al., 2021).

PCB, derived from the pyrolysis of waste tyres, has the potential to address two major challenges simultaneously: improving the performance of asphalt concrete and providing an environmentally friendly solution to waste tyres. Its high-temperature resistance and ability to reinforce bitumen's structural integrity make it a promising solution for road construction, especially in hot climates and high-traffic areas. This research will explore the optimal application of PCB in bitumen and evaluate its long-term performance, particularly through field studies of a road constructed using dry-mixed PCB.

1.3 Problem Statement

Bitumen pavements are prone to distress, such as rutting and cracking, especially in regions with extreme climates and heavy traffic. These limitations lead to high maintenance costs and frequent repairs, shortening the lifespan of road infrastructure. Therefore, bitumen modification has become a pathway to improving pavement performance.

Although laboratory studies indicate the potential of PCB to improve bitumen's properties, there is a lack of long-term field data on its effectiveness in real-world conditions. Due to the inconsistency of elemental composition in PCB samples with respect to the source and process, the modified bitumen performance varied.

Therefore, a comprehensive analysis of the behaviour of locally available PCB and modified bitumen properties is crucial to develop this technology as an industry application. The performance of PCB-modified asphalt, with respect to the PCB content and mixing parameters, is important to evaluate to find the optimum mixture. Moreover, incorporating PCB into bitumen—whether through dry or wet mixing—significantly affects the modifier's effectiveness. Dry mixing is commonly used due to its simplicity and cost-effectiveness, but it may lead to poor dispersion of PCB particles in the bitumen. On the other hand, wet mixing can achieve a more uniform distribution of the modifier but requires additional processing time and energy. This study aims to compare both methods to determine which is more effective in enhancing the performance of PCB-modified bitumen.

A road constructed using dry-mixed PCB has been in service for three years, providing an opportunity to evaluate its performance under actual traffic and environmental conditions. The research will assess the road's condition after this period to provide valuable insights into the long-term effectiveness of PCB-modified bitumen in real-world applications.

1.4 Significance of the Study

The use of PCB as a bitumen modifier promotes sustainability by utilizing waste tyres, which is a significant environmental concern (Kommineni et al., 2018). This study offers a practical solution to recycle end-of-life tyre waste while improving the quality of road construction materials. By recycling waste tyres into valuable road construction materials, this research contributes to both environmental conservation and infrastructure development.

Further, Sri Lanka requires more sustainable and performance improving modifier options (Nawela & Samaranayake, 2024). Although several experiments have been carried out to investigate the applicability of PCB as a bitumen modifier option in Sri Lankan context, it requires further analysis to bring out this novel technology into a practical approach (Ariyarathne et al., 2024). This research provides practical recommendations for engineers and road construction professionals, especially in the Sri Lankan context. This study will enable more efficient and durable road construction solutions by identifying the optimal mixing method and PCB proportions. Moreover, improving the durability of bitumen can reduce the frequency of maintenance and repairs, leading to lower long-term costs for road infrastructure. This research will explore whether PCB-modified bitumen offers a more cost-effective and long-lasting alternative to conventional bitumen, especially in the Sri Lankan scenario. By evaluating the performance of a road constructed with dry-mixed PCB after three years, this study provides real-world validation of the laboratory results, ensuring that the findings are applicable to practical road construction applications.

1.5 Research Objectives

This study aims to achieve the following objectives:

The main objective of the study is to investigate the physical and rheological properties of the PCB-modified bitumen and volumetric properties of the hot mix asphalt concrete mixtures while making practical recommendations for engineers and road construction professionals, especially in the Sri Lankan context.

The specific objectives of the study are elaborated as follows:

- To assess the effectiveness of PCB in comparison with conventional binder. This includes analysing the impact on environmental and economic aspects too.
- To examine how particle size and mixing speed (RPM) influence the performance of PCB-modified bitumen. This will help to determine the optimal parameters for PCB applications.
- To compare the effects of dry and wet mixing methods on the performance of PCB-modified bitumen, focusing on the uniformity of mixing and the overall stability of the asphalt mixture.
- To assess the condition of a road constructed using dry-mixed PCB after three years of exposure to traffic and environmental conditions, providing valuable field data on the long-term performance of PCB-modified asphalt pavement

CHAPTER 2

2. LITERATURE REVIEW

2.1 General

The evolution of road construction materials has been driven by the need for durability and cost-efficiency while being sustainable. Although bitumen is a widely used pavement construction material, it has several major limitations, such as susceptibility to high temperatures, heavy traffic-induced deformation, and environmental degradation. This chapter reviews the advances in bitumen modification using sustainable material, focusing on Pyrolysis Carbon Black (PCB). Moreover, it examines the effectiveness of dry and wet mixing methods in the preparation of modified asphalt concrete and identifies gaps in the long-term evaluation of modified pavements.

2.2 Bitumen Modification: An Overview

2.2.1 Necessity of Bitumen Modification

Asphalt pavements are highly demanded for road construction all over the world due to their better driving performance and lower cost levels associated with it (Kakade et al., 2024; Pang et al., 2018). The two major constituents of an asphalt pavement are aggregate and bitumen binder. Asphalt pavement contains roughly 93-97% of aggregates and 3-7% of bitumen where that tiny amount of bitumen has a drastic impact on the pavement performance (Olalekan et al., 2024).

Environmental conditions such as temperature variations directly affect pavement performance. At lower temperatures, binder stiffness gets reduced by resulting fatigue failures, while higher temperatures cause rutting on pavements due to increased stiffness of the binder (Mohamed et al., 2021). Further, the thermal cracks propagate by impacting the long-term performance of the pavement (Klinsky et al., 2018). Traffic load is the other major factor which affects the pavement performance by resulting in stresses such as shear, tensile and compressive on different parts of the pavement according to the contact area and the load (Shafabakhsh et al., 2020).

Although flexible pavements have become very popular worldwide, above mentioned distresses, which effect on long-term performance of the pavement, have become a major concern (Kakade et al., 2024). Therefore, different modifiers have been introduced in bitumen to improve pavement performance (Arabani, Sadeghnejad, et al., 2024). The improvement capabilities of different groups of modifiers such as bio-oils (Lei et al., 2015), rubber (Rowhani & Rainey, 2016),(Yu et al., 2023), antioxidants (Verma & Saboo, 2024), fillers (Xing et al., 2020), polymers (Emtiaz et al., 2023), nano-materials (Olalekan et al., 2024), ultraviolet absorbers (F. Ma et al., 2023), and rejuvenators (Loise et al., 2019) have been investigated.

With the emerging concept of sustainability, the conservation of existing non-renewable resources has become a crucial measure to be taken (Zhao & Yang, 2023). Bitumen, which is a derivative of fossil fuel, is one of the major depleting resources. According to Arabani et al. (2024) (Arabani, Sadeghnejad, et al., 2024)Due to this increasing consumption, world oil resources are predicted to be exhausted by 2052. The waste-based materials as bitumen modifiers and substitutes have become a rising field of research (Loise et al., 2024). The behaviour of waste-based materials such as Rice Husk Ash (Mistry et al., 2019), plastic waste (Naghawi et al., 2018), Waste Rice Straw Ash (Aliyu Yaro et al., 2022), used face mask polymers (Ayyadurai et al., 2023), fly ash (Oreto et al., 2021), and waste tyre pyrolysis carbon black (PCB) (H. Wang et al., 2019) have evaluated and obtained better performances as modifier options for bitumen. This reusing of waste-based materials has contributed to reduce GHG emissions while enhancing the circular economy (Arabani, Effati, et al., 2024). However, the regional applicability of these waste-based materials is influenced by several factors, such as climate conditions, regional availability and impurity contents (Arabani & Hassanjani, 2024)Therefore, this study has selected three commonly available waste-based modifiers and checked their suitability for the Sri Lankan context.

2.2.5 Pyrolysis Carbon Black (PCB) as a Modifier

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. The 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 CB in a higher percentage, is difficult to replace with CCB directly (Cardona et al., 2018; Hoang et al., 2020). Therefore, innovative methods to reuse PCB are highly needed under this scenario (Arabiourrutia et al., 2020). The ability to modify bitumen using PCB for better pavement performance has been explored in several studies (Chaala et al., 1996; Z. Feng et al., 2021).

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 and rheological properties in modified bitumen. Further, high-temperature rutting resistance and ageing resistance have 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 pyrolysis 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) have done a series of experiments to have clear understanding of the behaviour of PG 58-28 bitumen modified by adding FEF N-550 graded CB (0, 5, 10, and 15 wt%). The experiments revealed that the mixture turns more elastic and less susceptible to temperature changes. Guo et al. (2023) (Guo et al., 2023) have explored 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 2.1 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 abundant impurities contributing around 15-25% of the total mass. In this study, the chemical composition of the PCB, which is available in the Sri Lankan context, has been evaluated, and PCB-modified bitumen characteristics were further analysed. The comprehensive analysis carried out in this study has sorted out Pyrolysis Carbon Black as the best modifier option for the Sri Lankan context. Therefore, further investigation has been conducted on the literature regarding carbon black in the below sections.

Table 2.1: The chemical composition of the PCB from different resources

Element	**Weight by percentage in Past studies**		
	(Nkosi & Muzenda, 2014)	(Rikmann et al., 2024)	(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	-

2.3 An overview of carbon black

2.3.1 History and evolution of the carbon black industry

The evidence of carbon black goes far back to the date of today. Carbon black has been used as a pigment in wall paintings in ancient Paleolithic caves. There is evidence of ancient Egyptians' use of carbon black for paintings. The Chinese ancestral burned vegetable oils to collect carbon black, which was used as a pigment in 3000BC (M.-J. Wang et al., 2004).

Until 1870, vegetable and animal oils were burned under limited air supply conditions to produce carbon black, called the lump black process. When looking at the recent past, after 1870, natural gas was used instead of vegetable and animal oils. With time, a channel process was developed, and iron channels started to be used. Although the carbon black yield from this process was darker, the plumes of smoke at the manufacturing plants were visible for 50 miles. This indicates the inefficiency of methane or incomplete combustion of raw materials. Therefore, along with new technologies, lump black plants were gradually closed. In 1976, the last lump black plant in the USA was closed (M.-J. Wang et al., 2004).

In 1904, the rubber-reinforcing capability of carbon black was discovered making a turning point in the industry. In the 1920s, with the development of automobile technology, the consumption of carbon black increased with the increasing demand for pneumatic tyres. Furthermore, another two-carbon black manufacturing process was invented with this high demand at that period. They are the thermal black process and the gas furnace process. Out of them, the thermal black process is still in use. In 1943, Phillips Petroleum introduced the oil-furnace process at its plant in Borger, Texas. After that, it seems like the industry has gradually shifted to that technology. With the development of automobile technology, the rubber tyre has also developed. Along with evaluating tire types and qualities, the requirement of Carbon black quantities and their properties has evolved. At present, required carbon black properties are derived by adjusting the parameters of the manufacturing process, not only that ASTM has defined a standard, too (M.-J. Wang et al., 2004).

2.3.2 Texture & colour

Carbon black mainly consists of elemental carbon, which is very stable chemically and has the nature of an ultrafine fluffy power physically (M.-J. Wang et al., 2004). The particle size of carbon black varies between a vast range of 10 to 100 nm (Khabazipur & Eaves, 2024). There are many commercially carbon black-producing plants worldwide, as it is a highly popular nanomaterial (Okoye et al., 2021). An incomplete combustion is carried out under various procedures using oils or natural gases as the ingredients (M.-J. Wang et al., 2004).

The chemical and physical properties are mainly governed by the shape of the particles and their surface area. The fractal dimension is the major factor that defines the final carbon black product's value and quality. The fractal dimension is the most convenient parameter that conveys information about the morphology of the particle. The manufacturing process, temperature, gas flow rate, and residence time greatly impact on the fractal dimension. Therefore, according to the industrial requirements of morphology, the manufacturing process must be optimised (Khabazipur & Eaves, 2024).

The particle size and the surface area of carbon black are discovered by the iodine (I_2) adsorption test and the Brunauer-Emmett-Teller (BET) nitrogen adsorption test. Carbon black particles have the nature of combining and making aggregates due to their surface energy and large surface area. These aggregates can be categorised into low and high structures (Figure 2.1). When a small number of carbon black particles form a linear and short structure, it is called a low structure. High structures have a comparatively higher number of particles, forming a long, branched chain with a grape-like shape. High structures are the type used to reinforce materials (Bera et al., 2018). The dibutyl phthalate (DBP) absorption test is used to evaluate the structure of carbon black. The numerical test result expresses the amount of absorbed DBP in cubic centimetres by 100g of carbon black. Higher dispersing ability is observable with larger structures; while blackness is lower (Table 2.2). According to all these parameters, carbon blacks have been classified in ASTM D1765 (Bera et al., 2018).

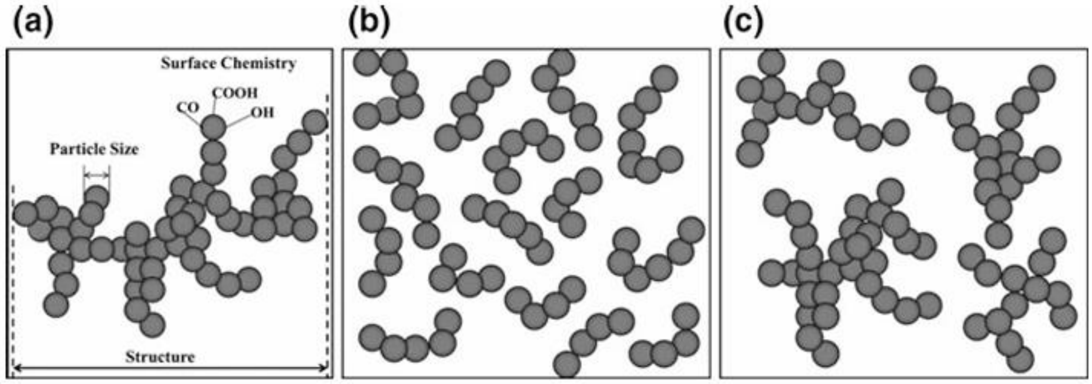


Figure 2.1: a) Schematic representation of particle size and surface chemistry of carbon black, b) low structure carbon black, c) high structure carbon black (Bera et al., 2018)

Table 2.2: Effect of structure on compound properties (Bera et al., 2018)

Property	**High Structure**	**Low structure**
Dispersibility	Easier	More difficult
Absorption	Low	High
Wetting	Slower	Faster
Gloss	Lower	Higher

Conductivity	Higher	Lower
Viscosity	Higher	Lower
Loading capacity	Lower	Higher
Tint strength	Lower	Higher

2.3.3 Difference from other C types

Carbon can be defined as the most versatile element in the world. Corban comes in the form of a fuel but simultaneously in the form of a sparkling diamond. Carbon is composed of the majority of living beings, which means that life on Earth highly depends on the existence of carbon. Different carbon-carbon linking forms result in various material forms. Graphite is very soft and slippery, while diamond is the strongest material. Figure 2.2 shows the different forms of carbon-based materials that are all completely made up of carbon elements but have different unique astonishing properties such as exceptional thermal and electrical conductivity, high strength, good corrosion resistance, and excellent thermal and mechanical stability (Bera et al., 2018).

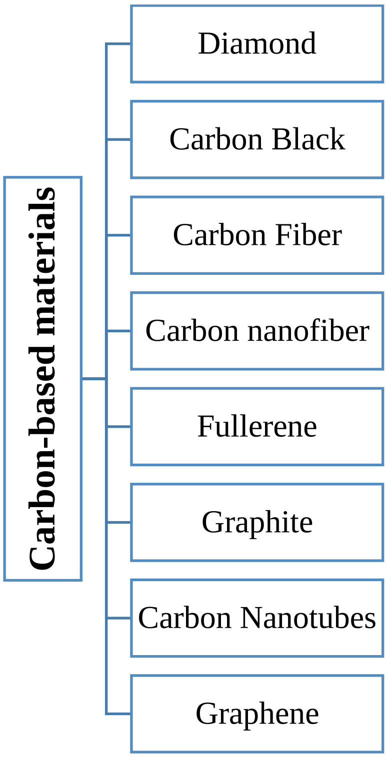


Figure 2.2: Different forms of carbon base material (Bera et al., 2018)

The quasi-graphitic structure and the complex configurations of the aggregates (Figure 2.3) composed of carbon black are the main reasons for its difference from other forms of carbon-based materials. The hydrocarbon's partial combustion and thermal decomposition phases of the carbon black manufacturing process undergo vapour phase homogeneous nucleation, which is the key difference from other bulk carbons. However, carbon black may contain different impurities that occur in the combustion process. But the chance of having inorganic contaminants is very less as carbon black production is carried out under a controlled process environment (M.-J. Wang et al., 2004).

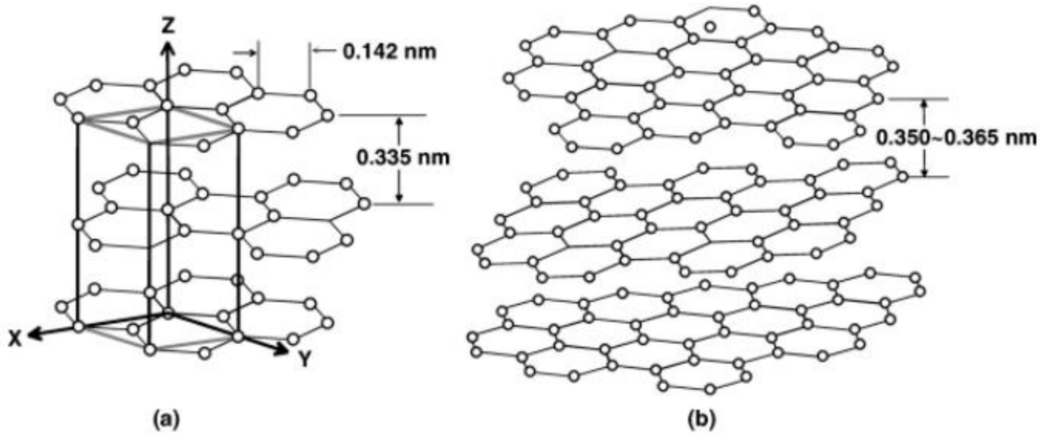


Figure 2.3: Atomic structural models of (a) graphite and (b) carbon black (M.-J. Wang et al., 2004)

2.3.4 Usage in Industry

Commercial carbon black contains almost pure elemental carbon (over 97%wt) as ultrafine particles made from gases or liquid hydrocarbons by thermal decomposition or incomplete combustion. The rubber industry consumes nearly 90% (Cardona et al., 2018) of carbon black production as an elastomer-reinforcing agent, while remaining 10% (Cardona et al., 2018) is used in various industries, such as pigments for printing inks, dyes, coatings, heavy metal removal, and ultra-violet (UV) stabilisers and electrical conductivity agents in batteries (Okoye et al., 2021). International Carbon Black Association has classified carbon black among the top 50 industrial chemicals of global production (International Carbon Black Association, 2016).

Although there are many carbon black manufacturing methods such as thermal, oil furnace, gas furnace, acetylene cracking, lamp, and channel processes, current methods highly used in the world are furnace and thermal processes (Cardona et al., 2018). However, according to Cardona et al. (2018) (Cardona et al., 2018) in 1976, the last channel black plant in the United States closed.

However, the production process directly affects the qualities of the resulting carbon black. According to the manufacturing method, the variation of properties can be observed in Table 2.3. The application of carbon black, such as reinforcement, abrasion, and functional modifications, depends on the properties (Song, 2017).

Table 2.3: property variations along with the manufacturing process (Song, 2017)

Category	Furnace	Channel	Thermal
Size (nm)	15-100	15-40	-
Processing	Hydrocarbon burning at 1200-1600C in the furnace	Natural gases burnt on an iron plate with limited oxygen	Degradation of hydrocarbons at 800-1000 C
pH	6.5-10	5.5	-
Features	High mechanical properties	The oxygen content of 2-10% in the form of carboxylic groups and dissolvable in water	Particles form chains and aggregates, and high oxygen content provides high surface activity.

2.3.5 How to produce Carbon Black commercially

As mentioned above, there are several Carbon Black manufacturing methods, such as furnace black, lamp black, channel black, acetylene black, and thermal black. The chemical processes of these methods, either thermal decomposition or thermal oxidative decomposition (Khabazipur & Eaves, 2024). The decomposition process also has two different ways depending on whether the system is closed or open. Incomplete combustion is done under furnace black process, channel black process, and lamp black process, while thermal decomposition of hydrocarbons at minimum oxygen zone is carried out under acetylene black and thermal black processes (Okoye et al., 2021).

However, the most popular method is the furnace method, which contributes to 90 to 95% of total carbon black percentage worldwide (Cardona et al., 2018). The main raw material of the method is heavy hydrocarbons such as natural gases, acetylene, and aromatic oil from fossil fuel by-products, for which 60% of total production expenditure. The feedstock continues pyrolysis process at a high-temperature furnace around 1500-2000K (Khabazipur & Eaves, 2024).

However, this combustion process directly increases recent global environmental problems, such as global warming and climate change. Therefore, finding the best options for Carbon black production is necessary. However, the main obstacle is maintaining the required properties of the resulting carbon Black, which is highly dependent on the production method. Therefore, the recognition of sustainable raw materials and methods for manufacturing carbon black has attracted the attention of researchers all over the world (Okoye et al., 2021).

2.3.6 CCB Grading

Due to property variations with respect to the manufacturing statutes, a comprehensive classification guideline or regulation is required to access the carbon black. That necessity is fulfilled by the ASTM codes from their grading system. N120, N330, N550, and N660 frequently use carbon black grades, which ASTM has classified. The letter 'N' refers to the normal cure rate, meaning no modifications have been made to the cure (Bera et al., 2018). The first nest number refers to the average particle size. Higher numbers can be used for reinforcing purposes as the specific surface area decreases with increasing numbers. Moreover, the N330 and N550 grades highly use carbon black types in the type manufacturing process. Table 2.4 provides more clarified comparative information on these carbon black grades (Cardona et al., 2018).

Table 2.4: Typical commercial carbon black properties and their application (Bera et al., 2018), (Cardona et al., 2018)

Name	**Standard Abbreviation**	**ASTM designation**	**Particle size (nm)**	**Average surface area (m^2/g)**	**Application**
Super abrasion furnace	SAF	N110	15-18	124-130	High reinforcement; high abrasion resistance; used in special and off-road type products
Intermediate SAF	ISAF	N220	20-25	112-115	High reinforcement and tear strength, good processing; used in passenger, off-road and special tyres.
High abrasion furnace	HAF	N330	28-36	76-80	Medium-high reinforcement. Low modulus, high elongation, goof flex, tear and fatigue resistance; used in tyre tread, carcass and sidewall compound, and bicycle tyres.
Fast extrusion Furnace	FEF	N550	39-55	39-41	Medium-high resistance, low modulus, high elongation, good flex, tear and fatigue resistance; used in the tyre tread, carcass and sidewall compounds and hose and other extruded goods.

General purpose furnace	GPF	N660	56-70	34-36	Medium reinforcement and modulus, good flex and fatigue resistance, low heat building up; used in tyre inner liners, carcass and sidewall, sealing rings, cable jackets, hose and extruded goods.
Semi reinforcing furnace	SRF	N770	71-96	31-32	Medium reinforcement, high loading capacity and low hysteresis. Easy extrusion black. Used in belts, hoses, moulded goods, and footwear.
Medium thermal	MT	N990	250-350	7-9	Low reinforcement, low modulus, hardness hysteresis and tensile strength, high elongation and loading capacity, used in wire insulation and jackets, mechanical goods, footwear, belts, hose, gaskets, O-rings and inner liners.

2.3.7 Health and Safety

Many studies have been carried out after the 1900s, with the sponsorship of the carbon black industry. They have focused on the mortality and health of the carbon black industry workers along with the outside population. North America-based research in 1939 has shown that mortality has not increased due to the Carbon Black industry effect. After that, many clinical studies have been conducted on that. But none of them provides any evidence of an increase in the mortality of carbon black industry workers (M.-J. Wang et al., 2004).

However, later in 1995, with long-term observations, it recognised the possibility of lung-associated censers (Driscoll et al., 2000). With that, the International Agency for Research on Cancer has updated Carbon Black from Category 3 to Category 2B, from ‘‘not classifiable as to its carcinogenicity to humans’’ to ‘‘possibly carcinogenic to humans’’ respectively. When considering the carcinogenic capacity of carbon black, the major reason is its ability to absorb polynuclear aromatic hydrocarbons (PAH). PAH is tightly attached to the surface of the carbon black particles, which has been the reason for skin tumours in rats (Driscoll et al., 2000).

After 2000, the Carbon Black exposure acceptance level has been defined by many organisations. In the United States, the Occupational Safety and Health

Administration (OSHA) says that it is 3.5 mg/m3 in total dust. The Health and Safety Executive (HSE) in the United Kingdom also defines the limit as 3.5 mg/m3 in terms of inhalable dust (M.-J. Wang et al., 2004).

It is difficult to extinguish a fire that started by ignition of carbon black. Therefore, longer hot spots can occur at a fire in a large storage. There is a risk of carbon monoxide gathering if a smouldering fire is placed in confined areas. However, normally, carbon black dust is considered non-combustible, as it needs high ignition energy and a long ignition time (M.-J. Wang et al., 2004).

2.4 Waste tyre and pyrolysis process

With global warming and related environmental problems, attention has been paid to renewable resources and reuse of value-added waste (Martínez et al., 2013). On the other hand, the depletion of fossil resources is also the main reason for this trend. With the rapid increase in vehicle usage, end-of-life tyres also increase, causing a huge environmental problem. However, in terms of calorific values, which means the heat energy release capacity of a unit mass of fuel in complete combustion, rubber tyres deserve a higher place than coal (Martínez et al., 2013). Therefore, attention should be paid to recovering and taking advantage of this energy.

2.4.1 Structure and composition of tire rubber

Basic components that tyres are made out of are rubber, carbon black, and other additives such as fillers and accelerators (Martínez et al., 2013). Rubber is considered a thermoset polymer that has a C_xH_y structure. The rubber content in a tire consists of both natural and synthetic rubber. Natural rubber is extracted from the sap of Hevea Brasiliense trees, while synthetic rubber, such as styrene-butadiene copolymer (SBR) and butyl rubber (BR), comes from petroleum-based products (Rowhani & Rainey, 2016). In 2010, 24.37 million tons of rubber were manufactured worldwide, as reported by the International Rubber Study Group (Martínez et al., 2013). The second major constituent in a tyre is carbon black, as discussed above. The primary objective of the CB is to provide abrasion resistance and strengthen the rubber. Organic and inorganic fillers are added to soften and improve the workability of rubber. Then, rubber undergoes the vulcanisation process, which is an irreversible reaction that makes a three-dimensional chemical network by newly propagating crosslinks (Figure 2.4) among elastomer molecular chains (Xiao et al., 2022). Then, the rubber becomes stronger and more difficult to decompose. Table 2.5 shows the content of a tyre and of compounds with the type of tyre (Rowhani & Rainey, 2016).

Table 2.5: Comparison of compound content amount with the tyre type (Xiao et al., 2022)

Material	**Car tyre**	**Truck tyre**
Natural and Synthetic Rubbers	47	45
Carbon Black and Silica	22.5	21

Metals (Steel Beads, Belts)	14	23.5
Textiles (Carcass)	5.5	1
Vulcanizing Agents (Sulphur Peroxides and metal oxides)	2.5	3
Additives (antioxidants, antiozonants, extenders)	8.5	6.5

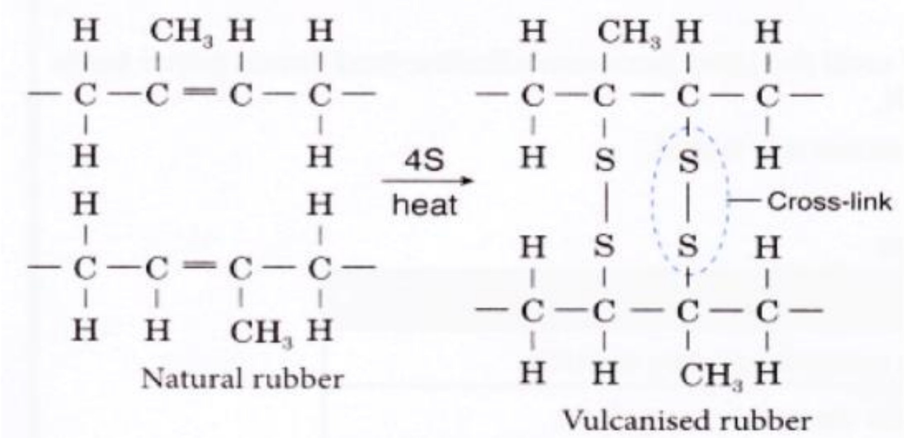


Figure 2.4: Schematic of molecular chain structure of normal rubber and effect of vulcanization to form cross linking (Xiao et al., 2022)

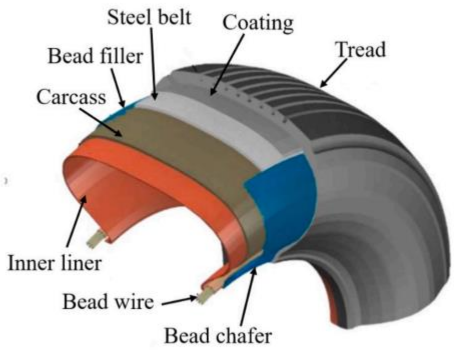


Figure 2.5: Typical tyre structure (Xiao et al., 2022)

Although in Table 2.5, the total percentage of each component has been presented, tyres have several layers with different properties. Figure 2.5 shows a cross-section of a typical car tyre (Czajczyńska et al., 2017). The rubber blend is adjusted to match the application, such as high rubber content at the tread and sidewalls. Synthetic fibres such as nylon, polyester, and rayon are used instead of metal to obtain tensile properties while reducing overall weight and the production cost of a tyre (Xiao et al., 2022).

2.4.2 End of Life tyre generation and related issues

With the rapid use of vehicles, the demand for tyres increased (Z. G. Feng et al., 2016). According to (Zerin et al., 2023), that 95 million cars have been produced worldwide in 2019, and it will be 110 million in 2025. It means that there will be higher tyre demand. However, in developed countries, the generation rate of end-of-life tyres is higher than that of developing countries. Figure 2.6 shows the annual end-of-life tyre generation of several countries in 2022 (Zerin et al., 2023).

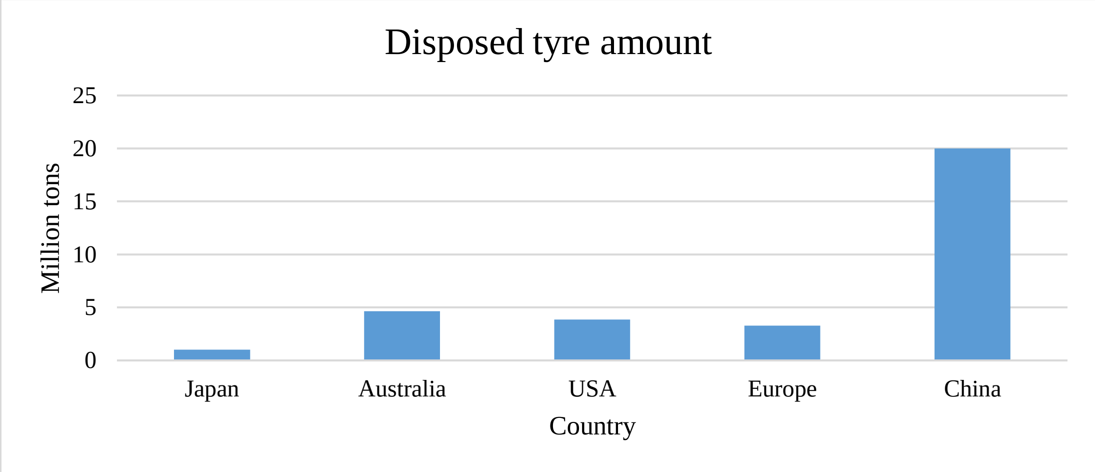


Figure 2.6: Waste tyre disposal amount of various countries in 2022 (Zerin et al., 2023)

In the recycling process of waste tyres, all the nun-rubber components need to be sorted because impurities within the tyre may directly impact the quality of the final recycled products. Truck tyres contain a greater amount of steel compared to car tyres, while car tyres contain a greater amount of textile (Koreňová et al., 2006). However, before recycling, both must be separated and undergo the relevant recycling process separately (Xiao et al., 2022).

As discussed above, the demand for tyres has increased with the rapid increase in population and technology. Although transportation has made life easier today, the drastically increasing waste of tyres has become challenging. According to predictions, this amount of tyre disposal may increase. As the easiest way to dispose of tyres, landfills have become popular in the past. Four billion tires have been disposed on the earth's surface up to now, which is estimated as 50 billion in 2030 (Zerin et al., 2023). Basically, because of the vulcanization process, waste tyres consist of sulphur bonds. Therefore, rubber tyres are difficult to decompose in a normal environment. Just because the tyres are made of non-biodegradable materials, landfills will remain the same for a long period. These waste tyre dumping are unpleasant in appearance and reduce space on the earth's surface. Moreover, the void space of the tyres also takes up a huge space. According to the literature, 75% of the landfill volume is void, leading to the risk of collecting toxic and explosive gases (Martínez et al., 2013). This void space provides good shelter for rodents and pests and grounds for breeding mosquitoes (J. Xu et al., 2021). Various dangerous diseases such as dengue, malaria, yellow fever, and leptospirosis can be spread among people in the surrounding (Czajczyńska et al., 2020). Furthermore, this inappropriate disposal of tyres may block the drainage patterns of the area, which may lead to flooding (Dwivedi et al., 2020). Due to the leach of harmful chemicals from tyres in landfills into the soil, the quality of groundwater and surface water is affected. The other threat is due to the high energy content of the tyres; it has a high risk of fire (Xiao et al., 2022). If a fire starts, it is very difficult to extinguish. As Xiao et al. (2022) report such fire had continued for 17 days at Tire King Recycling in Canada

(Xiao et al., 2022). Such a scenario brings another set of problems, which are very similar to those propagating open-air incineration.

The open-air burning of tyres has been identified as another recycling method to recover energy (Martínez et al., 2013). However, the black smoke that is generated by incineration is a cause of many health and environmental problems. Greenhouse gases such as carbon dioxide and hazardous compounds contained in black smoke are mentioned in Table 2.6 (Czajczyńska et al., 2020). However, in energy efficiency, only 25% of energy can be recovered from incineration. Furthermore, the influence of by-products such as char reduces the energy efficiency of open-air burns. Char remains on the ground will be absorbed and mixed with the soil, that will causes severe problems in soil and groundwater pollution, then absorbed into vegetation and get into the human body, causing serious health issues (Martínez et al., 2013). However, it is good to observe that the world has recognised this threat and imposed a legal ban. Certain limitations have been introduced in the European Union to undergo the incineration and landfilling of waste tyres strictly (Czajczyńska et al., 2020). However, this positive trend cannot be observed in many developing countries. They throw waste tyres here and there, along with other trash. For the time being, due to the inability to decompose, tyres accumulate. Then people put fire on those old tyres to get rid of them, which is the worst way of recycling (Okoye et al., 2021).

Table 2.6: Composition of the smoke emitted by open-air combustion of tyres

Component	**Emission, g/kg of tyre burned**
Carbon dioxide	1450
Carbon monoxide	35
Nitrous oxide	0.9
Nitric oxide	3.2
Sulphur oxide	15
Cryohydric acid	4
Hydrochloric acid	Not detected
Unburnt organics (toluene equivalents)	23
Dust	285
Metal (total) including aluminum and zinc	31.9
Polycyclic aromatic hydrocarbons	0.0633
Polychlorinated biphasic	2.66×10^{-4}
Dioxins/ furans (total)	6.44×10^{-7}

To extend the period of use, tyres are subjected to a replacement process of the outer layer, called the retreading process (Mavukwana & Sempuga, 2022). To undergo this process, tyres must be certified in wear and tear check. The tyres, which are not in good condition in the internal structure, are not allowed to be reused after retreading. However, normally, passenger car tyres are not subjected to the retreading process as the price of a new tyre is not higher comparatively with the retreading price

(Rowhani & Rainey, 2016). Truck tyres are commonly retreaded several times before being discarded. This retreading method saves a totally significant amount of rubber waste by reducing three to four new tyres buying (Sienkiewicz et al., 2012). New methods such as tyre retreading, rubber reclaiming, rubber grinding, and mechanical lapping have been developed to recycle waste tyres. However, all these methods can only transform from one physical mode to another physical mode, but not into any degradation (Sathiskumar & Karthikeyan, 2019).

According to the old practice, landfilling and open-air combustion are the common ways of deposing end-of-life tyres. However, according to the above investigation, it is obvious about the ineffectiveness and downsides of both recycling methods. Therefore, Pyrolysis can be an immerging solution for many drawbacks, which are discussed above (Zhou et al., 2010). Figure 2.7 illustrates existing waste tyre disposal methods for further explanation.

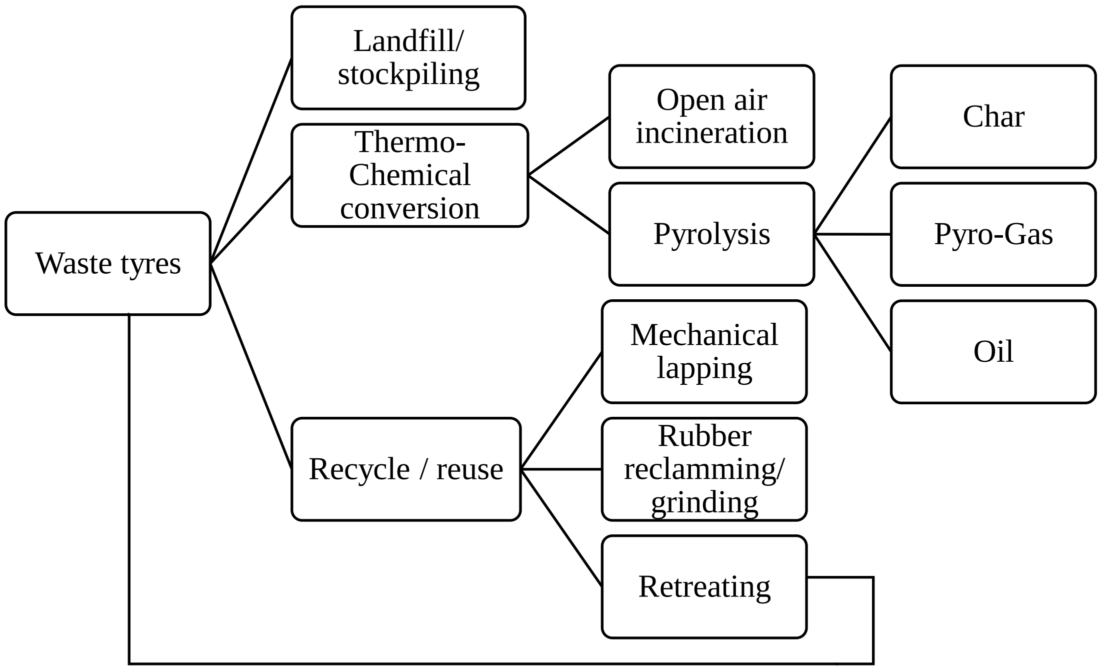


Figure 2.7: An overview of waste tyre disposal methods

2.5 Pyrolysis process and carbon black

Past records show that pyrolysis has been used to produce charcoal for over 5,000 years (Rowhani and Rainey 2016). Ancient Egyptians extracted tar and pyroligneous acids for the embalming industry. In the 1800s, at the industrial revelation, charcoal production using the wood pyrolysis process became a prominent industry for supplying the main heating fuel source at that time (Nkosi & Muzenda, 2014).

Organic matters are subjected to a thermochemical decomposition process through indirect heating without allowing oxygen to enter under the pyrolysis method (J. Xu et al., 2021). Depolymerisation, thermal cracking and thermolysis are the reactions conducted in the pyrolysis process (Rowhani & Rainey, 2016). The term pyrolysis is made out of two words from the Greeks, ‘pyro’ indicates the heat and ‘iysis’ indicates the breakdown (Rowhani & Rainey, 2016). The feedstock gets breakdown into three major phases in the pyrolysis process (Hoang et al., 2020). The gas phase majorly contains hydrocarbons, which can be utilized as a fuel source (Czajczyńska et al., 2020). The liquid phase contains pyrolysis oil, which is also can be used as a fuel source as it contains hydrocarbons (Dwivedi et al., 2020). The solid phase mainly contains char and steel. The highest constituent in char is carbon black (Lewandowski et al., 2019). However, the quantity of each phase depends on several factors, such as reactor type and furnace temperature (Lewandowski et al., 2019).

Normally, pyrolysis furnace temperature levels vary between 400 to 800°C. High-temperature levels enhance the production of the gas phase, while lower levels enhance the liquid phase (Nkosi & Muzenda, 2014). The rapid pyrolysis process also enhances the production of the liquid phase, while the slow process improves the production of the solid phase. Therefore, the speed of the pyrolysis process is another critical factor (Lewandowski et al., 2019). Adding pyrolysis media is also another way to change the product proportions. Hydrogen or steam can elevate the chemical reaction by providing adequate elemental oxygen. The porosity or surface area of the solid phase can be increased by externally providing steam or water (Xiao et al., 2022). Reactor type is the other major factor affecting the production proportions of each phase. Rotary reactors, fixed bed and fluidised bed reactors are some of the available reactor types as shown in Figure 2.8 (Lewandowski et al., 2019). According to Xiao et al. (2022) (Xiao et al., 2022) fixed bed reactor is the widespread reactor type to pyrolysis the waste tyres. However, by maintaining all these parameters affecting on tyre pyrolysis outcomes, it can be come up with the optimal parameters which suit to required recovery materials (Xiao et al., 2022).

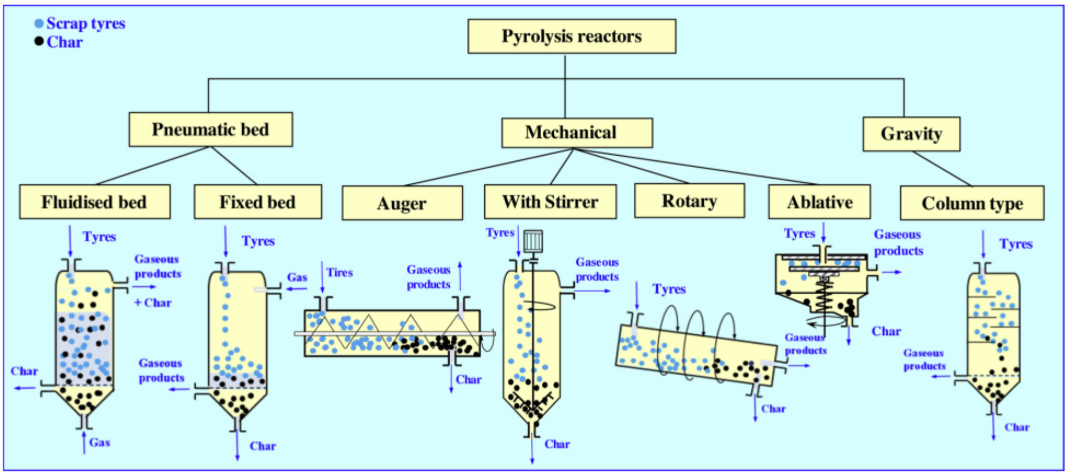


Figure 2.8: Pyrolysis reactor types

i. Gas phase

The hydrocarbon up to four carbon atoms, such as olefins and paraffin, belongs to the gas phase. Some other gasses, such as ammonia, Carbon dioxide, Carbon monoxide, Hydrogen sulphide and Hydrogen, are contained in the gas phase. Methane (CH_4) and butadiene (C_4H_6) are the major hydrocarbon types (Hoang et al., 2020).

ii. Liquid phase

Normally, the liquid faction is dark brown in colour, which contains predominantly hydrocarbons and is suitable to use as a fuel for engines. It contains C6 to C37 hydrocarbons, predominantly from C6 to C13. However, it holds 0.3-1.4 wt.% sulphur in the oil component due to the sulphur usage at the vulcanizing process of the tyre construction. Higher temperature levels at the reactor encourage more sulphur to retain in the liquid phase. Similarly, oxygen and nitrogen also contain in the pyrolysis oil as impurities (Hoang et al., 2020).

iii. Solid phase

Steel and char are contained in the solid phase of the pyrolysis products. This steel can be separated out and sent for the recycling process. But the char fraction is a combination of different elements. However, as in the previous section discussed, carbon is the highest constituent in the char phase (Koreňová et al., 2006).

This char phase consists of commercial carbon blacks, inorganic elements such as Zink, Calcium and Silicon, which are added at the manufacturing stage and carbonaceous deposits from secondary reactions (Cardona et al., 2018). However, it is introduced as pyrolysis carbon black due to its majority constituent, the mixture of CCBs. Yet, several differences (Table 2.7) between PCB and CCB have made some difficulties in directly applying PCB for industrial purposes (Cardona et al., 2018).

Table 2.7: Comparison of properties between PCB and CCB (J. Xu et al., 2021)

Characteristics	**Pyrolysis carbon Black**(J. Xu et al., 2021)	**Commercial Carbon Black (N330)** (J. Xu et al., 2021)
Specific Surface area (m^2/g)	60-90	83
Iodine absorption value (m^2/g)	117	82
Oil absorption value (mL/100g)	85	102
Heating loss (%)	1.2	<2.5

Moreover, the consistency of the PCB varies with respect to the tyre types, such as car tyres, truck tyres, farming tyres, etc. Further, different graded carbon blacks get collected from different parts of the same tyre. This variation in grades and inconsistency also creates difficulties in recovering CCB from PCB. In the pyrolysis process, the collected volatiles are subjected to a thermal cracking process, resulting in carbonaceous deposits. They deposit on the particles and reduce the particle surface area. That leads to smoother surfaces and decreases the capability of carbon blacks to bond with polymers. This nature directly makes PCB less efficient in reusing in the tyre manufacturing industry as lower bonding capabilities lower the reinforcing ability with elastomers (Catherine Billotte et al., 2024).

The CCB manufacturing process emits a significant amount of CO_2 into the atmosphere. Around 5.7 kg of ECO_2 release has been reported for one kilogram of

Carbon Black (Cardona et al., 2018). Therefore, putting efforts into recovering CCB from PCB is highly encouraged. Further, Carbon Black has been recognised as the second highest contributor to climate change after CO_2 (J. Xu et al., 2020)Therefore, considering the difficulties in recovering CCB from PCB, attempting to recycle and reuse PCB is also encouraged instead of releasing PCB directly into the environment. Incorporating PCB in the bitumen modification process can be introduced as a win-win solution that enhances pavement performance while providing a better way to recycle PCB.

2.6 PCB production process in Sri Lanka

The PCB samples used in this study were derived from the tyre pyrolysis plant in Puttlam district owned by Rivoga (Pvt) Ltd. They use a batch rotary kiln reactor (Figure 2.9) for tyre pyrolysis process which has a horizontal cylindrical drum consistent with rotary kilns. Waste tyres are shredded before inserting to the kiln to enhance reaction time and heat penetration resulting uniform pyrolysis than whole tires. An external heat source is used to maintain the required pyrolysis temperature. Dual-fuel combustion system (Figure 2.10) has established to enhance temperature efficiency by combining solid fuel combustion and pyrolysis syngas. The rotating mechanism is set for 1 rpm speed to ensure slow rotation and uniform heating of the reactor. Auger machine and a conveyer system have attached to removes char or PCB at the solid residue outlet. Further, this reactor is operating in batch mode, while approximately 15 hours required per batch to pyrolysis. Table 2.8 conveys the details of reactor operating conditions.

Table 2.8: Key Operating Conditions of the reactor

Parameter	Typical operating range in the reactor
Temperature	400–450°C
Heating Rate	5–20°C/min
Operating time per batch	15 hours
Rotation Speed	1 RPM
Pressure	atmospheric
Feedstock Size	Shredded tyre
Yield Composition	35–50% pyrolysis oil, 30–40% PCB, 10–15% syngas

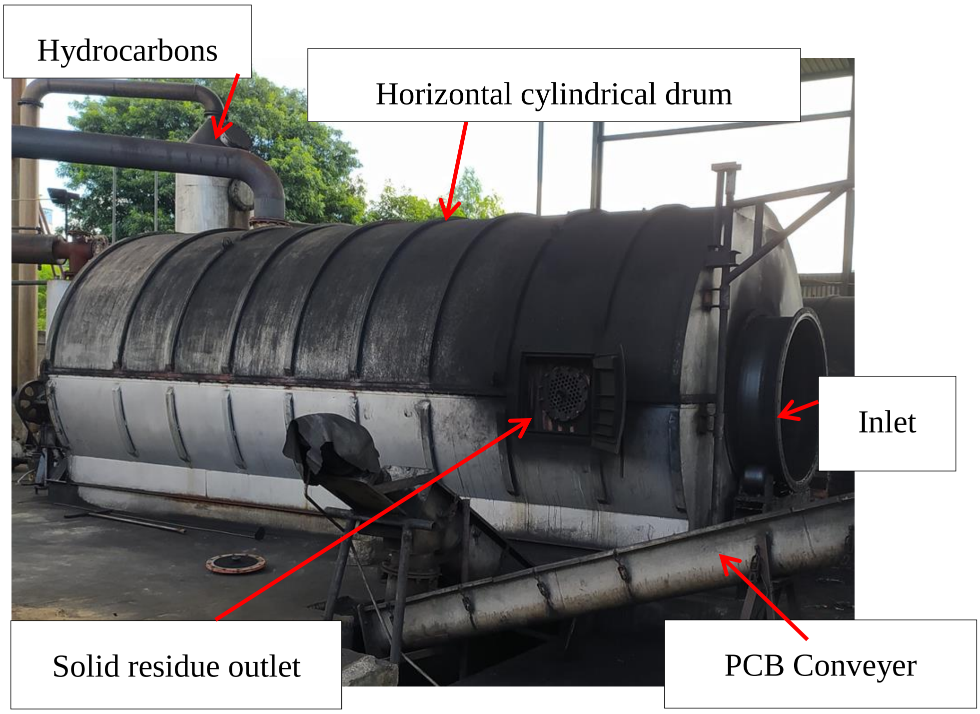


Figure 2.9: Batch rotary kiln reactor

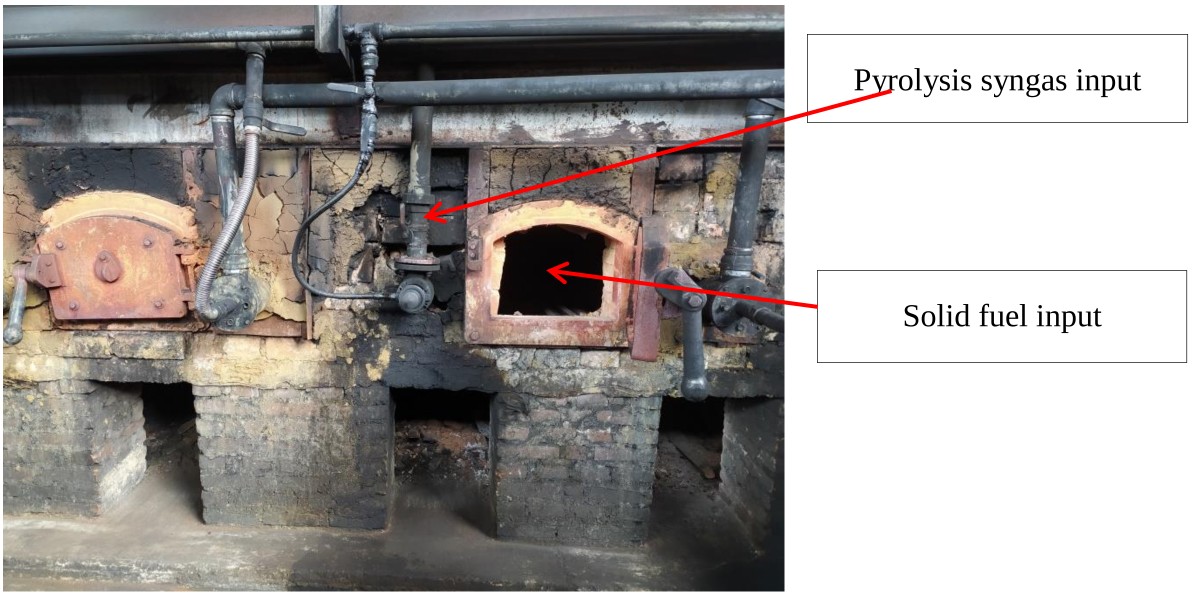


Figure 2.10: dual-fuel combustion system

Further analysis was conducted to evaluate properties of the PCB particle derived from this plant and details have mentioned in materials section in chapter 3.

2.7 Modification of Bitumen using Pyrolysis Carbon Black

There are several attempts recorded on bitumen modification with both PCB and CCB. Table 2.9 summarizes the available data on the trend pattern of the physical and rheological properties of PCB-modified bitumen. Moreover, similar patterns can be observed by modifying bitumen using CCB too. Table 2.10 displays the bitumen properties and their behaviour with the increasing modifier percentages available in the literature. Penetration provides the details about the stiffness and consistency of the binder after adding PCB (Jerin et al., 2020). The softening point provides the idea at what temperature the binder softens. Increasing both PCB and CCB decreases penetration values while softening point temperatures increase. The ductility value indicates how the binder is adhesive and stretching capability under traffic loads. However, ductility decreases with increasing carbon black percentage, which becomes a limiting parameter to carbon black loading. Rheological properties such as rutting resistance and high-temperature deformation resistance can be observed using the DSR test. It can be observed that carbon black loading increases the rutting resistance and becomes more suitable for application under high-temperature conditions. However, the creep stiffness tested from the BBR test presents increasing patterns, resulting in limitations in applicability at low-temperature conditions. Moreover, few researchers have attempted to go deeper into investigating Carbon black-modified bitumen properties. They have tested characteristics such as Thermal conductivity, Electrical resistivity, Self-healing properties, Surface free energy and cohesion. Although PCB-modified bitumen has a few limitations, further investigation is advantageous when considering available improvements in many aspects.

Table 2.9: Characteristics of PCB-modified bitumen from literature

Characteristics	**Trend with increasing PCB**	**Reference**
Penetration	Decrease	(Z. Feng et al., 2021), (H. Wang et al., 2019), (Jerin et al., 2020), (Z. G. Feng et al., 2016), (Ainabekov et al., 2024), (Tanzadeh & Shafabakhsh, 2020a)
Softening point	Increase	(Z. Feng et al., 2021), (H. Wang et al., 2019), (Gan et al., 2023), (Jerin et al., 2020), (Z. G. Feng et al., 2016), (Tanzadeh & Shafabakhsh, 2020a)
Ductility	Decrease	(Z. Feng et al., 2021), (H. Wang et al., 2019), (Jerin et al., 2020), (Z. G. Feng et al., 2016), (Ainabekov et al., 2024)
Specific Gravity	Increase	(Jerin et al., 2020), (F. Wang et al., 2022)
Flash point	Increase	(Ainabekov et al., 2024)
Rotational Viscosity	Increase	(Z. Feng et al., 2021), (H. Wang et al., 2019), (F. Wang et al., 2022), (Z. G. Feng et al., 2016), (Tanzadeh & Shafabakhsh, 2020a)
Rutting resistance from DSR test	Increase	(Z. Feng et al., 2021), (H. Wang et al., 2019), (Gan et al., 2023), (Casado-Barrasa et al., 2019)

Creep Stiffness from BBR test	Increase	(Z. Feng et al., 2021), (Gan et al., 2023)
Thermal conductivity of bitumen	Increase	(H. Wang et al., 2019)
Electrical resistivity	relatively low PCB contents- close neat asphalt binder, dramatic decline after 12%PCB	(H. Wang et al., 2019)
Self-healing properties	Increase	(F. Wang et al., 2022)
Surface free energy	Increase	(Tanzadeh & Shafabakhsh, 2020a)
Work of cohesion	Increase	(Tanzadeh & Shafabakhsh, 2020a)

Table 2.10: Characteristics of CCB modified bitumen from literature

Characteristics	**Trend with increasing CCB**	**Reference**
Penetration	Decrease	(Geckil et al., 2018), (Sun et al., 2023), (Ali et al., 2020), (Rodgers et al., 2010)
Softening point	Increase	(Geckil et al., 2018), (Sun et al., 2023), (Ali et al., 2020), (Rodgers et al., 2010)
Ductility	Decrease	(Geckil et al., 2018)
Rotational Viscosity	Increase	(Geckil et al., 2018), (Ali et al., 2020)
Rutting resistance from DSR test	Increase	(Geckil et al., 2018), (Guo et al., 2023), (Ali et al., 2020)
Creep Stiffness from BBR test	Increase	(Geckil et al., 2018)
Electrical resistivity	Decrease (a linear reduction)	(Rodgers et al., 2010)
After RTFOT		
Penetration	Decrease	(Geckil et al., 2018)
Softening point	Increase	(Geckil et al., 2018)
Change in softening point	Decrease	(Geckil et al., 2018)

2.7 Advances in Enhancing the Quality of Pyrolysis Carbon Black (PCB)

As mentioned above, although PCB has the potential to improve bitumen properties, there are a few characteristics that need further development. To address that issue, several attempts have been recorded to improve the quality of PCB, which displays further progress.

1) Coupling Treatment of CPCB

Gan et al. (2023)(Gan et al., 2023) have tried coupling treatment on PCB to reduce ash content on the particle surface. First PCB has mixed with 20 wt. % nitric acid and heated at 80°C. Then, it stirred at 200rpm for 60 minutes to activate the PCB sample. Titanate coupling agent mixed with isopropanol solution has used for the treatment. These treated particles have uniform dispersion compared to the initial PCB.

2) Carbon black microcapsules

Xu et al. (2024) (X. Xu et al., 2024) have developed a microcapsule using carbon black as a modified material, waste oil as the core material, and hexa-methoxy-methyl-melamine resin as the shell material. Adding carbon black gives the microcapsule a good round shape. The self-healing properties of the microcapsule have increased with respect to the carbon black content. Moreover, heat induction is another advantage gained from carbon black.

3) Use Aromatic hydrocarbon oil (AHO) as the softening agent

AHO contains mostly colloid and aromatics and sticky fluid in black colour. By dissolving it helps to improve the properties like ductility. Li et al. (2018) (C. Li et al., 2018) have successfully improved the low-temperature performance of PCB modified bitumen by adding AHO, although AHO have slightly impacted on high-temperature performance.

4) Pelleting

Feng et al. (2016) (Z. G. Feng et al., 2016) have compared the behaviour of pelleting PCB with initial PCB. These pelleted PCB particles are relatively larger in size after being subjected to the process. These larger particles influence the performance of bitumen more than the initial PCB.

5) Nano-carbon black

Tanzadeh et al. (2020) (Tanzadeh & Shafabakhsh, 2020a) have used a planetary ball mill to grind the PCB particle to prepare nano-carbon black (NPCB). They have observed that both penetration index and stiffness modulus have improved in NPCB compared to PCB. Surface free energy (SFE) is the main parameter evaluated in the study, which shows that NCB has increased SFE more than PCB.

Although this PCB-improving tendency indicates positive results, further investigation on the economic aspect is essential before they reach the industry application level. However, further PCB-improving methods are welcomed when considering the existing innovative methods.

2.8 Emerging Trends in Combining PCB with Other Modifiers

Further, instead of developing PCB, several researchers have tried to incorporate another material with PCB to address the limiting characteristics of PCB-only mixtures. (Refer Table 2.11) Especially low-temperature properties have been tried to develop with the collaboration of another or a few materials.

Gan et al. (2023) (Gan et al., 2023) have evaluated the performance of two samples of PCB derived from two different sources. Further they have incorporated SBS with both PCB samples and evaluated the characteristics. Although they have observed further improvements in the high-temperature performance of the bitumen, the improvements in low-temperature performance are very slight. Xia et al. (2023) (Xia et al., 2023) have premixed carbon black with Polyethylene (PE) by replacing 5%,10%, 20% and 30% of total PE weight. Then, the mixture is used to modify the bitumen. Although they have observed improved rutting and fatigue resistance by increasing CB content, low-temperature performance has gradually reduced. Evotherm is an additive that converts hot mix asphalt into warm mix asphalt by reducing mixing temperature. Casado-Barrasa et al. (2019) (Casado-Barrasa et al., 2019) have added both SBS and evotherm to PCB modified bitumen and have prepared WMA concrete in their research. High stiffness and good fatigue resistance have been observed in their mixtures while reducing mixing temperatures by 15℃.

By mixing chicken feather fibre with PCB, Li et al. (2023) (C. Li et al., 2023) have developed a novel modified bitumen where they have improved both low-temperature and high-temperature performances. Zhang et al. (2021) (Zhang et al., 2021) also have developed a modified bitumen which improves both high and low-temperature performances by adding Carbon Black and bio-oil. The carbon black that they used is N375-graded CCB, and bio-oil is extracted from the castor plant. Liu et al. (2021) (Liu et al., 2021) have prepared a Carbon Black and graphene mixture to modify the bitumen using a planetary ball mill machine. Then, they added the prepared mixture to virgin bitumen by weight percentages of 0.5%, 1.0%, and 2.0%, and prepared a series of samples to evaluate the properties. When adding a Carbon Black and graphene mixture, they have observed improvements in rutting resistance, storage stability and viscoelastic properties. Further, the increase in Thermal activation healing performance is another important improvement achieved by this novel binder. A binder modified with polypropylene and carbon black has developed by Wong et al. (2019) (Wong et al., 2019)They have recommended 14 wt.% polypropylene with 3 wt.% carbon black as the optimum modification combination. The modified bitumen has improved rutting resistance.

Although these options have improved performance up to a certain level, further innovation is essential to address the lack of low-temperature performance in PCB-modified bitumen.

Table 2.11: Carbon Black modified bitumen incorporating with other materials

Added materials	Improvement	Reference
SBS + PCB	• Increase in the rutting factor • Improve the high-temperature performance of asphalt • Low-temperature crack resistance in SBS+PCB modified samples has improved compared to PCB modified bitumen.	(Gan et al., 2023)
Polyethylene (PE) + carbon black (CB)	• Improve rutting and fatigue resistance • No considerable improvement in low-temperature performance	(Xia et al., 2023)
Carbon black + SBS + Evotherm	• High stiffness • Good fatigue resistance • slight increase in the stiffness in CB modified binder compared to commercial polymer-modified bitumen	(Casado-Barrasa et al., 2019)
chicken feather fiber + PCB	• Improve high-temperature and low-temperature performances • Increase the water stability of bitumen	(C. Li et al., 2023)
Carbon Black + Bio-Oil	• Improve both high-temperature performance and low temperature performance	(Zhang et al., 2021)
Graphene + Carbon Black	• Increase in Thermal activation healing performance • Improve viscoelastic properties, • Improve storage stability • Improve rutting resistance	(Liu et al., 2021)
Polypropylene + carbon black	• Improved rutting resistance • Increase viscosity value with increase of CB	(Wong et al., 2019)

2.9 Asphalt pavement manufacturing methods- wet mixing vs dry mixing

When manufacturing asphalt concrete, there are two processes in practice such as wet mixing and dry mixing (Soheil Heydari et al., 2024). This categorisation is basically depends on the order of the ingredients are mixing (Duarte & Faxina, 2021). In the dry mixing method, preheated modifiers are added to the preheated aggregates as the first step and mixed well. Later, heated bitumen is added and blended all three until obtain a uniform asphalt mixture (Bakheit & Xiaoming, 2019). First, bitumen and modifier are mixed at elevated temperatures in the wet mixing process. Then, the heated modified bitumen mixture is poured into the preheated aggregate sample. A uniform asphalt mixture is prepared with adequate mixing (Agha et al., 2023).

Table 2.12: Comparative insights in wet mixing vs. dry mixing methods

Characteristic	**Wet mixing method**	**Dry mixing method**
Homogeneity	High	Low
Performance	High	Moderate
Cost Efficiency	Moderate	High
Scalability	Moderate	High

However, there are many strengths and weaknesses incorporated with each method and selecting the suitable manufacturing method depends on the scenario by considering modifier type, available resources and performance. (Refer Table 2.12) Several researchers comment on each method's suitability according to their scenario. Chavez et al. (2019) (Chavez et al., 2019) illustrate the limitations of practicing a wet mixing process when manufacturing crumb rubber modifier asphalt. Both Chavez et al. (2019) (Chavez et al., 2019) and Bakheit et al. (2019) (Bakheit & Xiaoming, 2019) highlight that maintaining the stability of the binder when storing modified binder is expensive as it requires special equipment which is not required in dry process. However, they further elaborate that the wet mixing process is still a popular method for crumb rubber modifications as dry process methods result in inadequate performance due to the lack of interaction between binder and crumb rubber in this method.

However, Agha et al. (2023) (Agha et al., 2023) have observed a 2.1% cost reduction for wet mixing while a 4.6% cost increase in the dry mixing process when compared to 0% and 6% Polyethylene Terephthalate (PET) added asphalt mixtures. Moreover, the influence on the bitumen ageing caused by the continued heating and mixing of the modified binder in the wet mixing process has been emphasised by Li et al. (2024) (Y. Li et al., 2024) when discussing the performance of their modifier bitumen using SBS, PCB and pyrolysis oil of waste tyres. Jitsangiam et al. (2023)(Jitsangiam et al., 2023) discussed the practical difficulties in using the wet mixing process in Thailand with the available resources. They highlight the ability to directly add plastic waste (their modifier) to the asphalt mixture during the dry process, which helps to make an alternative waste recycling method popular in industrial practice.

Gan et al. (2023) (Gan et al., 2023) has observed improved stiffness in the wet mixing method compared to the dry mixing method for co-pyrolysis carbon black modified asphalt concrete. Although the wet method is considered as difficult in industry practice, Casado-Barrasa et al. (2019) (Casado-Barrasa et al., 2019) have successfully constructed a 100m long road section Toledo, Spain using a modified mobile bitumen modification plant to modify bitumen using carbon black and Evotherm. Although several researchers have evaluated the properties of PCB-modified binder, there is a lack of information about PCB-modified asphalt concrete properties to make a proper selection on the best mixing process for PCB-modified asphalt manufacturing.

2.10 Long-Term Pavement Performance

Maintaining a road is a very important factor which influences both vehicle emissions and durability (Al-Mansour & Shokri, 2022). Therefore, continuous observation and maintenance of a constructed pavement is crucial (Abu Dabous et al., 2021). Automatic road condition surveys associated with machine learning techniques have been developed for large-scale investigations while the older practice, visual observations, remains in use at a smaller scale (El Hakea & Fakhr, 2023; Guerrieri & Parla, 2022)When considering the Carbon Black modified asphalt, Casado-Barrasa et al. (2019) (Casado-Barrasa et al., 2019) has constructed a road in Toledo, Spain, using Carbon black and Evotherm modified bitumen. However, they have not published any source about the current performance condition of the road. Although numerous studies have cried out to investigate the PCB-modified asphalt concrete properties at laboratory scale, there is no evidence reported on the long-term performance of a real-scale asphalt pavement.

2.11 Identified Research Gaps

The above literature review reveals the growing importance of sustainable materials in bitumen modification. Thereafter, PCB emerges as the most promising modifier, addressing key challenges in thermal stability and elasticity. However, significant research gaps remain, particularly in field performance evaluation and the optimization of mixing processes. There is insufficient data on the influence of PCB particle size and RPM on bitumen properties. Moreover, there is a lack of comparative analysis of dry and wet mixing for long-term performance in hot climates. Further, there is a necessity of a thorough study before applying this modifier option to Sri Lankan industry while considering the inconsistency of the impurity content of PCB. This study aims to fill these gaps by focusing on PCB's field application, the evaluation of mixing methods, and long-term durability.

2.12 Summary of Literature Findings

The above sections provide a comprehensive exploration of bitumen modification and the role of pyrolysis carbon black (PCB) in asphalt pavement applications.

The necessity of bitumen modification is highlighted by the increasing demands for improved pavement performance, especially in regions with high traffic loads and extreme climatic conditions. Sustainable modifiers have gained significant attention due to environmental and economic concerns. Among these, Pyrolysis Carbon Black (PCB), obtained from waste tire pyrolysis, has emerged as a particularly effective modifier due to its carbonaceous structure and reinforcing capabilities.

An in-depth review of carbon black reveals its characteristic texture and colour characteristics, setting it unique from other carbon-based materials. Various carbon black types differ in structure, particle size, and industrial applications. Commercial production methods and classification systems provide insight into quality variations. The historical development of the carbon black industry and associated health and safety considerations highlight the need for sustainable and safe production practices.

Further, the structure and composition of tire rubber and the environmental challenges posed by end-of-life tires is emphasized. The pyrolysis process emerges as an effective method for converting waste tires into valuable by-products, including oil, gas, and PCB. This process not only mitigates waste management issues but also supports circular economy initiatives by repurposing waste materials.

Studies indicate that PCB-modified bitumen exhibits improved physical and rheological properties, enhancing pavement durability. The effectiveness of PCB in bitumen modification is influenced by factors such as particle size, surface area, and dispersion techniques. Researches on the enhancement of PCB quality suggest that further refinement processes, such as thermal or chemical treatments, can enhance its performance as a bitumen modifier.

Recent studies focus on optimizing PCB quality through improvement techniques and exploring its collaboration with other sustainable modifiers. The combination of PCB with polymer or fiber materials may lead to further performance improvements in bitumen applications.

Moreover, comparative analysis of wet and dry mixing methods reveals the advantages and limitations of each approach. While wet mixing ensures better homogeneity, dry mixing may offer practical and economic benefits. Long-term pavement performance studies highlight the significance of modifier selection in ensuring pavement resilience, cracking resistance, and overall sustainability.

In summary, the literature focuses the attention on the potential of PCB as a viable and sustainable bitumen modifier, particularly when optimized for particle size and mixing process. Thereby, future research should focus on refining PCB properties and exploring mixing techniques to maximize pavement durability and environmental benefits.

CHAPTER 3

3. METHODOLOGY

3.1 General

This chapter outlines the methodologies employed in this research to achieve the mentioned research objectives. The study comprises three major components. The first section compares PCB as bitumen modifier with conventional binder, investigating the performance, environmental and economic impact of modified binders. Secondly, investigate the impact factors on the overall performance of the modified bitumen, such as particle size and mixing speed. The third phase evaluates the influence of pavement performance by two asphalt concrete manufacturing methods: dry mixing and wet mixing methods. Additionally, this chapter includes details about evaluating the pavement condition of a road constructed using the dry mixing method three years ago.

The methodology is designed to ensure reproducibility and reliability of results. Figure 3.1 provides an overview of the methodology, which has eight sub-sections. First, the material selection was conducted according to locally available resources and the local practice. Then, other locally available sustainable modifier options were investigated for the comparison phase using the available literature. In the third step, tests were conducted to evaluate the PCB-modified bitumen properties. In that phase, the modifier percentage varied first to obtain the optimum percentage at the beginning. In the fourth phase, optimum percentages for the bitumen were selected under each modifier type and carried those values to the fifth phase for environmental and economic impact. Based on this phase's result, it was later decided to evaluate the effect of mixing speed and the PCB particle size on the modified bitumen performance.

The sixth phase involves preparing asphalt concrete using a PCB modifier. In that phase, wet and dry mixing methods were used to evaluate the behaviour of the modified asphalt concrete. In the seventh step, asphalt concrete performance evaluation testing was conducted. In the last phase, the long-term performance of a three-year-old PCB-based local road was evaluated.

The methodology was designed to comprehensively address the research objectives by combining laboratory experiments and field evaluations. By focusing on PCB as the primary modifier and exploring its performance in both laboratory and field conditions, this study aims to provide practical and sustainable solutions for road construction in the Sri Lankan context, especially for hot climates with heavy traffic.

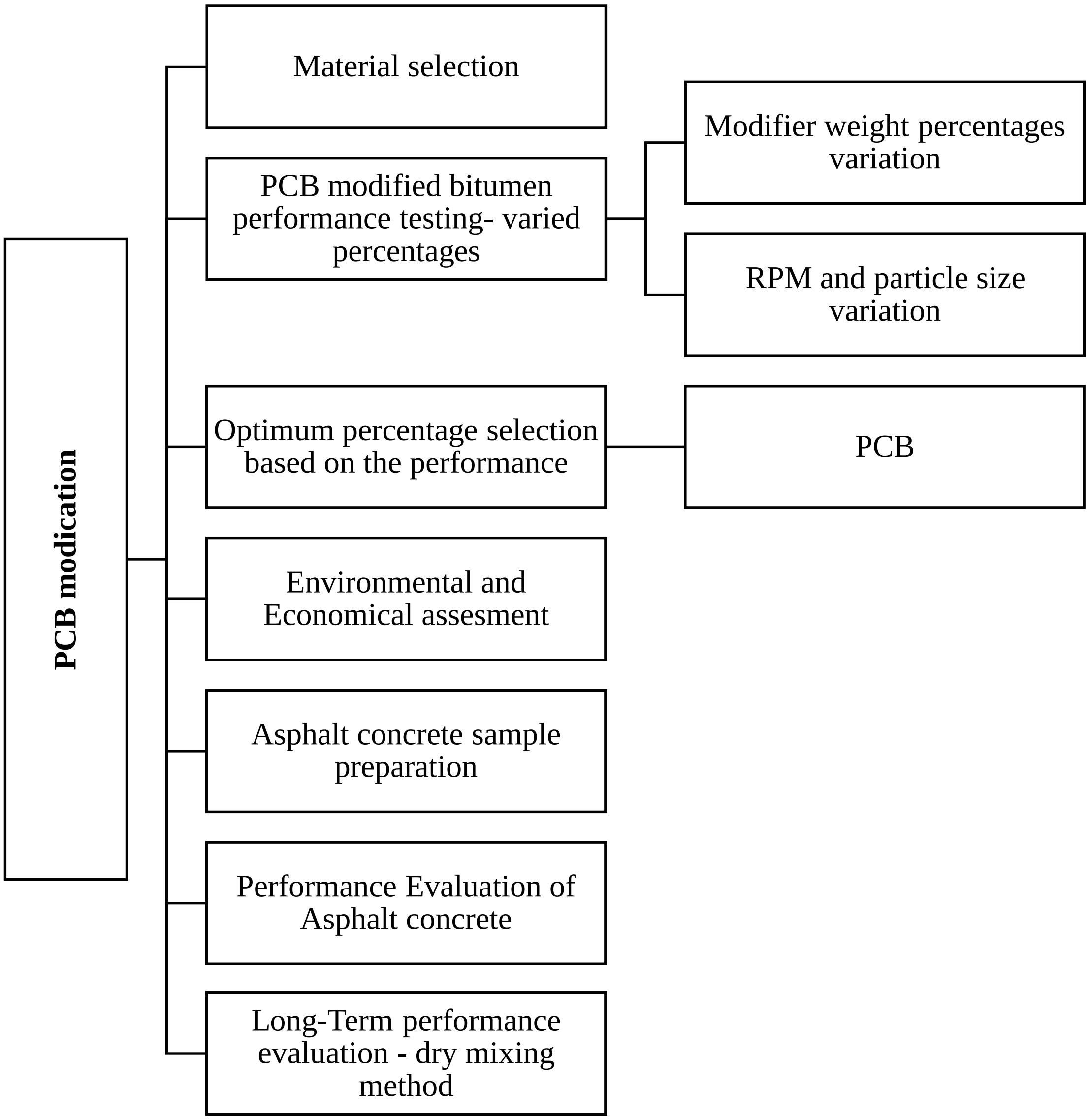


Figure 3.1: An overview of the methodology

3.2 Materials

This study uses three major materials: bitumen, aggregate and PCB for experiments. (Figure 3.2)

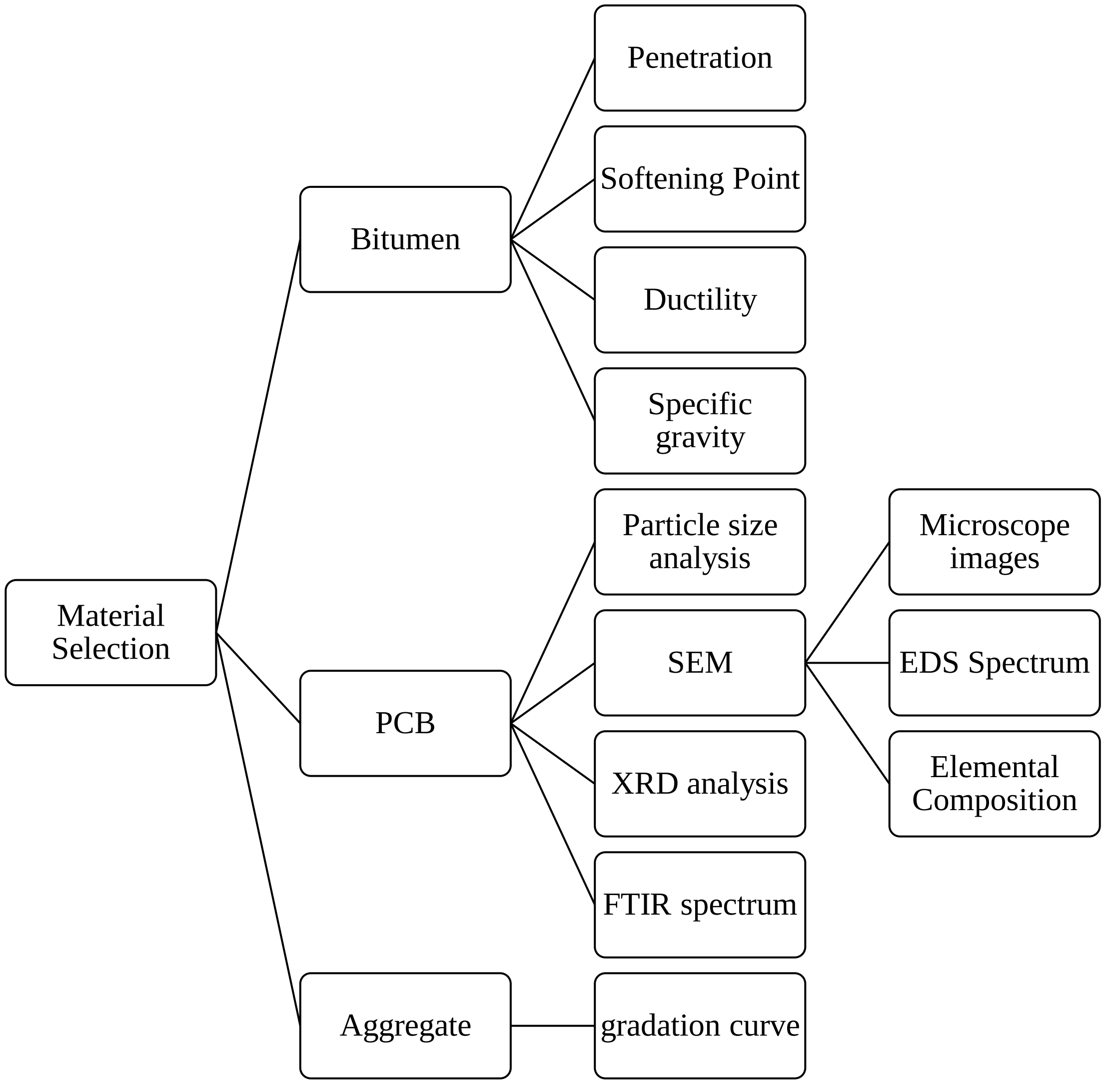


Figure 3.2: Material selection steps

3.2.1 Bitumen

As a tropical country, the frequently used bitumen type is 60/70 penetration grade bitumen in Sri Lanka (Mampearachchi et al., 2012). Therefore, this study used 60/70 penetration grade bitumen from Bitumix (Pvt) Ltd. The properties of the bitumen are mentioned in Table 3.1. The penetration was measured according to ASTM D5 (ASTM_International, 2006a) at 25℃. The softening point, ductility and specific gravity data were also derived by following ASTM D36 (ASTM_International, 2006b), ASTM D113 (ASTM D 113, 2007), ASTM D70 (ASTM_International, 2009) respectively. The approved specification limits were defined according to the Sri Lankan ICTAD specification (CIDA_SCA05, 2009). These four basic tests were performed to establish baseline properties of the unmodified bitumen.

Table 3.1: properties of base asphalt binder

Test	Test procedure	Results	Specification limits
Penetration (25°C; 0.1 mm)	ASTM D5	63	60/70
Softening point (°C)	ASTM D36	51	48/56
Ductility (25°C; cm)	ASTM D113	>100	>100
Specific gravity (25°C; g/cm^3)	ASTM D70	1.022	-

3.2.3 Pyrolysis Carbon Black (PCB)

The PCB was collected from a waste tyre pyrolysis plant in the Puttalam district, a local company, Rivoga (Pvt) Ltd. According to the literature, the basic particle size of PCB is 10 to 600 nm (F. Wang et al., 2022). The PCB has further agglomerated into primary aggregates in our sample. Therefore, the testing was carried out in two sets according to two particle size distributions: the first directly obtained from industry and the second modified sample. The particle size distribution of the PCB sample A is plotted in Figure 3.3, in which particle size has varied from 0.04 µm to 1100µm. Sample A is the direct industry-derived sample and sample B is derived by breaking the particles using a rubber hammer. The particle size distribution of sample B is potted in Figure 3.4, in which particle size has varied only up to 80µm. The particle size analysis was carried out using a 'Fritsch- Analysette 22 Nano Tec' particle size analyzer, in which the measuring range is between 0.08µm to 2100 µm, using the wet mode.

From the scanning electron micrograph (SEM) image in Figure 3.5, it can be observed that the PCB has a rough microstructure with a chain-branched layered structure. A similar extremely complex nature in shape can be observed in literature, too (LIU et al., 2020),(Z. Feng et al., 2021). The chemical composition of the PCB sample was evaluated using Energy-dispersive X-ray spectroscopy (EDS) analysis. Figure 3.6, which shows the EDS spectrum of PCB, represents the K series of elements such as carbon, oxygen, silicon, sulfur, Aluminum, Calcium Titanium, Iron, and Zink. According to Table 3.2, although the major component is carbon, over 25% by weight impurities are contained in the sample. The tyre composition, which is put into a pyrolysis batch of batch rotary kiln reactor at Rivoga (Pvt) Ltd, is presented in Table 3.3, which helps to maintain the impurity content closer to the Table 3.2 values of PCB in each and every waste tyre batch.

For further understanding of the impurities contained in locally available PCB samples, X-ray diffraction (XRD) analysis was conducted using a "Rigaku Ultima IV" X-ray diffractometer ($CuK_{\alpha 1}$:1.5406Å). Figure 3.7 shows the spectrum of the XRD analysis. Table 3.4 demonstrates the likely compound in the PCB sample, according to the five peaks in the XRD spectrum. It provides evidence of silicon and aluminium oxides existence in the PCB sample (Farahmandjou & Golabiyan, 2015; Tang et al., 2015).

Figure 3.8, which displays the FTIR spectrum of PCB, provides insights into its surface functional groups. Key peaks observed include a band at 2562.7 cm^{-1}, attributed to S–H stretching vibrations, which indicates the presence of sulfur-containing compounds, a remnant of the vulcanization process used in tyre manufacturing (Sáez Del Bosque et al., 2014). The peak at 2363.43 cm^{-1} corresponds to CO_2 asymmetric stretching, likely due to adsorbed carbon dioxide or gaseous residues trapped on the carbon black surface (Jackson et al., 2009). Peaks at 2208.97 cm^{-1} and 2164.44 cm^{-1} are associated with C≡N (nitrile) stretching vibrations, potentially formed from the degradation of nitrile-based rubber additives or polymers during pyrolysis (Wagner et al., 2019). Additionally, a peak at 2028.17 cm^{-1} suggests the presence of weak C≡C (alkyne) stretching vibrations or overtone bands indicative of conjugated aromatic systems within the carbon black structure (Kim et al., 2005).

These functional groups highlight the chemical complexity of PCB, a by-product of tyre thermal decomposition. The presence of sulphur, nitriles, and conjugated systems is significant as they influence the material's chemical reactivity, compatibility, and performance when used as a modifier in bitumen or other composite materials. This characterization underscores the potential of PCB as a sustainable and functional additive in material engineering applications.

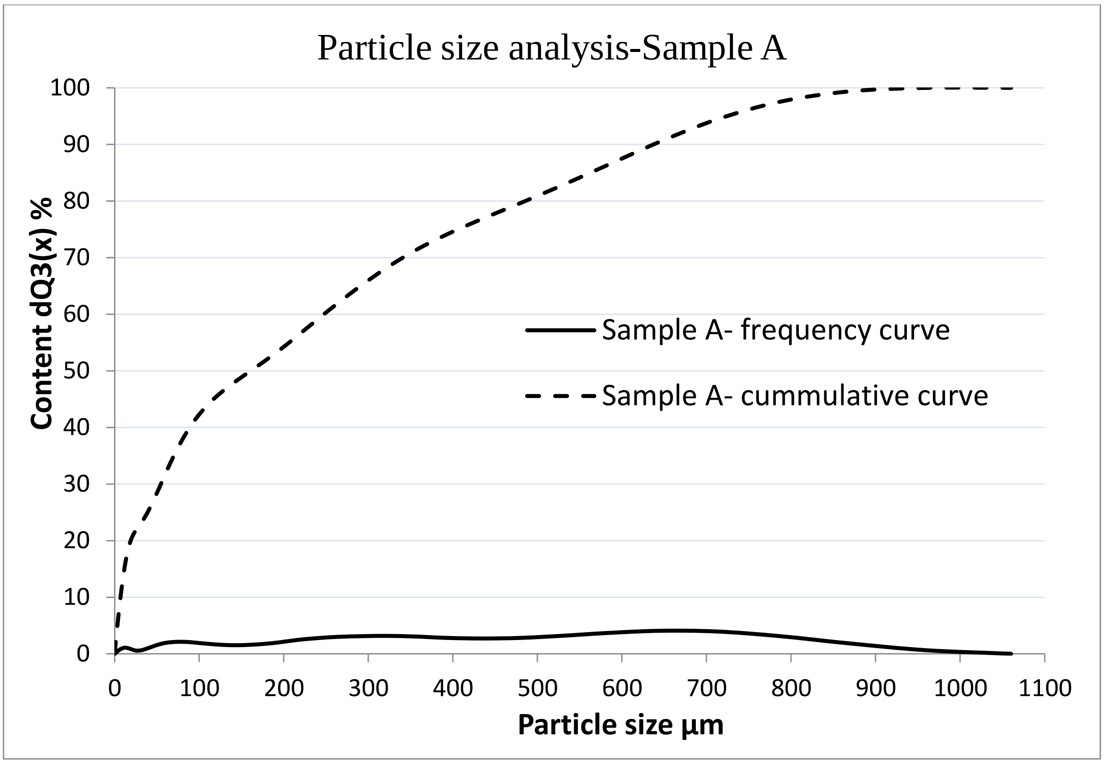


Figure 3.3: Particle size distribution of Sample A

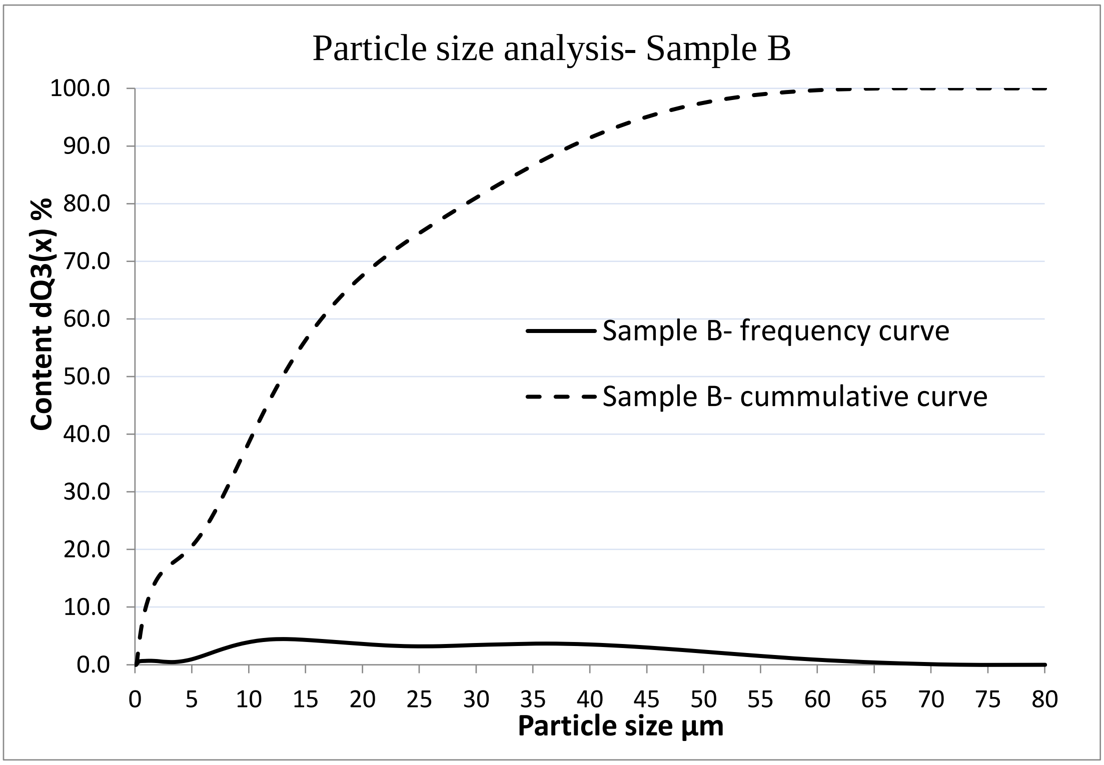
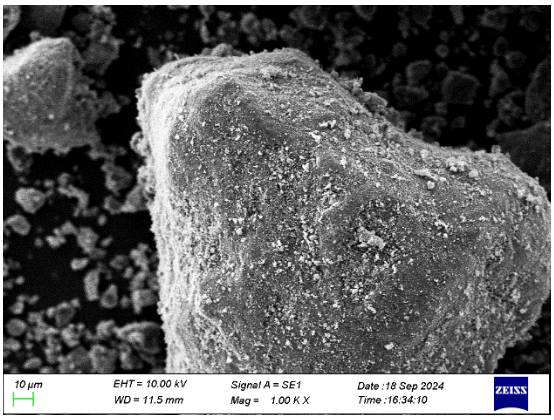
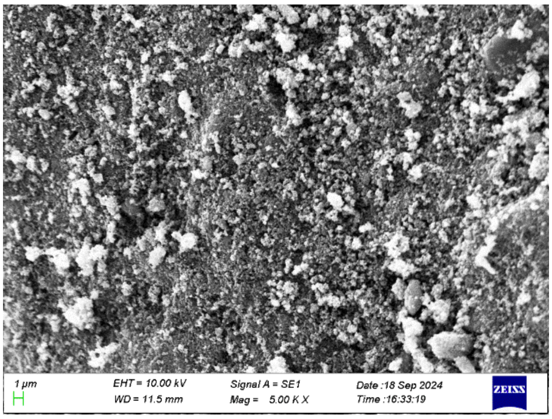


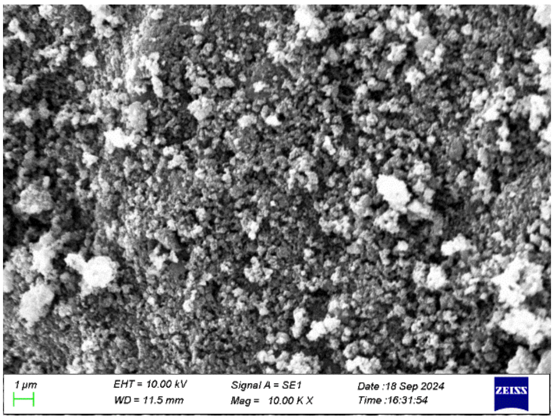
Figure 3.4: Particle size distribution of Sample B



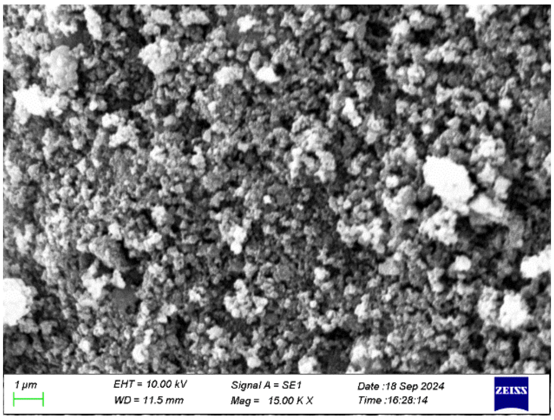
(a)



(b)



(c)



(d)

Figure 3.5: SEM images of PCB sample (a)100,00x, (b)500,000x, (c)1000,000x, (d)1500,000x

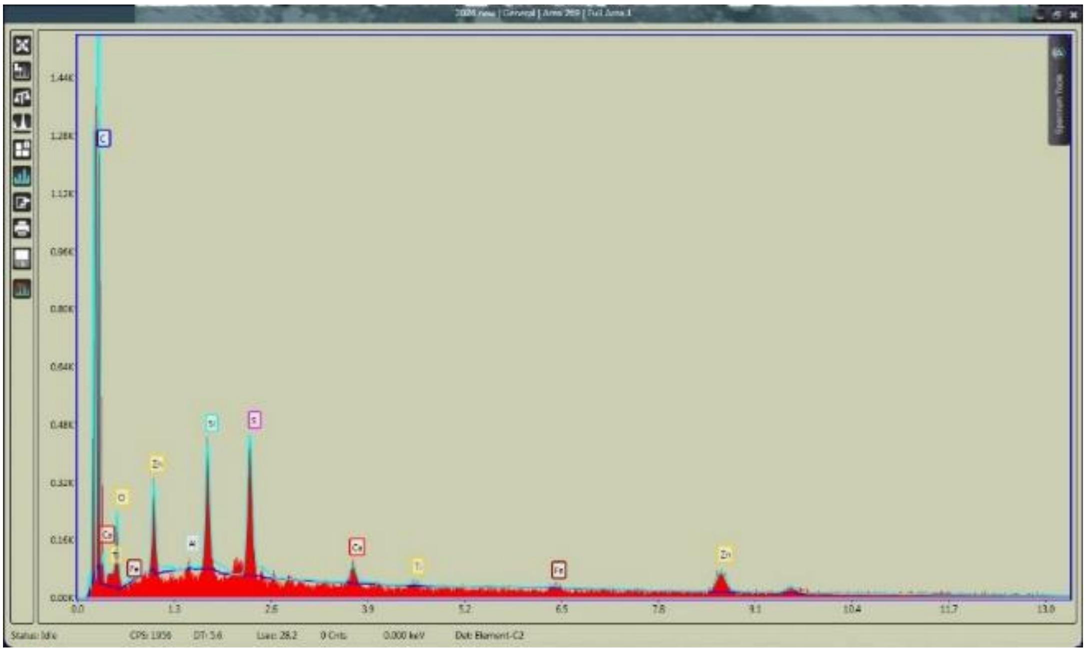


Figure 3.6: EDS spectrum of PCB sample

Table 3.2: Elemental composition of PCB by percentage of weight

Element	Weight %
C	72.67
O	8.21
Al	0.19
Si	3.71
S	5.52
Ca	1.37
Ti	0.32
Fe	0.35
Zn	7.67

Table 3.3: Tyre-type composition of a batch.

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

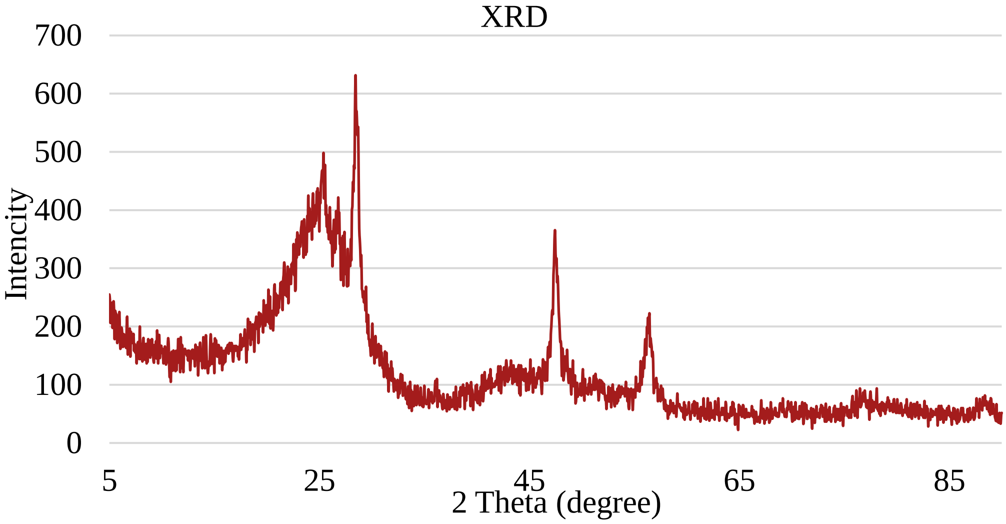


Figure 3.7: XRD spectrum of PCB

Table 3.4: Likely compounds according to XRD spectrum

Peak	2-theta (°)	d-spacing (Å)	Likely Compound
1	25.30(12)	3.518(17)	**α-quartz** (SiO_2)

2	28.52(5)	3.128(5)	**Cristobalite** (SiO_2)
3	47.405(14)	1.9162(5)	**Mullite** ($3Al_2O_3 \cdot 2SiO_2$)
4	56.41(8)	1.630(2)	**α-alumina** (Al_2O_3)
5	88.4(3)	1.105(3)	**Silicon** (Si)

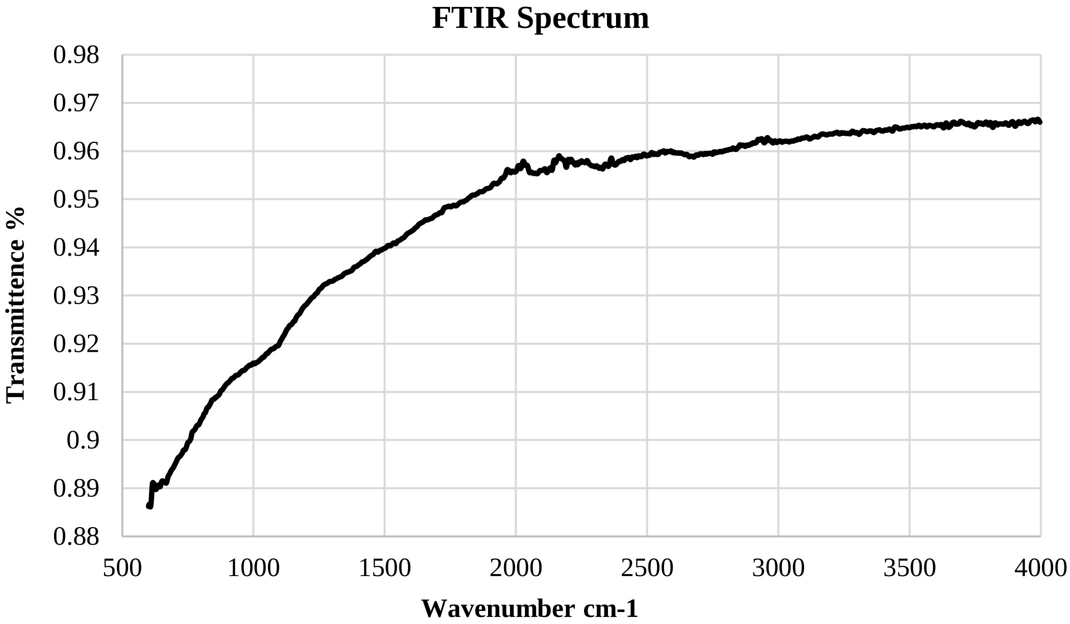


Figure 3.8: FTIR spectrum of the PCB sample

3.2.4 Aggregates

The aggregates were selected according to the guidelines given by Sri Lankan Standard Specification for Construction and Maintenance of Roads and Bridges (SSCM 05) (CIDA_SCA05, 2009). The gradation curve of aggregates is given in Figure 3.9.

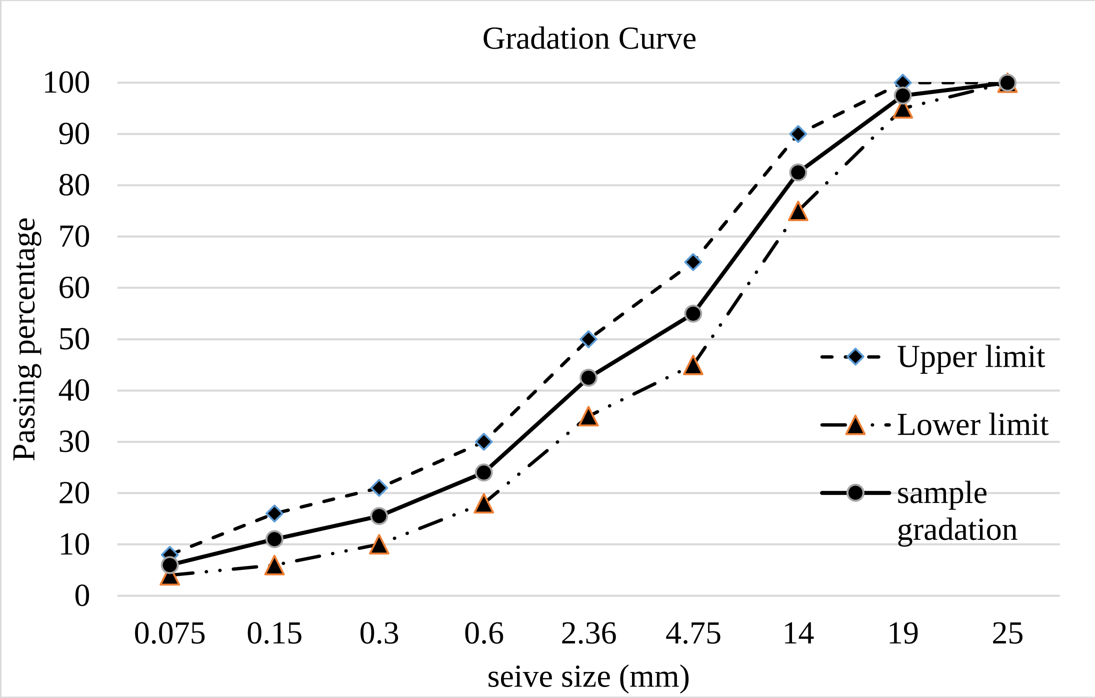


Figure 3.9: Gradation curve of the sample and specification limits

3.3 Bitumen modification

First, bitumen and the PCB were mixed using a high shear mixture. 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, 2020b; F. Wang et al., 2022) (Refer Table 3.5). The selected mixing percentages for PCB are 5%, 10%, and 15%. For the mixing speed of the high shear mixture, 2000rpm, 3000rpm, and 4000rpm are selected, and the mixing time is set at 1 hour. The mixing temperature was maintained between 155-160°C throughout the mixing time.

Table 3.5: Mixing parameters used in literature

Study No.	**CB % by weight**	**Temperature (°C)**	**Mixing Time**	**Mixing Speed (RPM)**	**Reference**
1	5% 10% 15%	130, 150, 170	0.5h, 1h	4000	(Z. Feng et al., 2021)
2	5% 10% 15%	160	1h	4000	(Jerin et al., 2020)
3	6%CB + 3%SBS	175	1.5h	300-500	(Casado-Barrasa et al., 2019)

4	CB-3%,5%,7%,10% NCB-1%,3%,5%,7%	135 135	40 minutes 50 minutes	2500-3500 4000-5000	(Tanzadeh & Shafabakhsh, 2020b)
5	3%, 6%, 9%, 12%, 15%, 18%	150	1h	2000	(H. Wang et al., 2019)
6	5%, 10%, 15%	150	1h	500	(Geckil et al., 2018)
	5%, 10%, 15%	**155-160°C**	**1 hour**	**2000, 3000, 4000**	**SELECTED**

3.4 PCB modified bitumen performance evaluation

To evaluate the bitumen performance, several tests were conducted. To analyse physical properties, penetration and softening point tests were conducted according to the ASTM D5 and ASTM D36. For further analysis Penetration Index (PI) was conducted according to Equation 1. Then, to analyse the rheological properties, a Dynamic Shear Rheometer (DSR) test was conducted. Moreover, to get an idea of the chemical reaction, an FTIR test was conducted on modified bitumen samples. To observe the bitumen properties after ageing, a Pressure Age Vessel (PAV) was used to age the modified bitumen sample. After that, penetration and softening point tests were repeated for the aged samples, too.

3.4.1 Penetration test

Penetration gives a rating for the hardness or softness of the bitumen. This value derives from the standard needle-driven depth into the bitumen sample. This penetration value measures the consistency of the bitumen sample. Softer bitumen has higher penetration values.

Apparatus

- Penetration Apparatus
- Sample container
- Water bath
- Timing Device
- Thermometer

Sample preparation

Heat the sample until it is melted sufficiently to pour. (stir, when possible, to prevent local overheating, to have a homogeneous sample and to avoid bubbles)

Pour the sample into the container (Container depth needs to be at least 120% of the expected penetration depth of the needle)

Cool the sample according to Table 3.6

Table 3.6: Cooling requirement before the test conduct

Medium	Temperature℃	Time	container
1)In Air	15-30	45min- 1.5hr	Small containers (33x16mm >=)
		1hr – 1.5hr	Medium container (55x35mm)
		1.5hr-2hr	Large container
2)Water bath	According to the test condition	45min- 1.5hr	Small containers (33x16mm >=)
		1hr – 1.5hr	Medium container (55x35mm)
		1.5hr-2hr	Large container

Test Conditions

All the samples were tested under the normal scenario, (Table 3.7)

Table 3.7: Test condition defined for the normal scenario

Temperature	25℃ (77F)
Load	100g
Time	5s

Procedure

1) Clean the needle and insert it into the penetrometer (Figure 3.10)

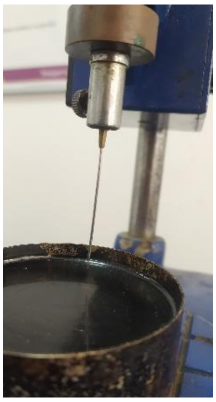


Figure 3.10: Clean needle

2) Place the container on the stand of the penetrometer (Figure 3.11)

Figure 3.11: Place the container

3) Make sure the apparatus is level, using a levelling indicator
4) Bring the needle tip into contact with the sample surface. (Actual tip and reflecting image tip need to be contacted) (Figure 3.12)

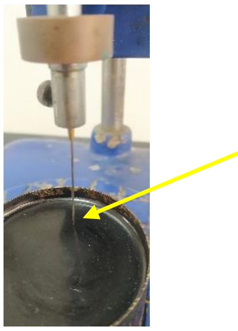


Figure 3.12: Needle tip adjustment

5) Bring the penetrometer dial pointer to zero or take the dial reading. (Figure 3.13)

Figure 3.13: Zero the gauge reading

6) Quickly release the needle and instantly start 5s of time (time may change in special scenarios) (Figure 3.14)

Figure 3.14: After releasing the load

7) After 5s hold the needle and measure driven the depth in tenths of millimetres. (Figure 3.15)

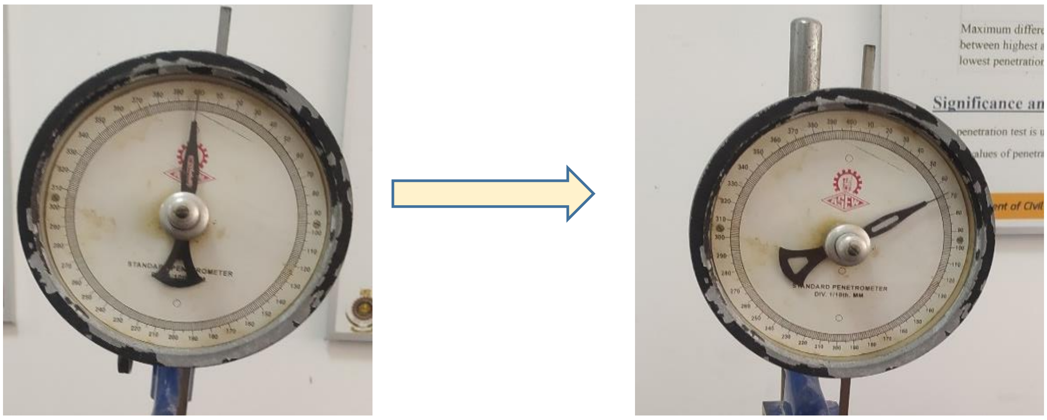


Figure 3.15: Dial gauge change

8) Tack 3 readings for each sample to increase the accuracy.

- Clean the needle after each reading
- Distance between two points (D) >10mm
- Average of three penetration values need to be; (Table 3.8)

Table 3.8: Maximum allowable deference between readings

Penetration Value	**0-49**	**50-149**	**150-249**	**250-500**
Allowed maximum difference between highest and lowest penetration	2	4	12	20

3.4.2 Softening point test

The ASTM D36 standard (ASTM_International, 2006b) outlines the procedure for determining the softening point of bitumen using the Ring-and-Ball apparatus (Figure 3.16). This test helps identify the temperature at which bitumen transitions from semi-solid to liquid.

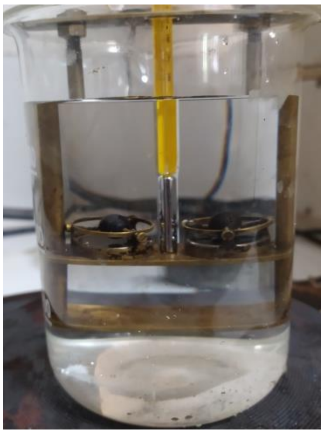


Figure 3.16: Ring and Ball apparatus

Apparatus

- Rings

- Pouring Plate
- Balls with the mass of 3.5 ± 0.05 g (Figure 3.17)
- Ball-Centring Guides
- Bath - A glass vessel having the capability to be heated
- Ring Holder and Assembly
- Thermometers

Figure 3.17: Rings, balls and ball-centering guides

Sample Preparation

1) Heat the bitumen and pour it into two metallic rings. Allow the sample to cool and solidify in a controlled environment. (Figure)
2) Make sure not to have air bubbles in the sample while pouring (Figure 3.18)

Figure 3.18: Pour bitumen into two metallic rings

Apparatus Setup

3) Place the rings, along with steel balls, in a specialized holder. Submerge them in a liquid bath (either water or glycerine) maintained at room temperature.
4) Select the suitable bath according to Table 3.9

Table 3.9: Suitable temperature rangers relevant to the liquid for the bath

Temperature	Bath liquid
from 30 to 80°C	Water
from 80°C to 157°C	USP glycerine
From 30 to 110°C	Ethylene glycol

Heating Process

5) Gradually heat the bath at a standardized rate (5°C per minute) to ensure a uniform temperature increase.

Observation

6) Monitor the bitumen as the temperature rises.
7) The softening point is recorded when the bitumen, under the weight of the steel ball, deforms and drops to a predefined mark in the bath. (touch the ring holder bottom plate)
8) The test results should not be accepted if the two temperatures differ by more than 1°C.

This test helps evaluate bitumen's suitability for various applications based on its thermal performance.

3.4.3 Penetration Index

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.

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

Where,

P_{25}= penetration at 25°C

SP = Softening point

3.4.4 DSR test

The 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 to 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 determine the high-temperature performance. When selecting the optimum binder, the intended application must be considered. 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.

3.4.5 Pressure Age Vessel (PAV)

The Pressure Aging Vessel (PAV) was used according to ASTM D6521 (ASTM_International, 2022) to simulate the long-term ageing of asphalt binders and to evaluate their performance over time. The procedure involves exposing asphalt samples to high pressure and temperature to replicate oxidative ageing.

Sample Preparation

1) Precondition the asphalt binder using the Rolling Thin Film Oven (RTFO) test to simulate short-term ageing before performing the PAV test. Pour the aged binder into specified metal pans. (Figure 3.19)

Figure 3.19: metal pans to pour binder

PAV Apparatus Setup

2) Place the prepared pans in the Pressure Aging Vessel. Seal the chamber and ensure it is properly pressurized. (Figure 3.20)

Figure 3.20: Pressure Aging Vessel

Test Conditions

3) Set the temperature (typically between 85°C and 110°C) and apply a constant air pressure of 2.1 MPa (300 psi). These conditions are maintained for a standard ageing period of 20 hours.

Cooling and Removal

4) After the test duration, allow the vessel to cool before carefully removing the pans with the aged binder. (Figure 3.21)

Figure 3.21: Aged bitumen in pans

Post-Test Evaluation

5) Analyse the aged binder to assess changes in physical properties, such as penetration and softening point.

This procedure helps predict the long-term performance of asphalt binders under field conditions.

3.5 Environmental and Economical Assessment

To properly compare sustainable industrial alternatives, both environmental impact and cost need to be assessed further. The embodied GHG Emissions ($ECO_{2\text{-}e}$) and embodied energy (EE) parameters are calculated to evaluate the environmental impact.

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 et al., 2021), (Liew et al., 2024) .

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

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 3.10 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 which the virgin bitumen was bought for tests.

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

(Dissanayake et al., 2017). In this study, for PCB modifier EE value is taken as zero as it is waste material. However according to the ICE database (Geoff Hammond, 2008) 0.1MJ/kg is considered for handling purposes for each waste material. As these three 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 2024 price rates in the Ceylon Electricity Board (CEB).

The EE and $ECO_{2\text{-}e}$ 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 considering CEB electricity rates and labour costs in Sri Lanka.

Table 3.10: The environmental and cost factors of raw materials

Material	**Embodied Energy (EE) (MJ/kg)**	**$ECO_{2\text{-}e}$ (kg CO_{2e}/kg)**	**Cost (LRK/kg)**
bitumen	2.201	0.222	189.00
PCB	-	0.100	-
Processing	0.300	0.150	35.50

3.6 Asphalt concrete preparation

Asphalt concrete preparation was conducted in three phases: Optimum Bitumen Content (OBC) with virgin bitumen, wet missing with PCB-modified bitumen, and dry missing with PCB. The two mixing methods are simply interpreted in Figure 3.22.

3.6.1 Wet mixing process

The wet mixing process is the conventional way of preparing asphalt concrete with polymer modifiers (Mishra & Gupta, 2020). Here, the wet mixing process is implemented at laboratory conditions for PCB, a mineral modifier. First, bitumen and the PCB were mixed using a high-shear mixture. The mixing conditions were selected after an extensive analysis of the available literature (Z. Feng et al., 2021)(F. Wang et al., 2022). The mixing temperature is 150°C, the mixing speed is 3000rpm, and the mixing time is 1 hour. Then, the modified bitumen is poured and directly mixed with the prepared aggregate sample, which was pre-heated to 165°C before mixing. The conventional Marshall mix design method was followed hereafter. The aggregate and modified bitumen were thoroughly mixed using an asphalt mixing machine for 2 minutes at 165°C. Then, the Marshall mixture was prepared according to ASTM D6926 (ASTM D 6926, 2014) and the Marshall stability and flow test was done according to ASTM D6927 (ASTM_International, 2015) to evaluate the performance.

3.6.2 Dry mixing process

In the dry mixing process, first, aggregates are heated to 165°C, and then PCB is added according to the required proportions. Then, pre-heated virgin bitumen is added up to the required amount. Like the wet mixing process, the Marshall mixture was prepared according to ASTM D6926 (ASTM D 6926 2014), and Marshall Stability and flow were evaluated.

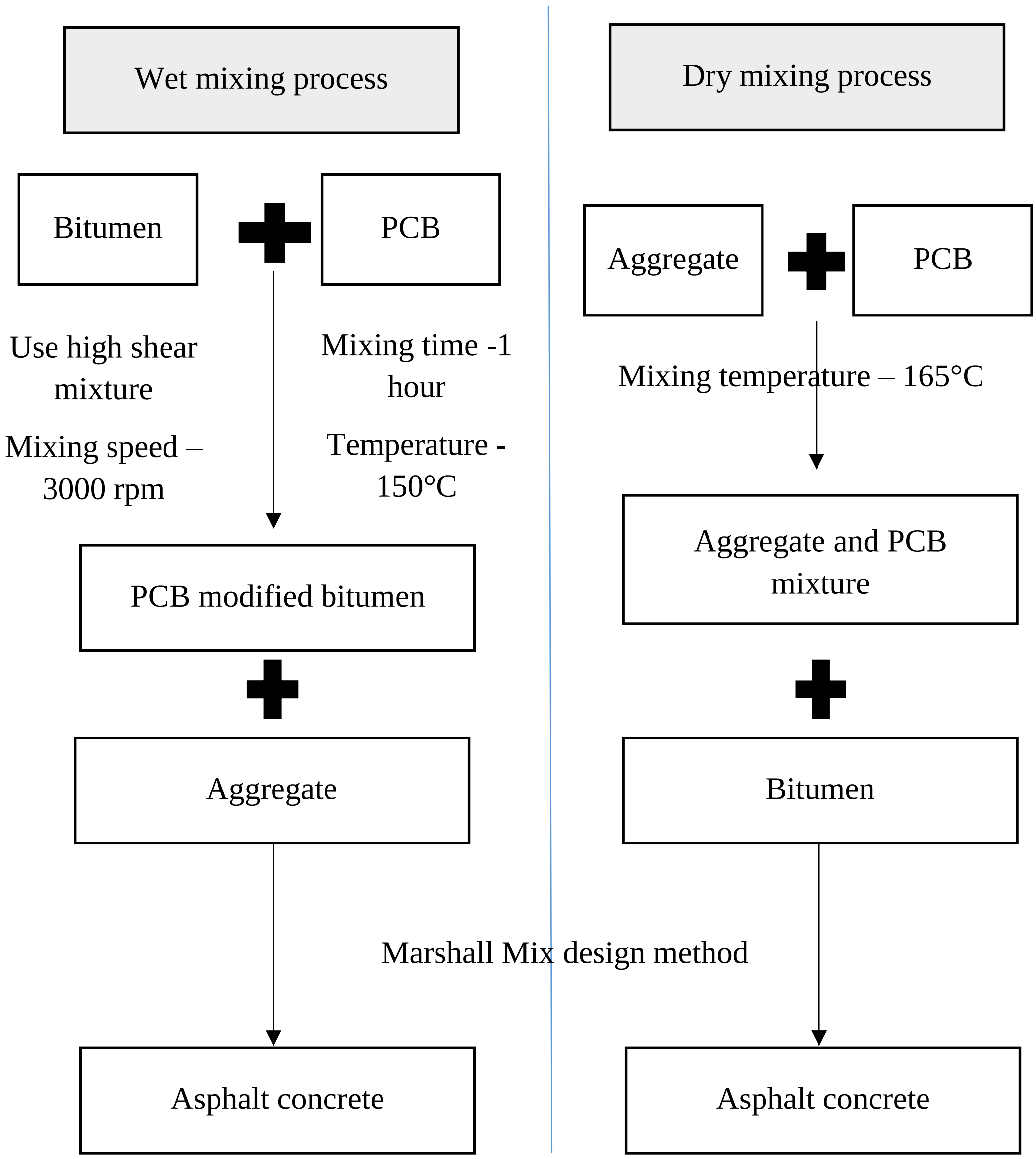


Figure 3.22: Wet mixing and Dry mixing processes

3.6.3 Design criteria and optimum bitumen content derivation

The guidelines given in the Sri Lankan specification “Standard Specification for Construction and Maintenance of Roads and Bridges” (SSCM 05) are used to determine the optimum specimen at all three phases (CIDA_SCA05, 2009). Table 3.11 mentions the following design criteria for the mixtures used for wearing and binder courses in high-traffic conditions. Furthermore, the Asphalt Institute’s method, given in Equation 3, is used to select the optimum binder percentage.

Table 3.11: Design Criteria

Stability (kN)	Not less than 8
Flow (0.25mm)	8 to 16
Va (%)	3 to 7
VMA (%)	Not less than 13

$$\text{Optimum Binder Content } = \frac{B_1 + B_2 + B_3}{3}$$ ----------------------- Equation 3

Where,

B_1 - Percentage of bitumen at a maximum bulk specific gravity of the mix

B_2 - Percentage of bitumen at maximum stability of the mix

B_3 - Percentage of bitumen at 4% air voids of the mix

3.7 Testing for Performance Evaluation

3.7.1 Marshall Mix design

Marshall mix design was done referring to the ASTM D6926 (ASTM D 6926, 2014) standards and Sri Lankan specification “Standard Specification for Construction and Maintenance of Roads and Bridges” (SSCM 05) (CIDA_SCA05, 2009). In this study, Marshall Specimens were prepared considering high traffic conditions. Therefore, 75 blows per face were applied when preparing the Marshall specimens. Three specimens were prepared for each mixture, and 15 specimens were prepared in the first phase. Similarly, 12 specimens were done for each of the remaining two phases.

3.7.2 Test for Bulk Specific Gravity (G_{mb})

The standard ASTM D2726 (ASTM_International, 2014) is used to calculate the Bulk Specific Gravity (G_{mb}) of these specimens. Prepared specimens were extracted using a sample extractor after allowing them to cool at room temperature for 24 hours. Dry mass, submerged mass and saturated surface dry mass were measured for all specimens before proceeding. The Bulk Specific Gravity was calculated using the Equation 4.

$$\text{Bulk Specific Gravity} = \frac{\text{Dry mass}}{(\text{Saturated surface dry mass} - \text{Submerged mass})} \text{ --------Equation 4}$$

3.7.3 Flow and stability test

Then, the diameter and the height of each specimen were measured using Vernier calliper. To determine the Marshall properties Marshall stability and flow tester was used according to ASTM D6927 (ASTM_International, 2015). Specimens were placed in a water bath at 60°C for 30-40 minutes. Then samples were taken out of the bath and wiped with a dry cloth and placed in the stability testing machine.

3.7.4 Test for Air Voids and Voids in Mineral Aggregates

I. Theoretical maximum specific gravity (G_{mm})

Theoretical maximum specific gravity (G_{mm}) was calculated according to ASTM D204 (ASTM_International, 2018). A loose sample of 2500g which was dried to a constant mass was put into the container of the apparatus (Figure 3.23). Then, add 25°C water to cover the whole sample (Figure 3.24). After assembling the apparatus (Figure 3.25), vacuum pressure of 27.5 mm Hg was applied within 4 minutes by the vacuum pump. Then, the agitation was continued for 15 minutes to release the entrapped air. The new weight is taken as container filled with water, sample and glass lid (Figure 3.26). Then using the Equation 5, Theoretical maximum specific gravity (G_{mm}) was calculated.

$$Gmm = \frac{m_d}{(m_d + m - m_t)} \text{ ------------------------------ Equation 5}$$

Where,

Gmm – Theoretical maximum specific gravity
m_d - Dry mass of sample at 25°C
m – Mass of the container filled with water and glass lid
m_t – Mass of the container filled with water, sample, and glass lid

Figure 3.23: Loose sample in the container

Figure 3.24: Add water to cover the sample

Figure 3.25: assembled apparatus

Figure 3.26: Mass of the container filled with water, sample, and glass lid

Subsequently, ASTM D3203 (ASTM_International, 2012) is referred to for the calculations of air voids (V_a), voids in mineral aggregates (VMA), and Voids Filled with Bitumen (VFB), which are mentioned in Equations 6,7 and 8, respectively.

I. Air Voids (V_a)

$$P_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}}$$ --Equation 6

Where,

P_a - Air voids ratio of the compacted mix
G_{mm} - Theoretical maximum specific gravity
G_{mb} - Bulk specific gravity of the compacted mix

II. Voids in Mineral Aggregate (VMA)

$$VMA = 100 - \frac{G_{mb} \times P_s}{G_{sb}} \text{------------------------------------ Equation 7}$$

Where,

G_{mb} - Bulk Specific Gravity of Compacted mixture
G_{sb} - Bulk Specific Gravity of the aggregate mixture
P_s - Percentage of total aggregate by mass in the mixture

III. Voids Filled with Bitumen (VFB)

$$VFB = 100 \times \frac{VMA - VIM}{VMA} \text{ ----------------------------------Equation 8}$$

Where,

VMA - Voids in Mineral Aggregates
VIM - Air voids in compacted mix, percentage of total volume
VFB - Voids Filled with Bitumen, percentage of VMA

3.7.5 Scanning Electron Micrograph (SEM) analysis

For further understanding between Dry method HMA and Wet method HMA, SEM analysis was carried out. Two modified asphalt concrete mixtures and conventional asphalt concrete mixtures underwent SEM analysis to investigate the morphology of the microstructure. External morphology was investigated using the two-dimensional images produced by the SEM test.

3.8 Long-Term Performance Evaluation - dry mixing method

3.8.1 Introduction of the Study Area

To understand the long-term field performance, a 226m long road section at Migahakubuara Road, Egaloya, Bulathsinhala, was evaluated (Figure 3.27). That road section has been prepared by replacing 1% of bitumen with PCB as a paving trial. The calculated optimum binder content is 4.7% for the conventional asphalt pavement. The 226m section has been modified by adding PCB in the dry mixing method reducing bitumen content to 3.7%. The road was constructed in 2021 by the Road Development Authority under the ADB-funded iRoad project.

As it is already 3 years ago, in January 2025, a distress survey was conducted under this research to understand the current status of the PCB-modified pavement manufacture by dry mixing method (Figure 3.28). A similar section with conventional asphalt pavement was selected as “Section A” to get a clearer picture, while PCB modified section was denoted as “Section B”. Both sections are on the same road (Figure 3.27), undergoing the same climate conditions and traffic loads.

This road has a low traffic volume. The geographical coordinates of the starting point of the Section B are 6°43'00.1"N and 80°08'50.8"E.

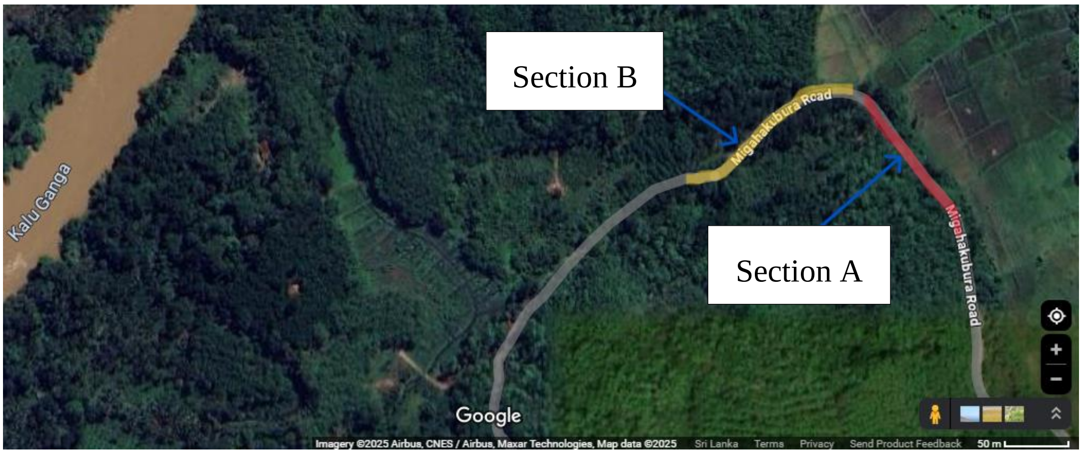


Figure 3.27: Megahakumbura road

Figure 3.28: Meegahakumbura Road- PCB modified section

3.8.2 Pavement Condition Rating

A pavement condition rating system was used to numerically represent the current conditions of the pavement and compare both sections. The concept of pavement condition index developed in ASTM D6433 (ASTM_International 2023) was used to scale the observed distress (Figure 3.29).

Figure 3.29: Pavement Condition Index (PCI) according to ASTM D6433

3.8.3 PCI Calculation Steps

According to the distress type, extent and severity ASTM D6433 (ASTM_International, 2023) has introduced a grading system for 20 types of distresses. Although the ASTM D6433 guided dividing the road into sections and evaluating each section, sections A and B were considered as two sections to simplify the evaluation, considering the shorter length of the PCB modified section.

Then, a field visit was arranged to investigate each distress type, their distribution area and the severity levels. With that observation, the observed distresses are sorted out under three severity categories: Low, Medium and High. From the area or length calculation for distress distribution of each distress type, the percentage density is calculated for the section of 226m length and 3.75m width. Then Deduct Value (DV) was calculated for each using the graphs provided in ASTM D6433-23 (ASTM_International, 2023). The total deducts value (TDV) is calculated by adding all DV values. Using TDV, Corrected DV (CDV) values were computed. For CDV calculation, firstly an allowable number of deducts (m) needs to be computed (Equation 9).

$\text{Allowable number of deducts (m)} = 1 + \left(\frac{9}{98}\right)(100 - HDV) \leq 10$------Equation 9

Where,

HDV = highest individual deduct value.

Then, maximum CDV is calculated iteratively. The number of deducts with a value greater than 2.0 is defined as q, where iteration continues until q becomes 1. Then, the obtained maximum value out of all iterations is selected as CDV, which is taken according to the q value and TDV from the graph given in ASTM D6433-23 (ASTM_International 2023). In the end, PCI is calculated out of 100 by deducting the maximum CDV from 100 (Equation 10).

$PCI = 100 - max.CDV$--- Equation 10

PCI values are calculated for both Section A and Section B, the unmodified and modified sections, respectively, and two PCI values are compared to elaborate on the long-term performance level further.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 General

This chapter presents and discusses the findings obtained from the laboratory tests and the field observations regarding the performance of Pyrolysis Carbon Black (PCB)-modified bitumen and asphalt concrete. This chapter contains four main sections. In the first phase, the performance of PCB-modified bitumen is compared with the conventional binder, in terms of rheological and physical performance, and economic and environmental impact. In the second phase, the influence of the mixing time and PCB particle size on final bitumen performance is evaluated. Under the third phase, the effect of two asphalt manufacturing methods, dry mixing and wet mixing, was assessed. In the fourth phase, the long-term performance of the PCB-modified pavement, which was constructed using the dry mixing method, is evaluated after three years of service.

4.2 Comparison of PCB modifier option with conventional binder under Sri Lankan context

4.2.1 Rheological and physical performance

Table 4.1 displays the results of the performance tests for PCB-modified binders.

Table 4.1: Properties of PCB-modified binder

Test	Specification/ Reference	PCB % by weight			
		0	5	10	15
Penetration (25°C; 0.1 mm)	ASTM D5 (ASTM_International, 2006a)	63	64	63	60
Softening point (°C)	ASTM D36 (ASTM_International, 2006b)	51.5	52	53	57
Penetration Index (PI)	(Geckil et al., 2018)	-0.3	-0.1	0.1	0.9
temperature (°C); when rutting resistance (G*/sinδ) = 1 kPa	ASTM D7175 (ASTM_International, 2024)	64	68	70	74

4.2.2 Optimization Approach

When the penetration value decreases, the binder becomes stiff and reduces the risk of rutting under high temperatures. The binder can withstand elevated temperatures without deforming when the softening point increases. Therefore, with the increasing modifier percentage, penetration and softening points show a positive trend. However, according to the Standard specification for construction and maintenance of roads and bridges (CIDA_SCA05, 2009), the recommended softening point range is between 48°C-56°C and 47°C-55°C for 60/70 and 80/100 penetration graded bitumen, respectively. However, a study done by Sitinamaluwa et al. (2014) (Sitinamaluwa & Mampearachchi, 2014) has 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 the Sri Lankan context, the 47°C-65°C softening point range is considered in this study. Further, according to Meegahage et al. (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, the samples (with respect to PCB percentages) which were not had PI within between -1 and +1 range, were 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 country's maximum and minimum temperature variations. Therefore, for the rutting parameter, 58°C is considered the boundary minimum temperature in this study. This means the binder with 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, PCB modifier displays an increasing trend in $G^*/\sin\delta$ value, which reflects the strong rutting resistance and suitability for Sri Lanka's climate.

Table 4.2 conveys the selected modifier percentage, considering the above criteria as the most appropriate binder for the Sri Lankan context.

Table 4.2: Optimum percentages for PCB modifier

Modifier type	**Percentage by total weight of binder**
PCB	15%

4.2.3 Economic and environmental impact

According to the above derived optimum modifier percentage, the mass required from each ingredient to create 1kg of binder is calculated in Table 4.3. Using the data from Tables 3.10 and 4.3, EE, $ECO_{2\text{-}e}$, and cost values for modified binders are calculated. (Refer Table 4.4)

Table 4.3: The mass of mixing for 1kg binder

Modified binder	**Modifier (g)**	**Bitumen (g)**

Conventional binder	-	1000
PCB	150	850

Table 4.4: Calculated EE, ECO_{2-e} and Cost values for modified binders

Binder	Embodied Energy (EE) (MJ/kg)	ECO_{2-e} (kg CO_{2e}/kg)	Cost (LRK/kg)
Conventional binder	2.501	0.372	224.50
PCB	2.171	0.354	196.15

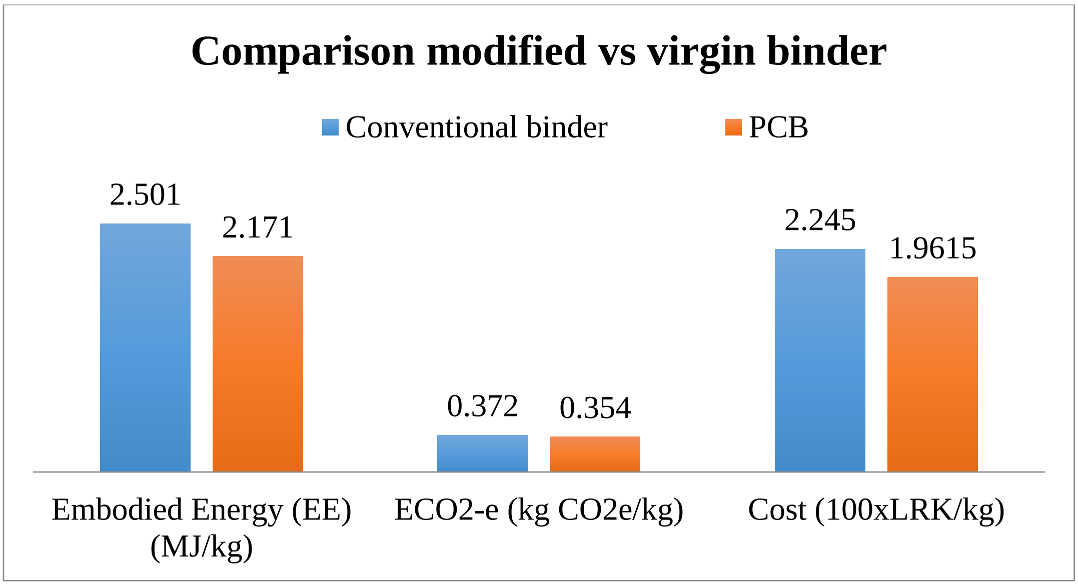


Figure 4.1: Comparison of PCB modified binder vs conventional binder

Figures 4.1, displays the lowest EE, ECO_{2-e} and cost values of PCB-modified binder. From the experimental and calculated data results, PCB can be recommended as a highly sustainable modifier option for Sri Lanka, concerning performance, environmental, and economic impact. PCB-modified binder decreased the EE value by 13% and the ECO_{2-e} value by 5% compared to conventional binder. Additionally, PCB reduced costs by 13%, making it a precise cost-effective option. Adding 15% PCB by total weight for bitumen modification is recommended as the optimal percentage for use in Sri Lanka. Therefore, further analysis of the behaviour of the PCB 15% by total weight added modified bitumen is carried out in the following sections.

4.3 PCB Modification: Performance Impact Factors

4.3.1 Physical properties of the bitumen

The impact of particle size and mixing speed is evaluated for further clarification. Table 4.5 presents the physical properties of PCB-modified bitumen respective to particle size and mixing speed. Binder no. 1 is the control sample, which has only virgin bitumen. Binders 2 and 3 were compared to evaluate the influence of the PCB particle size on the binder. The particle size distributions of samples A and B are in Figures 3.3 and 3.4, respectively. Then, binders 3, 4 and 5 were compared to evaluate the influence of mixing speed on the bitumen properties.

Table 4.5: PCB Modified bitumen properties- respective to particle size and rpm

Binder No.	CB %	Mixing temperature	Mixing Time	Mixing Speed (rpm)	Penetration (25°C; 0.1 mm)	Softening point (°C)
1	0	-	-	-	63	51
2	15%- Sample A	155-160°C	1 hour	3000	60	56
3	15%- Sample B	155-160°C	1 hour	3000	40	55
4	15%- Sample B	155-160°C	1 hour	2000	44	57
5	15%- Sample B	155-160°C	1 hour	4000	39	54

4.3.1.1 Variation with respect to particle size

Figure 4.2 presents the penetration vitiation with respect to particle size of the PCB. According to Figures 3.3 and 3.4, sample A and sample B have drastic differences in particle size. That influence can be observed in the rapid decrease of penetration between binders 2 and 3. However, such a dramatic change cannot be observed in softening point data (Figure 4.3). Moreover, sample B, which has smaller size particles, was selected for further PCB modification experiments in this study. Gan et al. (2023) (Gan et al., 2023) have received similar patterns between PCB and coupling-treated PCB, where coupling-treated PCB had smaller particle sizes. The attempts made to partial size reductions help to eliminate the ash deposits on the PCB surface by resulting in specific surface area improvement (Y. Ma et al., 2022). Subsequently, prioritizing the reduction of PCB particle size instead of using it directly in its industrial disposal form can be recommended as a more effective and beneficial approach.

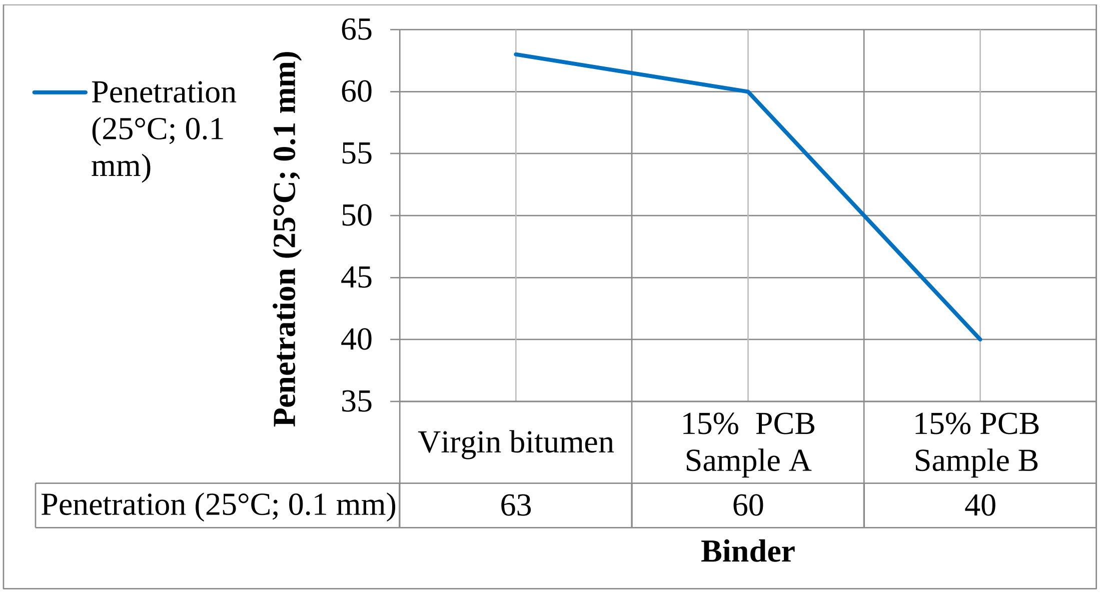


Figure 4.2: Penetration variation with respect to particle size

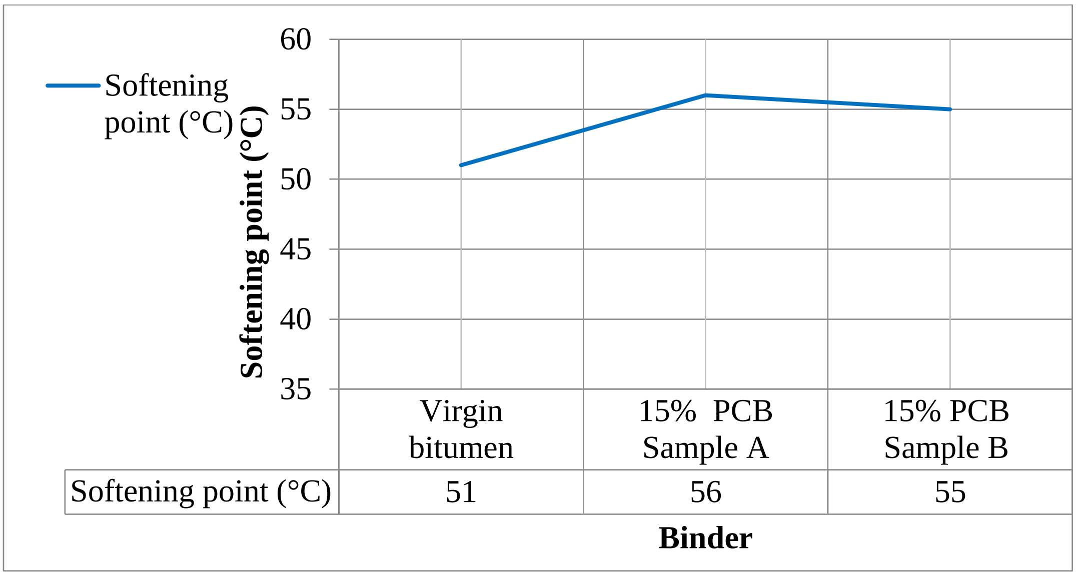
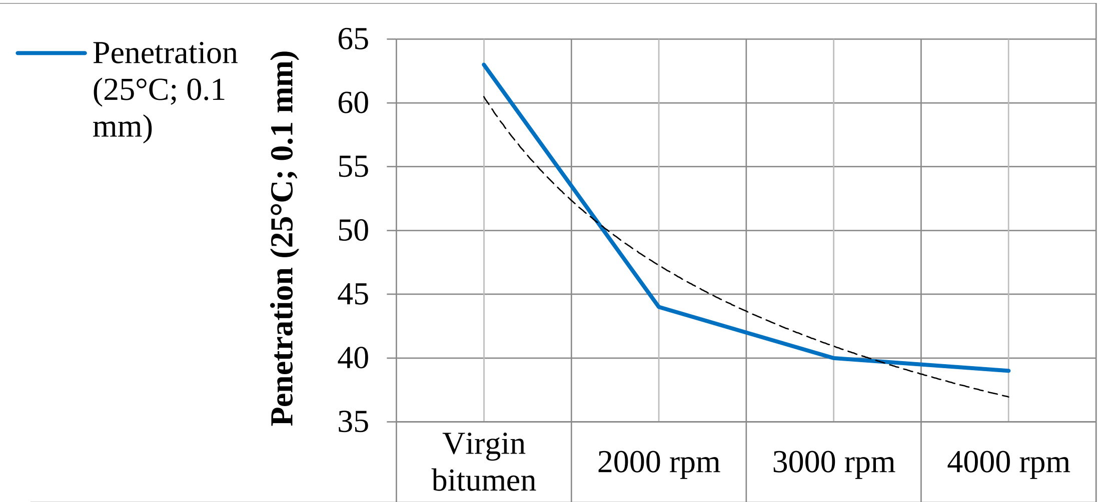


Figure 4.3: Softening point variation with respect to particle size

4.3.1.2 Variation with respect to mixing speed

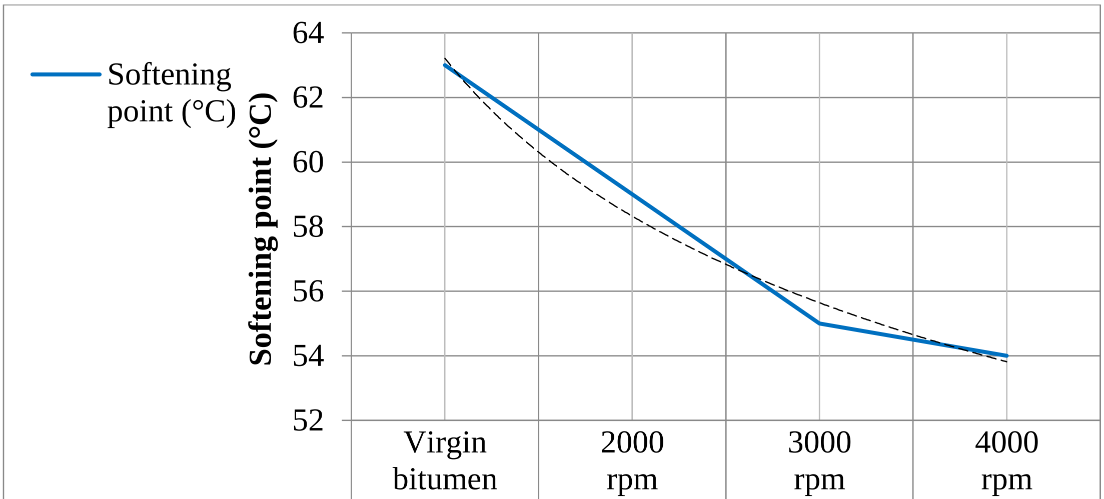
Shear mixing facilities are required for PCB-based bitumen modification (F. Wang et al., 2022). However, the additional energy demand associated with shear mixing poses an important concern for industrial-scale applications. Therefore, it is essential to investigate the impact of mixing speed on the performance of modified bitumen. Figures 4.4 and 4.5 present the variation of penetration and softening point values with increasing rpm. Both graphs display the exponential decay trend with the increase in mixing speed. Although the influence of mixing speed on PCB-modified bitumen has not been documented in the literature, Table 3.5 highlights a significant variation in the RPM values selected for experimental purposes. It reveals that lower RPM values have been selected for the PCB modifications associated with polymer-based material. However, higher RPM values have been used for PCB-only modifications. However, by considering the decay exponential pattern in modified binder properties with respect to mixing speed, 3000rpm is selected for further investigations in this study.



	Virgin bitumen	2000 rpm	3000 rpm	4000 rpm
Penetration (25°C; 0.1 mm)	63	44	40	39

Binder

Figure 4.4: Penetration variation with respect to mixing speed



	Virgin bitumen	2000 rpm	3000 rpm	4000 rpm
Softening point (°C)	63	59	55	54

Binder

Figure 4.5: Softening point variation with mixing speed

4.3.2 FTIR results of modified bitumen

To evaluate the PCB's effect on the chemical structure and performance of bitumen, FTIR analysis was conducted on binder no. 1, 2, and 3 samples. Figure 4.6 illustrates the FTIR spectrums of three samples.

The peak at 3038.02 cm^{-1} in virgin bitumen represents the C–H stretching of aromatic C–H bonds (Sun et al., 2023). The peaks in virgin and modified bitumen, 2879.04 cm^{-1} and 2878.95 cm^{-1}, have been caused by C–H stretching of aliphatic C–

H bonds (Gan et al., 2023). The peaks in virgin and modified bitumen 1524.97 cm^{-1} and 1525.81 cm^{-1} reveal that the aromatic structure of bitumen has been retained, with no significant changes in aromatic content after modification (C. Li et al., 2023). Similarly, three graphs indicate very coinciding peaks without any unique peaks. Therefore, it can be concluded that long-chain hydrocarbons in bitumen have not been affected considerably due to PCB modification. Further, peaks such as 1525 cm^{-1} (C=C stretching), 736 cm^{-1} and 838 cm^{-1} provide strong evidence of preserving aromatic structure after modification (Y. Li et al., 2024).

Modifying bitumen with PCB does not induce the formation of new chemical bonds compared to the virgin bitumen. Although the particle size of PCB improves the performance characteristics of the modified bitumen, it does not lead to significant alterations in the chemical structure of the bitumen. The observed changes in the FTIR spectra, such as shifts in absorbance bands, suggest potential interactions at a physical or molecular level rather than the formation of new chemical species within the binder matrix. Therefore, the enhancement in performance is likely attributed to the physical properties of the PCB particles rather than the chemical modification of the bitumen itself.

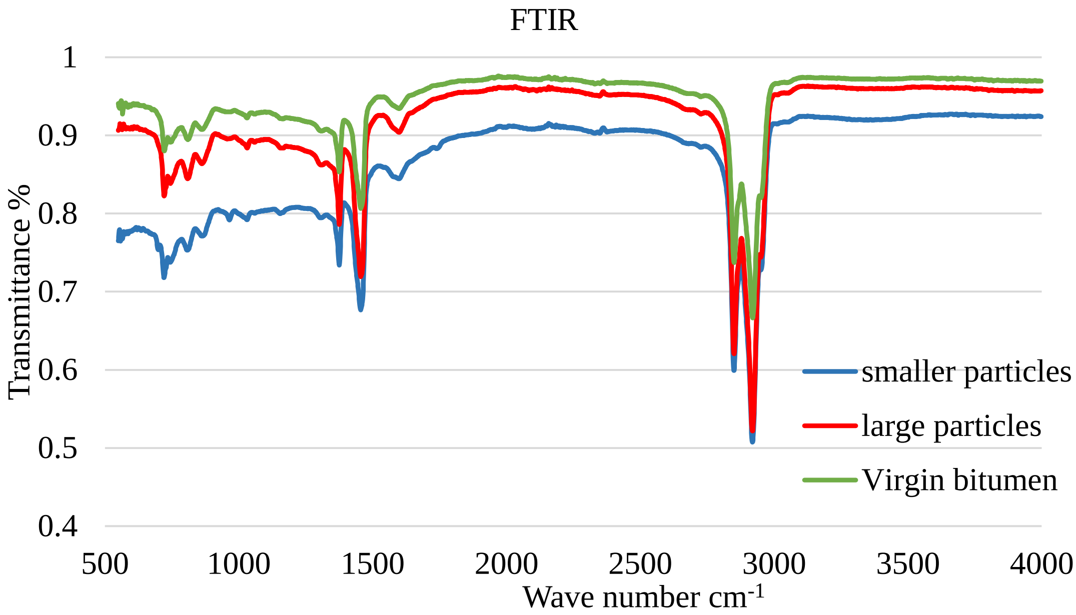


Figure 4.6: FTIR spectrums of binder samples No. 1, 2 and 3.

4.3.3 Influence of the ageing

The prepared 5 samples were investigated for long term ageing using PAV machine. Then penetration and softening point tests were conducted to compare before and after property variations. Table 4.6 presents the physical properties of 5 binder samples before and after ageing.

Table 4.6: PCB Modified bitumen properties- before and after ageing

Binder No.	Before Ageing		After Ageing	
	Penetration (25°C; 0.1 mm)	**Softening point (°C)**	**Penetration (25°C; 0.1 mm)**	**Softening point (°C)**
1	63	51	24	64
2	60	56	22	60
3	40	55	21	61
4	44	59	23	62
5	39	54	19	57

Figure 4.7 illustrates the variation of penetration values with respect to the particle size of the PCB after ageing and before ageing. Although ageing values also presents the decreasing pattern, the difference between values is very less. Both PCB modified samples and virgin bitumen sample shows very closer penetration values after ageing.

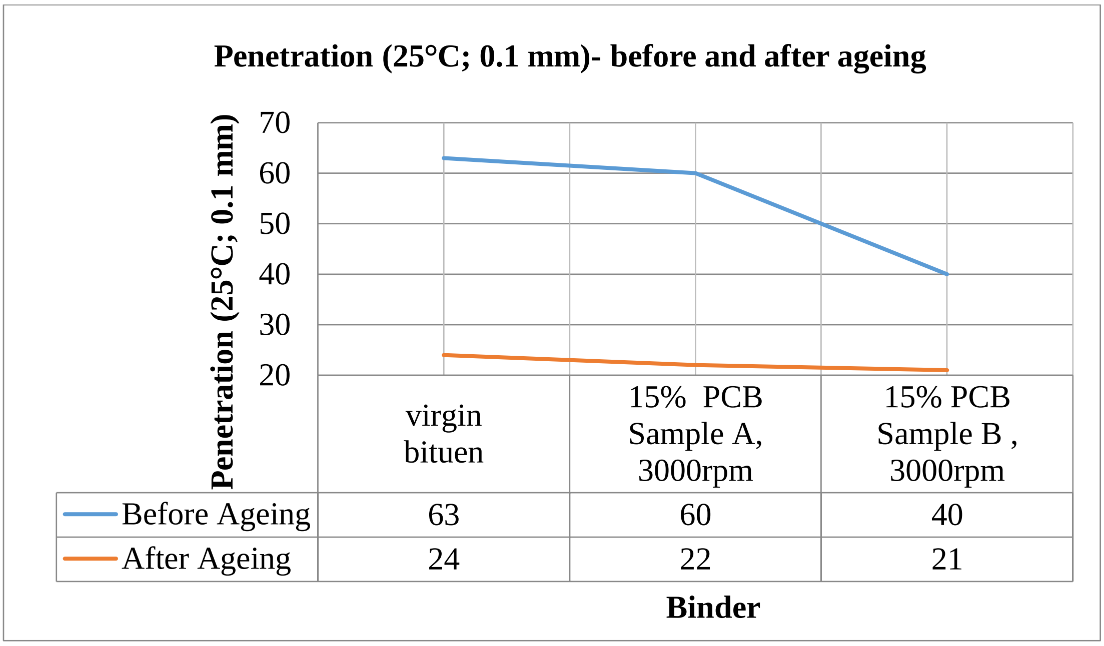


Figure 4.7: Penetration variation with particle size (before and after ageing)

Figure 4.8 presents the deviation of softening point with respect to the particle size variations. Ageing has increased the softening point values of binders indicating that binder has become harder. However, although penetration values presents considerable variations with particle size of PCB, both softening point values after and before aging present closer values. The effect of particle size of PCB on softening point values is negligible.

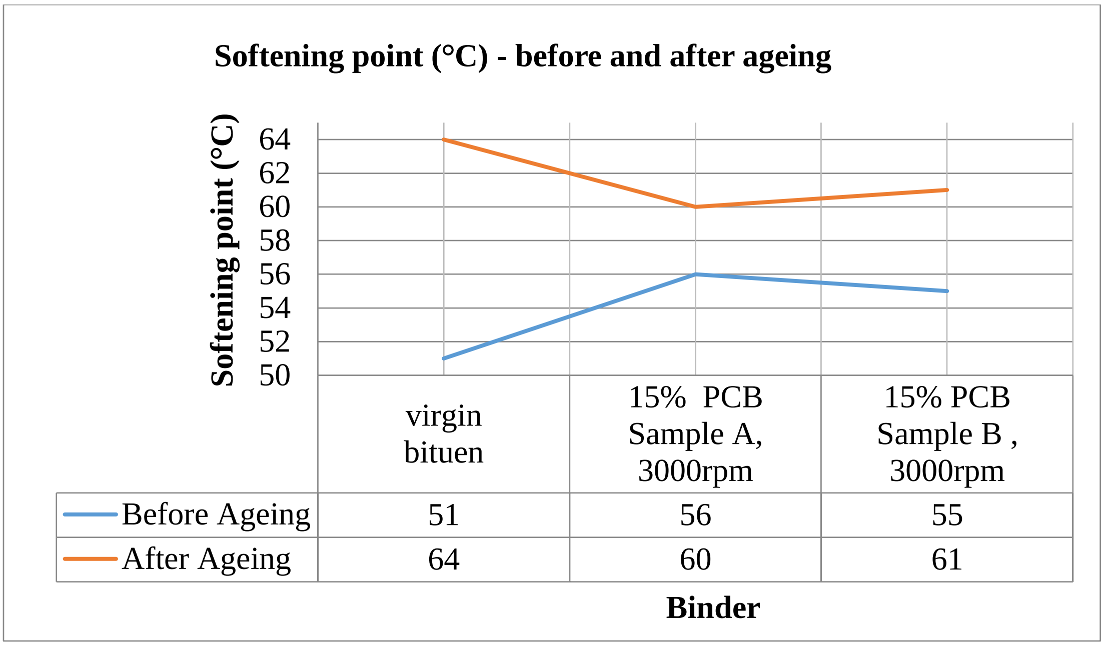


Figure 4.8: Softening point variation with particle size (before and after ageing)

Figure 4.9 presents the change of penetration value with respect to the mixing speed. Although the penetration values before ageing presents a decay exponential variation, after ageing values presents a decay liner variation with the increase of mixing speed. Figure 4.10 presents the softening point values of binders with the increase of mixing time. Both softening point series demonstrate the decreasing pattern while the aged binder’s softening point value has increased compared to the un-aged value of relevant binder. However, obviously PCB can improve the ageing resistance of bitumen according to the study conducted by Wang et al. (2019) (H. Wang et al., 2019). They have proved that age resistance can be improved by increasing PCB. Moreover, similar variations between un-aged and aged properties of PCB modified bitumen has observed for two types of PCB samples by Feng et al. (2016) (Z. G. Feng et al., 2016).

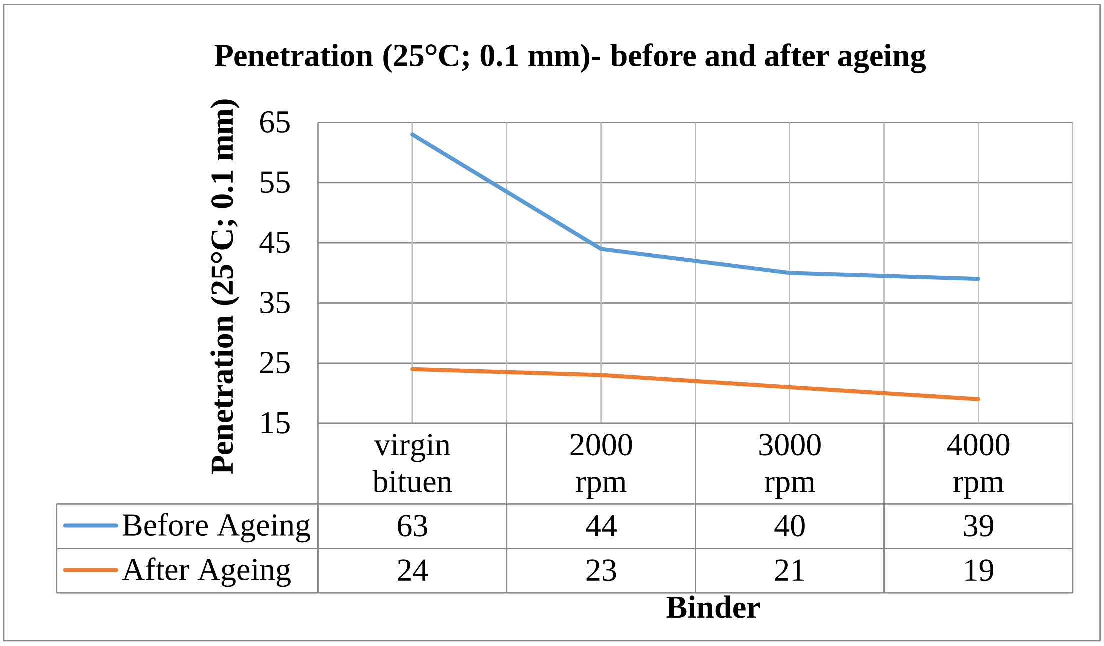


Figure 4.9: Penetration variation with respect to mixing speed (before and after ageing)

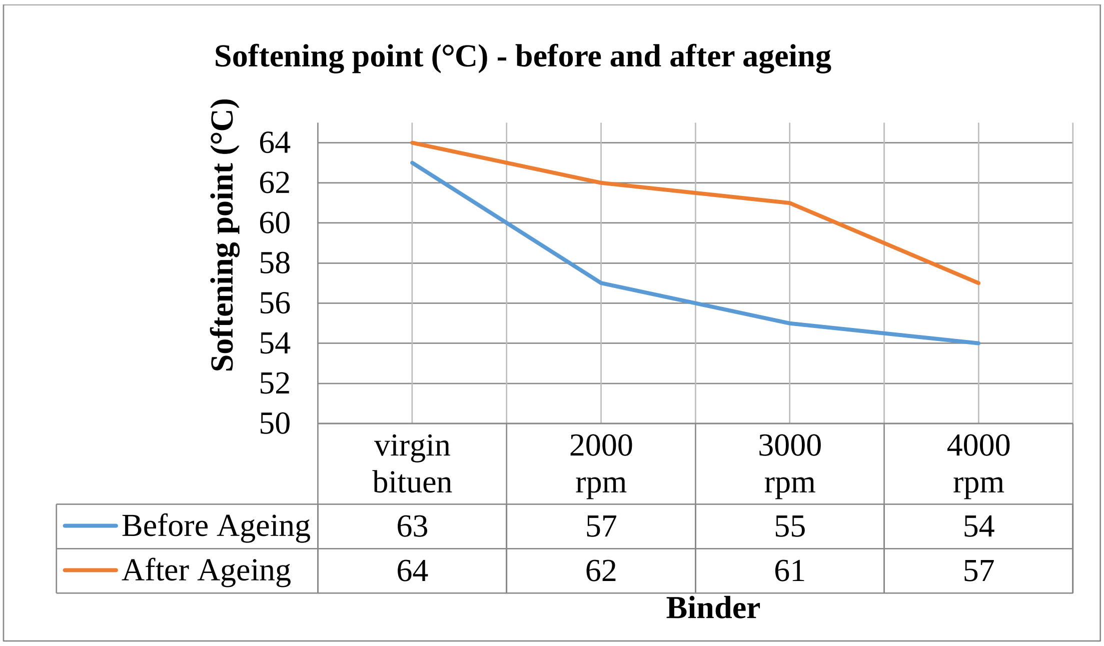


Figure 4.10: Softening point variation with respect to mixing speed (before and after ageing)

4.4 Performance Evaluation of Asphalt Concrete

This evaluation is carried out in three main sections (Figure 4.11). First, the OBC was found for the virgin bitumen sample. In the second phase, mixing method evaluation was conducted using that derived OBC. Performance was evaluated by replacing 0.5%, 1%, 1.5% and 2% bitumen by PCB from total mix. The third phase used the developed optimum PCB binder in the previous section. Modified bitumen preparation parameters were also selected from the results of the bitumen modification section. New OBC has been defined for modified bitumen. Then, virgin OBC asphalt concrete properties and PCB-modified asphalt concrete properties are compared for better understanding.

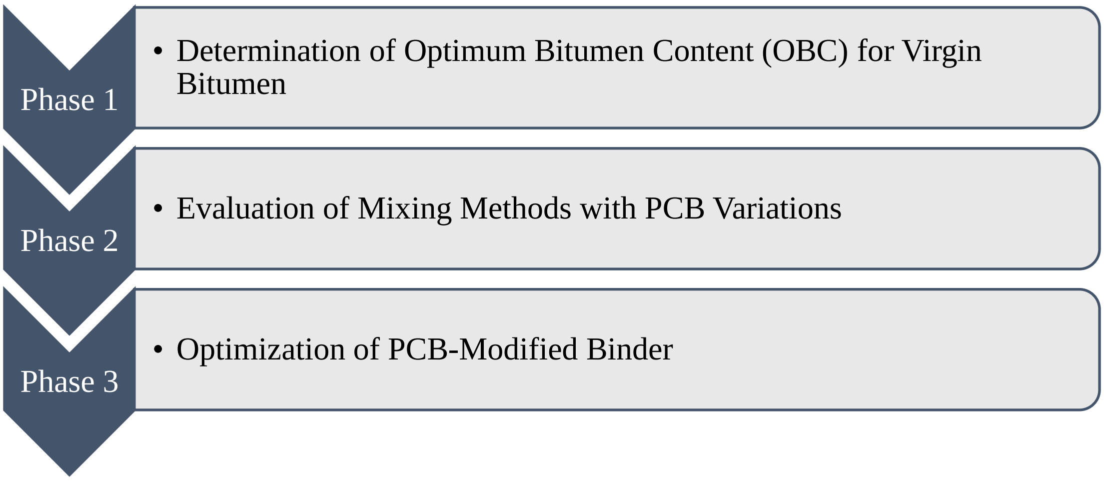


Figure 4.11: Performance evaluation phases of Asphalt concrete

4.4.1 Determination of Optimum Bitumen Content (OBC) for Virgin Bitumen

To determine OBC for conventional asphalt mixture, 15 specimens were prepared by adding different bitumen contents: 4%, 4.5%, 5%, 5.5%, and 6% by weight. From the tests mentioned in the method section, the volumetric properties of 15 specimens were calculated which are mentioned in Table 4.7.

To determine the OBC, the four curves were plotted in Figure 4.12, where the design criteria are marked in red straight lines.

Table 4.7: Volumetric properties of virgin bitumen asphalt concrete mixtures

Bitumen Content (%)	Stability (kN)	Flow (0.25mm)	V_a (%)	VMA (%)	Bulk Specific Gravity (G_{mb})
4	9.26	6.93	9.06	15.71	2.42
4.5	12.06	8.59	6.85	14.82	2.45
5	14.88	8.8	4.57	13.9	2.49
5.5	14.66	13.33	3.24	13.85	2.48

6	9.31	14.56	3.46	15.19	2.48

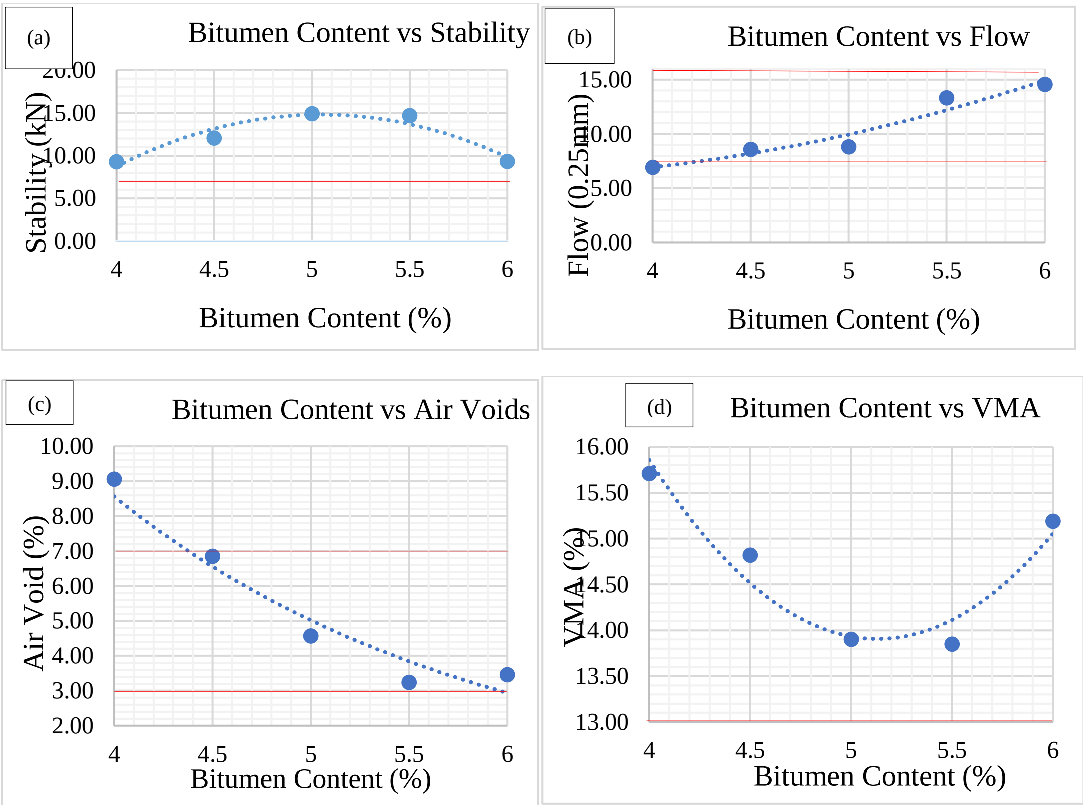


Figure 4.12: volumetric graphs for conventional Marshall Mixture

The OBC is calculated using Table 4.7 data according to the design criteria.

OBC = (5+5+5.4)/3

= 5.1% by weight

4.4.2 Evaluation of Mixing Methods with PCB Variations

4.4.2.1 Wet mixing

Throughout this phase, the total binder content is kept constant at 5.1% by weight, which is the calculated OBC in phase 1. However, four mixtures are prepared by replacing bitumen by PCB from 0.5% to 2% by weight. Volumetric properties, presented in Table 4.8, have been calculated using the above-mentioned tests.

Table 4.8: Volumetric properties for PCB wet mixing asphalt concrete mixture

Bitumen content	4.60%	4.10%	3.60%	3.10%
PCB content	**0.50%**	**1.00%**	**1.50%**	**2.00%**
Stability (kN)	16.86	14.94	14.83	13.58
Flow (0.25mm)	14.04	13.44	12.80	11.65
Bulk Specific Gravity (Gmb)	2.49	2.45	2.43	2.37

V_a (%)	3.01	4.74	5.41	7.80
VMA (%)	13.98	15.51	16.11	18.23

According to the design criteria, the mixture with 3.2% bitumen and 2% PCB is not within the required limits. Therefore, the permissible PCB content is 1.5%.

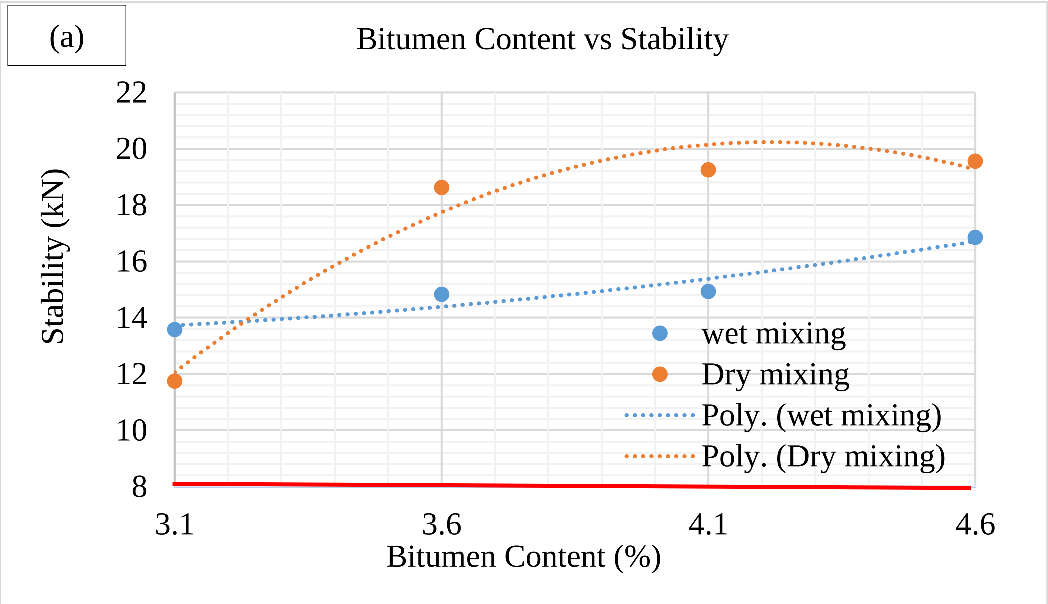
4.4.2.2 Dry mixing

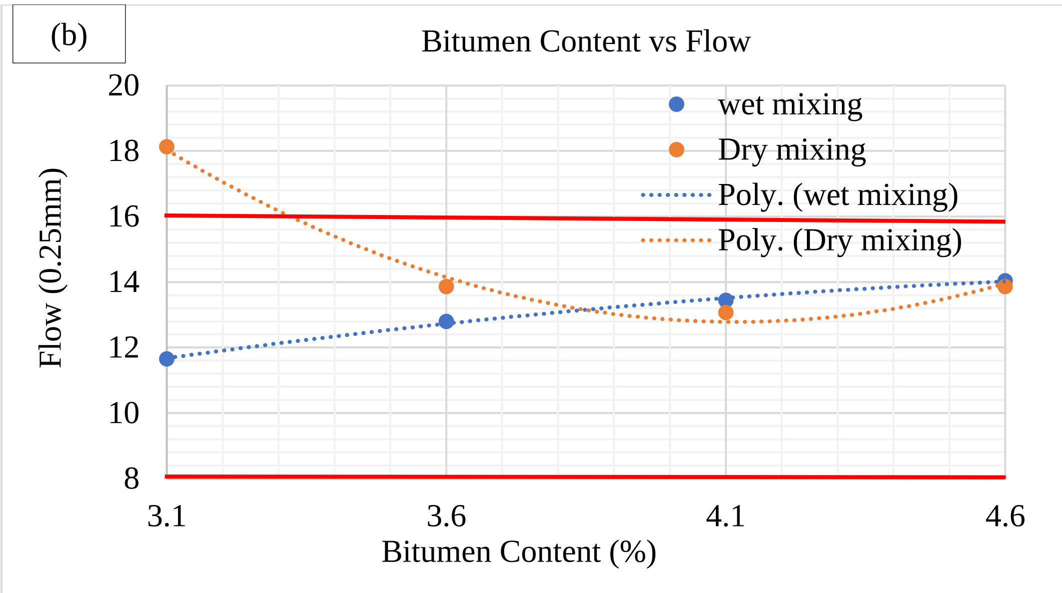
The same proportions of bitumen and PCB were used for dry mixing. The derived volumetric properties are presented in Table 4.9. The deviation in the volumetric properties between wet mixing and dry mixing methods is monitored by plotting the results. In Figure 4.13, both values have been plotted for better observation with suggested trend lines.

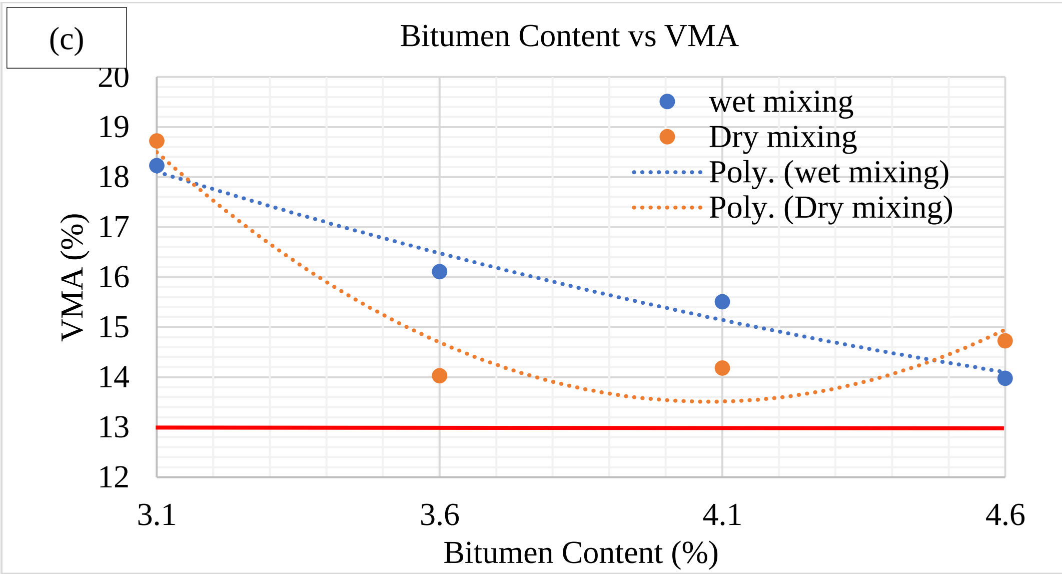
Table 4.9: Volumetric properties for PCB dry mixing asphalt concrete mixture

Bitumen content	4.60%	4.10%	3.60%	3.10%
PCB content	0.50%	1.00%	1.50%	2.00%
Stability (kN)	19.56	19.26	18.63	11.76
Flow (0.25mm)	13.86	13.07	13.86	18.13
Bulk Specific Gravity (Gmb)	2.42	2.43	2.42	2.28
Va (%)	5.99	5.99	6.84	12.34
VMA (%)	14.73	14.18	14.03	18.72

It was noted that the asphalt mixers with carbon black contents of 0.5%, 1.0%, and 1.5% were in accordance with the specifications (Table 3.11). Further, the carbon content replacement of 2% does not fulfil the specification. Therefore, the average value of the above three carbon black content, which is 1.0%, is determined as the optimum carbon black content for the dry mixing process.




(b)
Bitumen Content vs Flow
Flow (0.25mm)
20
18
16
14
12
10
8
3.1
3.6
4.1
4.6
Bitumen Content (%)
wet mixing
Dry mixing
Poly. (wet mixing)
Poly. (Dry mixing)


(c)
Bitumen Content vs VMA
VMA (%)
20
19
18
17
16
15
14
13
12
3.1
3.6
4.1
4.6
Bitumen Content (%)
wet mixing
Dry mixing
Poly. (wet mixing)
Poly. (Dry mixing)

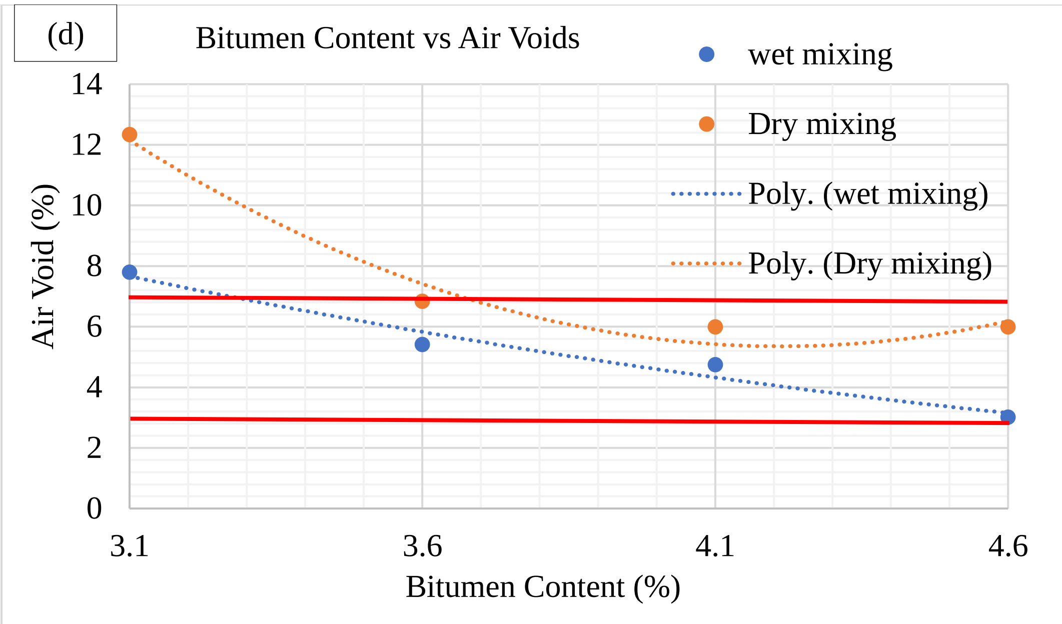


Figure 4.13: Volumetric graphs for PCB-modified Marshall Mixtures

4.8.2.3 Comparison of volumetric properties

Table 4.10 shows the volumetric properties of selected optimum mixtures and their percentage increase. Overall, the volumetric properties of the original mixture have improved in the modified mixtures. However, there are significant differences between the values derived for the same PCB proportions in the two preparation methods. The Marshall stability values of all four mixtures in dry mixing are greater than the stability values of the respective wet mixing mixtures. Pavement resistance to rutting and permanent deformation is enhanced with increasing stability (Naghawi et al., 2018). Further, the flow has increased in both modified samples compared to the conventional mixture, where the flow increase in wet mixing and dry mixing mixtures is 26.73% and 37.23%, respectively. That indicates the modified mixtures are more flexible and have improved fatigue resistance (Agha et al., 2023). Therefore, further studies to check its suitability for low temperatures are recommended, as countries with cold climates can benefit from the enhanced flow values of PCB, resulting in enhanced fatigue resistance. Further, the air voids are increased by 20.22% in the wet mixing mixture with a 52.00% increase in the dry mixing mixture (Figure 4.14). The percentage of air voids is essential to be within the optimal range as it affects the performance and the durability of the pavement (Ibrahim et al., 2009).

Similar patterns can also be observed for wet and dry mixing in the literature. Gan et al. (2023) [30] have observed improved stiffness in the wet mixing method compared to the dry mixing method for Co-PCB-modified asphalt concrete. Although the wet method is considered as difficult in industry practice, Casado-Barrasa et al. (2019) [9] have successfully constructed a 100m long road section in Toledo, Spain, using a modified mobile bitumen modification plant to modify bitumen using CCB and Evotherm. Although several researchers have evaluated the properties of PCB-modified binders, there is a lack of information about PCB-modified asphalt concrete properties to properly select the best mixing process for PCB-modified asphalt manufacturing.

Table 4.10: Volumetric properties of selected optimum mixtures

Volumetric property	values for selected optimum sample			Percentage increase		Design Criteria
	conventional mixture	wet mixing mixture	dry mixing mixture	wet mixing mixture	dry mixing mixture	
Stability (kN)	15	14.83	18.63	-1.13%	24.20%	Not less than 8
Flow (0.25mm)	10.1	12.8	13.86	26.73%	37.23%	8 to 16
Va (%)	4.5	5.41	6.84	20.22%	52.00%	3 to 7
VMA (%)	13.5	16.11	14.03	19.33%	3.93%	Not less than 13

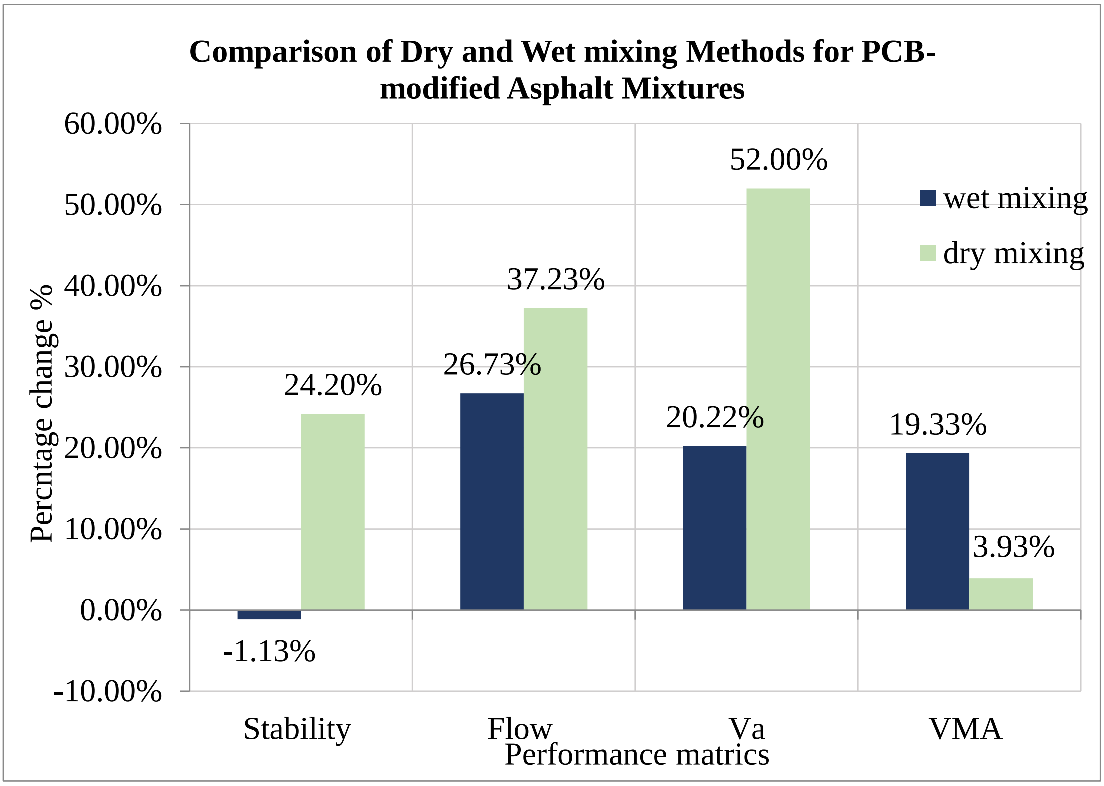


Figure 4.14: Comparison of Dry and Wet mixing Methods for PCB-modified Asphalt Mixtures

4.8.2.4 Scanning Electron Micrograph (SEM) analysis

Figures 4.15, 4.16, and 4.17 present the three asphalt mixture SEM images: (a) conventional mixture with 5.1% bitumen, (b) wet mixing sample with 3.6% bitumen and 1.5% PCB, (c) dry mixing sample with 3.6% bitumen and 1.5% PCB.

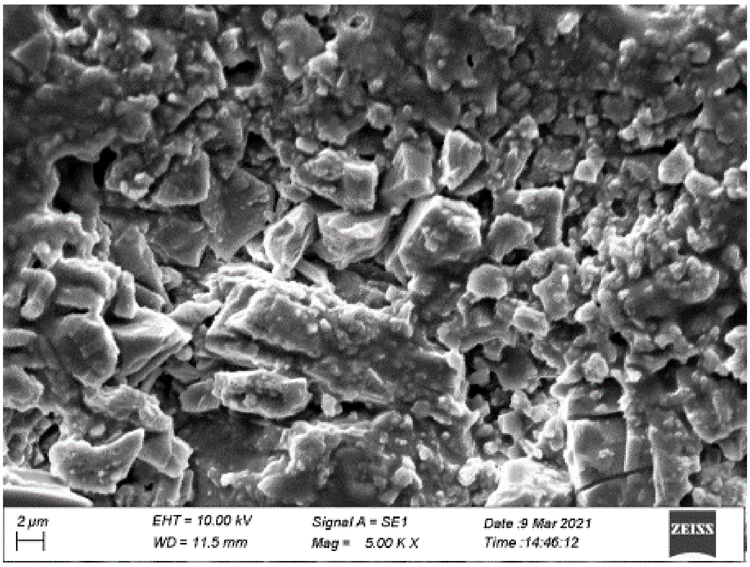


Figure 4.15: SEM image of conventional asphalt mixture with 5.1% bitumen

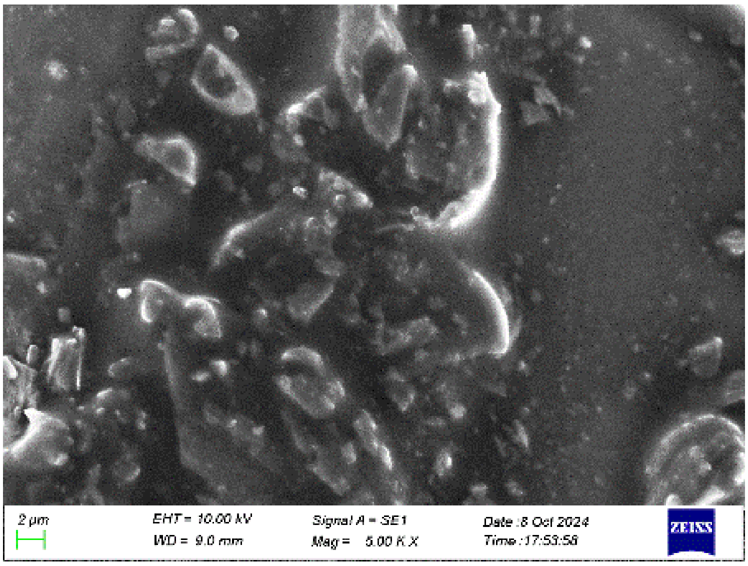


Figure 4.16: SEM image of wet mixing asphalt sample with 3.6% bitumen and 1.5% PCB

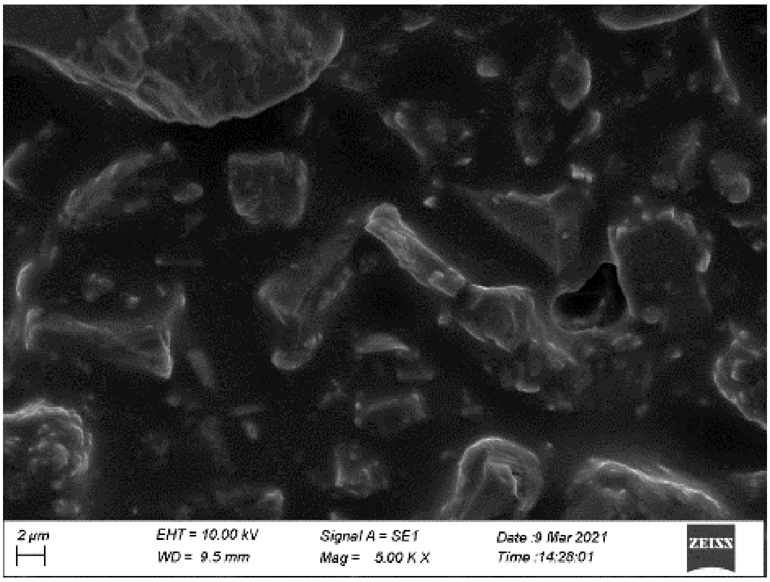


Figure 4.17: SEM image of dry mixing asphalt sample with 3.6% bitumen and 1.5% PCB

A considerable increase in binder aggregate interaction can be observed in modified mixtures (Figures 4.16 and 4.17) compared to conventional mixtures (Figure 4.15). Mazumder et al. (2018) have investigated the potential of using SEM images to detect the cohesion and adhesion between binder and the other materials of asphalt mixtures (Mazumder et al., 2018)They ensure that SEM images are a promising way of detecting material dispersion, modification mechanism, and Fracture morphology.

The SEM analysis reveals significant microstructural differences between unmodified asphalt concrete and PCB-modified asphalt concretes prepared through dry and wet mixing methods. The unmodified asphalt concrete exhibits a smooth, homogeneous binder matrix with separate voids at the aggregate-binder interface (Figure 4.15). It provides evidence of weaker adhesion and susceptibility to cracking under stress.

In contrast, PCB-modified asphalt concrete prepared through the dry mixing process shows localised agglomerations of PCB particles and a rougher matrix with uneven dispersion (Figure 4.17). The lack of chemical integration between the binder and PCB results in weaker bonding, leading to marginal improvements in adhesion and cohesion (Mai Alawneh & Soliman, 2023). Therefore, adhesion has moderately improved in dry mixing samples.

However, the wet mixing process (Figure 4.16) produces a well-dispersed and homogeneous matrix, with PCB particles uniformly integrated into the binder. PCB particles have thoroughly dispersed within the binder at elevated temperatures and mixing speeds, resulting in uniform distribution. The fine PCB particles have combined due to high surface area while enhancing mechanical interlocking with the binder (Mazumder et al., 2018). Furthermore, the surface chemistry of PCB promotes chemical interactions with the asphalt binder as it contains oxygen-associated functional groups (e.g., hydroxyl and carboxyl groups) (J. Xu et al., 2021). These interactions strengthen the adhesion at the binder-aggregate interface by forming stronger bonds and reducing voids.

The SEM images highlight the reduced voids at the binder-aggregate interface and enhanced particle-matrix bonding, contributing to a denser microstructure. As evidenced by SEM images, these mechanisms explain the significant reduction in voids due to the better coating at wet mixing has facilitated the interlocking of particles. The enhanced interlocking at the binder-aggregate particles and improved coating directly influence into superior resistance to rutting, fatigue, and moisture damage, making the material more suitable for heavy traffic and hot climates. Moreover, the increase of the flow confirms the easiness of the compaction resulting lower voids content. Table 4.11 clearly compares SEM image characteristics and expected performance improvements.

Table 4.11: Characteristic comparison of SEM images

Characteristic	**Conventional asphalt mixture with 5.1% bitumen**	**Dry mixing asphalt sample with 3.6% bitumen and 1.5% PCB.**	**Wet mixing asphalt sample with 3.6% bitumen and 1.5% PCB**
PCB Distribution	Not present	Non-uniform, agglomerated	Uniform, well-dispersed
Surface Homogeneity	Smooth but with voids at interfaces	Rough and uneven	Smooth, dense, and cohesive
Particle-Matrix Bonding	Not applicable	Weak	Strong, chemically integrated
Interfacial Voids	Clear separation between phases	Moderate voids at interfaces	Minimal voids, strong adhesion
Mechanical Performance expectation	Low rutting and fatigue resistance	Moderate improvement	Significant improvement

However, when comparing these production processes, the practical approach of both asphalt concrete manufacturing methods was considered when selecting a method for further investigations. Jitsangiam et al. (2023) (Jitsangiam et al., 2023) discussed the practical difficulties of using the wet mixing process in Thailand with the available resources. They highlight the ability of directly adding plastic waste, (their modifier) into to asphalt mixture in the dry mixing process helps to make an alternative waste recycling method popular in industrial practice. Similarly, as PCB is also a waste waste-based modifier option and Sri Lanka is a developing country, the dry mixing method is convenient for the Sri Lankan industry to adapt. As the last step, a field trial of dry mixing PCB asphalt concrete was conducted using laboratory data.

4.4.3 Optimization of PCB-Modified Binder

This is the other approach of finding optimum PCB for asphalt concrete. In this method, first optimum PCB modified binder was found as presented in above binder properties evaluation sections. The selected binder was 15% PCB mixed bitumen mixture. The mixture was prepared by mixing PCB with bitumen using a high shear mixture for 1 hour while maintaining the mixing temperature between 150-155℃, mixing speed at 3000rpm and mixing time for 1 hour. An optimum mixing percentage was calculated for this modified binder.

Table 4.12: Volumetric properties of PCB modified bitumen asphalt concrete mixtures

Bitumen Content (%)	Stability (kN)	Flow (0.25mm)	V_a (%)	VMA (%)	Bulk Specific Gravity (G_{mb})
4	14.90	8.35	6.97	16.54	2.39
4.5	13.66	9.08	6.92	16.93	2.39
5	16.51	10.08	5.93	16.49	2.42
5.5	18.45	8.64	5.23	16.30	2.44
6	9.31	9.56	5.38	16.87	2.43
Conventional mixture with 5% virgin bitumen	14.88	8.8	4.57	13.9	2.49

To determine OBC for modified bitumen asphalt mixture, 15 specimens were prepared by adding different bitumen contents: 4%, 4.5%, 5%, 5.5%, and 6% by weight (Figure 4.18). From the tests mentioned in the method section, the volumetric properties of 15 specimens were calculated which are mentioned in Table 4.12. (Refer Appendix I)

Figure 4.18 : 15 Marshall Test specimens from PCB modified asphalt

To determine the OBC, the four curves were plotted in Figures 4.19 to 4.22, where the design criteria are marked in red straight lines.

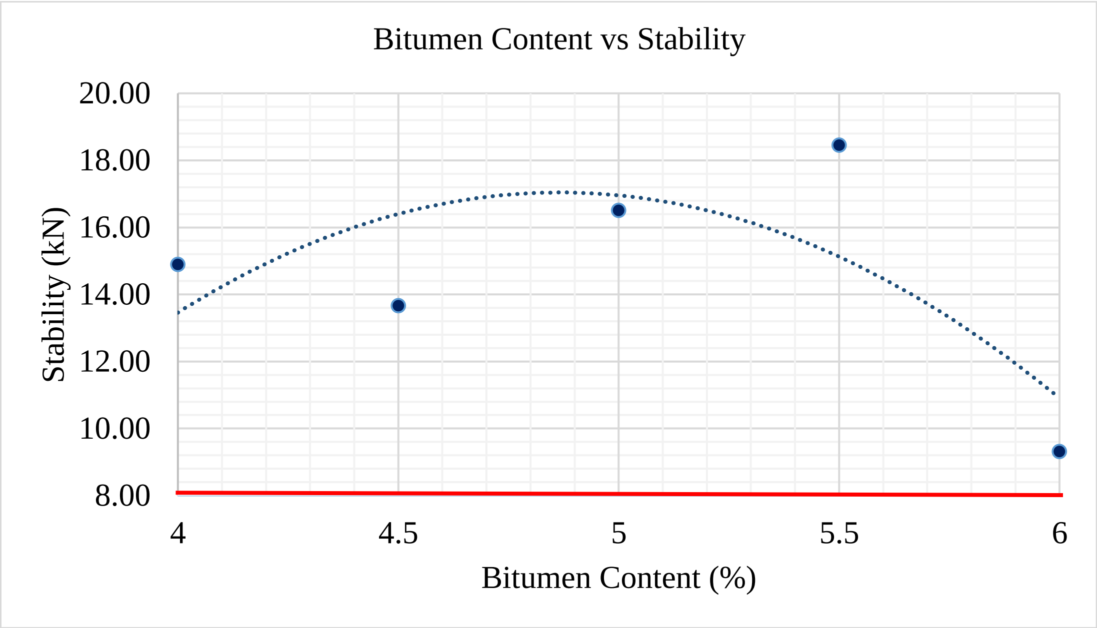


Figure 4.19: Bitumen Content vs Stability graph for 15% PCB modified bitumen Asphalt Concrete

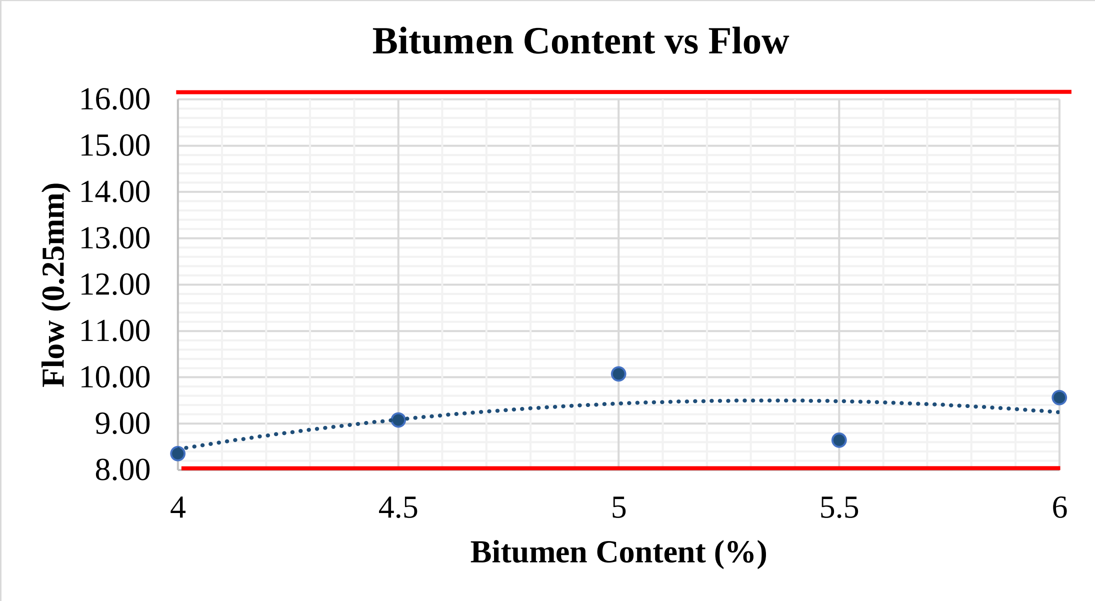


Figure 4.20: Bitumen content vs Flow graph for 15% PCB modified bitumen Asphalt Concrete

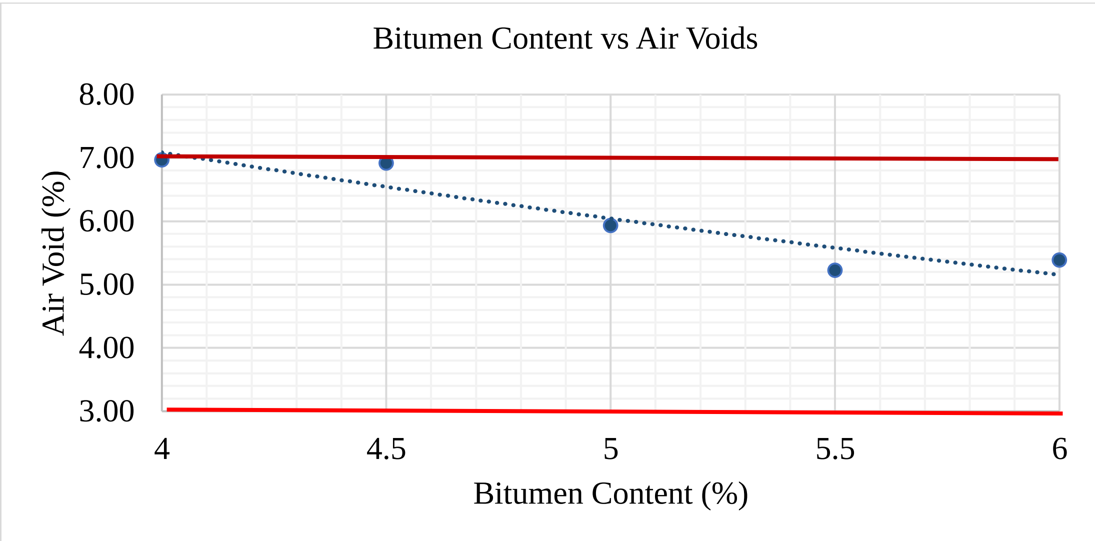


Figure 4.21: Bitumen Content vs Air Voids graph for 15% PCB modified bitumen Asphalt Concrete

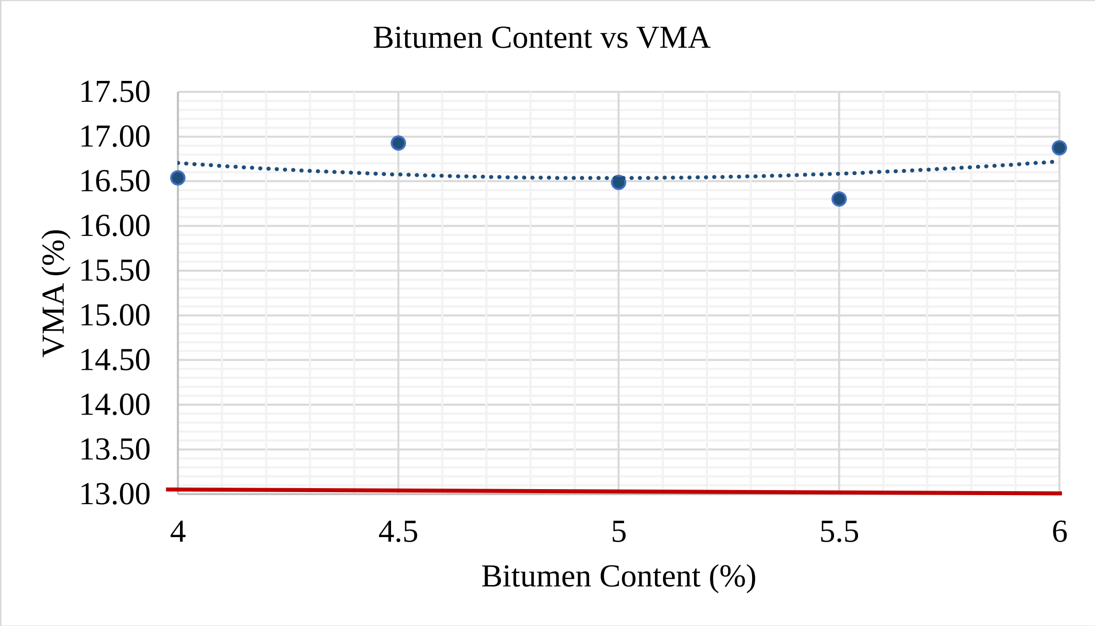


Figure 4.22: Bitumen Content vs VMA graph for 15% PCB modified bitumen Asphalt Concrete

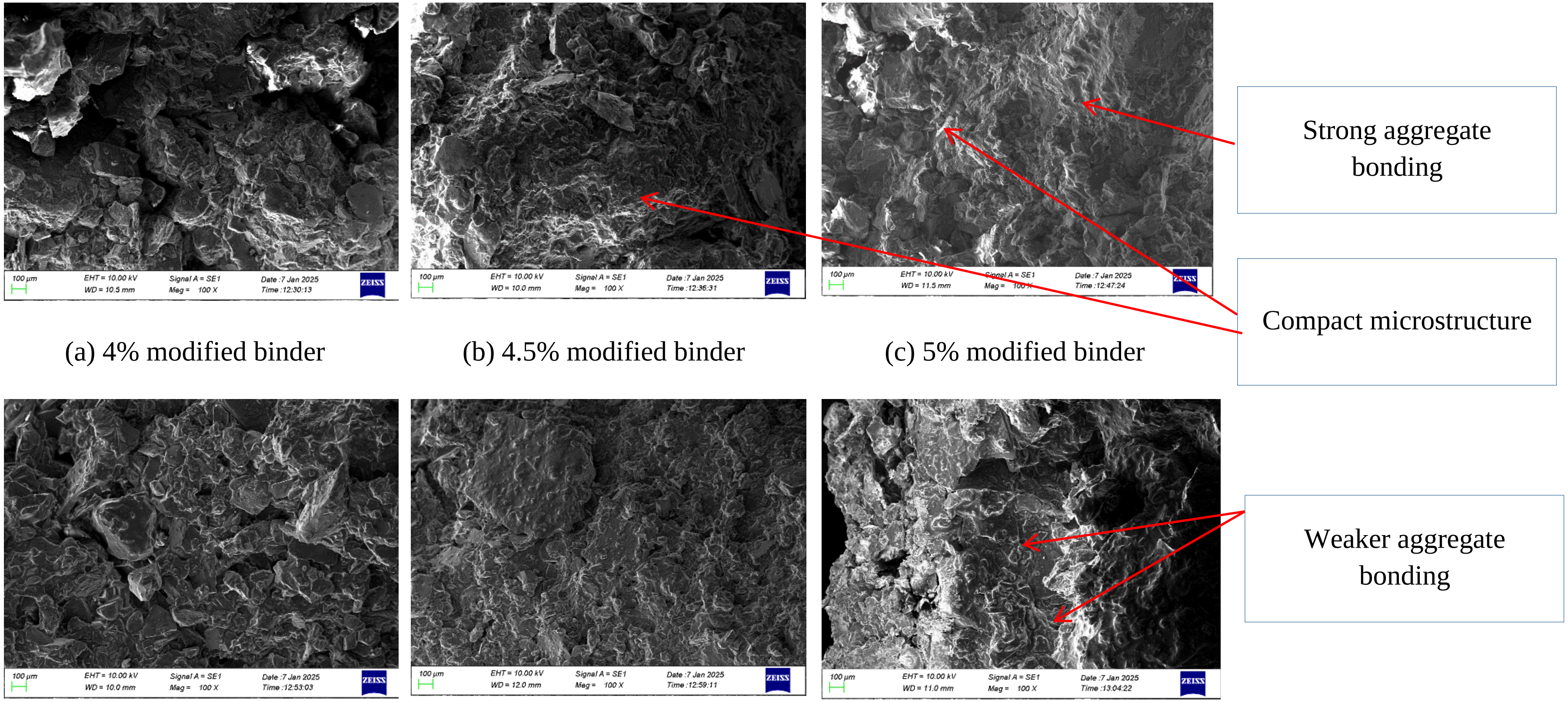
The OBC is calculated using Table 4.12 data according to the design criteria.

OBC = (5+4.85+7)/3

= 5.6% by weight

Volumetric properties of 15% PCB modified bitumen mixed asphalt concrete illustrate special improvement by being align all the test specimens to the specification limits.

Further, Figure 4.23 presents the microstructural validation for the obtained results, where SEM images are presented for samples of all five modification percentages and unmodified optimum asphalt concrete sample. Strong aggregate-binder bonding can be observed in all modified samples by indicating enhanced adhesion between binder and aggregates (Mai Alawneh & Soliman, 2023). But the unmodified sample has weaker bonding compared to modified samples by resulting more voids & micro-cracks. This indicates the less cohesive interaction and the vulnerability to deformation under traffic loads. The compact microstructure in modified samples indicates the enhanced a denser composition with fewer voids, improving durability and resistance to moisture damage (Mazumder et al., 2018).



(a) 4% modified binder (b) 4.5% modified binder (c) 5% modified binder

(d) 5.5% modified binder (e) 6% modified binder (f) virgin bitumen

Figure 4.23: SEM images of Asphalt concrete prepared with respective binder percentages.

Moreover, these observations get confirmed from the evidence available in literature. For an asphalt concrete mixture prepared with CCB 10% weight modified binder, Jahanbakhsh et al. (2018) have observed improved indirect tensile strength and uniaxial compression strength at intermediate temperatures (Jahanbakhsh et al., 2018) . Further they have illustrated that low temperature cracking resistance of asphalt concrete prepared with 10% CCB modified bitumen remains unchanged and the importance to evaluate the low temperature cracking resistance at higher CB percentages. Gan et al. (2023) (Gan et al., 2023) also observed that PCB modified asphalt concrete has improved temperature performance compared to conventional asphalt. Further they have provided recommended PCB percentages for bitumen modification for two types of PCB source such as 20% and 10%–15%. Therefore, all these results indicate superior volumetric properties compared to virgin bitumen while resulting a more durable, deformation-resistant, and well-balanced asphalt mixture.

In regions with high temperatures and heavy traffic, conventional virgin bitumen mixtures become soft easily, leading to rutting and permanent deformation of roads. With the addition of PCB, binder get stiff and more resistant to heat-induced softening while maintaining enough flexibility to avoid cracking. This nature can construct longer-lasting roads that require less frequent maintenance, reducing lifecycle costs compared to conventional roads.

Moreover, as PCB is derived from waste tire pyrolysis, this approach helps in waste management by repurposing tire waste into a useful material. By incorporating 15% PCB in bitumen, the demand for virgin bitumen (which is a non- renewable resource) is reduced, leading to cost savings and a more sustainable road construction practice. This innovation can support eco-friendly construction as current world is moving toward green infrastructure.

Conventional asphalt mixtures often develop cracks, raveling, or rutting, and require frequent repair work and resurfacing. However, with the higher stability and optimized air voids, 15% PCB-modified bitumen based asphalt mixture provides better resistance to water damage, oxidation, and fatigue cracking. Therefore, roads can last longer by minimizing disruption due to repairs, which is especially beneficial to the transport and logistics sectors.

4.5 Evaluation of Long-Term Field Performance

4.5.1 Distresses and their Severity Levels Calculation

The recorded distresses from the field visit to the Meegahakubuara Road, Egaloya, Bulathsinhala, are presented in Tables 4.13 and 4.14 for Section A and Section B, respectively. Section A is conventional asphalt pavement, and Section B is PCB-modified asphalt pavement.

Table 4.13: Section A- Distresses and their severity levels

	Distress type	Total distress quantity recorded for each severity level		
		L	**M**	**H**
1	Alligator cracking (fatigue)	Not recorded	Not recorded	Not recorded
2	Bleeding	Not recorded	Not recorded	Not recorded
3	Block cracking	Not recorded	Not recorded	Not recorded
4	Bumps and sags	Not recorded	Not recorded	Not recorded
5	Corrugation	Not recorded	Not recorded	Not recorded
6	Depression	$1.5m^2$	Not recorded	Not recorded
7	Edge cracking	1.2m	Not recorded	Not recorded
8	Joint reflection cracking (From Longitudinal and Transverse PCC Slabs)	Not applicable		
9	Longitudinal and transverse cracking (non-PCC slab joint reflective)	Not recorded	Not recorded	Not recorded
10	Lane/shoulder drop-off	5.6m	Not recorded	Not recorded
11	Patching and utility cut patching	Not applicable due to no patching		
12	Polished aggregate	$23m^2$		
13	Potholes	Not recorded	Not recorded	Not recorded
14	Railroad crossing	Not applicable		
15	Rutting	$5.3m^2$	Not recorded	Not recorded
16	Shoving	Not recorded	Not recorded	Not recorded
17	Slippage cracking	Not recorded	Not recorded	Not recorded
18	Swell	Not recorded	Not recorded	Not recorded
19	Raveling – dense mix asphalt	$2.25m^2$	Not recorded	Not recorded
20	Weathering (surface wear) – dense mix asphalt	$3.5m^2$	Not recorded	Not recorded

Table 4.14: Section B- Distresses and their severity levels PCB modified pavement

	Distress type	Total distress quantity recorded for each severity level		
		L	**M**	**H**

1	Alligator cracking (fatigue)	Not recorded	Not recorded	Not recorded
2	Bleeding	Not recorded	Not recorded	Not recorded
3	Block cracking	Not recorded	Not recorded	Not recorded
4	Bumps and sags	Not recorded	Not recorded	Not recorded
5	Corrugation	Not recorded	Not recorded	Not recorded
6	Depression	360mm^2	Not recorded	Not recorded
7	Edge cracking	Not recorded	Not recorded	Not recorded
8	Joint reflection cracking (From Longitudinal and Transverse PCC Slabs)	Not applicable		
9	Longitudinal and transverse cracking (non-PCC slab joint reflective)	Not recorded	Not recorded	Not recorded
10	Lane/shoulder drop-off	5m	Not recorded	Not recorded
11	Patching and utility cut patching	Not recorded any patching		
12	Polished aggregate	25m^2		
13	Potholes	Not recorded	Not recorded	Not recorded
14	Railroad crossing	Not applicable		
15	Rutting	5m^2	Not recorded	Not recorded
16	Shoving	Not recorded	Not recorded	Not recorded
17	Slippage cracking	Not recorded	Not recorded	Not recorded
18	Swell	Not recorded	Not recorded	Not recorded
19	Raveling – dense mix asphalt	2.5m^2	Not recorded	Not recorded
20	Weathering (surface wear) – dense mix asphalt	3m^2	Not recorded	Not recorded

The figures from 4.24 to 4.36 demonstrate the detected distresses and their severity levels from the field visit to Sections A and B.

1) Depression

Figure 4.24: Section A - depression (Low-Severity level)

Figure 4.25: Section B – depression (Low-Severity level)

2) Edge cracking

Figure 4.26: Section A- Edge cracking (Low-Severity level)

3) Lane/shoulder drop-off

Figure 4.27: Section A- Lane/shoulder drop-off (Low-Severity level)

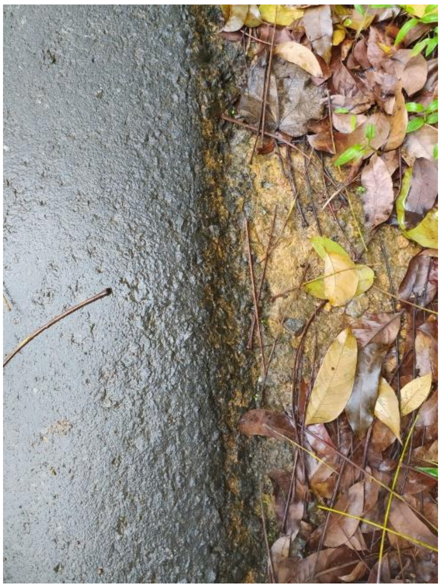


Figure 4.28: Section B- Lane/shoulder drop-off (Low-Severity level)

4) Polished aggregate

Figure 4.29: Section A - Polished aggregate (Low-Severity level)

Figure 4.30: Section B- Polished aggregate (Low-Severity level)

5) Rutting

Figure 4.31: Section A- Rutting (Low-Severity level)

Figure 4.32: Section B- Rutting (Low-Severity level)

6) Raveling – dense mix asphalt

Figure 4.33: Section A - Raveling – dense mix asphalt (Low-Severity level)

Figure 4.34: Section B - Raveling – dense mix asphalt (Low-Severity level)

7) Weathering (surface wear) – dense mix asphalt

Figure 4.35: Section A - Weathering (surface wear) - dense mix asphalt (Low-Severity level)

Figure 4.36: Section B - Weathering (surface wear) – dense (Low-Severity level)

4.5.2 Deduct value calculation

Many types of distress are defined in ASTM D6433-23 (ASTM_International, 2023) were not visible in both pavement sections. Only seven types of distress were observed in Section A, while 6 types were observed in Section B. Tables 4.15 and 4.16 were developed for percentage density and Deduct Value (DV) calculations.

Table 4.15: Section A deduct value calculation

Distress type	Total distress quantity recorded for each severity level			Density (%)	Deduct value
	L	M	H		
Depression	1.5m^2	-	-	0.17	5
Edge cracking	1.2m	-	-	0.53	3

Lane/shoulder drop-off	5.6m	-	-	2.48	4
Polished aggregate	$23m^2$	-	-	2.71	0
Rutting	$5.3m^2$	-	-	0.63	7
Raveling – dense mix asphalt	$2.25m^2$	-	-	0.29	7
Weathering (surface wear) – dense mix asphalt	$3.5m^2$	-	-	0.41	0

Table 4.16: Section B deduct value calculation

Distress type	Total distress quantity recorded for each severity level			Density (%)	Deduct value
	L	M	H		
Depression	$0.00036m^2$	-	-	0.0000425	0
Lane/shoulder drop-off	5m	-	-	2.21	4
Polished aggregate	$25m^2$	-	-	2.95	0
Rutting	$5m^2$	-	-	0.59	5
Raveling – dense mix asphalt	$2.5m^2$	-	-	0.29	8
Weathering (surface wear) – dense mix asphalt	$3m^2$	-	-	0.35	0

Although depression distress has occurred in both sections, Section B quantity is much less compared to Section A. However, edge cracking distress was observed only in section A, conventional asphalt pavement. Shoulder drop-off distress was observed in both sections where defected lengths are very close values. Rutting can also be found along the tyre paths in both sections. Polished aggregate is the highly observed distress type in sections A and B, which have affected 2.7% and 2.9% out of the total area of the pavement. Raveling and weathering are the other two types of defects observed which have similar affected levels in both sections.

4.5.3 Corrected Deduct Value (CDV) Calculation

For section A;

‘m’ value is calculated using Equation 9;

Allowable number of deducts, m = 1 + (9/98)(100-7) = 9.54

As available deduct values are less than m, all the deduct values are used for first iteration. Then, according to Table 4.17, iterations were carried out.

Table 4.17: Section A- Corrected Deduct Value iterations

Iteration	Deduct Values						Total DV	q	CDV
1	7	7	5	4	3		26	5	0
2	7	7	5	4	2		25	4	9

3	7	7	5	2	2		23	3	11.5
4	7	7	2	2	2		20	2	14
5	7	2	2	2	2		15	1	**15**

The maximum CDV = 15

For section B;

‘m’ value is calculated using Equation 9;

Allowable number of deducts, m = 1 + (9/98)(100-8) = 9.45

As available deduct values are less than m, all the deduct values are used for the first iteration. Then, according to Table 4.18, iterations were carried out.

Table 4.18: Section B - Corrected Deduct Value iterations

Iteration	**Deduct Values**				**Total**	**q**	**CDV**
1	8	5	4		17	3	9
2	8	5	2		15	2	10
3	8	2	2		12	1	**12**

The maximum CDV = 12

4.9.4 Pavement condition index (PCI) value

By deducting CDV from 100, the PCI value is calculated. According to ASTM D6433-23 (ASTM_International, 2023)Section B fits the rating of ‘Good’, and Section A is the merging of the ‘Good’ and ‘Satisfactory’ regions (Figure 4.37).

	Section A – Conventional Asphalt Pavement	Section B- PCB modified Asphalt pavement
Corrected Deduct Value (CDV)	15	12
Pavement condition index (PCI)	**85%**	**88%**

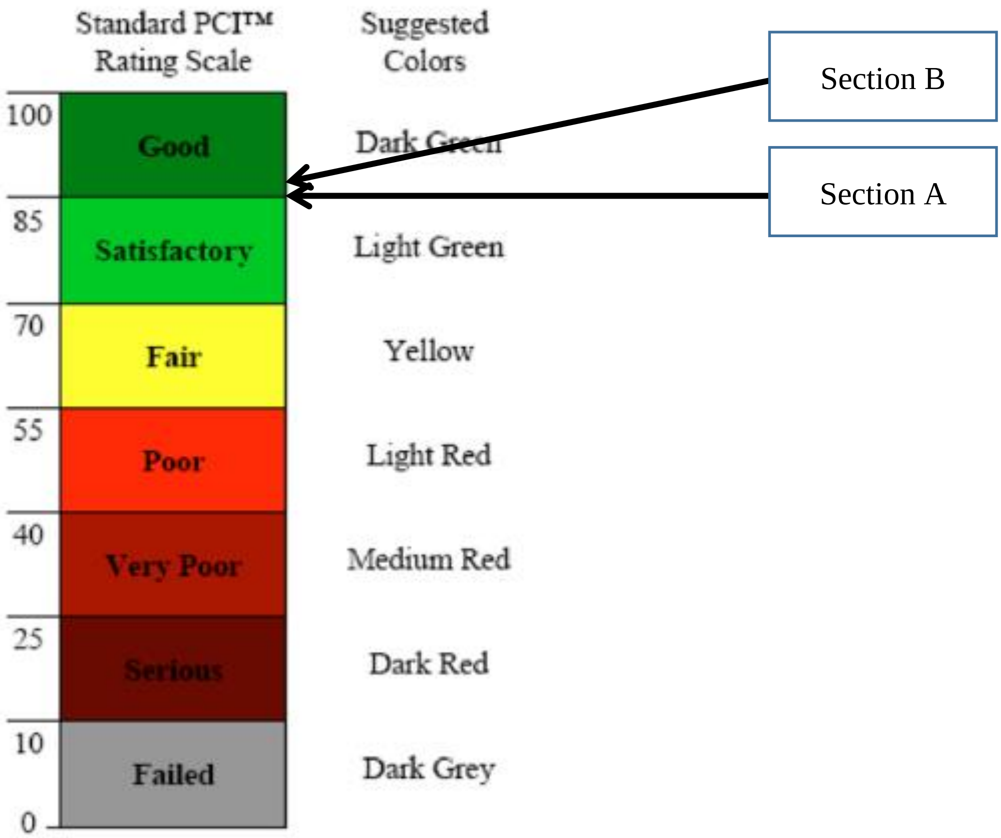


Figure 4.37: PCI rating of sections A and B

According to these PCI calculations and the visual observations, it can be strongly stated that PCB-modified pavement performs well similarly to conventional asphalt pavement after the 3 years of construction. As no literature is recorded on the long-term performance of PCB-modified pavements, this study can address that gap in the literature. Moreover, Zafar et al. (2019) have calculated PCI values as 57.45% (Zafar et al., 2019) for Lakhi-Larkana National Highway (N-105) in Pakistan, a heavy traffic road. Boyapati et al. (2015) (Boyapati & Prasanna Kumar, 2015) has calculated PCI values for worst-condition roads, 7km between Thanjavur and Ayyampetai and 4km between Sathamagalam and Keelapur. They have derived PCI values in the 40-50% range. Therefore, it is obvious that the 85% PCI value derived for Section A (Conventional asphalt pavement) is under good conditions. Furthermore, when compared with Section A, Section B is performing quite well after 3 years of construction.

CHAPTER 5

5. CONCLUSIONS AND RECOMENDATIONS

This study basically aimed to analyse the performance of the PCB bitumen and asphalt concrete. The evaluation was conducted under 4 phases. First, PCB modified binder compared with conventional binder under performance, environmental and economic impact. Second phase was on selecting optimum performance impact factors for PCB-bitumen modification. The effect of mixing speed and the particle size of PCB was evaluated. Third phase is asphalt concrete preparation and performance evaluation. Both preparation methods: wet mixing and dry mixing was evaluated under this section. Last section is long term performance evaluation of a three year old PCB modified asphalt pavement which is currently successfully operating. The following key findings summarize the outcomes of this research:

1. Effectiveness of PCB as a Modifier

The results from penetration, softening point and DSR test confirm that PCB significantly improves the high-temperature performance of bitumen. Especially, the softening point increased with higher PCB content, indicating better resistance to rutting under hot weather conditions. Further, the modified bitumen with PCB showed reduced temperature susceptibility, making it suitable for areas with hot climates.

2. Comparison with conventional binder/ virgin bitumen

When comparing with conventional binder, PCB can be recommended as a suitable modifier option for Sri Lanka, with regard to performance, environmental, and economic impact. PCB-modified binder decreased the EE value by 13% and the $ECO_{2\text{-}e}$ 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.

The use of PCB as a modifier not only improves the performance of bitumen but also offers an environmentally sustainable alternative to traditional modifiers. By incorporating waste tyres into road construction, this approach contributes to waste reduction and offers a potential solution for the growing problem of tyre waste in many countries.

3. Performance Impact Factors of PCB Modification

The increases of mixing speed can reduce the penetration and increase the softening point parameters. Further the smaller particles of PCB can increase the impact on final performance of modified binder without having any chemical interaction. Father, aged samples also presents the similar trend with increase of mixing speed and reduction of PCB particle size. However, the remarkable penetration change incorporated with un-aged modified bitumen cannot observe after ageing. To be a good bitumen penetration loss need to be lower. Therefore, reducing particle size of the PCB and increasing mixing speed can recommend as good measures to improve aged bitumen properties.

4. Mixing Methods – Dry Mixing vs Wet Mixing:

Marshall Stability of optimum dry mixing mixtures has increased compared to conventional asphalt mixture, indicating a significant improvement in the load-bearing capacity and resistance to deformation under heavy traffic. The flow value has increased by enhancing flexibility and deformation resistance without cracking compared to conventional asphalt mixture. However, Air Voids (V_a) have increased significantly in dry mixing asphalt, which reflects a considerable increase of void within the mixture. This increase in void content can affect the permeability of the pavement, which needs to be considered in future studies. The increase of Voids in Mineral Aggregate (VMA) represents a slight improvement in aggregate structure, which supports better adhering and overall durability.

However, Marshall stability reduction can be observed in the wet mixing mixture. Although Marshall stability gets slightly reduced, values remain in the allowable range given by the standard. Again, the flow value of the wet mixing mixture shows an increase compared to the conventional mixture while improving flexibility and deformation resistance, which is important for preventing cracks under high traffic loads. Similarly, in the dry mixture, VMA of the wet mixture also have increased, resulting in better adhering and durability of the mixture. Further, Air Voids (V_a) content has increased moderately compared to the conventional mixture. This balanced increase ensures durability and resistance to cracking while maintaining structural integrity. Therefore, detailed investigations on the behaviour and field applicability of PCB-modified wet-mixing asphalt concrete are highly encouraged. Moreover, the strong evidence provided on SEM images regarding the capabilities of pavement property improvement by wet mixing process highlights promising avenues for future research, offering valuable insights that could lead to further advancements in this field.

Moreover, both dry and wet mixing mixtures have increased flow values. The flow value indicates the workability of the mixture, with a higher flow value facilitating easier construction and requiring less energy for compaction. Therefore, further investigations on PCB-modified asphalt about low-temperature behaviour are recommended.

Additionally, the permissible PCB content is 1.5% for asphalt mixtures prepared by wet mixing using high shear mixture for one hour at 3000 rpm mixing speed and 150°C mixing temperature.

The 1.5% PCB replacement brings up the 1.5% bitumen saving which results the higher cost saving and reduce the further bitumen extraction while contributing to circular economy and sustainability of the materials.

5. Field Performance of Dry-Mixed PCB Pavement

As PCB pavement has been successfully operating for 3 years, PCI was calculated according to ASTM D6433-23 to evaluate the current pavement performance. A similar section on the same road with conventional asphalt pavement was also evaluated for a clear comparison. After 3 years of operation, both pavements are in good condition. Calculated PCI values are 85% and 88% for conventional and PCB-modified asphalt pavements, respectively.

The field trial using dry mixing has shown promising results; however, morphology analysis indicates that the modified wet mixing approach yields even better outcomes. Therefore, real scale application of PCB modified asphalt pavements by wet mixing method is highly encouraged for the future implications.

However, improved method effectively addresses the mixing challenges encountered in the dry mixing field trials, making the wet mixing method a more reliable solution. Consequently, the PCB wet mixing method can be recommended as one of the most sustainable and effective alternatives for asphalt pavement applications in Sri Lanka.

6. Limitations

However, the major limitation of PCB modifications is that chemical composition and types of impurities in PCB can vary according to the source. Chemical composition directly depends on the ingredients used in the tyre manufacturing process. However, the types of disposal tyres, such as car tyres, truck tyres and bike tyres, and their quantities are different from country to country. Keeping constant propositions between types of tyres in a pyrolysis batch can maintain the same chemical composition throughout the production 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

Moreover, the limited infrastructure facilities in Sri Lanka for PCB high shear mixing with bitumen in industrial level had hindered the real scale application of PCB wet mixing asphalt concrete. However, with the promising performance improving results of wet missing, it is encouraged to implement wet mixing method in the industrial applications.

7. Recommendation for future studies.

Future researchers are encouraged to investigate the long-term fatigue resistance and aging behaviour of PCB-modified asphalt under Sri Lanka’s hot climate and heavy traffic conditions for the pavements constructed by wet mixing method. Field trials using the wet mixing method are recommended to validate lab results and evaluate large-scale applicability. Special attention should be given to optimizing high-shear mixing parameters at plant level—including mixing speed, duration, and temperature—to ensure uniform dispersion and performance consistency of PCB, binder and aggregate. Standardization of PCB quality in terms of particle size, purity, and source uniformity is also essential. Additionally, conducting a localized life cycle assessment (LCA) is encouraged to quantify the environmental and economic advantages of incorporating PCB in asphalt pavements.

8. Policy and Regulatory Recommendations

As PCB modification is a promising way to improve pavement performance and durability, it is better to implement policies and regulations on this novel technology. Governments and road construction agencies should consider promoting the use of PCB-modified bitumen through policy incentives and regulations that encourage sustainable practices. This could include offering subsidies or tax breaks for the use of recycled materials in construction projects, as well as establishing industry standards for the use of PCB-modified bitumen.

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APPENDIX I- MARSHALL TEST RESULTS

Observations of the Marshall test for OBC of PCB modified binder set-1

Sample No.	Thickness (mm)					weight (g)			Stability reading	Flow reading
	Reading 1	Reading 2	Reading 3	Reading 4	Average	In Air Dry	In Water	In Air SSD		
1.1	61.4	61.3	61.1	61.3	61.275	1225.00	734.02	1226.50	165	32.6
1.2	59.95	59.8	60	60.15	59.975	1198.50	720.56	1200.50	130	37.6
1.3	63.5	64.3	64.15	63.55	63.875	1268.00	761.56	1269.50	134	-
2.1	65.75	65.7	65.2	65.7	65.588	1248.00	731.60	1249.50	100	-
2.2	60.05	60.5	60.4	60.4	60.338	1200.50	717.17	1205.00	138	24.5
2.3	63	63	63	63.4	63.1	1249.00	746.80	1251.00	147	29.5
3.1	62.4	62.8	62.45	62.3	62.488	1214.50	722.15	1217.00	100	32.2
3.2	62.2	62.2	62.1	62.3	62.2	1205.50	709.03	1209.00	130	35
3.3	55.2	55.05	55.1	55.3	55.163	1088.00	641.40	1089.00	126	33.6
4.1	62.7	62.4	62.9	62.7	62.675	1206.50	698.69	1205.00	121	-
4.2	65.65	66.1	66	65.9	65.913	1255.00	727.33	1255.50	142	33
4.3	62.45	62.9	62.5	62.8	62.663	1206.00	693.33	1206.00	106	31

Calculations of the Marshall test set-1

Mix Design No.	02	Mixing Temperature	Minimum 135℃ and Maximum 170℃
Test Date :	02/09/2024	Grade of Bitumen : 60/70	Mould diameter : 100 mm
Bulk Specific Gravity of Aggregate Design Blend :		Effective Specific gravity of Aggregate Design Blend : 2.843	

Specimen Number	Bitumen (%)	PCB (%)	% Asphalt by Total Weight of Mix	Average % Asphalt by Total Weight of Mix	Average Thickness of Specimen (mm)	Weight of Specimen (g) In Air Dry	Weight of Specimen (g) In Water	Weight of Specimen (g) In Air SSD	Avearge Height (mm)	Bulk Volume (cm3)	Bulk Specific Gravity [Gmb]	Average Bulk Specific Gravity [Gmb]	Maximum Theoretical Specific Gravity [Gmm]
1	4.60	0.50	5.1	5.1	61.275	1225.00	734.02	1226.50	61.275	492.5	2.487	2.494	2.571
2	4.60	0.50	5.1		59.975	1198.50	720.56	1200.50	59.975	479.9	2.497		2.571
3	4.60	0.50	5.1		63.875	1268.00	761.56	1269.50	63.875	507.9	2.496		2.571
4	4.10	1.00	5.1	6.1	65.588	1248.00	731.60	1249.50	65.588	517.9	2.41	2.449	2.571
5	4.10	1.00	5.1		60.338	1200.50	717.17	1205.00	60.338	487.8	2.461		2.571
6	4.10	1.00	5.1		63.1	1249.00	746.80	1251.00	63.1	504.2	2.477		2.571
7	3.60	1.50	5.1	7.1	62.488	1214.50	722.15	1217.00	62.488	494.9	2.454	2.432	2.571
8	3.60	1.50	5.1		62.2	1205.50	709.03	1209.00	62.2	500	2.411		2.571
9	3.60	1.50	5.1		55.163	1088.00	641.40	1089.00	55.163	447.6	2.431		2.571
10	3.10	2.00	5.1	8.1	62.675	1206.50	698.69	1205.00	62.675	506.3	2.383	2.37	2.571
11	3.10	2.00	5.1		65.913	1255.00	727.33	1255.50	65.913	528.2	2.376		2.571
12	3.10	2.00	5.1		62.663	1206.00	693.33	1206.00	62.663	512.7	2.352		2.571

Blows per Side : 75	Specific Gravity of Bitumen : 1.030	Method of Compaction : Automatic Marshall Compactor

Average Maximum Theoretical Specific Gravity [Gmm]	% Air Voids in Compacted Mix [VIM] (%)	Average % Air Voids in Compacted Mix [VIM] (%)	Aggregate Content by weight %	% Air Voids in Mineral Aggregate	Average % Air Voids in Mineral Aggregate	Stability						
						Reading	Gauged Load (kN)	Correlation Ratio	Corrected Load (kN)	Average Corrected Load	Corrected Load (kg)	Average Corrected Load (kg)
2.571	3.26	3.01	94.9	14.1994	13.98	165	18.942	1.04	19.7	16.86	2008.808	1719.427
	2.88		94.9	13.8622		130	14.924	1.08	16.12		1643.57	
	2.91		94.9	13.8908		134	15.383	0.96	14.77		1505.904	
2.571	6.28	4.74	94.9	16.8789	15.51	100	11.48	0.93	10.68	14.94	1167.102	1229.652
	4.29		94.9	15.1139		138	15.842	1.09	17.27		1233.841	
	3.65		94.9	14.5519		147	16.876	1	16.88		1288.014	
2.571	4.54	5.41	94.9	15.3423	16.11	100	11.48	1	11.48	14.83	1382.355	1516.98
	6.22		94.9	16.8301		130	14.924	1	14.92		1366.692	
	5.46		94.9	16.1541		126	14.465	1.25	18.08		1801.894	
2.571	7.32	7.8	94.9	17.8034	18.23	121	13.891	1	13.89	13.58	1654.047	1494.596
	7.58		94.9	18.038		142	16.302	0.93	15.16		1178.862	
	8.51		94.9	18.8568		106	12.169	0.96	11.68		1650.88	

Flow (1/100	Average Flow	Voids Filled	Average [VFB]

cm Units)	(1/100 cm Units)	Bitumen [VFB] (%)	(%)
32.6	35.1	77.07	78.46
37.6		79.25	
		79.07	
	27	62.81	69.78
24.5		71.63	
29.5		74.89	
32.2	33.6	70.38	66.54
35		63.03	
33.6		66.2	
	32	58.89	57.24
33		57.95	
31		54.88	

Observations of the Marshall test for OBC of PCB modified binder set 2

Sample No.	Thickness (mm)					weight (g)			Stability reading	Flow reading
	Reading 1	Reading 2	Reading 3	Reading 4	Average	In Air Dry	In Water	In Air SSD		
1.1	63.10	64.25	64.40	64.50	64.06	1225.50	716.81	1227.00	132	290
1.2	65.75	66.10	65.90	66.20	65.99	1257.00	735.15	1263.50	117	350
1.3	65.95	65.70	65.50	65.70	65.71	1267.50	739.68	1269.00	131	362
2.1	64.10	64.20	64.30	64.00	64.15	1243.00	727.72	1244.00	137	383
2.2	65.50	64.90	65.30	65.40	65.28	1257.00	732.15	1259.50	96	305
2.3	67.70	67.70	67.70	67.70	67.70	1289.00	754.82	1294.50	125	401
3.1	65.85	66.00	65.75	66.00	65.90	1282.50	753.52	1283.50	139	342
3.2	66.10	66.30	66.10	66.00	66.13	1284.00	756.29	1287.50	140	453
3.3	66.85	66.90	66.60	66.75	66.78	1296.50	762.45	1298.50	122	414
4.1	64.40	64.90	64.20	64.25	64.44	1272.50	752.10	1273.50	146	367
4.2	63.20	63.15	63.00	63.40	63.19	1264.00	748.15	1264.50	216	258
4.3	65.60	66.10	66.00	66.80	66.13	1272.50	751.56	1277.00	141	412
5.1	60.50	60.70	60.25	60.00	60.36	1119.50	715.91	1197.50	141	387
5.2	60.40	60.25	60.50	60.50	60.41	1220.00	729.20	1220.00	131	370
5.3	60.10	60.10	60.25	60.40	60.21	1207.50	722.78	1208.00	109	390

Calculations of the Marshall test set 2

Mix Design No. 3														
Test Date : 12/11/2024						Grade of Bitumen / 60/70			Mould diameter : 100 mm					
Bulk Specific Gravity of Aggregate Design Blend :							Effective Specific gravity of Aggregate Design Blend : 2.843							
Specimen Number	**% Asphalt by Total Weight of Mix**	**Average % Asphalt by Total Weight of Mix**	**Average Thickness of Specimen**	**Weight of Specimen (g)**			**Average Height (mm)**	**Bulk Volume**	**Bulk Specific Gravity**	**Average Bulk Specific Gravity**	**Maximum Theoretical Specific Gravity**	**Average Maximum Theoretical Specific Gravity**	**% Air Voids in Compacted Mix**	**Average % Air Voids in Compacted Mix**
				In Air Dry	**In Water**	**In Air SSD**							**(%)**	**(%)**
			(mm)					**(cm^3)**	**[G_{mb}]**	**[G_{mb}]**	**[G_{mm}]**	**[G_{mm}]**	**[VIM]**	**[VIM]**
1	4		64.063	1225.50	716.81	1227.0	64.063	510.2	2.402		2.571		6.58	
2	4	4	65.988	1257.00	735.15	1263.5	65.988	528.4	2.379	2.392	2.571	2.571	7.47	6.97
3	4		65.713	1267.50	739.68	1269.0	65.713	529.3	2.395		2.571		6.87	
4	4.5		64.150	1243.00	727.72	1244.0	64.150	516.3	2.408		2.571		6.36	
5	4.5	4.5	65.275	1257.00	732.15	1259.5	65.275	527.4	2.384	2.393	2.571	2.571	7.29	6.92
6	4.5		67.700	1289.00	754.82	1294.5	67.700	539.7	2.388		2.571		7.10	
7	5		65.900	1282.50	753.52	1283.5	65.900	530.0	2.420		2.571		5.88	
8	5	5	66.125	1284.00	756.29	1287.5	66.125	531.2	2.417	2.419	2.571	2.571	5.99	5.93
9	5		66.775	1296.50	762.45	1298.5	66.775	536.1	2.419		2.571		5.93	
10	5.5		64.438	1272.50	752.10	1273.5	64.438	521.4	2.441		2.571		5.08	
11	5.5	5.5	63.188	1264.00	748.15	1264.5	63.188	516.4	2.448	2.437	2.571	2.571	4.79	5.23
12	5.5		66.125	1272.50	751.56	1277.0	66.125	525.4	2.422		2.571		5.81	
13	6		60.363	1119.50	715.91	1197.5	60.363	473.8	2.325		2.571		9.60	
14	6	6	60.413	1220.00	729.20	1220.0	60.413	474.2	2.486	2.433	2.571	2.571	3.33	5.38
15	6		60.213	1207.50	722.78	1208.0	60.213	472.7	2.489		2.571		3.22	
Average									**2.415**		**2.571**		**6.087**	

Blows per Side : 75						Specific Gravity of Bitumen : 1.030						
Specimen Number	% Asphalt by Total Weight of Mix	Average Height (mm)	Aggregate Content by weight %	% Air Voids in Mineral Aggregate	Average % Air Voids in Mineral Aggregate	Stability						
						Reading	Gauged Load	Correlation Ratio	Corrected Load	Average Corrected Load	Corrected Load	Average Corrected Load
				(%)	(%)							
				[VMA]	[VMA]		(k N)		(kN)		(kg)	(kg)
1	4	64.063	96.0	16.1836	16.54	132	15.154	1.040	15.76	14.90	1607.046	1519.483
2	4	65.988	96.0	16.9841		117	13.432	1.080	14.51		1479.213	
3	4	65.713	96.0	16.4440		131	15.039	0.960	14.44		1472.189	
4	4.5	64.150	95.5	16.4270	16.93	137	15.728	0.930	14.63	13.66	1167.102	1229.652
5	4.5	65.275	95.5	17.2599		96	11.021	1.090	12.01		1233.841	
6	4.5	67.700	95.5	17.0920		125	14.350	1.000	14.35		1288.014	
7	5	65.900	95.0	16.4401	16.49	139	15.957	1.000	15.96	16.51	1382.355	1516.980
8	5	66.125	95.0	16.5360		140	16.072	1.000	16.07		1366.692	
9	5	66.775	95.0	16.4844		122	14.006	1.250	17.51		1801.894	
10	5.5	64.438	94.5	16.1708	16.30	146	16.761	1.000	16.76	18.45	1654.047	1494.596
11	5.5	63.188	94.5	15.9164		216	24.797	0.930	23.06		1178.862	
12	5.5	66.125	94.5	16.8154		141	16.187	0.960	15.54		1650.880	
13	6	60.363	94.0	20.5761	16.87	141	9.760	1.010	9.86	9.31	1005.199	949.859
14	6	60.413	94.0	15.0703		131	9.074	0.945	8.57		874.403	
15	6	60.213	94.0	14.9738		109	9.418	1.010	9.51		969.976	

Average			**16.625**								

Flow	**Average Flow**	**Voids Filled Bitumen**	Average
1/100 cm Units	**1/100 cm Units**	**%**	%
		[VFB]	[VFB]
29.00	33.40	59.37	57.88
35.00		56.03	
36.20		58.24	
38.30	36.30	61.28	59.15
30.50		57.75	
40.10		58.43	
34.20	40.30	64.22	64.01
45.30		63.78	
41.40		64.02	
36.70	34.57	68.59	67.98
25.80		69.90	
41.20		65.46	
38.70	38.23	53.35	69.90
37.00		77.89	
39.00		78.48	