Engineering Characterization and Environmental Analysis of Natural Rubber Latex Modified Asphalt Mixture

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Natural Rubber Latex (NRL) has attracted considerable interest as a resource for renewable paving materials due to its potential to lessen environmental impact. In order to gain a thorough understanding of the performance of NRL, this study evaluated the mechanical properties and environmental impact of Stone Mastic Asphalt (SMA) mixtures with a 6.6% binder content, 5% air voids content, and 5% NRL by weight of binder. The performance of this NRL asphalt mixture was compared to a control asphalt mixture using a commercially available polymer modified Styrene Butadiene Styrene (SBS) binder. The performance of the asphalt mixtures, such as their tensile strength, stiffness modulus, and resistance to fatigue and rutting, as well as their Global Warming Potential (GWP) impact, were studied. The results indicate that the addition of NRL increased tensile strength, stiffness modulus, and fatigue life in comparison to a conventional, unmodified asphalt mixture but had slightly lower values in comparison to the SBS mixture. Moreover, in terms of environmental concern, life-cycle assessment reveals that NRL-modified mixtures are more sustainable than SBS-modified mixtures in terms of GWP value.

Keywords: natural rubber latex, asphalt, performance, life-cycle assessment

1. Introduction

Environmental conservation and preservation issues have become an integral aspect of our society in recent years. Environmental challenges have drawn the interest of political, economic, and social decision-makers. Among this concern, the issue of resources and conservation of non-renewable materials become one of the most critical considerations. Many authorities and researchers would therefore seek an approach to utilise renewable material in an environmentally responsible manner. Pavement practitioners, as well as researchers, are concerned with the use of alternative modifiers for asphalt pavement manufacture when considering the issues related to non-renewable resources such as decreasing oil reserves (Fini et al., 2011). This is due to the fact that asphalt mixture utilises a considerable quantity of non-renewable resources every year, putting a large amount of strain on the environment (Franzitta, Longo, Sollazzo, Cellura, & Celauro, 2020; Thives & Ghisi, 2017) and thus become one of the hot spots and challenging problems. Consequently, the use of materials that potentially can be used to replace non–renewable resources, such as bitumen, has gained a lot of attention since it may achieve a solution in lowering environmental impacts such as emissions and greenhouse gases (Farina, Zanetti, Santagata, & Blengini, 2017). Furthermore, more research has been undertaken on bio-binders and additives that can replace synthetic additives in the production of modified binders and asphalt mixtures. Asphalt producers are therefore becoming more inclined to use alternative modifiers, such as Natural Rubber Latex (NRL), to improve asphalt mixture performance. For example, Thailand and Indonesia as the leading countries for the production of NRL, extracted by tapping from the rubber tree, have started to use NRL to modify bitumen (Indonesian Investment, 2018; Sowcharoensuk, 2021).

NRL can be used to improve the rheological properties of modified asphalt emulsion residue (Shafii, Ahmad, & Shaffie, 2013). (Al-Mansob et al., 2017) stated in their study that the performance of an asphalt pavement can be enhanced by incorporating epoxidized natural rubber as a modifier to counter major road distress. Another advantage is that NRL modified asphalt mixtures have better resistance to rutting (Poovaneshvaran, Mohd Hasan, & Putra Jaya, 2020; Saowapark, Jubsilp, & Rimdusit, 2019). This can be achieved due to the fact that The incorporation of latex into the original asphalt binder was found to effectively improve the stiffness, thus enhancing the resistance to rutting (Aziz, Hasan, Poovaneshvaran, Tai, & Wang, 2020; Jitsangiam, Nusit, Phenrat, Kumlai, & Pra-ai, 2021). Additionally in comparison to Styrene Butadiene Rubber (SBR), NRL showed greater stiffness values, indicating that more rut resistant mixes can be achieved (Khadivar & Kavussi, 2013). Furthermore, research results indicate that the addition of Natural Rubber leads to improved performance-related responses for fatigue life, rutting, fracture strength, and thermal cracking (Y. Wen, Wang, Zhao, & Sumalee, 2017; Wititanapanit, Carvajal-Munoz, & Airey, 2021).

Natural rubber is available in the vulcanised state (powder form) and latex state (liquid form). Utilising rubber in its vulcanised state requires a higher mixing temperature and extended mixing time (J. Read & Whiteoak, 2003). This is due to the high molecular weight of the rubber powder used in rubber asphalt, which does not combine well with the asphalt, making it difficult to store rubber asphalt in a stable manner. This leads to difficulties in ensuring quality control during production, transportation, and use, which ultimately affects the performance of the asphalt mixture on the pavement (Yildirim, 2007). As a result, widespread adoption and utilisation of rubber asphalt in the powder form is hindered. The above problems can be avoided by utilising rubber polymer in its liquid state (Suresh & Pal, 2021; M. Wang et al., 2019). Moreover, NR latex requires only half as much material as powder form (Al-Sabaeei, Nur, Napiah, & Sutanto, 2019). In addition, although natural rubber latex contains almost 40 percent water, the water evaporates at high mixing temperatures and developing homogeneous and ready-to-use pre-mixture rubberized asphalt (Suaryana & Sofyan, 2019). Along with this, despite the fact that foaming occurs during the mixing process as a result of the water content, It was shown that the foamed asphalt mixture did not provide any substantial impacts on the moisture susceptibility (Aziz et al., 2020). Bitumen modified with NRL foamed rubber appears to performs better as NRL has greater elasticity and adhesion properties to adhere to aggregates and bitumen and strengthens its performance (Ansari, Jakarni, Muniandy, Hassim, & Elahi, 2021).

In some cases, vulcanized rubber (e.g., crumb rubber, waste tire) has been used.

However, crumb rubber is difficult to disperse throughout the bitumen because the rubbers have been used in a vulcanized state. In addition, the reclaiming process, in which vulcanised rubber is forced to devulcanize, requires advanced thermal, chemical, and mechanical techniques to break down the vulcanised structure (Mente & Tshwafo, 2016). Moreover, compared to NRL in the pre-vulcanised state, crumb rubber particle is considerably bigger in size; creating a uniform dispersion within the asphalt is especially challenging (Al-mansob et al., 2014; Hunter, 2015). Contrary to crumb rubber, NRL can produce binder that is more homogeneous because the rubber particles are dispersed in the liquid phase, which improves the stability of asphalt binders, considering the equilibrium between Brownian and gravitational forces (Y. Wen et al., 2017) and thus ensuring that the rubber material dissolves more easily comparatively minimal mixing speed and time compared to crumb rubber-modified asphalt (Xiang, Cheng, & Que, 2009). As a result, NRL will have the potential to reduce energy consumption and its carbon footprint during the mixing process. In addition, NRL has several advantages over crumb rubber in terms of performance. NRL provides better torsional recovery properties, has higher stiffness, and has a higher viscosity than crumb rubber (Poovaneshvaran et al., 2020). Furthermore, it was discovered that NRL treated bitumen exhibits greater resilience to ageing than crumb rubber modified bitumen, which will improve the long-term performance of the asphalt mixture (Al-mansob, Ismail, Izzi, & Ismael, 2016; Al-sabaeei, Sunarjono, & Bala, 2020; Moghadas, Aghajani, Modarres, & Firoozifar, 2012).

Nevertheless, although there have been numerous studies on the performance of NRL, there have not been sufficient studies on the comparison of NRL and readily available polymers or to what extent it can substitute available polymers when compared to the same percentage of polymers. Currently, the most commonly used and the most appropriate polymer for bitumen modification is styrene–butadiene–styrene (SBS) (Francisco, Júnior, Aparecida, & Stolte, 2012; Yildirim, 2007). Prior studies have shown that SBS-modified mixtures exhibited good performance in both asphalt cements and mixtures (Chen, Liao, & Shiah, 2002; Sengoz & Isikyakar, 2008; Valkering, Vonk, & Whiteoak, 1992). SBS also has similar advantages with NRL in increasing the rut resistance at high temperatures and the fatigue cracking resistance at low/intermediate temperatures (Kanitpong & Bahia, 2005). Conversely, the unrenewable modifiers failed to provide a sustainable solution and the lack of available resources have motivated highway engineers to explore alternatives for the construction of new roads. Nonetheless, despite the fact that NRL offers many benefits, it cannot be argued that it can replace commercial polymers such as SBS polymer, as SBS is recognized as one of the most suitable and widely used polymers for bitumen modification. Research on Laboratory comparison of the crumb-rubber and SBS modified bitumen has been conducted by (Francisco et al., 2012; Vural & Çolak, 2011), however the comparison between NRL and SBS has never been carried out before. Consequently, NRL performance investigation and comparison with the norm standards for asphalt modified with SBS is required. Comparing NRL directly to SBS modified asphalt allows for a meaningful assessment of how NRL performs relative to a well-known and established material, providing valuable insights into its potential as an alternative.

In terms of cost, the utilization of the NRL-modified binder is a feasible option when compared to the traditional binder. This is because implementing the NRL-modified binder has the potential to enhance road quality, prolong its lifespan, and decrease expenses associated with road maintenance (Azahar et al., 2016). Replacing the SBS content in the modified asphalt with NRL was also conducive to reducing the cost. Considering the relatively high cost of polymers, it becomes crucial to explore alternative materials that are more affordable (Moreno, Sol, Martín, Pérez, & Rubio, 2013). A typical example of this, according to data (Thailand Department of Rural Road, 2023), NRL binders are 30% higher in price than virgin binders but 15% less expensive than SBS binders. The cost of NRL is comparatively lower because the manufacturing of NRL is straightforward and doesn't involve complex modification processes (Al-sabaeei et al., 2020; Yunus et al., 2021). Furthermore, during the mixing stages, the use of NRL-modified bitumen is found to be an economic system as it can be directly incorporated into bitumen, resulting in cost savings (Ansari et al., 2021).

Furthermore, the sustainability of asphalt mixtures used as road pavement materials in transportation infrastructure must consider efficiency in terms of environmental impact. Therefore, the introduction of new materials into asphalt mixtures should always be accompanied by a life cycle assessment (LCA) to confirm whether or not these are the most optimal solutions for the materials. In fact, the sustainability of those solutions is a complex interaction of many aspects that need to be explored in future works to determine all the pros and cons of such solutions. However, to this date, research on LCA to evaluate the environmental impacts of asphalt mixtures containing NRL is not yet available. This is in contrast to the growing consideration for assessing the environmental burdens of pavement construction by using the life-cycle approach. LCA is used to evaluate the environmental impacts of a product, technique, or service during its service life. It comprises a wide range of pavement life cycle frameworks in all stages, from material processing to end-of-life of pavement, as established by the Federal Highway Administration (FHWA) (Harvey et al., 2016).

With this in mind, the aim of this study was to determine the viability of substituting non-renewable polymers with NRL in order to produce pavements with high mechanical performance without harming the environment. This is in line with the UN's

9th sustainable development goals (Giannetti et al., 2020), to build resilient infrastructures, promote sustainable industry, and support innovation to minimise resource and energy consumption. And this can be achieved by examining both engineering characteristics and environmental assessment of asphalt mixture. Therefore, this paper presents a comprehensive assessment of an asphalt mix by presenting an interdisciplinary study on the mechanical performance of NRL and emissions relevant to the carbon footprint impact using comprehensive life-cycle analysis. Accordingly, the present research described in this paper has two objectives. First, in order to evaluate mixture performance, mixes were constructed using the volumetric method and pavement performance was tested and evaluated. Second, to determine the environmental aspect, an evaluation of how the mixture can reduce the environmental burden regarding the carbon footprint was undertaken using Global Warming Potential (GWP) impact analysis. In addition, these attributes were then compared to those of the control virgin mixture and mixture produced with SBS-modifier mixtures. The comparison can then be used to investigate the enhanced properties of the new mixtures. This will provide for more transparent and comparable studies and help decision-makers in using the study results.

2. Materials and experimental methods

2.1. Materials

In this study, the selection of materials was based on a case study representation of the A60 road in Nottinghamshire, United Kingdom. The coarse and fine aggregates employed in this study are crushed granite from Bardon Hill quarry. A 40/60 penetration grade bitumen was selected as the base bitumen. The binder was then modified with NRL and compared with a control asphalt mixture and a mixture using

Styrene Butadiene Styrene (SBS) binder with the percentages of 5% by the weight of the binder. Technocel cellulose fibres were added at a percentage of 0.3% of the total mixture to reduce the binder drain down during the mixing process. This value has been suggested by the supplier and is also the most commonly used percentage for this type of application according to the literature (Putman & Amirkhanian, 2004; Woodside, Woodward, & Akbulut, 1998).

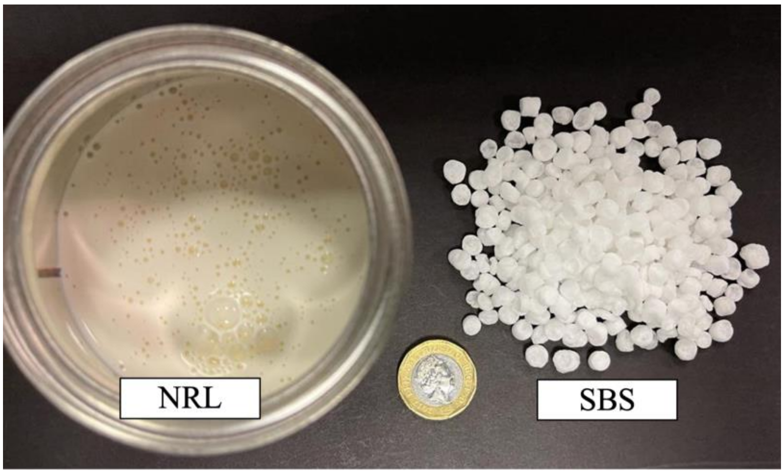


Figure 1. Polymer compound in the study

Figure 1 depicts a container of NRL and SBS polymer pellets with a one-pound coin for size reference. NRL is extracted from trees through tapping and is used to modify bitumen as a biopolymer. The fresh latex obtained on tapping has about 30-35% dry rubber content (DRC) with the remainder as non-rubber solids and water. Through centrifuging, fresh latex was processed into concentrated latex, which is a liquid latex containing at least 60% DRC. Subsequently, the definition of NRL in this study is the concentrated latex which contain 60% DRC. The addition of 5% NRL content in the overall weight of modified bitumen involves taking into account the present in the NRL. Hence, the amount of NRL added is calculated to ensure that the resulting mixture contains 5% DRC. For the SBS polymer, this study considered the polymer in its granular form, as the most common polymer type used in Europe (Eurobitume, 2012).

A high-shear mixing method was used to ensure homogeneity between the virgin 40/60 penetration binder and NRL and SBS. Mixing consisted of 120±5 min, 3000 rpm, and at 150±5°C and 180±5°C respectively for the NRL and SBS. The properties of the binders were tested and the results are shown in Table 1.

Table 1. Properties of Bitumen

Test Property	Standard	40/60 pen	SBS	NRL
Specific gravity	BS EN 15326	1.03	1.02	1.02
Penetration (0.1 mm)	BS EN 1426	46	35	36
Softening Point (°C)	BS EN 1427	52.6	78.5	64.2
Viscosity at 135°C (Pa.s)	BS EN 13302	0.442	2.094	4.163
Viscosity at 160°C (Pa.s)	BS EN 13302	0.141	0.6419	1.38
Viscosity at 180°C (Pa.s)	BS EN 13302	0.067	0.2999	0.683

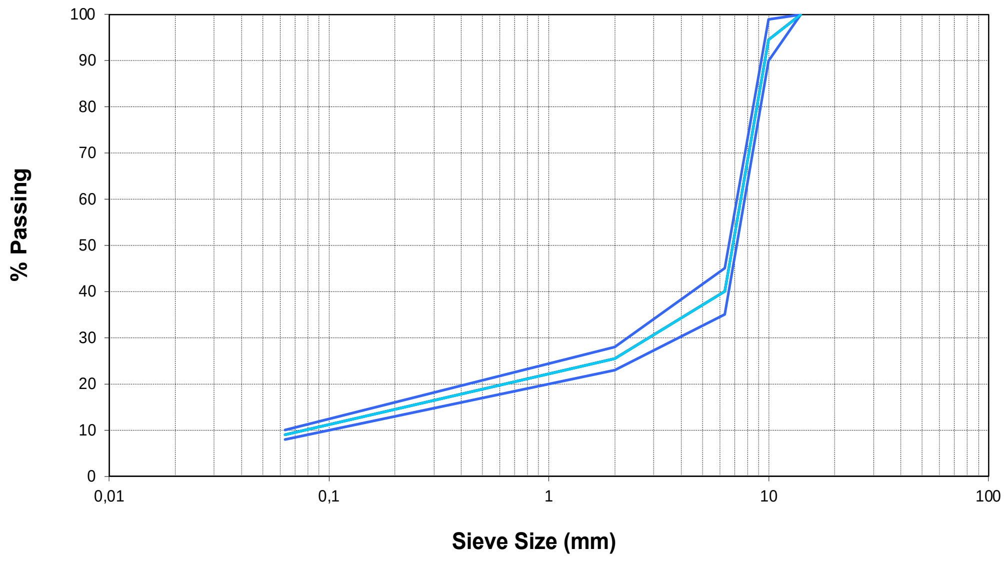


Figure 2. SMA Surface Coarse Aggregate Gradation

A typical SMA10 gradation used for pavement construction in the United Kingdom, as shown in Figure 2, was designed with 6.6% binder content (by weight of mixture). Subsequently, a gyratory compactor with a mould diameter size of 100 mm was used to manufacture all the specimens in this study, as referred to in BS EN 12697-10. All asphalt mixtures were compacted to a target air voids content of 5% and sawn to the required thickness according to testing specifications. The compaction effort was adjusted for all mixtures so that the air voids content in the final testing specimens would fall within ±0.5% from the target air voids content.

2.2. Mixture Performance Methodology

2.2.1. Indirect Tensile Strength

The Indirect Tensile Strength (ITS) was carried out for all investigated mixtures to define the maximum tensile stress at failure of each specimen. This test applies a compressive load at a constant displacement rate of 50 mm/min diametrically on the cylindrical asphalt mixture specimen with the diameter of 100mm and height of 60mm, as demonstrated in Figure 3. The test was conducted at 20°C and followed the EN 12697-23 standard. This loading form produced a distributed tensile stress at the plane perpendicular to the applied load.

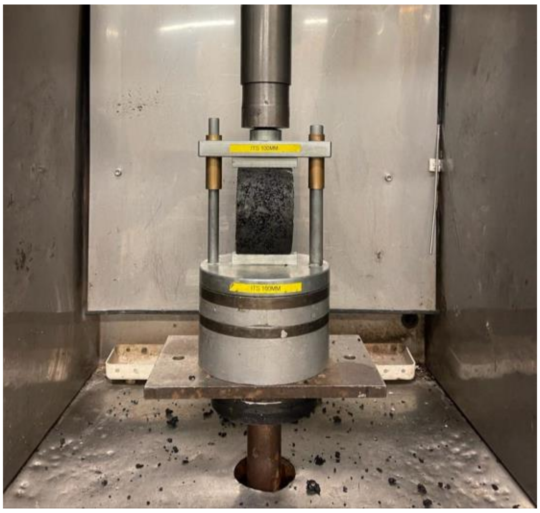


Figure 3. ITS test configuration

This test typically results in the specimen breaking along the loading plane (Anagnos & Kennedy, 1972). The ITS value was then determined based on the maximum tensile stress from the peak load applied when the test specimen fails, using the Equation (1).

$$ITS = \frac{2P}{\mu D H} \qquad (1)$$

where ITS = indirect tensile strength (MPa); P = peak load (kN); π = diameter-circumference ratio equal to 3.14159, D = specimen diameter (mm); and H = specimen thickness (mm). In this study, three replicate samples for each type of asphalt mixture were tested. The indirect tensile strength of the mixture is the mean value of the three values obtained for each of the cylinders.

2.2.2. Indirect Tensile Stiffness Modulus

A strain-controlled indirect tensile stiffness modulus (ITSM) test was carried out to evaluate the bearing capacity of each mixture, as specified in standard EN 12697-26 (Annex C). The ITSM device and sample configuration is shown in Figure 4. Three-cylinder specimens, with a diameter of 100 mm and height of 40mm, were made for each asphalt mixture combination to ensure replicability. This test determined the stiffness modulus based on a sequence of haversine waveform loading pulses applied along the vertical diameter of the specimen. In addition, two linear LDVTs were attached to record the amplitude of the peak horizontal deformation during the test.

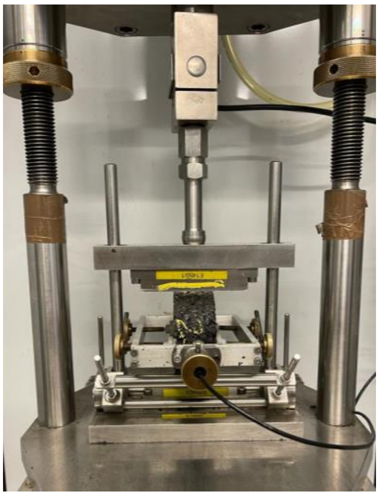


Figure 4. ITSM test machine and specimen configuration

Accordingly, the stiffness modulus value was calculated using Equation (2)

$$S_m = \frac{F \cdot (v + 0.27)}{(z \cdot h)} \quad (2)$$

Where S_m = stiffness modulus (MPa); F = peak vertical load (N); ν = Poisson's ratio (assumed to be 0.35) z = the mean amplitude of the horizontal deformation obtained from the five load pulse applications (mm); h = thickness of the test sample (mm). Once this value had been determined, the cylindrical sample was rotated to find the second modulus value along the perpendicular diameter. The mean stiffness modulus measured for subsequent tests should be between +10% or -20% of the mean value result for the initial test. The stiffness modulus of each mixture is represented by the mean value of the results obtained for the three test cylinders.

2.2.3. Indirect Tensile Fatigue Test

The fatigue life of the three mixtures was evaluated using the Nottingham Indirect Tensile Fatigue Test (ITFT). Ten samples were tested in the range between 175 kPa and 600 kPa for the virgin SMA, and between 225 kPa and 600 kPa for the two modified binders SMA asphalt mixtures. In this test, as displayed in Figure 5, the specimen with a thickness of 40 mm and a diameter of 100 mm is loaded diametrically at 20 °C with a vertical compressive force. This indirectly generates tensile stress across the vertical diameter (horizontal tensile stress).

Figure 5. ITFT test configuration

The following equations determine the maximum tensile stress at the specimen's centre and the corresponding horizontal tensile strain for any indicated stress level.

$$\sigma_{x\,max} = \frac{2P}{\pi dt} \tag{3}$$

$$\varepsilon_{x\,max} = \frac{\sigma_{x\,max}}{E} * \left(1 + (3 * \nu)\right) * 1000 \tag{4}$$

Where P = vertical compressive load (kN), σ_{xmax} = maximum horizontal tensile stress (kPa), ε_{xmax} = maximum horizontal tensile strain (με), ν = Poisson's ratio, d = diameter of the sample (m), t = thickness of the sample (m), E =stiffness modulus of the specimen (MPa).

The test is carried out until the specimen experiences a failure. According to the definition given by (J. M. Read & Brown, 1996), failure is considered when the specimen splits directly or when the vertical deformation reaches 9 millimetres. Subsequently, the initial horizontal tensile strain is plotted against the number of load cycles to failure on a log-log graph. Nonlinear regression is then utilized to create the correlation between the applied initial strain and the number of load cycles to failure.

2.2.4. Repeated Load Axial Test

The Repeated Load Axial Test (RLAT) was used to determine the rutting resistance of the asphalt mixtures. Following the gyratory compaction production, specimens with a 100 mm diameter and 40 mm thickness were subjected to a block pulse loading stress of 100 kPa. A direct uniaxial compression procedure in accordance with EN 12697-25 was used to perform the test. The test configuration utilised for this work is depicted in Figure 6. In this study, two different temperatures, 40 °C and 50 °C were used for the test.

Figure 6. RLAT test configuration

To ensure reliability, three samples were tested for each mixture and temperature. The results of the test are then summarised in terms of the creep curve, cumulative-permanent deformation, and creep rate, which are affected by the asphalt mixtures' resistance to rutting.

2.3 Life Cycle Assessment Methodology

2.3.1. Functional Unit

The objective of the LCA is to analyse the environmental impact of NRL modified asphalt mixtures. This study is essential for providing information to be incorporated in the early phases of the development of new asphalt mixtures. The designated functional unit (FU), which represents the reference unit for measuring system performance in this LCA study is 1 tonne. Global Warming Potential (GWP) impact categories are quantified and SimaPro 9.0 software was used to perform the LCA calculations.

In this study the GWP is evaluated using the baseline method outlined in (Guinée & Lindeijer, 2002) to calculate the total global warming potential impact that is expressed on an equivalency basis relative to CO^2 – in kg in a 100-year time horizon.

2.3.2. *System Boundary*

The selected system boundary is "from cradle to gate". This approach is preferred as cradle-to-gate analysis is appropriate for novel products with insufficient data on their impacts and other implications (Franklin Associates, 2011). The utilization of a cradle-to-gate LCA is deemed useful since it allows the focus on the specific stages of the life cycle that are considered the most significant when evaluating the sustainability performance of the materials considered (Tokede, Whittaker, Mankaa, & Traverso, 2020). Therefore, the scope of the analysis is limited to the asphalt production phase and focuses primarily on the asphalt material, including information regarding the raw materials and fuel sources, as well as transportation and manufacturing processes during asphalt mixture production, while the usage and disposal stages of the product are excluded due to insufficient information and uncertainties regarding the long-term performance and end-of-life of the new product. The analysis adheres to the guidelines of the BS EN-17472 (2020) standards. This means that the A1(raw material production), A2 (transportation), and A3 (asphalt mixing process) stages were considered in the LCA study, as depicted in Figure 7. Modules A4 through D (i.e., construction process, use, end-of-life process, end-of-life stages, and benefits and loads beyond the system boundary) were considered beyond the scope of this work and, as such, were not included in the analysis.

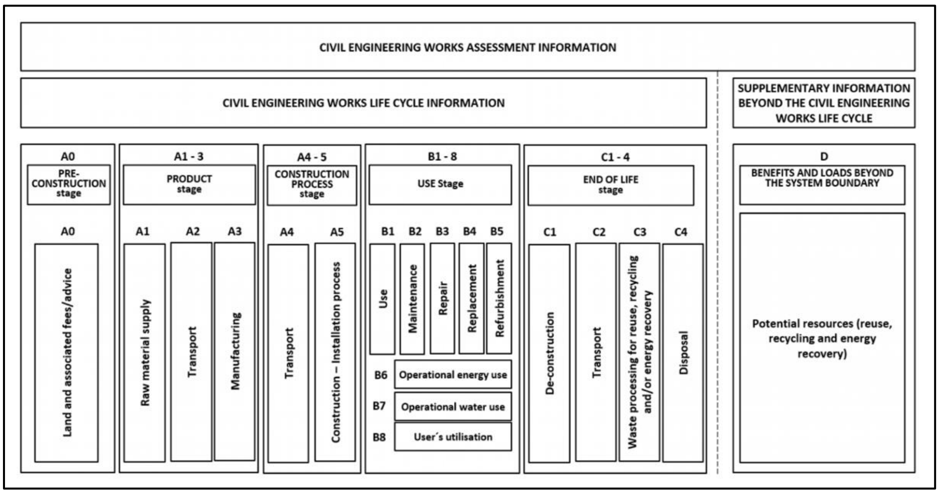


Figure 7. Life cycle modules according to BS EN-17472: 2020

In raw material production, the emissions are quantified from raw material extraction activities and manufacturing processes. These materials are then transported to the asphalt mixing plant location, which involves a fuel-related distance from all material handling processes. In the asphalt mixing plant, the process includes all plant mixing processes with a consequent increase in emissions during this stage.

3. Mixture Performance

3.1. Indirect Tensile Strength

The pavement structure is built to withstand compressive, tensile and shear stresses and remain serviceable during its design life. The indirect tensile strength test can be used to assess the resistance of the asphalt mixture component of a pavement to tensile forces. In this paper, the indirect tensile strength (ITS) values have been compared between that found for a control SMA asphalt mixture and the ITS values obtained for SMA asphalt mixtures incorporating NRL and standard SBS PMB as shown in Figure 8. Generally, the modified asphalt mixtures demonstrated improved tensile strength values compared to the control asphalt mixture. The additives have increased the ITS, which indicate a stronger binding between the binder and aggregates. This improvement will lead to better resistance to pavement damage, for example, fatigue cracking.

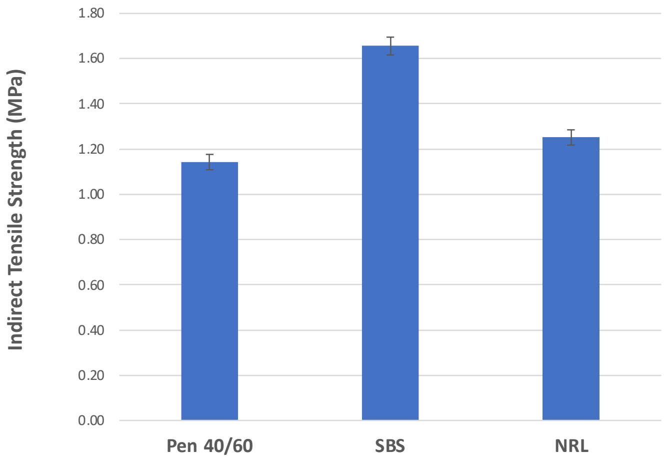


Figure 8. ITS on the studied mixtures

The results showed a slight increase of approximately 10% in ITS for the NRL SMA mixture compared to the control pen 40/60 SMA mixture, as also reported by (Aziz et al., 2020; Krishnapriya, 2015; Shaffie, Ahmad, Arshad, Kamarun, & Kamaruddin, 2015). In the other hand, a more significant improvement was found for the SBS PMB SMA mixture with the tensile strength of this asphalt mixture increasing up to 45% compared to the control SMA. ITS is mainly attributed to the cohesion and adhesion of the binder (Kanitpong & Bahia, 2005; X. Wang et al., 2021). Rubber modified mixtures generally have lower mixture cohesion if compared with SBS mixtures, which can be reflected by lower cohesion force and spalling rate than SBS asphalt (Yang et al., 2021). Regarding adhesion ability, NRL was reported to have much lower adhesion between the asphalt cement and the aggregate than other rubber PMB. As stated by (Poovaneshvaran et al., 2020) that conducting a bond test, NRL has less adhesion than crumb rubber. This is because latex, which is liquid, comprises discrete rubber particles that can disperse in the binder during blending, resulting in a combination with lower tensile strength. In contrast, the crumb rubber has a more subtle powdered form, which prohibits the rubber particles from depolymerizing during the blending process resulting in rough-textured crumb rubber-modified asphalt binder having higher bonding resistance towards tensile strength. This in line with (Zhang & Yu, 2010) that suggested that toughness is a critical property related to adhesion ability. Consequently, the tensile strength of NRL cannot be increased as significantly as that of SBS polymer.

3.2. Indirect Tensile Stiffness Modulus

An indirect tensile stiffness modulus (ITSM) test was carried out to examine how the natural rubber impacted the SMA mixture's bearing capacity. All three SMA asphalt mixtures were subjected to ITSM testing at 20°C. According to the results in Figure 9, NRL and SBS SMA mixtures exhibited a stiffness modulus value higher than the control SMA mixture. This suggests that the modified combination will have a more substantial capacity for load distribution and higher resistance of the material to undergo elastic strain under traffic loading when applied to the pavement.

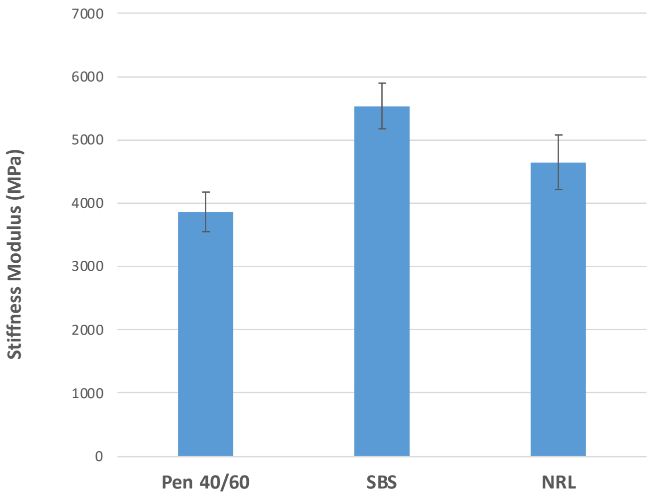


Figure 9. Stiffness Modulus of SMA asphalt mixtures

Additionally, the results show that when compared to other combinations, the SBS

PMB SMA mixture had the highest stiffness modulus with a 43% and 19% increase in stiffness modulus compared with the unmodified and NRL SMA mixtures. Accordingly, it can be concluded that stiffness modulus affects tensile strength, as evidenced by similar trends in the ITS test, which was also highlighted in studies by (Pettinari & Simone, 2015) and (Graziani, Godenzoni, Cardone, & Bocci, 2016). In general, there is a strong interdependency between mechanical performance indicators, such as ITS and ITSM, as noted by (Li, Leng, Wang, & Zou, 2020). Both ITS and ITSM are strength performance indexes. The stiffness modulus signifies the ability of an asphalt mixture to withstand deformation and is commonly employed to assess the potential resistance of asphalt pavements to fatigue cracking. ITS measures the maximum tensile stress that an asphalt mixture can withstand before failure. It indicates the tensile strength of the mixture and is used to assess its resistance to cracking before failure (Christensen & Bonaquist, 2004). As the stiffness modulus of the mixture increases, the resulting strain caused by stress force decreases. Therefore, the asphalt can endure fracturing in the ITS test more effectively.

3.3. Indirect Tensile Fatigue Test

Fatigue life in asphalt mixtures is described as the number of load cycles to failure (Nf). It shows the mixture's capacity to endure repetitive traffic stresses (Muniandy, Binti Che Md Akhir, Hassim, & Moazami, 2014). Fatigue life is linked to service life in the sense that a longer fatigue life equals a longer service life (Guo, Li, Cheng, Jiao, & Xu, 2015). Figure 10 illustrates the horizontal strain vs the number of cycles to failure at 20°C on a logarithmic scale for the investigated mixtures (N-S plot). The fatigue life law equations and the correlation coefficient (R^2) are also shown in this graph. This R^2 value varies from 0.987 to 0.990, indicating that the results obtained to define each fatigue feature have a solid statistical association.

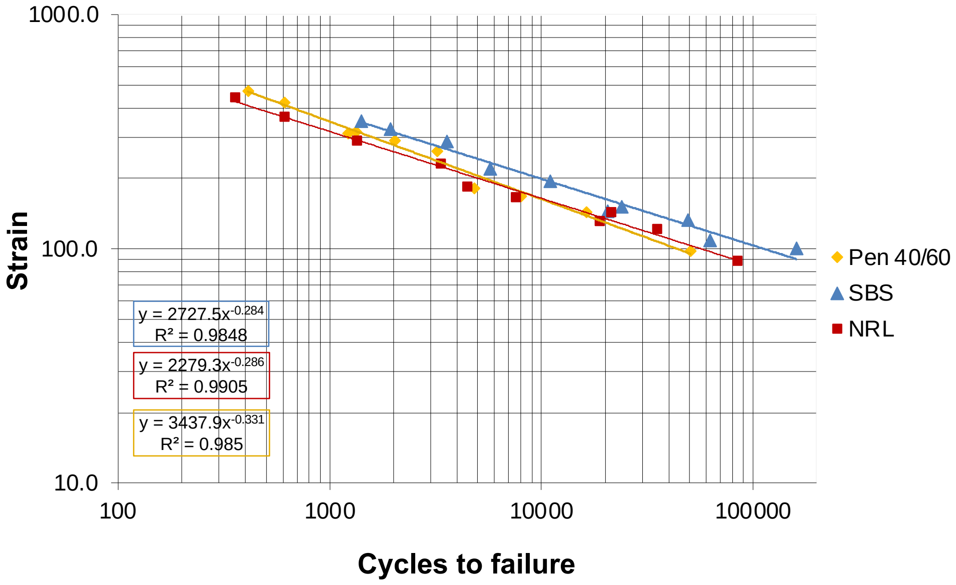


Figure 10. Fatigue line of studied mixtures

As seen in Figure 10, the NRL SMA mixture has a slightly flatter slope than the 40/60 pen control SMA mixture. For higher initial microstrain, mixtures made with NRL present lower fatigue life. In contrast, for lower initial microstrains, mixtures made with NRL have higher fatigue life than the control mixture. On the other hand, when compared with the SBS PMB SMA mixture, NRL has lower fatigue life for both high and low initial microstrain values. These results were also reflected in the ITS results, since ITS can be used to evaluate the asphalt mixture's resistance to cracking (Christensen & Bonaquist, 2004). This is because the ITS value is determined by the amount of force required to fracture the specimens. In the ITS test, the region below the load-displacement diagram to the point of fracture equals the fracture energy, which represents the energy required for the fracture to crack. Prior research has demonstrated that this energy is used to evaluate the cracking resistance of asphalt pavements (Bahadori, Khaki, & Ameri, 2015; Vamegh, Ameri, & Chavoshian Naeni, 2019; H. Wen, 2002). Other studies also mention that cracking occurs when the applied stress exceeds its tensile strength, hence the higher the tensile strength, the better the asphalt can withstand higher strains before to crack (Poovaneshvaran et al., 2020).

Table 3. Results of the indirect tensile fatigue test for SMA asphalt mixtures

Binder Type	**Nf** = **k1**(ξ)$^{\mathbf{k2}}$		Failure Cycle at 100 microstrain
	k1	k2	
40/60 Pen	2.632E+10	-2.92033	38,000
NRL	3.442E+11	-3.41632	50,600
SBS	3.817E+11	-3.3087	92,100

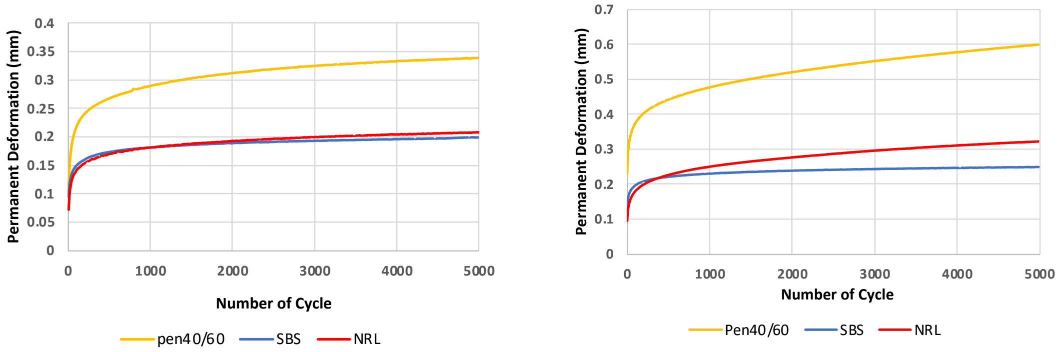
Furthermore, the fatigue line can be represented using the power equation that can expressed as:

$$Nf = k1(\xi)k2 \quad (5)$$

Where the k1 and k2 are the model parameters of each mixture calculated by a fitting process to the power function. The tensile stresses generated at the bottom of the asphalt layer under a typical axle load range between 0 and 200 microstrains (Yu et al., 2018). Accordingly, a microstrain value of 100 wase used in this study to compare the ITFT fatigue performance for the three SMA asphalt mixtures by inputting 100 microstrain as the strain value in equation 5. The fatigue life at 100 microstrain for each asphalt mixture is shown in Table 3. A more significant number of cycles indicates a longer fatigue life. The results reveal that the addition of NRL improved fatigue performance slightly compared to control mixture. (Suaryana & Sofyan, 2019) also reported that NRL modified asphalt has slightly higher resistance for fatigue damage. In the other hand, SBS modified mixture increased fatigue life by a factor of two compared to virgin mixture. In other words, it is reasonable to state that NRL is beneficial in preventing fatigue cracking in field applications that generate lower strain. However, when compared with the SBS mixture, NRL will experience cracking damage earlier than that of the SBS mixture.

3.4. Repeated Load Axial Test

The cumulative strain, which describes asphalt rutting behaviour, generally consists of three specific stages: the primary stage in which strain is immediately accumulated with loading cycles; the secondary stage in which accumulative strain increases at a constant rate; and the tertiary stage in which strain rate rapidly increases (Baghaee Moghaddam, Soltani, & Karim, 2014; Zhao & Zhang, 2009).

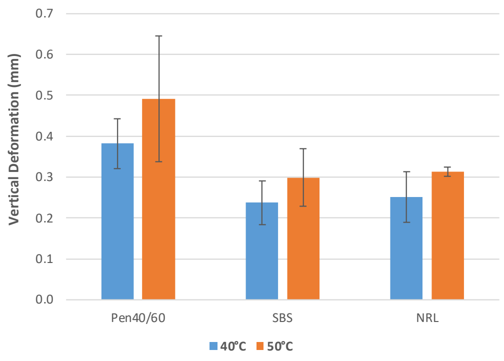


(a) (b)

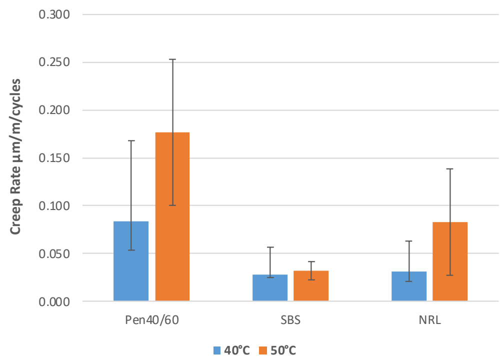
Figure 11. Creep curve RLAT on a) 40C b)50C

Figure 11 summarises the accumulation of vertical plastic strain of compacted SMA specimens as a function of the number of load cycles. This diagram demonstrates the accumulation of plastic deformation with number of load cycles at a constant stress of 100 kPa. The results shows that only two rutting stages are reached after 5000-cycles. The primary stage is led by the initial compaction or densification. It is well understood that rutting is influenced by volumetric composition (Sunarjono, 2013). In the secondary stage, it appears that the control mixtures have the lowest rutting resistance for both temperatures compared to the modified mixtures. According to the findings the addition of latex to bitumen mixtures has increased their resistance to rutting. This is in line with the research report from (Siswanto, 2017) and (Aziz et al., 2020).

Subsequently, when comparing both modified asphalt mixtures, at a temperature of 40°C, NRL and SBS have almost identical rates of permanent deformation. However, as the temperature increased to 50°C, NRL modified mixture exhibited a decrease in rutting resistance which was reflected by a significantly increased deformation rate than that of the SBS modified mixture.



(a)



(b)

Figure 12. a) Total Permanent Deformation b) Creep rate at secondary stage

Furthermore, the total vertical deformation values are tabulated in Figure 12a to emphasize the test results in terms of the total ruth depth of each mixture for a temperature change. As the test temperature was increased, results demonstrated that SBS and NRL modified binder only exhibited a slight increase in total deformation by 24.5% and 54.8%, respectively. While for the control mixture, a temperature change of 10 degrees resulted in a 77% increase in total deformation. This result is in accordance with the creep rate calculated on the secondary stage, presented in Figure 12b, which shows a significant increase in creep rate for the control mixture with the highest rise, followed by NRL and SBS modified asphalt mixtures.

4. Life cycle assessment: cradle to gate analysis

4.1. Life Cycle Inventory

The life cycle inventory comprises primary and secondary data collection.

Primary data was collected under actual conditions based on interviews with road construction experts in the case study area. Transport distances of raw material to the asphalt mixing plant is an example of primary data. In this study, all location presumptions have been validated through consultations and interviews with the road pavement contractor to ensure that the presumed project location makes practical sense in the field. Subsequently, secondary data are the generic or average data taken from sources including literature, Environmental Product Declarations (EPDs) and international databases. In this study, both data sets were taken to be as representative as possible in terms of geography, time and technology.

A peer-review process, consisting of an examination of data collection, was conducted to judge the assumptions that are made in order to ensure the quality and uncertainty of the primary data use in the pavement LCA. While for the secondary data, a pedigree matrix was use to evaluate the quality of data sources by assessing method compatibility, assurance, temporal correlation, geographical, compatibility, and transparency of each data source (Weidema et al., 2013). Detailed data employed in this work is explained in the following subparagraphs.

4.1.1. Raw Material Production

Table 4. Carbon equivalent emissions for different raw materials production

Material	GWP (kg CO2-eq -ton)	Sources
Binder	156	(Eurobitume, 2020)
NRL	279.17	(Usubharatana & Phungrassami, 2018)
SBS	3570	(Eurobitume, 2012)

Aggregate	6.36	(Bre Global EPD, 2018)
Cellulose fibre	329	Ecoinvent Library

The inventory analysis for raw material production is presented in Table 4. The carbon footprint emission data of virgin aggregates for the surface course were obtained from Bardon Hill EPD in accordance with EN 15804:2012 (Bre Global EPD, 2018). The process comprises all the flows to produce granite aggregate from drilling, blasting, loading, crushing, and screening to produce different size aggregates from 225 mm gabion stone to 0-2 mm crushed rock fines. The finished product is the crushed granite at the factory gate. In addition, binder as refinery data was taken from (Eurobitume, 2020). This dataset cover cradle-to-grave LCIs of bituminous materials, specifically from the extraction of crude oil, transportation of the crude oil from the country, refining of bitumen from crude oil, and finally, storage of the refined bitumen within the refinery. Inventory data from (Eurobitume, 2012) was utilized for SBS polymers since the new Eurobitume report no longer includes polymers in the analysis. Data on NRL as a binder polymer was adopted from (Usubharatana & Phungrassami, 2018). Here, the process accounted for was the cultivation of fresh latex from the farm and the production of NRL (concentrated latex), i.e. field latex storage, centrifuged process, and latex storage with High Ammonia (HA) as preservatives. With regard to Cellulose Fibre in the SMA mixture, the inventory is selected from the Ecoinvent v3 Professional database in the Simapro software. This dataset covers the process describing the production of cellulose fibre from wastepaper.

4.1.2. Transport to Asphalt Plant

All the raw materials required to produce asphalt mixture need to be transported to the Asphalt Mixing Plant location. The summary of the distances and modes used in this study is presented in Table 5. In this research, distances for transportation phase have been calculated based on key manager interviews with the involved companies in the case study area. Furthermore, the inventory data related to transportation have been derived from the Ecoinvent v3 database. In particular, ‘Truck 10-20t, EURO5, 100% LF” has been chosen for all the transport phases by road. Whereas, for overseas sea transportation, Global Transoceanic ship is selected.

Table 5. Distances and modes scenario

Material	Distance (km)			mode
	Virgin SMA	NRL SMA	SBS SMA	
Binder	150	150	220	Truck
NRL	–	15000	–	Ship
	–	300	–	Truck
SBS	–	–	1000	Truck
SBS PMB	–	–	200	Truck
Aggregate	15	15	150	Truck
Cellulose Fiber	265	265	265	Truck

Aggregate and Cellulose Fibre transport distance is the same for all three mixtures. Granite aggregate is extracted from Bardon Hill. While the cellulose fibre is taken from a manufacturer in Aberdare and then shipped to the asphalt mixing plant that is located in Loughborough, near the construction sites. The binder used in the production of Virgin and NRL SMA mixture comes directly from a refinery located in Immingham, to the asphalt mixing plant using freight truck, with a transport distance of 150 km. However, for the SBS SMA mixture, virgin binder has to be milled in the PMB milling plant in Preston with a transport distance of 220 km. After the virgin binder is milled with SBS to produce SBS PMB, the produce material will be transported again to the asphalt mixing plan as far as 200 km from the PMB milling plant. In term of polymer material, NRL is obtained from Thailand as the largest natural rubber producer. The NRL is shipped by Transoceanic Ship with the distance of 15,000 km. Upon arrival in the UK, NRL will continue to be transported directly to asphalt mixing plant by truck. Whilst for SBS polymer, the material is obtained from European manufacturer located

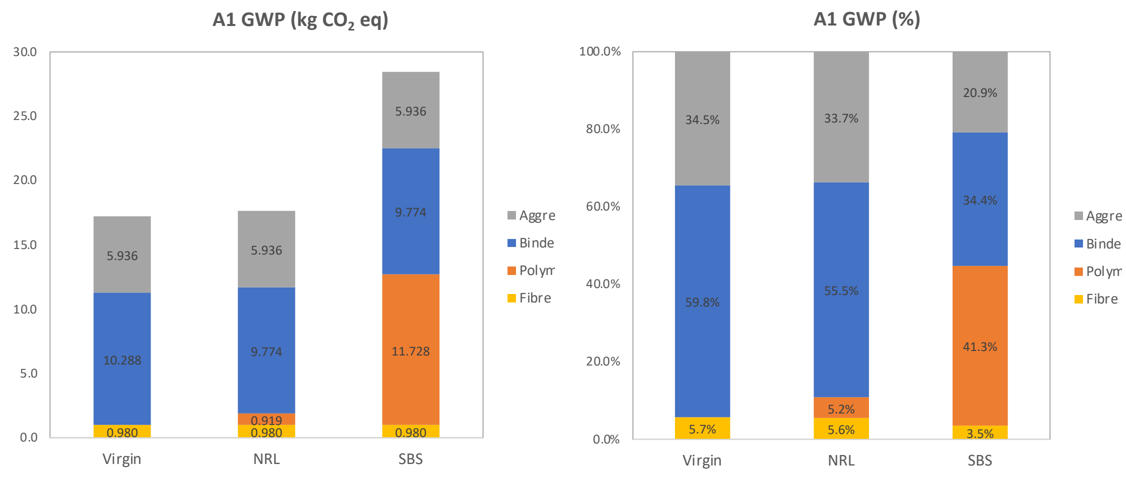
1000 km away from the PMB plant and carried by road using freight truck.

For this research, the empty return scenario was chosen for aggregate and binder shipments since generally this material is bound for a single supplier and cannot be sent all together with other materials. Conversely, for fibre and polymers, distribution was not assumed as empty return since the freight will continue to transport other goods elsewhere.

4.1.3. Asphalt Mixing Process

Regarding the energy source and emissions in the asphalt mixing stage, the plant used is a fix batch mixing plant, with a capacity of 160 metric ton/hour. The thermal power for this type is 12,000 kWh (Santos, Candido, Baulé, Oliveira, & Thives, 2020). Thus, it means that 75 kWh energy is consumed in the asphalt plant to produce one tonne of asphalt mixture. In this analysis, “heat, district or industrial, other than natural gas, heat production, light fuel oil, at industrial furnace” is used as a model input. It is assumed that NRL and SBS as a form of polymer binder requiring higher mixing temperature. Consequently, for these two mixtures, thermal energy is increased to 12% more than the reference mixture (Bueche & Dumont, 2012).

4.2. *Global warming potential*



(**a**) (**b**)

Figure 13. GWP result during stage raw material production (A1): a) Total Contribution; b) Percentage Con-tribution

The LCA analysis demonstrated that during raw material production, SBS SMA resulted in the highest GWP per 1 tonne asphalt mixture with total 28.42 kg CO2 eq compared with GWP impact for Virgin SMA with only 17.21 kg CO2 eq and NRL mixture with 17.61 kg CO2 eq as can be seen in Figure 13. The high number of GWP for SBS SMA mixture is caused by the quantity of emissions released in the production of the SBS polymer itself, with the amount of 11.73 kg CO2 eq or 41.3% of the total GWP in the raw material extraction stage. Meanwhile, the production of NRL as bio polymer only accounts for 5.2 % of the total GWP in this phase.

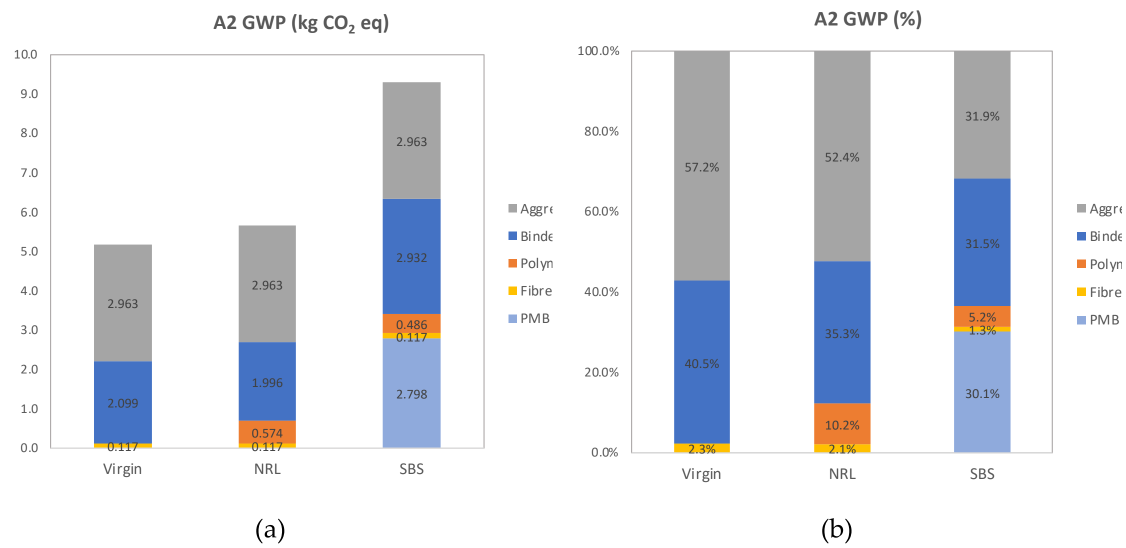


Figure 14. GWP result during transportation stage (A2): a) Total Contribution; b) Percentage Contribution

Figure 14 presents the GWP output as the result of the transport of the materials (i.e. fibre, aggregate, polymer, and binder) to the asphalt mixing plant location. It is evident that aggregate transportation effort has resulted in the highest GWP emission. This occurs due to a large amount of aggregate material required compared with other materials, although the transportation distance is relatively short, within 15 km distance, compared with other materials that need longer haul distance. It is also worth noting that SBS SMA has a slightly greater GWP impact, amounting to 9.30 kg CO2 eq, while other mixtures only produce less than 6 kg CO2 eq. This is due to the additional kilometres to transport binder and SBS polymer to the PMB manufacturing plant, from which the finished PMB product can be transported to the asphalt mixing plant. Thus, the extra transportation distance for PMB resulted in 30.1% of total GWP for SBS mixture. This process is different from the Virgin and NRL SMA mixtures, where all the materials were transported directly to the asphalt mixing plant location.

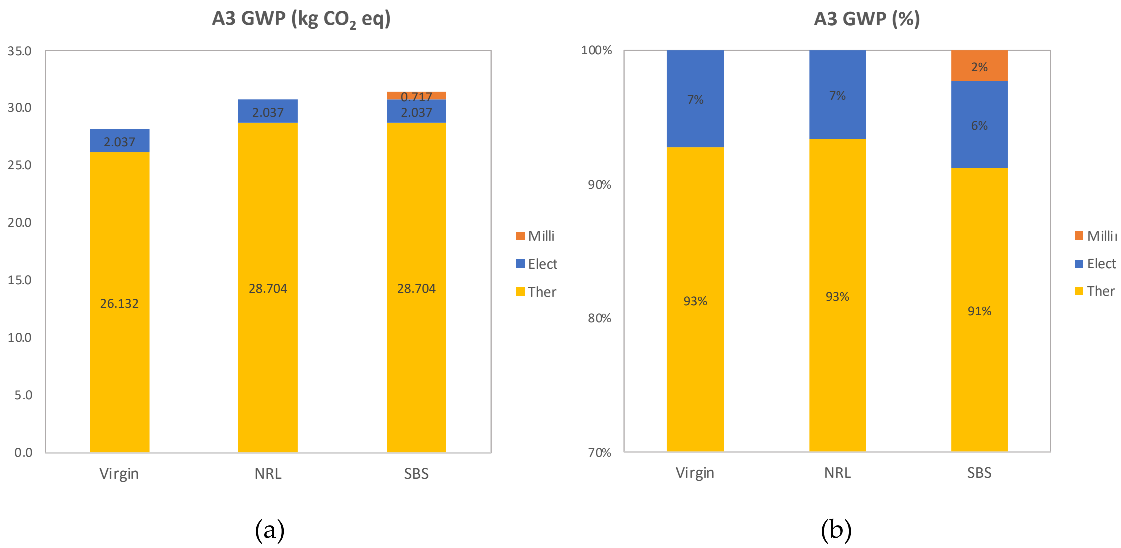


Figure 15. GWP result during asphalt mixing (A3) : a) Total Contribution; b) Percentage Contribution

Regarding stage A3 or asphalt mixing process, NRL and SBS generally released more emissions than the reference mixture, as shown in Figure 15. This is due to the increased thermal energy used to mix polymers, which requires a higher temperature. Furthermore, due to the additional PMB milling process, the GWP of the SBS mixture was higher than that of the NRL, with PMB milling contributing to a 2% increase in GWP. It can also be noticed that thermal energy is the dominant source of GWP emission, ac-counting for more than 90% of all emissions.

Based on the analysis of the aforementioned three LCA stages, it can be determined that the SBS mixture resulted in the highest GWP in every stage. Conversely, NRL has a carbon footprint value that is nearly equal to Virgin SMA. This indicates that NRL is more sustainable than SBS in terms of GWP impact during cradle-to-gate production.

5. Conclusions

The main objective of this study was to investigate the technical and environmental feasibility of an asphalt mixture incorporating Natural Rubber Latex (NRL). SMA mixtures were produced with NRL, and their mechanical performance as well as environmental characteristics were evaluated in comparison to reference mixtures produced with a virgin bitumen and SBS as a commercially available PMB. A series of laboratory tests was conducted to investigate performance of the mixture i.e. tensile strength, stiffness modulus, and resistance to fatigue and rutting. Life-cycle analysis (LCA) was carried out and the environmental impacts were evaluated through Global Warming Potential (GWP) to monitor greenhouse gases in the atmosphere for 1 tonne of FU. The outcomes are summarized as:

- The addition of NRL to SMA enhanced Indirect Tensile Strength by 10% compared with the virgin SMA mixture, although the NRL SMA asphalt mixture was still below the SBS PMB SMA mixture by 30%.

- NRL and SBS mixtures exhibited stiffness modulus values higher than the virgin mixture. NRL increased stiffness modulus by up to 20% while the SBS PMB increased asphalt mixture stiffness by up to 43%.

- Mixtures made with NRL present lower fatigue life for higher initial microstrain but have higher fatigue life for lower initial microstrains compared to the virgin mixture. On the other hand, when compared with the SBS PMB mixture, NRL has lower fatigue life for both high and low initial microstrains.

- NRL and SBS PMB asphalt mixtures have almost identical rates of permanent de-formation at a temperature of 40°C, but as the temperature increased to 50°C, NRL modified mixture exhibited a decrease in rutting resistance compared to the SBS modified mixture.

- The laboratory investigation results indicate that although it has slightly lower performance compared to SBS mixtures, incorporating NRL can increase stiffness, tensile strength, fatigue life, and rutting resistance compared to virgin mixtures. Thus, it is reasonable to presume that NRL-modified asphalt will improve the quality of road pavement, which can withstand greater stresses and strains and therefore contributes to the prolonged pavement's expected service life.

- With regard to environmental impact, for cradle to gate (A1-A3), NRL has slightly higher GWP impact compared to the virgin mixture (6% difference in value). However, NRL was more environmental-friendly compared to the SBS PMB mixture, which showed an increase in the GWP impact of 36% more than the virgin mixture. This higher GWP impact for the SBS PMB asphalt mixture was mainly due to changes to the asphalt composition and mixing temperature.

- The result shows from comparing performance from both an engineering characteristic and environment perspective, NRL SMA is superior to Virgin SMA but slightly lower to SBS SMA from an engineering standpoint, and in contrast, NRL has a GWP value that is significantly lower compared to SBS in terms of environmental perspective. Therefore, NRL considered to be the most suitable polymer for road construction, as it could conserve significant natural resources and produce good-quality asphalt in an environmentally friendly manner.

This study has demonstrated the feasibility of NRL to be used as a renewable polymer modifier for asphalt mixtures. The results show improved asphalt mixture performance without compromising the environmental impact considering the laboratory performance and GWP value. However, limitations of this study should be acknowledged. This study does not account for the carbon footprint associated with the construction and maintenance phases of all pavement types. This omission is not only due to substantial emissions during the considered life cycle stages but also insufficient information and uncertainties regarding the long-term performance and end-of-life of the new product. In addition, this study does not consider the economy analyses of NRL. While utilizing NRL as a substitute for SBS modification presents a considerable opportunity for cost reduction due to the high price of SBS. Nevertheless, the issue of long-term durability needs to be further investigated as the cost of pavement would depend on the cost of the maintenance frequency. Therefore, more in-depth investigations on long-term pavement LCA and Life cycle cost analysis (LCCA) that including construction phase and maintenance phase are envisaged in the future studies. Enhancing and optimizing both the LCA and LCCA models can greatly benefit decision makers involved in the pavement management system (PMS). Finally, the results of this research could be used as quantitative references for decision-making, and the estimated carbon footprint contributions of each life cycle stage could be useful in determining methods to facilitate improvements in the sustainability of pavement.

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