PROGRAMA DE DOCTORADO EN INGENIERÍA CIVIL

TESIS DOCTORAL

ESTUDIO PARA LA MEJORA DE MEZCLAS ASFÁLTICAS POROSAS CON UNA SELECCIÓN MULTICRITERIO DE ADITIVOS Y UN NUEVO BETÚN MODIFICADO CON POLÍMEROS

PhD THESIS

STUDY FOR IMPROVEMENT OF POROUS ASPHALT MIXTURES WITH A MULTI-CRITERIA SELECTION OF ADDITIVES AND A NEW POLYMER MODIFIED BITUMEN

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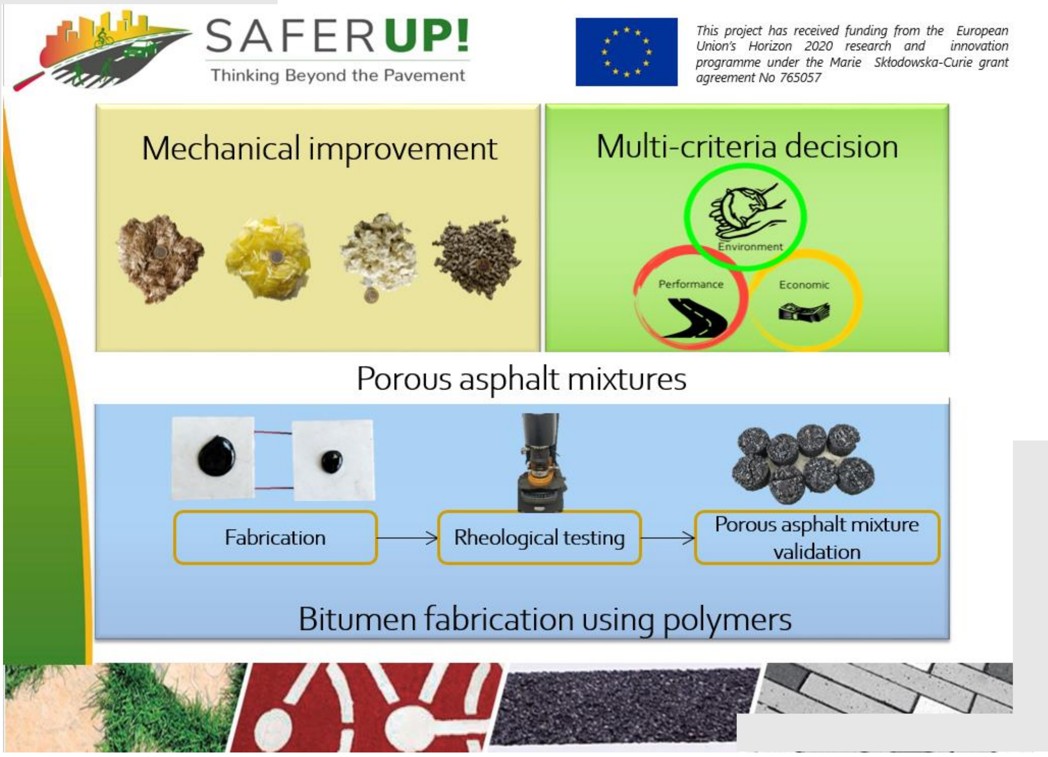

Las mezclas de asfalto porosas son más silenciosas y seguras debido a su alta reducción de ruido y características de resistencia al deslizamiento que mezclas densas graduadas. Sin embargo, estas mezclas son más propensas a sufrir daños, como desgaste, formación de baches, etc. A pesar de sus muchos beneficios, las limitaciones de las mezclas de asfalto poroso limitan su uso. Por ello, se realizan continuas investigaciones para potenciar la resistencia mecánica de las mezclas asfálticas porosas para que su uso pueda ser más extendido. Se está estudiando si la adición directa de aditivos o la incorporación de betún modificado puede ser útil para mejorar la resistencia al desgaste y la capacidad portante de las mezclas asfálticas porosas.

En el presente estudio, se pretende encontrar soluciones novedosas y sostenibles para contribuir a la mejora de las mezclas asfálticas porosas. En la primera fase de esta investigación, se calculó la influencia de variedad de aditivos en el desempeño mecánico, hidrológico, económico y ambiental de las mezclas asfálticas porosas. En la segunda fase, se preparó un nuevo betún experimental para satisfacer los requisitos de las mezclas asfálticas porosas y se evaluaron sus propiedades físicas y reológicas. Además, se realizó un análisis multi-criterio para la toma de decisiones entre los distintos aditivos utilizados en el estudio, asignando un valor unificado considerando el desempeño general.

Como principales conclusiones destacan la completa caracterización de las mejoras que ofrecen varios aditivos a las mezclas bituminosas porosas y el desarrollo de un nuevo betún modificado.

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To my family for their unconditional love and support.

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Abstract

Porous asphalt (PA) mixtures are becoming popular in recent decades in pavement application. These mixtures provide sustainable solutions to problems associated with dense-graded mixtures. The final pavements with these mixtures are quieter and safer than dense-graded pavements due to their high noise reduction and skid resistance characteristics. PA mixtures have a high amount of air voids (≈20%), which is achieved by lowering the fraction of fine aggregates. However, that makes them more prone to pavement distresses such as raveling, pothole formation, etc. The limitations of PA mixtures make them unsuitable for high traffic intensity. There is continual research ongoing to enhance the mechanical resistance of the PA mixtures so that their use can be more widespread. The present study is intended to thoroughly investigate the incorporation of additives and the use of modified bitumen for the enhancement of PA mix design and find novel and sustainable solutions to improve their resilience.

This thesis presents a framework to improve the overall performance of PA mixtures by modifying the mixture parameters through the selection of additives and at the binder level through the development of polymer-modified bitumen. In the first phase of this research, the influence of a variety of additives on the mechanical, hydraulic, economic, and environmental performance of the PA mixtures was computed. The additives included aramid fibers, glass-hybrid fibers, cellulose fibers, and hydrated lime. Furthermore, a multi-criteria decision-making analysis was performed to quantify the benefits and limitations of the additives used and to allot a unified value considering their overall performance. The mechanical performance was computed based on Cantabro tests, indirect tensile strength, and moisture susceptibility. The impacts on hydraulic performance were obtained by laboratory testing that included volumetric analysis and permeability tests. Economic impacts were computed by initial investments required for the asphalt mixture produced per ton. The environmental impacts were computed using the ReCiPe method involving global warming potential, human toxicity potential, and marine aqua-toxicity potential. In the second phase, a new experimental bitumen was prepared with high vinyl content (>35%) to cater to the requirements of PA mixtures. The physical properties of the new bitumen were assessed by the penetration, softening, viscosity tests, while rheological properties were evaluated by complex modulus, phase angle, creep compliance, and fatigue behavior. Porous asphalt mixtures are prepared to see the effect of the addition of experimental bitumen.

Among the most relevant results, it was found that the most promising fibers with considerable impact on the abrasion resistance were aramid pulp, which almost halved the particle loss. The lowest environmental impact was caused by the incorporation of cellulose fibers. While in the second phase of the research, it was concluded that the experimental bitumen prepared using high-vinyl SBS copolymer had higher stiffness, better fatigue behavior and higher creep recovery than the commercially used polymer modified bitumen.

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1. Introduction

1.1. Background of the research

The majority of roads that are used around Europe are topped with dense-graded asphalt mixtures. These roads are impermeable, which leads to stagnation of water in rainy seasons. Porous asphalt (PA) mixtures have been popular in the last few decades due to their eco-friendly structure. PA mixtures are hot mastic asphalt mixtures that have a high volume of air voids due to which water can seep down their structure and pass through the drainage systems or sewers. These mixtures are also sometimes coupled with pervious base layers which helps in replenishing groundwater. Pavements with the surface course of porous asphalt are also known as quiet pavements, particularly useful in urban areas since they reduce noise up to 5dB than conventional dense graded asphalt mixtures (Bichajło and Kołodziej 2018). Moreover, these mixtures contribute to the mitigation of the urban heat island by thermal transmission to the underlying layers and rapid cooling (Z. Zhang et al. 2020; U.S. Department of Transportation - Federal Highway Administration 2015; Ting 2012). In highways, these mixtures enhance safety because of higher skid resistance and lower water splashing (Rungruangvirojn and Kanitpong 2010).

However, PA mixtures suffer high durability and strength problems owing to high amounts of voids as a result of their gap graded gradation and lower proportion of fine aggregates (Wu et al. 2020). The fine aggregates help in the formation of the bitumen matrix that is responsible for efficient aggregate packing and the strength of the binder-aggregate interface. Moreover, due to high air voids content and high bitumen content, the bitumen tends to draindown due to the action of gravity, which leads to binder stability issues. PA mixtures are more exposed to environmental factors which leads to a higher rate of aging. This results in the stiffening of the binder and higher particle loss. Therefore, the benefits of porous asphalt mixtures are overshadowed by their lower durability. Researchers are constantly trying to find solutions to address the limitations of PA mixtures.

Additives can be incorporated to improve the performance of the PA mixtures, either in the bitumen or directly with aggregates in the mixtures (Ma et al. 2018). Natural fibers like cellulose and glass fibers are widely used in PA mixtures by adding directly with aggregates to improve the binder stability. Meanwhile, synthetic fibers like aramid fibers can be added to improve the mechanical resistance and provide strong reinforcement to the matrix of PA mixtures (Decoene 1990; Wiśniewski et al. 2020). The content and the process of additives are equally important because these fibers improve the matrix, but they can also block the air voids of the mixtures which can compromise the permeability of the mixtures. Some additives like polymers are added to modify bitumen and help in enhancing the durability of the PA mixtures because of their higher elasticity, which reduces particle loss. Additionally, polymer-modified bitumen (PMB) improves the low-temperature crack resistance and high-temperature performance of the asphalt mixtures.

Additives also have an economic and environmental impact, and it is important to quantify these impacts to determine the overall potential of any additive on the asphalt mixtures (Rodríguez-Fernández et al. 2020). The road industry is responsible for high emissions due to high temperatures used in asphalt production, the requirement of large quantities of raw materials, and long hauling distances, etc. For sustainable solutions, any additives that may be used in the asphalt mixtures should not contribute more towards the emissions. Greenhouse gas emissions, global warming potential, human toxicity potential, and marine aqua-toxicity potential are among the many impacts of road materials on the environment.

1.2. Framework of the thesis

This work was possible thanks to the research project entitled *"Resilient and sustainable Permeable Pavements For Urban Flood Mitigation* (RePP4FM)" in work package 3 (Resilient, sustainable, smart pavements) of the SAFERUP! Project (Sustainable, Accessible, Safe, Resilient, and Smart Urban Pavements) funded by the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 765057. SAFERUP! Project aims to provide the European community with innovative solutions that will form the urban paved environment of the future. The ultimate objective of SAFERUP! is to train new professionals (15 ESRs: Early-Stage Researchers) able to provide future generations with more livable cities by applying solutions developed through cutting-edge research.

SAFERUP! (https://site.unibo.it/saferup/en) aims to create a multidisciplinary European Training Network that brings together internationally known researchers and highly qualified industrial and social partners under 6 main pillars: sustainable, accessible, safe, resilient, smart, and urban.

The specific fields of interest are: users' behavior and protection (especially of the disabled and elderly), intelligibility and accessibility of pavements, road safety and urban acoustics, pavement management systems, durable and smart paving materials (fast-repairing and self-sensing), energy harvesting, and geothermal pavements, Urban Heat Island and flood risk mitigation, bioremediation of wash-off waters, pavement and industrial waste recycling and Life Cycle Assessment of construction products and technologies.

1.3. Normative for the elaboration of the thesis as a compendium

This thesis has been written as a compendium of research articles based on the specifications of the Doctoral Program in Civil Engineering at the University of Cantabria (Spain) as shown below.

- Regulations of Academic Management of Doctoral studies regulated by the Royal Decree 99/2011 approved by the Governing Council of the University of Cantabria on March 4, 2015, in its title IX. "Preparation of the thesis as a compendium of articles".

- Regulations for the elaboration of the thesis as a compendium of articles within the Doctoral Program in Civil Engineering of the Doctoral School of the University of Cantabria.

The compendium of research articles that supports the present Ph.D. thesis is as follows:

Article 1. Selection of fibers to improve porous asphalt mixtures using multi-criteria analysis. (DOI: 10.1016/j.conbuildmat.2020.121198). Accepted for publication on September 30 of 2020.

Article 2. Multi-Criteria Selection of Additives in Porous Asphalt Mixtures Using Mechanical, Hydraulic, Economic, and Environmental Indicators. (DOI: 10.3390/su13042146). Accepted for publication on February 10 of 2021.

Article 3. Critical assessment of new polymer-modified bitumen for porous asphalt mixtures (DOI: under process). (DOI: 10.1016/j.conbuildmat.2021.124957). Accepted for publication on September 16, 2021.

1.4. Relationship between the articles constituting the thesis

This dissertation is composed of three articles indexed in journal citation reports (JCR). Two of the three articles are published in a first quartile journal (Q1) while the remaining one is published in a second quartile journal (Q2) based on the most favorable category in JCR. The published articles are comprised of the analysis done based on the results obtained by testing in the laboratory and the decision-making analysis. The results discuss the mechanism of fibers in which they influence the performance of the porous asphalt mixtures, followed by a multi-criteria decision-making analysis to select the additives and development of a new experimental bitumen and the benefit of using it in porous asphalt mixtures.

The first phase is comprised of two papers: Article 1: Selection of fibers to improve porous asphalt mixtures using multi-criteria analysis (DOI: 10.1016/j.conbuildmat.2020.121198); and Article 2: Multi-criteria selection of additives in porous asphalt mixtures using mechanical, hydraulic, economic, and environmental indicators (DOI: 10.3390/su13042146). In this phase, various additives were considered and their physical properties were analysed. They were incorporated in the PA mixtures and the influence of the additives on the mechanical and hydraulic performance of the PA mixtures was discussed. Some additives were also included in the environmental and economic impacts based on their suitability and availability. This was done by employing a multi-criteria decision-making analysis that weighs each parameter implicitly and quantifies the effect of the additives by allocation of a value that contributes to making a better and well-informed decision. The weights of each contributing to the mechanical, hydraulic, economic, and environmental performance of asphalt mixtures were evaluated by a set of 10 realistic scenarios, CRITIC (a multi-objective based approach), and Delphi (a multi-subjective based approach). The final values were provided by multi-criteria decision-making methods: WASPAS, EDAS, and TOPSIS. It was concluded that multi-criteria decision-making is a novel methodology that can be applied for the selection of various additives in the PA asphalt mixtures to improve their characteristics.

The first phase comprises Article 3: Critical assessment of new polymer-modified bitumen for porous asphalt mixtures (DOI: 10.1016/j.conbuildmat.2021.124957). In this phase, a new experimental bitumen was prepared by the addition of high-vinyl content (>35%) SBS polymer. The prepared bitumen was assessed both for its physical properties such as penetration, viscosity, etc.; and rheological characteristics such as stiffness, fatigue behavior, and high-temperature performance. The new bitumen performed better than the commercially used polymer modified bitumen and virgin bitumen of similar penetration values. Further, porous asphalt mixtures were prepared with the new experimental bitumen to assess the variation in the characteristics of PA mixtures on adding experimental bitumen.

1.5. Structure of the document

This document is composed of seven chapters: Introduction, a summary of the state of the art, objectives, methodology, published articles, summary of results and discussions, and conclusions.

The first chapter presents the background of the research, the project associated with the completion of the thesis, the specifications fulfilled for the realization of the thesis, the relationship among the articles that conform to the compendium, and the structure of the document. The second chapter of this document summarizes the literature available on the research topics that are as follows: PA mixtures and their performance, additives and bitumen used, multi-criteria decision-making analysis, and the recent developments in PA mixtures. The third chapter comprises the research objectives and the structure of the research study. This is followed by the fourth chapter that outlines the materials and methods that were utilized to achieve the research objectives. The fifth chapter contains the three published articles and the information of the journals according to the citation report. The sixth chapter discusses the results and their discussions in brief. The final chapter presents the main general conclusions, particular conclusions, and the future scope of work.

2. Summary of the state of the art

The literature review presented from Sections 2.1 to 2.3 has been part of the journal article (Gupta, et al. 2019) published in the first year of the doctoral thesis. Section 2.4 presents the state of art on multi-criteria analysis and Section 2.5 presents the latest developments in the porous asphalt mixtures from 2019 till date.

2.1. Porous asphalt mixtures

Due to soil sealing, large amounts of runoff lead to ponding in urban areas and erosion in the unsealed neighboring areas (Li et al. 2016). The present drainage systems have limited capacity to hold runoffs, thus leading to urban flooding problems during overflow. Floods have now become more frequent and have greater impacts on the livelihood of society. Even in regions of high rainfall, the lowering of groundwater due to soil sealing has resulted in a scarcity of water for plants and vegetation. An increase in impervious surface areas has also reduced the ability of soil to filter water, which has increased the number of impurities and contaminants entering the water cycle (Vale et al. 2013). In this situation, it is vital to spread the idea of building sustainable systems with the ability to restore balance in the natural ecosystem.

Sustainable urban drainage systems (SUDS) are structures that imitate the drainage pattern of the natural land surface. Types of SUDS include bio-retention cells, green roofs, infiltration trenches, rain barrels, rain gardens, permeable pavements, rooftop disconnection, and vegetative swales (Jato-Espino et al. 2016). Permeable pavement systems (PPS) are one of the most complete SUDS and they have attracted attention due to their ability to withstand sufficient vehicular loads (Yu et al. 2017). PPS generate flow attenuation, which allows water to infiltrate through their structure thereby, delaying, reducing, and filtering the water flows (Marchioni and Becciu 2015; Rodríguez-Rojas et al. 2018). The advantages of PPS include reduction in noise, water splashing, skidding, and soil erosion. They mitigate the urban heat island effect, and diminish the damage to pavement caused by stagnant water, and facilitate high infiltration capacity (Cetin 2013; Hansen 2008; Hein, 2010). Even the poorest performing PPS have greater drainage capacity than the stormwater discharge from normal rainstorm events (Rodríguez-Rojas et al. 2018; Kumar et al. 2016; Jato-Espino 2018). The structure of PPS provides better skid resistance and more safety to road users. By replacing pavements with PPS, the number of accidents occurring in wet weather can be reduced up to 80% (Mohammadinia et al. 2018).

The surface of the PPS is mainly constructed with PA mixtures. In PA mixtures, very small amounts of fines or none are added to form an open-graded structure to allow water to flow through it. There is a stone-to-stone contact, resulting in higher air void content as compared to dense-graded mixtures. Subsequently, due to more environmental exposure, aging is faster in PA mixtures (Molenaar, et al. 2010; Rodriguez-Hernandez et al. 2011; Tholibon et al. 2016). The constant environmental exposure increases the asphaltene content, which makes bitumen stiffer and brittle, leading to raveling and cracking (Kumbargeri and Biligiri 2016; Großegger 2017). Raveling is the most significant damage in PA mixtures as it spreads very quickly and results in a huge reduction of pavement life span (Apostolidis et al. 2019). At the same time, due to clogging, functionality is affected, and porous pavement is not able to facilitate drainage, reduce noise and prevent damage due to water stagnation. The rate of clogging depends on factors like the type of materials used in the pavement such as cement concrete or asphalt, the slope of pavement, maintenance adopted, environmental conditions, erosion rate around the surface, etc. (Kumar et al. 2016; Chen et al. 2005).

Due to different vehicle loads, rainfall duration, and rainfall intensities, there are different requirements of PPS in urban regions (Yu et al. 2017). For instance, in residential areas, noise reduction may be the most prime concern whereas, for highways, skid resistance may be the most significant parameter. The development of multifunctional PPS during urban planning requires materials that endure different loading conditions while maintaining the integrity of the structure. The idea of including additives in the mixtures, especially fibers, is relatively new in permeable pavements as very limited literature is available. In the 2000s, the need to implement PPS led researchers to search for ways to improve the quality of permeable pavements by incorporating various additives (Katman 2005; Ameri et al., 2008). Additives like nanosilica have been shown to improve the abrasion resistance of the PA mixtures considerably (Tang et al. 2018). Natural fiber such as cellulose fibers is among the most commonly used fiber in PA mixtures as they improve the binder stability (Vale, 2013; Ma et al. 2018; Afonso et al., 2017; Andrés-Valeri et al. 2018; Mansour et al. 2012; Chen et al. 2012; Putman, et al. 2012). For low-temperature crack resistance, glass fibers can be used. To enhance properties such as elastic modulus, tensile strength (ITS), synthetic fibers have shown promising results (Slebi-Acevedo, et al. 2019a). Acrylic fibers improve mechanical performance under extreme conditions, so they can be utilized in cold and warm regions (Moreno-Navarro et al. 2016). Studies have also shown that recycled aggregates can also be used to replace virgin aggregates on low-intensity traffic roads (Chen et al. 2013; Chen and Wong 2014). The type of binder is another important factor, as a high viscosity bitumen will improve the cohesion of the binder. Meanwhile, polymer-modified bitumen (PMB) improves the adhesion between aggregates and the binder (Tholibon et al. 2016; Chen et al. 2012; Chen et al. 2013).

2.2. Performance of Porous asphalt mixtures

There are not many standards available for evaluating the functional performance of porous asphalt; therefore, the functionality of pavements cannot be determined during the mix design (Chu, et al. 2018). In the case of permeable pavements, functional performance (mainly permeability and sound absorption) is equally important as structural performance. The following Table 1 is the simplified version from the review article to quantify the performance of the PA mixtures.

Table 1. Tests for mechanical resistance and functional performance of PA mixtures.

Test	Standards	Observations
Dry Cantabro Test	EN-12697-17, Tex-245-F, T0733-2011	Developed in the University of Cantabria in the 1980s (Hanim et al. 2009). To quantify minimum binder content for PA mixtures design. Also used to measure the raveling resistance. The Cantabro test does not consider the stresses due to braking, shear kneading failure, common in urban areas.
Wet Cantabro Test	Spanish NLT 362/92	Samples are conditioned at 60°C in water to calculate the abrasion resistance in wet conditions (Ma et al., 2018).
Rotating Surface Abrasion Test (RSAT)		This test accurately simulates the vehicle tire's contact on porous asphalt by application of tangential stresses of the full-sized tire (Tang et al., 2018; Liu et al., 2014; Voskuilen et al., 2004).
Draindown Test	AASHTO T305, EN-12697-18, T0732-2011	To quantify the maximum binder content for PA mixtures design. Virgin binder is unable to prevent draindown. Additives or modifiers are used to improve the stability of the mix (Ma et al. 2018; Lyons and Putman 2013; Afonso et. al, Fael 2017; Andrés-Valeri et al. 2018).
Loaded Wheel Tracker (LWT) Test	AASHTO T324, EN 12697-22	Rutting resistance of PA mixtures reduces considerably due to high moisture, temperature, and loading conditions (Wang et al. 2018). Large stone porous mixtures have better rutting resistance (Cheng et al. 2019).
Indirect Tensile Strength (ITS)	ASTM D 4123, EN 12697-23	The strength of PA mixtures varies considerably when additives and modifiers are added.
Tensile Strength Ratio	AASHTO T283, EN-12697-12	PA mixtures have very high moisture susceptibility; nanosilica is added to reduce the moisture susceptibility of mixes (Yusoff et al. 2014).
Resilient Modulus	ASTM D4123	Resilient modulus represents the ability to recover under repeated loads (Cetin 2013). PA mixtures are susceptible to temperature, as temperature increases the stiffness reduces. Additions of diatomite may reduce the thermal susceptibility of PA mixtures (Mohd Shukry et al. 2018). An increase in the amount and size of crumb rubber usually results in the reduction of resilient modulus (Cetin 2013).
Thermal Stress Restrained Specimen Test (TSRST)	AASHTO TP10-93	In frozen regions, PA mixtures incorporated with warm mix additives can be used to reduce cracking resistance (Zhao and Huang 2010).
Permeability Test	ASTM D2434-68; AASHTO T215-14; ASTM PS 129-01	Permeability depends on the interconnected air voids; constant head tests assume laminar flow which is not the case for PA mixtures (Chu and Fwa 2019). Fully clogged mixes have negligible permeability.
Air Void Content	EN 12697-8	If the air voids are high, more clogging cycles will be required to clog the sample (Hamzah et al. 2013; Chu and Fwa 2019; J. Chen et al. 2015).
Acoustic Impedance Tube	ASTM 1050-10	In low-speed vehicles, the noise produced is mainly dependent on the micro-texture of the pavement. The macro-texture is responsible for noise caused due to high-speed vehicles. The noise reduction depends on the content, size, and distribution of air voids (Ye and Jian 2019; Chen and Wong 2017).
British Pendulum Tester (BPT)	ASTM E303	These do not simulate the interaction between the rubber tire and the surface of the pavement as both the tests measure the on-spot friction of the pavement (Hanim et al. 2009).
Dynamic Friction Tester (DFT)	ASTM: E-1911-98	

2.3. Fibers and additives in the porous asphalt mixtures

Fibers are additions that are commonly used in conventional dense-graded asphalt mixes to improve the mechanical properties (Kumbargeri and Biligiri 2016; Großegger 2017; Slebi-Acevedo, et al. 2019). The mechanism of action of fibers in asphalt mixtures is complex. Under tension, the stress is transferred from medium to fiber, and fiber bears a portion of stress. Hence, the ability to withstand stress depends on the fiber content. Moreover, the interaction of fibers and aggregates acts as a medium for aggregates to bond together. Fibers increase the bitumen stiffness which may lead to brittleness, responsible for distresses in the structure of pavement (Chen and Lin 2005). In PA mixtures, fibers are used to prevent binder draindown and facilitate a higher optimum binder content (Tholibon et al. 2016; Großegger 2017). The incorporation of fibers leads to a reduction in air voids in PA mixtures as they interrupt the water flow through connected voids (Marchioni and Becciu 2015). However, very limited literature is available on the use of fibers in PA mixtures, therefore the influence of fibers in PA mixtures needs to be evaluated in detail for each case. Table 2 and Table 3 summarize the literature review done to quantify the effect of additives and fibers, respectively, on the mechanical resistance and functionality of PA mixtures based on their content and type. In this study, the division between the additive and the fibers is done based on their physical shape.

2.3.1. Nanosilica

Nanotechnology has received great attention around the world in the past few decades. Nanosilica materials are not only abundantly available but also have a large surface area that facilitates high adsorption, high dispersion ability, and high purity (Yao et al. 2012). They are commonly used to improve the moisture susceptibility of the asphalt mixes (Taherkhani, et al. 2017; Masri et al. 2019). Nanosilica is a very stable material with low toxicity. The most appropriate dosage of nanosilica is 2-6% by weight of binder (Baldi-Sevilla et al. 2016; Yusoff et al. 2014; Tanzadeh et al. 2019; Tanzadeh and Shahrezagamasaei 2017). Silica also increases the polarity of the coarse aggregates, which subsequently improves the adhesion between aggregates and binder which in turn reduces the particle loss due to abrasion (Hamedi and Nejad 2015). On increasing the content of nanosilica, the rut depth is found to be decreased (Yao et al. 2012; Tanzadeh et al.,2019; Arshad et al. 2019). Nevertheless, in PA mixtures, rutting is an important parameter due to the large air void presence and the tendency of aggregates to shift their location (Lyons and Putman 2013).

J. Tanzadeh and Shahrezagamasaei, 2017 pointed out that nanosilica in combination with fibers has synergistic benefits. On the one hand, fibers improve the mechanical strength, while on the other hand, nanosilica improves various properties such as adhesion, stability, and abrasion resistance of the PA mixtures. Composite additives have a better effect on the properties of the PA mixtures in comparison to the adding single additive (Baldi-Sevilla et al. 2016; Luo et al. 2019). Moreover, nanosilica increases the shear modulus and viscosity of the asphalt which results in anti-oxidation, improved temperature stability, and better fatigue resistance in PA mixtures (Tanzadeh et al., 2019; Sangiorgi et al. 2016; J. Tanzadeh and Shahrezagamasaei 2017; Arshad et al. 2019). Nazari et al., 2018 explained that nanosilica induces crack path deflection due to its high dispersion, arresting the propagation of cracks.

Table 2. Additives in porous asphalt mixtures.

Fibers	Content (%)	Binder	Binder Content	Cantabro (dry)	Draindown	ITS	TSR	Permeability	Porosity	Rutting
Nano-silica/ (Tanzadeh, et al. 2019)	2 (mix)	VB 60/70	5	O	O	O	O	X	X	
Nano-silica/ (Baldi-Sevilla et al. 2016)	2 (bit)					O	O			
Nano-silica/ (Arshad et al. 2019)	2 (bit)		5.16							O
Crumb rubber/ (Lyons and Putman 2013)	5 (bit)	PG 64-22	5.50	X		O	O	XX	X	X
Crumb rubber (additive)/ (Cetin 2013)	10 (bit)	VB 50/70	6.50	O		O	XX			
Crumb rubber (additive) /(Cetin 2013)	15 (bit)	VB 50/70		XX		XX	XX			
Crumb rubber (additive) /(Cetin 2013)	3,6,9 and 12 (bit)	VB 80/100	5	XX				X	X	
Crumb rubber (additive) /(Enieb, et al., 2019)	1 (agg)	SBS	6	O		X	O	XX		
Sasobit®/(Ranieri et al. 2017)	2.5 (bit)	PMB 45/80-65	5.20	XX		O	XX	O		
Evotherm/(Z. Liu et al. 2013)	0.5 (bit)	PG 76-22	5.70	O	O			O	O	XX
Stearic acid amide/(Zhao and Huang 2010)	3 (bit)	SBS		XX				O	O	O
Diatomite/(Tholibon et al. 2016)	2 (agg)	PG76	5.25	XX				O		
Hydrated lime/(Tholibon et al. 2016)	2 (agg)	PG76	5	XX				O		

Note: *SBS modified bitumen
#VB Virgin binder

O means improvement with respect to control mixtures
X refers to no significant differences
XX refers to adverse effects@ by the weight of aggregate

Table 3. Fibers in porous asphalt mixtures.

Fibers/ Reference	Content (%)	Binder	Binder Content (%)	Cantabro (dry)	Draindown	ITS	TSR	Stiffness	Permeability	Porosity	Rutting
Cellulose/ (Ma et al. 2018)	2.5 (agg)	HVB	5.10	XX	O	-	X	-			-
Cellulose/ (Lyons and Putman 2013)	0.3 (mix)	PG 64-22	5.50	XX	O	X	O	X	X	XX	O
Cellulose/ (Afonso et al., 2017)	0-0.5	PMB 45/80	4.70	XX	O	X	X	X	O		O
Cellulose/ (Ye and Jian 2019; Andrés-Valeri et al. 2018)	0.1, 0.3, 0.5	SBS*	5		O		O				
Cellulose/ (Chen et al. 2013)	0.25, 0.5, 0.75 (mix)	VB 50/70	4.50	O	O	XX	XX		XX		
Cellulose/	0.30 (mix)	AR-80	5.20	X		X	X		XX		O
Mineral (basalt)/ (Tanzadeh et al., 2019)	0.2 (mix)	VB 60/70	6	XX	O	O	XX		XX	X	
Glass/ (Tanzadeh, et al.,2019)	0.2 (mix)	VB 60/70	5	XX	O	O	XX		XX	X	
Polypropylene/ (Ye and Jian 2019)	0.1 - 0.5	SBS*	5		O		O				
Polyester/ (Ma et al. 2018)	2.5 (agg)@	HVB	5.1	O	O	XX	X	X X	XX		O
Polyester/ (Ye and Jian 2019)	0.1 - 0.5	SBS*	5		O		O				
Polyester/ (Tang et al. 2018)	0.10	SK70	4.4	O	X						
Mineral/ (Ma et al. 2018)	2.5 (agg)	HVB	5.1	O	O	-	X	-			-

Note: *SBS modified bitumen
#VB Virgin binder

O means improvement with respect to control mixtures
X refers to no significant differences
XX refers to adverse effects@ by the weight of aggregate

2.3.2. Crumb rubber

In Crumb Rubber Modified Bitumen (CRMB), the bitumen is modified by the rubber to increase the viscosity, whereas if used as an additive in the mix, then the rubber is added by dry process (Shell bitumen handbook, 2003). In the former case, the rubber is added to the bitumen at high temperature, when blending of rubber and bitumen is very efficient, and crumb rubber modifies the chemical connections of the binder, and it results in a more viscous modified binder. While, in the dry process, the crumb rubber (CR) is mixed with the aggregate during the preparation of asphalt and its interaction with the binder is limited. Shell handbook, 2003 explained its behavior as ‘Elastic Mineral aggregate’.

Eskandarsefat et al., 2019 presented a new procedure to add crumb rubber with cellulose fibers to analyse the composite behavior. It was stated that rubber increases ductility and improves the stiffness of the mix at high temperatures. Sangiorgi et al., 2017 presented a study of adding crumb rubber in PA mixtures. It was highlighted that, at low temperatures, the crumb rubber reduces the binder's rigidity, resulting in higher low-temperature crack resistance. While, at high temperatures, CR improves the viscosity of the binder, and hence binders are stiffer at high temperatures. This was further explained by Cheng et al. 2019, that if crumb rubber is uniformly distributed in the binder, improves the toughness of the binder and result in higher low-temperature crack resistance. CR also enhanced the affinity of bitumen resulting in less oxidation, lower stripping, and high raveling resistance (Enieb et al., 2019; Frigio and Canestrari 2018).

It was observed that the performance of the mix was dependent on the size of the CR as #20~#200 (smallest size) CR reduced the particle loss, whereas the samples with larger size had even worse particle loss than the control mix. Moreover, increasing the rubber content led to lesser abrasion resistance. The optimum content of rubber was found to be 10% (Cetin 2013). The smaller size of rubber can blend in the mixture more homogeneously (Cetin 2013; Ameri et al., 2008). Furthermore, crumb rubber reduced the ITS, moisture susceptibility, permeability, and resilient modulus of the mixture with the only exception of #20~#200 size which improved the performance of PA mixtures marginally. However, there is no observed effect on the permeability of the samples (Ameri et al., 2008). However, high temperatures are required for the use of crumb rubbers, which results in higher greenhouse gas emissions, and their storage may lead to the problem of sedimentation at bottom of the container (Vale, et al., 2013; Shell bitumen handbook, 2003).

2.3.3. Warm mix additives

Warm mix asphalt (WMA) technology is a sustainable measure to reduce the temperature (up to 40°C lower) for mixing and compacting asphalt pavements in comparison to the conventional hot mix asphalt. WMA technology reduces energy consumption and CO_2 emissions. Moreover, using WMA technology with porous asphalt pavements can have synergetic benefits. Ranieri et al., 2017 carried out a study with a commercial warm mix additive called Sasobit® (2.5% of binder weight) in combination with cellulose fibers (0.4% by aggregate weight). Due to less compaction temperature in warm mixes, the air voids increase at the same compaction effort, which is desirable in PA mixtures. In cold weather, WMA porous mix with stearic acid can be used, as for same dry ITS, the compaction temperature can be reduced up to 20°C. Moreover, there will be reduced aging of the binder due to reduction in mixing temperature, although WMA performs worse than HMA in moisture susceptibility and abrasion resistance (Lastra-gonzález et al. 2017; Frigio and Canestrari 2018; Ranieri et al. 2017; Z. Liu et al. 2013; Senior-Arrieta et al., 2017). Lastra-González et al. (2017) analysed PA mixtures with CRM binder in combination with fatty acid amide wax. Sasobit® and fatty acid amide wax were shown to have adverse effects on the cohesion of binder, reducing resistance against abrasion and moisture susceptibility (Lastra-gonzález et al. 2017; Ranieri et al. 2017).

Frigio and Canestrari, 2018 found that while using the WMA technology, the need to use stabilizing fiber was eliminated when producing similar quality PA mixtures. The warm PA mixtures outperformed HMA without fiber in terms of permeability, durability, draindown, and abrasion resistance tests. Due to the reduction in temperature in WMA technology, the aging of binder is reduced which improves the better resistance to fatigue cracks.

To summarize, studies have found that Nanosilica enhances binder stability, TSR, and ITS of PA mixtures while crumb rubber decreases the abrasion resistance with a few exceptions (Frigio and Canestrari 2018) and has no effect on the stiffness of the mixtures. While warm mix additives improve the permeability but reduce the abrasion resistance.

2.3.4. Cellulose fibers

Cellulose fibers are obtained from the bark, wood, or leaves of plants. The surface area of commonly used cellulose fibers is ten times greater than that of mineral fibers and polyester fibers, which explains the ability of cellulose fibers to bind more binder (Chen and Lin 2005). According to a study by Ye and Jian, 2019, the incorporation of 0.3-0.5% of cellulose fibers in an open-graded friction course (OGFC), gives better stability to the binder than polypropylene and polyester fiber.

Afonso et al., 2017 explained that due to high bitumen absorption, cellulose fibers improve the rutting resistance of the PA mixtures whereas no improvement on raveling resistance was observed in combination with neat binders. Especially, in the case of the wet Cantabro test, cellulose fibers had adverse effects as they increased the particle loss. Regarding this, Andrés-Valeri et al., 2019 observed that up to optimum fiber content, cellulose improves the raveling resistance, but on increasing further, raveling resistance reduces. As explained by the author, due to higher fiber content in comparison to binder content, the cohesiveness of binder reduces leading to particle loss. With all, cellulose fibers in combination with modified binder improve the raveling resistance.

To account for stiffness, moisture susceptibility, and ITS, no effect was observed by adding cellulose fibers (Lyons and Putman 2013; Afonso et al., 2017). Lyons and Putman, 2013 used cellulose fibers of 6mm length and highlighted that cellulose fibers reduce the porosity up to 22%. If cellulose fibers are well dispersed, high absorption of binder by cellulose fibers is observed, which may be responsible for lesser binder drainage and lesser permeability. Eskandarsefat et al., 2019, found that the mixtures with cellulose fibers exhibited high Marshal Stability due to the high binder absorption ability of cellulose fibers.

2.3.5. Mineral and Glass fibers

Mineral fibers are rigid fibers as they do not entangle. Mineral fibers have the lowest softening point as compared to polyester fibers and cellulose fibers. The complex modulus increases up to an optimum content until the fiber content the stiffness and resistance to rutting are improved, beyond that point the phenomena is reversed due to fiber-fiber contact (Chen and Lin 2005). They reduce the binder draindown of the mixes (Ma et al. 2018; Tanzadeh et al., 2019); however, the performance of mixes with mineral fibers is worse in the case of the aged and unaged Cantabro test. Glass fibers improve the ITS (Chen and Lin 2005; Tanzadeh et al. 2019) but, the moisture susceptibility resistance is reduced by adding mineral fibers (Tanzadeh et al. 2019).

Glass fibers are traditionally used in the textile processing industry. The tensile modulus of glass fibers is very high and its thermal susceptibility is very low. Therefore, a noticeable increase is observed in the ITS value of mixtures by adding glass fibers (Tanzadeh et. al 2019; Enieb et al., 2019). Glass fibers absorb the binder and hence increase the air void content and the binder content of the mix without the risk of binder drainage (Slebi-Acevedo, et al. 2019). According to Wang et al. 2019, glass fibers improve the crack resistance of the asphalt mixtures, especially at low temperatures. Tanzadeh et al., 2019 carried out a study with 12 mm long glass fibers, they reported improvements in stiffness and tensile strength. However, the glass fibers led to a decrease in the permeability of the mix which can compromise the water drainage ability of the PA mixtures.

Glass fiber acts as an elastic medium to reinforce the viscoelastic characteristics of the mixture which subsequently improves the strain value, making the mixture stiffer. Therefore, glass fibers can be added in mixtures to reduce the rut depth (Enieb et al. 2019). Moreover, glass fiber enhances the ductility, improves the fatigue strength, and also preserves the high-temperature stability of the mixture by improving its rutting resistance (Luo et al. 2019).

2.3.6. Steel fibers

Steel fibers not only improve the mechanical performance of the fibers but also impart healing ability. They are used to heal the PA mixtures by electro-thermal procedures. As steel fibers are conductive, during induction heating, steel fibers conduct heat and warm the surrounding binder matrix. Then the binder melts and fills the micro-cracks and thus prevents crack propagation (Taylor et al. 2011; Liu et al. 2011; Lastra-González et al. 2019).

This phenomenon of self-healing is even more pronounced in PA mixtures. Moreover, adding steel fibers improves the resistance to particle loss considerably (Lastra-González et al. 2019; Serin et al. 2012). Lastra-Gonzalez et al., 2019 indicated that steel wool, as well as steel grit, improve the moisture susceptibility and ITS value of PA mixtures. At the same time, it makes the mixture stiffer and more resistant to fatigue cracking. Moreover, steel fibers do not reduce the workability of the PA mixtures, which suggests that they can be compacted at the same compaction effort. In a study by Liu et al., 2011, three different types of steel fibers were used. Steel fibers of small diameter and longer length, performed better than steel fibers of large diameter and shorter length as the fiber-to-fiber contact is better in the former case, which results in more conductivity.

Serin et al., 2012 carried out a study on different contents varying from 0% to 2.5%. The maximum stability value was observed at 0.75% fiber content. It was also found that, at higher fiber content, the stability values were worse than control samples with no fiber content, which is in agreement with the study done by Tabaković et al., 2019 explaining that very long steel fibers and high contents can lead to cluster formation. Additionally, clusters can also result due to bad mixing (Liu et al. 2014). These clusters may later become high-temperature zones which weaken the structure of the specimen. Steel fibers improve the particle loss resistance of PA mixtures as well.

2.3.7. Aramid fibers

Aramid fibers are becoming more popular in the road construction industry in the past decade due to their many benefits on the mechanical, economical, and environmental aspects of asphalt mixtures owing to their remarkable properties (S. Qian et al. 2014; Mitchell et al. 2010; Badeli et al. 2018; Slebi-Acevedo et al. 2019; Noorvand et al. 2020; Wiśniewski et al. 2020; Slebi-Acevedo et al. 2020; Ziari et al. 2020; Gupta et al. 2021). Aramid fibers are synthetic fibers with long-chain synthetic polyamide and more than 85% of amid are linked directly to aromatic rings (Chawla and Chawla 2018). These types of fiber do not undergo any degradation at the manufacturing temperature of asphalt mixtures (Bueno and Poulikakos 2020). Xing et al., 2019 investigated the effect of composites in asphalt binders by assessing rheological parameters and micromorphology using a scanning electron microscope. It was found that aramid fibers reinforced the asphalt mixture and enhanced the strain recovery rate in multiple stress creep recovery tests (MSCRT). Badeli et al., 2018 added aramid pulp fibers to the dense-graded asphalt mixtures and found that these fibers improve the stiffness at medium and high temperatures.

Furthermore, aramid fibers reinforce the asphalt mixtures so their addition results in improvement of fracture toughness and fracture energy (Tafti et al. 2019; Al-bared and Marto 2019). Xing et al., 2020 mentioned that the binder adsorption of the fiber reflects the stabilizing ability of the fiber. It was pointed out that aramid fibers absorb more binder due to their complex bundle shape as compared to basalt fibers; however, their binder absorption was lower than the lignin fibers. Kassem et al., 2018 studied the effect of fibers using the Visco-elasto-plastic continuum damage (VEPCD) model. The authors stated that warm mix additive enhanced the dispersion of aramid fibers in asphalt concrete and improved its rutting resistance. In another study by Daniel 2020, it was suggested that aramid fiber improves the stiffness and fatigue life of asphalt mixtures at low-frequency loads (high-speed traffic conditions).

Limited literature was available on the use of aramid fibers in PA mixtures (<10 articles in the last decade). Slebi-Acevedo et al., 2020 conducted research on polyacrinite and polyolefin plus aramid fibers in PA mixtures. It was found that the use of polyolefin plus aramid fibers enhanced abrasion resistance, reduced binder drainage, and improved the toughness of PA mixtures. Aramid fibers are not commonly used in PA mixtures, but they have an important potential to improve PA as their use can act as reinforcement in the binder-aggregate matrix, which may result in high resistance towards abrasion loss and fatigue cracking.

2.4. Bitumen in porous asphalt mixtures

Most commonly, polymer modified bitumen (PMB), crumb rubber modified bitumen (CRMB), styrene-butadiene-styrene (SBS) modified bitumen, high viscosity bitumen (HVB), are used to improve the performance of PA mixtures. Ma et al., 2018 conducted a study involving four types of binders: HVB, SBS modified binder, PG76-22, and PG70-22. A uniaxial compressive test was performed at 15 °C under the loading rate of 2 mm/min, concluding HVB improves the compressive strength of the PA mixtures as compared to SBS modified binder. The high viscosity of bitumen improves the cohesion, so less draindown is observed (Chen et al. 2012). Moreover, due to the high viscosity of the binder, the stability and the resistance towards abrasion are also improved (Ma et al. 2018; J. S. Chen et al. 2013; Liu and Cao 2009). It is also worth mentioning here that Cantabro test results worsen with the aging of the binder, which agrees to the fact that due to aging the binder becomes stiffer and brittle, leading to more abrasion loss (Chen et al. 2012). However, if the binder is more viscous, the asphalt mixes show more resistance to particle loss. Hence, the high viscosity of the binder will lead to a better mixture in terms of compressive strength, cohesion, draindown, rutting performance, and abrasion resistance.

All binders stiffen due to the aging process; however, the binder at the upper surface ages more than the lower layers, even if the layers have the same air void content (X. Lu, Sandman, and Redelius 2010). The rate of degradation of polymers is very high, in the attempts of enhancing the aging resistance of SBS copolymers, the use of high vinyl content SBS copolymers have become popular as these copolymers' structure facilitates lower viscosity and higher stability (Zhu, Birgisson, and Kringos 2014). This results in lower susceptibility to abrasion, moisture, and temperature changes (Tholibon et al. 2016; Chen et al. 2013).

Rubber-modified binders are used to increase the elasticity and lessen the thermal susceptibility of the mixtures (Sangiorgi et al. 2017). Rubber improves the viscosity of binder which in turn enables the use of higher binder content without the risk of binder drainage (Cetin 2013). Lyons and Putman, 2013 used four different kinds of binder; i.e., a neat binder, a modified binder (3% SBS + PG 64-22 binder), CRM 5% (neat binder + 5% CRM), and CRM 12% (neat binder + 12%CRM). The draindown was measured after every hour, three times to analyse the influence of time on the draindown. Higher percentages of CRM (12%) were required to prevent draindown in comparison to using 5% CRM. In the case of PMB, fiber was essential for preventing draindown. However, CRMB has two major limitations, one of which is the reduced permeability due to greater binder film thickness and the other one is the requirement of high temperatures, which result in greater greenhouse gas emissions (Arrieta and Maquilón 2014).

Adhesion properties of the binder are equally important in predicting the possibility of stripping in PA mixtures. Baldi-Sevilla et al., 2016 studied the behavior of binders in unaged and aged conditions. The contact angle of the binder has a direct relation with its mechanical resistance as if the contact angle is high, the binder is too cohesive, and the resistance to rutting and fatigue will be lower. This may be because with less cohesion the molecules are more likely to adjust, and recovery is quick.

The stripping phenomenon is a thermodynamically favorable condition, as in the presence of water, the adhesion of aggregate and bitumen is worse than that of aggregate and water (Alvarez et al. 2018; Bhasin et al. 2007; Hamedi and Nejad 2015). In the absence of fillers, using additives may improve the adhesion between aggregates and bitumen (Ji et al. 2017). Ye and Jian, 2019 mention that the adhesion of fiber and bitumen is better than bitumen and aggregates, so adding fiber will lead to better resistance to moisture. Although additives like diatomite have adverse effects on the adhesion of binder, they enhance the moisture resistance, which is possibly due to an increment in energy ratio (resistance to moisture increases with an increase in energy ratio). Moreover, types of aggregates also influence the adhesion, as lime aggregates show better bonding with bitumen than granite due to their larger surface area (Kakar et al. 2016).

To summarize, high viscosity binder improves cohesion, which is responsible for enhanced strength, lesser draindown, better durability, and higher rutting resistance in PA mixtures. Meanwhile, PMB and rubber-modified binders are effective especially to reduce the thermal susceptibility of mixtures. However, in the case of rubber-modified binders, high amounts are required to avoid draindown. Moreover, additives and fibers improve the adhesion properties of binder and aggregate, thereby improving the moisture susceptibility and avoiding distresses caused due to rutting and fatigue.

2.5. Multi-criteria decision-making tools

Multi-criteria decision analysis is widely used to select the best choice among a set of alternatives taking into consideration several criteria. Studies have used multi-criteria analysis to evaluate the performance of asphalt mixtures (Torres-Machi et al. 2019; Jato-Espino et al. 2018; Slebi-Acevedo et al. 2019). It is composed of two main stages; the first stage involves allotting weight to the criteria involved in the analysis based on their relative importance, the second stage is analyzing the various alternatives based on the criteria.

2.5.1. Allotting weights to the criteria

In multi-criteria analysis, an alternative is selected according to the criteria which comprise different parameters. The criteria are allotted by weights based on their relative importance on the selection of alternatives. There are either multi-subjective weighing approaches or multi-objective weighing approaches to allot the criteria their respective weights. The multi-subjective weighing approach follows an inclusion of judgment of experts in the field. The methods that compute the relative importance of the various criteria by this approach are the analytic hierarchy process (AHP) and the Delphi method. AHP is the most commonly used method in the road construction sector (Cao et al. 2019; Torres-Machi et al. 2019; Loc et al. 2017; Jato-Espino et al. 2018). The scores in this method are computed by pairwise comparisons and opinions of experts (Saaty 1987). Another method of great relevance is the Delphi method that directly computes the subjective weightings. Shrestha and Shrestha 2019 employed the Delphi method to analyse road maintenance routines. In this method, the opinions of experts are asked more than one time to achieve a consensus to minimize uncertainty and improve accuracy. Nevertheless, there are methods such as criteria importance through inter-criteria correlation (CRITIC) that do not require human intervention, which can be useful to obtain the scores quickly or avoid human errors. Based on this method, the normalization of each criterion is done based on whether it is a beneficial or non-beneficial criterion (Ighravwe and Babatunde 2018). Ariza et al., 2019, employed multi-criteria analysis for the selection of sustainable urban drainage systems (SUDS) based on environmental, social, and economic aspects using CRITIC.

2.5.2. Multi-criteria analysis

After the allotment of scores, the multi-criteria decision methodology is applied to select the best alternative. Multi-criteria decision-making methods (MCDMs) that can be utilized include integrated value model for structural assessment (MIVES), weighted aggregated sum product assessment (WASPAS), elimination et choix traduisant la realité (ELECTRE) (elimination and choice translating reality in original French), technique for order of the preference by similarity to ideal solution (TOPSIS), evaluation based on distance from average solution (EDAS), preference ranking organization method for enrichment evaluation (PROMETHEE).

The computation of the WASPAS method utilizes the weighted sum model (WSM) and weighted product model (WPM) methods. WSM and WPM are popular methods; however, they suffer from some disadvantages like high susceptibility to units' ranges and overestimation of definite scores (Kolios et al. 2016). WASPAS increases the accuracy of WPM by up to 30% and 60% in the case of WSM (Zavadskas et al. 2012). Slebi-Acevedo et al., 2019 carried out a multi-objective optimization using the CRITIC-TOPSIS methodology in PA mixtures. In another study, a stochastic optimization model was developed by Noori et al., 2014 for selecting the most suitable reflective cracking mitigation solution. Jato-Espino et al., 2018 used multi-criteria analysis in the selection of asphalt wearing courses on roads subjected to heavy traffic. To consider the variability and vagueness of the results, fuzzy logic was also applied.

Jato-Espino et al., 2018 employed TOPSIS for the selection of asphalt wearing courses in highly trafficked roads. In another study (Slebi-Acevedo, et al. 2019a), the optimization of asphalt mixtures incorporating nylon fibers was done using the WASPAS method, where different bitumen and fiber contents were considered for optimization of an open-graded asphalt mixture.

However, there was a lack of literature assessing the 'complete' performance of additives in PA mixtures in terms of mechanical, hydraulic, economical, and environmental indicators based on multi-criteria analysis. Consequently, in this thesis, a multi-criteria decision-making method is employed to select the best additive among the six different types of additives in the PA mixtures based on its effect on mechanical, hydraulic, economic, and environmental factors. The hypothesis is that although the additives improve the mechanical performance of PA mixtures, they may not improve other aspects proportionally. This doctoral study investigates whether this improvement is in overall performance based on hydraulic, economic, and environmental indicators.

2.6. Recent Developments in porous asphalt mixtures

Recent years have witnessed a prominent interest of researchers in PA mixtures. More than 200 articles can be found on the Scopus website under the keywords 'porous asphalt mixtures', 'open-graded friction course', and 'permeable pavements' in the years 2019, 2020, and 2021. The following paragraphs present in brief the recent state of the art on the influence of novel materials, gradation, aggregates type and structure, conditions of mixing, and testing.

The air void content has a considerable effect on the performance of PA mixtures. The air voids influence mainly the resistance towards deformation at high temperatures (Dan et al. 2021) and bending ability at lower temperatures (Wang et al. 2021). Method and conditions of mixing are crucial for the resultant air void content and aggregate structure. Many pieces of research were carried out to investigate the effectiveness of the conventional method of mixing. Kiselev et al., 2021 adopted a two-phase mixing method for mixing asphalt. Coarse aggregates and a portion of bitumen were mixed first, then the fine aggregates, filler remaining portion of bitumen was added. It was concluded that the two-phase mixing method improved the mechanical resistance in terms of splitting, fatigue, and rutting resistance. Wang et al., 2021 performed a study to compute the optimum number of gyrations for PA mixtures. It was found that both under and over-compaction can have a negative influence on the durability of PA mixtures and the computation of gyrations should be dependent on the traffic levels. It was concluded that the optimum number of gyrations for PA mixtures was 45 for low traffic levels and 75 for heavy traffic levels. In addition to compaction effort the type, size, and shape of aggregates influence the air void characteristics of the PA mixtures (Kusumawardani and Wong 2021; Dan, Jing, et al. 2021). Higher sphericity of aggregates contributes towards better compaction and thus enhances the mechanical performance of the PA mixtures (Kusumawardani and Wong 2021; Qian et al. 2021). For better compaction, a higher amount of fine aggregates (<1.18mm) and a lower amount of 2.36-4.75 mm-sized aggregates were suggested (Qian et al. 2021). In one study (Dan et al. 2021), the effect of deformation on the reduction of air voids was investigated by taking into consideration gradation type, air void content, and loading frequency under the hydraulic effect. At the same nominal maximum-sized aggregate (NMAS), the deformation resistance reduces on increase in air voids content. In addition, at higher saturation depth, the anti-deformation resistance was higher which means that PA mixtures have better performance while also storing water in their structure. This phenomenon may be due to a lower magnitude of effective stress due to the presence of water in the structure which is commonly observed in the soils. After the removal of moisture from the structure (during the moisture cycles), the load-carrying capacity of PA mixtures worsens due to high moisture susceptibility (Dan et al. 2021). Wang et al., 2021 investigated the effect of porosity, bitumen content, aging condition, and the temperature of the test on the low-temperature performance in terms of bending resistance of PA mixtures. The change in bitumen content was found to have a maximum influence on the tensile strength and bending strain (Wang et al. 2021; Ren et al. 2021). Under freeze and thaw conditions, the strength of the PA mixtures follows an exponential decay relationship indicating the strength reduces in the beginning, however, after conditioning cycles the damage becomes constant (Dan et al. 2021).

Various new materials can be incorporated in the bitumen or directly in PA mixtures to improve the performance of PA mixtures. Lu et al., 2021 developed a new bio-based epoxy asphalt binder by using epoxidized soybean oil to improve the raveling resistance and stability without reducing the permeability. Mikhailenko et al., 2021 investigated the possibility of using recycled concrete aggregates (RCA) aggregates that may enhance the rutting resistance. It was concluded that the RCA may improve the rutting resistance of PA mixtures. Xu et al., 2021 designed a porous asphalt mixture with polyurethane binder instead of asphalt binder, and different binder-aggregate ratios were assessed. The polyurethane mixtures showed better performance than the conventional asphalt mixtures. In addition, it was concluded that on increasing the binder-aggregate ratio, the pavement service performance improved. Also, an increase in viscosity of the binder enhances of cohesive strength of asphalt (Xiaowei et al. 2021), rutting resistance, low-temperature performance, and reduction in moisture susceptibility

(Hu et al. 2021; Ren et al. 2021). In one study on rubber-modified bitumen and SBS modified bitumen, it was found that the SBS copolymer enhances the low and high-temperature performance of the PA mixtures (Pakholak et al., 2021); whereas the performance of the crumb rubber modified binder depends on the swelling and degradation degree. Moreover, replacing 20% aggregate with rubber granulate reduces the stiffness of the PA mixtures (Pakholak et al. 2021).

Fibers can be incorporated in the PA mixtures to improve the mechanical performance of PA (S. Wang et al. 2019; Radzi et al. 2020; Zhang et al. 2021; Cheng, et al. 2019). In a study, sugarcane fiber was added to the PA mixture to improve the binder stability and increase stiffness. Ahn et al., 2021 assessed the suitability of geocell composites in the base layer of the PA pavement by plate load test, falling weight deflectometer, and rainfall simulation tests. On the use of these composites, the thickness of the base layer is reduced due to the provision of high elastic modulus.

Many researches were carried out to assess the behavior of asphalt mixtures using numerical methods such as finite element modeling, discrete element method, among others. Numerical methods result in high level of accuracy and act as more inexpensive options in contrary to laboratory testing that requires manpower and higher investment (Liu et al. 2021). Caro et al., 2021 assessed the long-term raveling susceptibility of the PA mixtures using finite element modeling and found that the raveling susceptibility depends vastly on the load magnitude, vehicle braking, and vehicle speed. Hu et al., 2021, simulated the clogging and degradation of air voids in double-layer porous asphalt pavement using discrete element method in combination with computational field dynamics (DEM-CFD) model. It was concluded that clogging depends mostly on the air voids of the upper layer of the PA mixtures and the clogging is reduced up to 34% due to two layers. In another study (J. Ren et al. 2021), the role of aggregate structure on the strength mechanism was evaluated using the 2D-DEM by computing mesoscopic contact force characteristics. It was concluded that the aggregate structure functions with strong contact forces and the aggregates of higher size (9.5-13.2 mm) contribute to the main body of the structure. Zheng et al., 2021 discuss the effect of dynamic load of vehicle tires on the pores of PA mixtures under hydrodynamic pressure and frost using MATLAB and finite element analysis. It was concluded the 2D numerical methods can only provide qualitative results and for quantitative results, experimental methods must be performed or 3D FE models must be developed (Liu et al. 2021).

3. Hypothesis and objectives

The main hypothesis of this thesis is that the limitations of porous asphalt mixtures in carrying high-intensity traffic are due to their conventional mix design and with certain modifications in design, it is possible to improve the durability of these mixtures. The additives have been known to improve the durability of asphalt mixtures, but certain fibers might provide higher benefits than others when used in porous asphalt matrices, which presently is largely unknown. Consequently, the main objective of this doctoral thesis is to study different alternatives and develop a framework for the improvement of the performance of porous asphalt mixtures. The structure of the research is presented in Figure 1, and the hypothesis & objectives corresponding to each phase are described below:

<u>Phase 1. Selection of additives based on multi-criteria performance.</u>

Hypothesis and main objective:

The additives may improve the mechanical performance of PA mixtures, however, their impacts on the economy and environment may be significantly different, which can be quantified and controlled. Therefore, the main objective is to investigate the improvement in overall performance based on mechanical, hydraulic, economic, and environmental indicators.

Particular objectives:

a. To assess the influence of a variety of additives on the mechanical and hydraulic performance of the PA mixtures.

b. To perform a multi-criteria decision-making analysis to contemplate the effect of incorporation of additives and assess which additive has the maximum influence on the performance of PA mixtures.

Summary of the research:

The mixtures are designed with the optimum amount of fibers by investigating the void characteristics, permeability, abrasion resistance, and indirect tensile strength test, and moisture susceptibility. The allotment of the weights of the criteria is done by considering ten possible case scenarios, multi-objective methods (CRITIC), and a questionnaire-based multi-subjective method (Delphi). For the selection of an alternative, WASPAS, EDAS, and TOPSIS are employed. Article 1 covers the mechanical performance of the additives in porous asphalt mixtures while Article 2 deals with the multi-criteria selection of additives based on mechanical, hydraulic, economic, and environmental factors.

<u>Phase 2. Preparation of experimental binder that can cater to the requirements of the PA mixtures.</u>

Hypothesis and main objective:

A new polymer-modified bitumen with a high-vinyl SBS copolymer may improve the raveling resistance of PA mixtures as compared to virgin bitumen and commercial PMB. The main objective is to prepare a stable bitumen that improves the raveling resistance of porous asphalt mixtures.

Particular objectives:

c. To develop a new stable bitumen by adding a high-vinyl content SBS polymer by trial and error approach.

d. To compare the physical and rheological properties of the new experimental bitumen with the commercially used virgin bitumen and polymer modified bitumen.

e. To use the experimental bitumen in porous asphalt mixtures and investigate its influence on the characteristics of porous asphalt mixtures.

Summary of the research:

The stability of the bitumen is assessed by storage stability and gelation tests. Experimental bitumen is compared to the virgin bitumen 50/70 and a commercial PMB 45/60-85. The performance of the three bitumen is analysed using physical tests and rheological tests. It is based on results obtained by dynamic shear rheometer (DSR), linear amplitude sweep (LAS), binder yield energy test (BYET), and multi-stress creep and recovery (MSCR) tests. Article 3 covers the fulfillment of this objective.

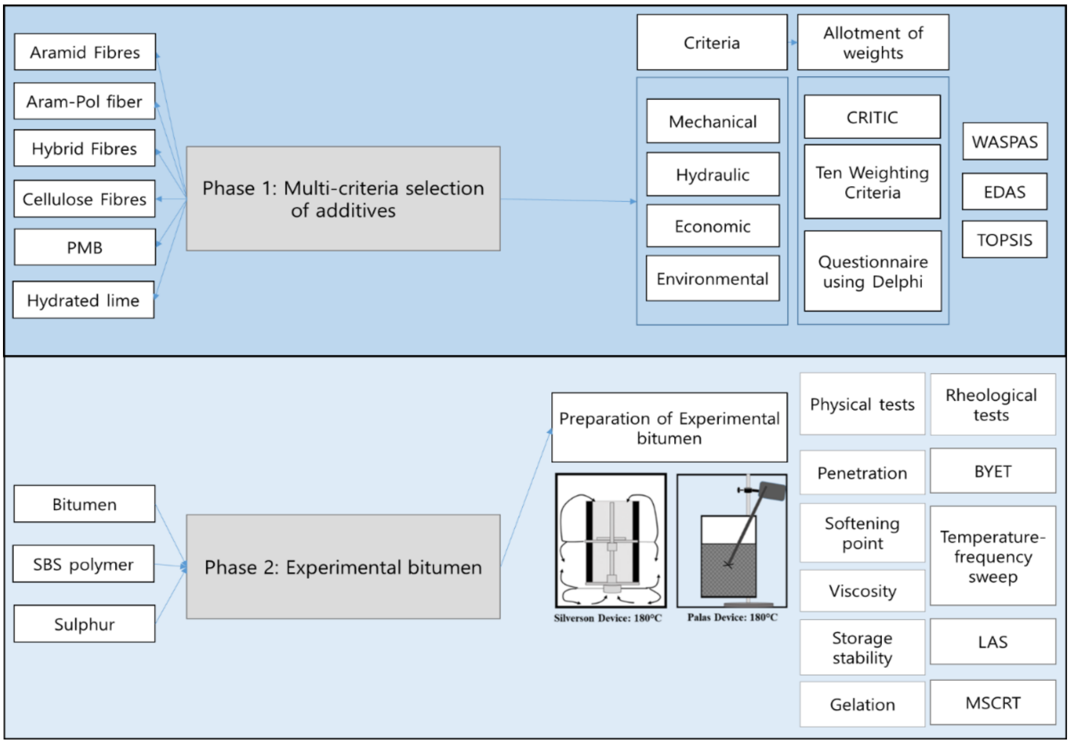

Figure 1. Structure of the study

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4. Methodology

In the first phase of the study, additives were incorporated in the asphalt mixtures, and they were analysed based on their mechanical, hydraulic, economic, and environmental impacts. The study of additives includes two types of binders, seven types of fibers, and two different fillers. The multi-criteria decision analysis (MCDA) was used to select the best additive that enhanced the PA mixtures.

In the second phase, a new experimental polymer modified bitumen was prepared at CEPSA's facilities Departmento Técnico de Asfaltos in CEPSA at Alcalá de Henares, Spain. The bitumen was prepared to enhance the properties of PA mixtures. This bitumen was afterward analysed based on the physical and rheological characteristics. Further, the variation on characteristics of the porous asphalt mixture with the binder was evaluated.

Consequently, the methodology section is divided into these two main phases:

Phase 1 Porous asphalt mixtures characterization: Assessment of mechanical, hydraulic, economic, and environmental indicators of using additives in PA mixtures and MCDA, done in the Roads Laboratory of the University of Cantabria.

Phase 2 Experimental bitumen: Preparation of new experimental polymer-modified bitumen for PA mixtures, done in CEPSA's facilities.

4.1. Materials

4.1.1. Bitumen and aggregates

In phase 1, PA mixtures were prepared with two different commercially available bitumen detailed in Table 4.

The selection of the base bitumen in phase 2 was fundamental. On addition of polymer, the viscosity and the penetration of the bitumen are reduced. Therefore, a soft bitumen of low viscosity and high penetration 70/100 was chosen to prepare the new experimental bitumen. The polymer for modification of the bitumen was styrene butadiene styrene (SBS) with high vinyl content (>35%) with sulfur as a cross-linker. The properties of the SBS polymer are given in Table 5. For the characterization and evaluation of the new experimental bitumen, two reference bitumen were used. The properties of the two reference binders are shown in Table 4.

For both phases, PA mixtures were prepared with a combination of Ophite aggregates for coarse fraction, and limestone as finer fraction and filler (size < 0.063mm). The aggregates were washed and dried to remove any dirt particles. The properties of aggregates are given in Table 6.

Table 4. Properties of bitumen used in the study.

Properties	Standards	Virgin bitumen 50/70 (VIRBIT)	PMB 45/80-65 (PMB)
Penetration, (0.1mm)	EN 1426	57	55
Softening Point (°C)	EN 1427	51.6	74.1
Density (g/cm3)		1.035	1,028
Elastic Recovery at 25ºC (%)	EN 13398	-	92
Frass Point (°C)		-13	-

Table 5. Typical values of polymer used in the study (Kraton D0243).

Properties	Standard	Typical Value
Tensile strength (MPa)	ISO37	2
Specific gravity	ISO 2781	0.94
Vinyl content (%)	KM03	>35
Hardness (shore A, 10sec)	ISO 868	70
Volatile matter (%m)	KM 04	≤0.3
Ash (%m)	ISO 247	0.2-0.5

Table 6. Properties of fibers and aggregates used in the study.

Properties	Standard	Value	Limits
Coarse aggregates			
Specific Weight (g/cm3)	EN 1097-6	2.787	-
Water absorption (%)	EN 1097 - 6	0.6	-
Los Angeles abrasion (%)	EN 1097-2	15	≤15
Flakiness Index (%)	EN 933-3	12	≤20
Sand equivalent (%)	EN 933-8	-	>55
Fine aggregates			
Specific Weight (g/cm3)	EN 1097-6	2.705	-
Flakiness Index (%)	EN 933-3	-	≤20
Sand equivalent (%)	EN 933-8	78	>55

4.1.2. Additives

A selected variety of eleven additives were used to try to enhance the performance of the PA mixtures (Figure 2). They were one alternative filler and 10 fibers: seven different types of aramid fibers, two different types of glass-hybrid fibers, and a cellulose fiber were investigated. The properties of the fibers used in the study are given in Table 7. In addition to limestone filler (control mixture), hydrated lime as filler was included in the study looking for improvements.

Table 7. Physical properties of the fibers.

Short name	Colour	Density (g/cm3)	Length (mm)	Tensile Strength (GPa)	Decomposition temperature (°C)	Remarks
ARA-POL	Aramid Yellow Polyolefin Yellow	Aramid 1.44 Polyolefin 0.91	19 19	Aramid 2.758 Polyolefin 0.483	Aramid > 450 Polyolefin 157	13% aramid fiber and 87% polyolefin fiber
PULP	Yellow	1.44	1-1.5	2.7–3.6	500	Aramid pulp: Waste from aramid fibers
ARA1	Yellow	1.44	6	2.7–3.6	500	Aramid fiber
ARA2	Dark Yellow	1.39	6	3.2–3.5	500	Aramid fiber
ARLat	Bronze	1.39	6	3.2–3.5	500	Aramid fiber, coating: Resorcinal formaldehyde latex (RFL)
ARPoly	Yellow	1.44	6	2.7–3.6	500	Aramid fiber, coating: Polyurethane
AR12	Yellow	1.44	12	2.7–3.6	500	Aramid fiber
GLCV	Gray to brown	0.55-0.75	1.1	2.0-3.0	-	Hybrid of cellulose fiber & natural glass fiber
GLST	Brown to black	0.35-0.55	1.1	>1	-	Hybrid of cellulose fiber & glass fiber+ synthetic fibers
CELLU	Brown	0.44-0.54	1.1		-	90% cellulose and 10% bitumen

Figure 2. Additives used in the study.

4.2. Specimen preparation

For phase 1 and phase 2, PA mixtures were prepared according to the Spanish guidelines PG3 (PG-3 Pliego de prescripciones técnicas generales 2001) with 16 mm as the maximum size of aggregates. The size distribution of all the aggregates is according to Figure 3. The minimum requirement of the air void content for PA mixtures is 20%. The filler content of 3% was kept constant throughout the whole study.

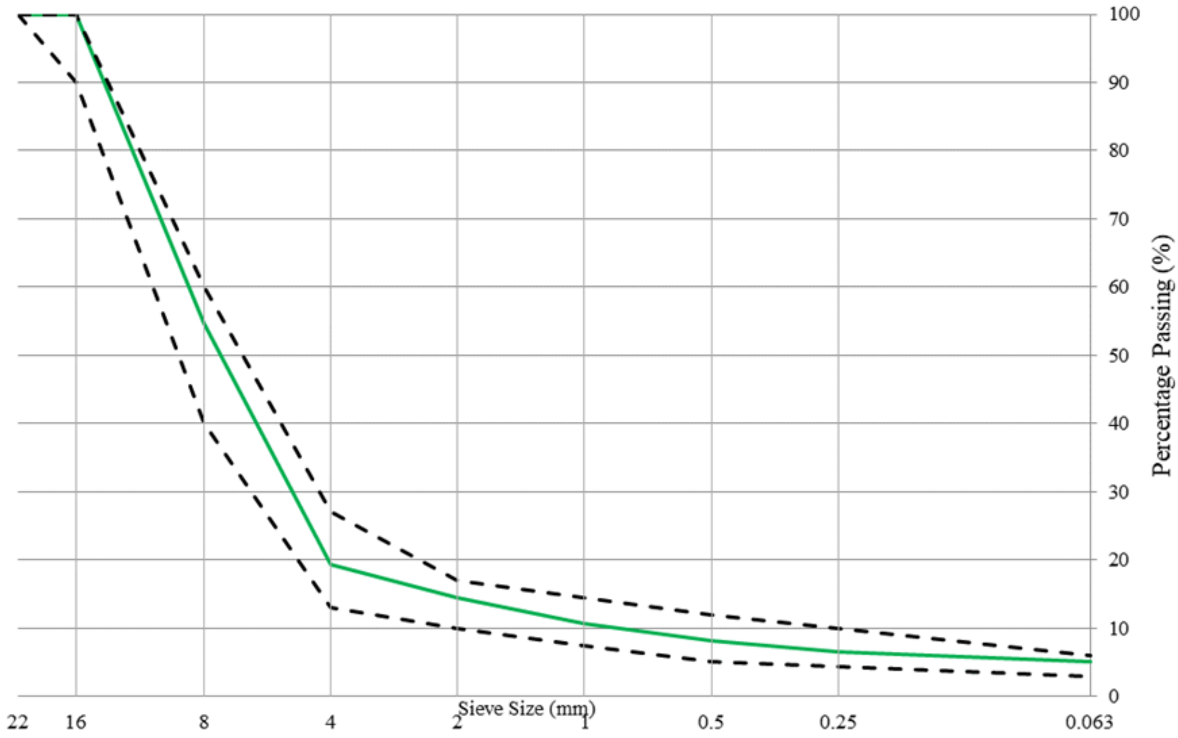

Figure 3. PA 16 design mixtures.

For the preparation of all the specimens, the aggregates were kept for heating at 170°C for 6 hours before mixing. After that, the fibers were added to the aggregates based on the dry mixing method and mixed for approximately 30s. The bitumen was heated at 150°C temperature for two hours and was added to the fiber-aggregate mixture (Figure 4) and mixed thoroughly for five minutes. Next, compaction was done by applying 50 blows on each side with a Marshall hammer according to EN 12697-34 and then specimens were left at room temperature for 24hours before being demolded.

The volumetric analysis was done according to the European standard EN 12697-8. The idea was to compare the mixtures under the same conditions and check whether fibers improve the properties of mixtures by themselves, without increasing the percentage of bitumen. Therefore, high binder content was not used. Due to a high volume of air voids, the binder drainage and abrasion loss are significant factors that determine the performance of the PA mixtures. It was found that the optimum bitumen content for aramid fibers was 4.5% and 5% for glass-hybrid and cellulose fibers.

Figure 4. Addition of fibers in the aggregates

4.3. Bitumen tests

The bitumen tests are conducted only in phase 2 for the analysis of the properties of the new experimental bitumen.

4.3.1. Storage Stability

After preparation of polymer modified bitumen, the polymer on heating can separate from the bitumen and can give rise to a coarse dispersion on cooling, which results in deposition of bitumen at the bottom and polymer at the top. The storage stability of modified bitumen can be influenced by factors such as amount, molecular weight and structure of polymer used, type of bitumen used, and storage conditions such as temperature, time, and mixing systems. While using a high amount of polymer, it is important to take proper care of this phenomenon, as the modified bitumen is more susceptible to disintegration. Sulfur vulcanization is done to improve the storage stability as it acts as a link between the bitumen and the polymer (The Shell bitumen handbook, 2003).

For sulfur vulcanization, a very small amount of sulfur is added. In this study, the amount of sulfur added is 0.05% of the total modified bitumen. The storage stability test is carried out as per ASTM D7173 or EN 13399. In this test, the fabricated bitumen is poured carefully to avoid the incorporation of air bubbles in the tubes of height 100 mm to 120 mm. The tubes are kept in the oven at a temperature of 180°C for 3 days, then they are cut into three equal parts. Later, the top and the bottom of the tube are tested for their penetration and softening point (Mubaraki 2018).

4.3.2. Gelation

In the previous section, it was described that the addition of sulfur is required to avoid the phase separation of the modified bitumen. However, the correct amount of sulfur is very important, as sulfur can lead to gelation of the modified bitumen and serious problems in the bitumen plants. The gelation test was performed by keeping a container of modified bitumen in the oven at the temperature of 180°C for 7 days and checked every day for signs of gelation.

4.3.3. Viscosity

The viscosity of the binder was determined by Brookfield viscometer according to EN 13302. The rotational viscosity of bitumen is normally determined at 135 or 150°C, but with Brookfield viscometer, the viscosity can be determined over a wide range of temperatures (i.e., between 120 and 180°C). The rotational viscometer test can determine the workability at the time of mixing and compaction stages of a bitumen (Saltan et al., 2017). The temperature influences the value of viscosity, due to the temperature rise, the bitumen tends to soften, and it hardens when subjected to a drop in temperature. Different varieties of bitumen have different characteristics and influences on viscosity due to temperature (Mubaraki 2018). Therefore, even if high viscosity bitumen is required in the case of PA mixtures, the high viscosity may lead to the requirement of high temperatures in the asphalt plants; this may lead to more economical and environmental effects (The Shell bitumen handbook, 2003).

4.3.4. Temperature-frequency sweep test

The temperature-frequency sweep test determines the stiffness and the phase angle of the bitumen. It is well known that the stiffness of the binder increases with aging which signifies that it hardens due to aging. The test was performed using the dynamic shear rheometer. The silicon molds were used to prepare samples of 8mm and 25mm diameter. In the present study, the stiffness and phase angle were determined at a wide range of temperatures 10°C to 80°C at 10°C range, to compute the low temperature as well as high-temperature performance. The distance between the two plates was kept 2mm for the 8mm spindle which was used for temperatures 10°C to 40°C. For higher temperatures of 40°C to 80°C, 1mm gap and 25mm geometry was used. The test samples of 8mm and 25mm diameters are shown in Figure 5.

The test was performed at the same frequency of 1.59 hertz. The top clamp is movable, the zero gaps are ensured by moving the top clamp, then the setting is done depending on the gap required based on the spindle used. After that a conditioning of 15 minutes is done where the temperature should not vary, then the equipment automatically takes reading. The dynamic shear rheometer setup is shown in Figure 6.

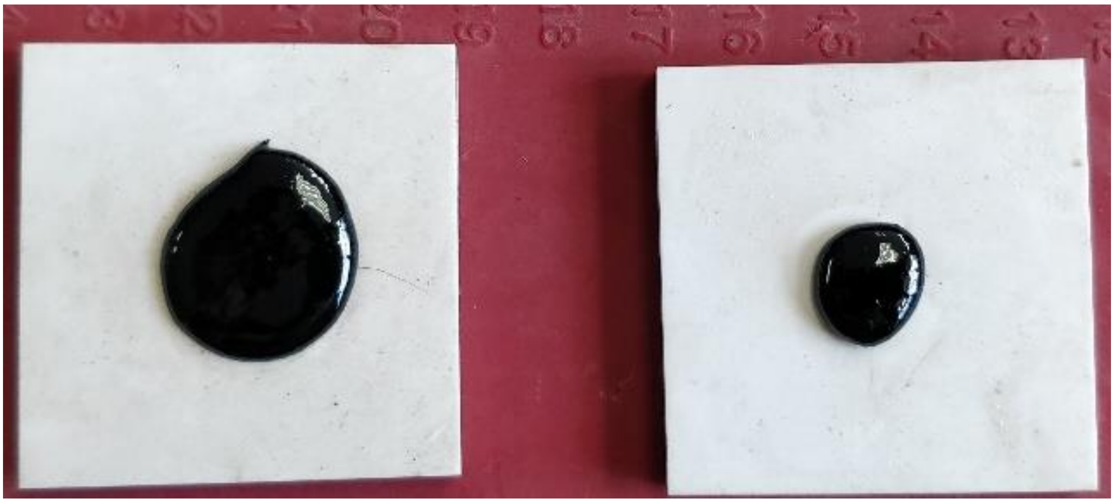

Figure 5. Bitumen samples for rheological tests.

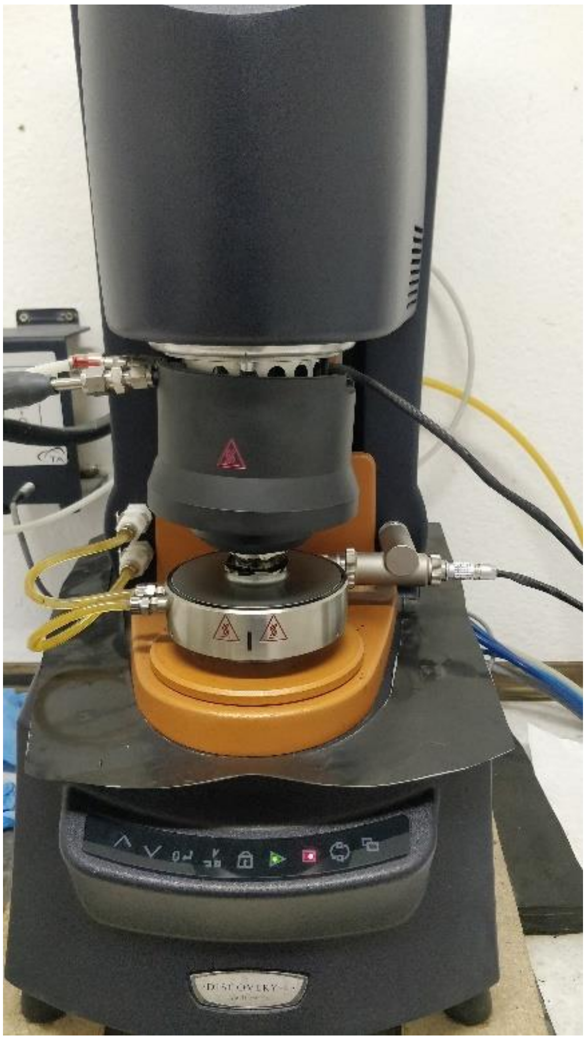

Figure 6. Dynamic Shear Rheometer setup (DSR)

4.3.5. Linear Amplitude Sweep (LAS) test

Linear amplitude sweep (LAS) test comprises two steps:

Frequency sweep: the frequency is increased from 0.2-30 Hz at 0.1% shear strain amplitude, this is done to obtain rheological properties within the linear viscoelastic range. A graph is plotted of storage modulus versus frequency. Then, the parameter B is computed from the slope of the graph (Equation 1)

$$\alpha = \frac{1}{m} \qquad (1)$$

Amplitude sweep: the amplitude of the shear strain is increased from 0.1 to 30% to assess the damage to the specimen. The parameter A is computed by visco-elastic continuum damage (VECD) theory.

A, B parameters are used to compute the total number of the cycles to failure (N_f) using Equation 2.

$$N_f = A.\ (\gamma_{max})^{-B} \qquad (2)$$

Where,

A is computed by visco-elastic continuum damage (VECD) theory

B = 2α

γmax = the maximum expected binder strain for a given pavement structure.

4.3.6. Binder Yield Energy Test (BYET)

In the binder yield energy test (BYET), a constant monotonic shear loading of the specimen at a constant shear rate is used to compute the fracture cracking. The main objective is to test the sample using a constant shear rate until the sample yields and peak shear strength is obtained. This test is conducted according to AASHTO TP 123 using the dynamic shear rheometer device with a 2 mm gap and 8 mm spindle at 25°C temperature. The constant strain rate of 2.315% s^{-1} is applied for 30 minutes until 4167% strain is achieved by the specimen. A stress-strain graph is plotted where the peak indicates the maximum yield stress and the area under the curve up to the strain corresponding to the maximum yield point indicates the binder yield energy.

4.3.7. Multi Stress Creep and Recovery Test (MSCRT)

The multi stress creep and recovery test (MSCRT) is performed to compute the stress sensitivity of bitumen at the selected temperature. This test was performed according to EN: 16659 with a 1 mm gap using a 25 mm spindle at 60°C. In this test, specimens were subjected to the constant stress of 0.1 kPa for 1s followed by 9 s rest, the process was terminated after 10 cycles. The percent recovery and non-recoverable creep compliance of the bitumen were computed and were averaged for the ten cycles to obtain the non-recoverable creep compliance (J_{nr}) and the percentage of recovery (%R) at the stress levels 0.1 kPa and 3.2 kPa. The parameter J_{nr} indicates the sensitivity of bitumen towards permanent deformation under the repetition of applied stress (Equation 3). The parameter %R (Equation 4) indicates the ability of bitumen to recover from deformation. It also estimates the degree of polymer modification in a binder. Equation 5 enables the calculation of the stress sensitivity of the binder.

$$\text{Non-recoverable creep compliance } (J_{nr}) = \frac{\text{non-recovered strain}}{\text{applied stress}} \quad (3)$$

$$\%R = \frac{\text{recovered strain}}{\text{Total strain}} \quad (4)$$

$$J_{nr\text{-}diff}\ (\%) = \frac{J_{nr3.2} - J_{nr0.1}}{J_{nr0.1}} * 100 \quad (5)$$

Where, %R is the percentage recovery, $J_{nr\text{-}diff}$ is the percentage of variation of the non-recoverable creep compliance value corresponding to stress level 3.2 ($J_{nr3.2}$) compared with the non-recoverable creep compliance value corresponding to the stress of 0.1 kPa ($J_{nr0.1}$).

4.4. Porous asphalt mixture tests

4.4.1. Air Voids

Air void content is the most important parameter that influences the structural as well as functional characteristics of the PA mixtures. PA mixtures with high air voids have high permeability, they can drain a large amount of water through their structure. However, PA mixtures with high air voids have low durability due to limited resistance towards raveling and cracking. According to Spanish guidelines, the minimum amount of air voids in PA mixtures is 20%. The air voids were calculated using European standards EN 12697-8. Air void content was calculated using Equation 6.

$$\text{Air void content} = \frac{\text{Maximum density} - \text{bulk density}}{\text{Maximum density}} \quad (6)$$

4.4.2. Permeability test

Permeability tests were performed to understand the hydraulic functionality of the PA mixtures and their ability to permeate water. In this study, permeability tests were conducted by using a radial flow falling head permeameter. The permeability was measured in terms of the time of discharge which indicates the time taken in seconds for a specified volume of water to pass through a compacted sample. The test is performed at 25°C.

Permeability (k) is calculated using Darcy's law shown in Equation 7.

$$k = 2.3\,\frac{aL}{At}\left[\log\left(\frac{h_1}{h_2}\right)\right] \quad (7)$$

Where a is the area of the tube (cm^2), L is the thickness of the specimen (cm), A is the area of the specimen cross-section (cm^2), t is the time for water to flow water from heights of water h_1 to h_2 (cm).

4.4.3. Cantabro test

Since raveling is one of the most common types of failures that are presented in PA mixtures (Mo et al. 2010)(Y. Zhang and Leng 2017)(Manrique-Sanchez, Caro, and Arámbula-Mercado 2018). The Cantabro test in dry and wet conditions was chosen to characterize raveling. The Cantabro test is conducted following EN 12697-17, similar to the Los Angeles test but without the steel balls. The initial weight of the PA mixtures sample is noted, then the sample is placed in the Cantabro machine for 300 revolutions. Afterwards, the samples are removed from the machine and weighed again. The particle loss is the difference between the initial and final weight of the sample. Wet Cantabro test is conducted to compute the particle loss in wet conditions according to Spanish NLT 362/92. In wet Cantabro test, the samples are kept at 25°C then they are immersed in 60°C for 24 hours and then the samples are again kept at 25°C and allowed to drain further. After that, the same procedure is followed to calculate the particle loss. The maximum particle loss in dry and wet conditions is limited to 20 and 35% respectively.

4.4.4. Draindown test

Draindown test is of particular importance in PA mixtures due to their high air voids. This is because, at elevated temperatures, the binder tends to drain from the aggregate structure. This test is conducted according to EN 12697-18. In this test, the uncompacted mixture is placed in the wire mesh basket positioned on a dry paper/plate. Further, the entire set is placed in the oven for 3h at the test temperature. Then the set is removed from the oven and the paper/plate is weighed again. The binder draindown is computed by Equation 8. The binder draindown value must not exceed 0.3%.

$$\text{Binder draindown} = \frac{\text{final paper/plate weight} - \text{initial paper/plate weight}}{\text{Initial mixture weight}} \qquad (8)$$

4.4.5. Indirect tensile strength test and moisture susceptibility

The indirect tensile strength is computed according to EN 12697-23 in dry and wet conditions. Four replicates were prepared for each dry and wet condition using Marshal Compactor. The specimens at dry conditions were kept at ambient temperature for 24h before performing the test. A material testing system is utilized to determine the ITS, with a maximum capacity of 100kN. The test is done at a constant rate displacement of 50mm/min. For the wet conditions, the samples are kept in distilled water for 30 minutes in a vacuumed vessel filled at ambient temperature than are kept for 68-72 hours at 40 ºC. The replicates of all mixture types are then placed at 15ºC for 3hours before breaking every sample. The maximum load at which the failure occurs is the indirect strength of the sample. Indirect Tensile

Strength Ratio (ITSR) is representative of moisture susceptibility of the mixture, low ITSR signifies that the samples are more sensitive to the presence of moisture. The Indirect Tensile Strength Ratio (ITSR) is calculated according to Equation 9, according to EN 12697-12. ITSR of 85% is required to pass the minimum requirements (Spanish guidelines).

$$\text{ITSR} = 100 \times \frac{\text{ITS}_\text{w}}{\text{ITS}_\text{d}} \quad (9)$$

Where ITS_w is the Indirect Tensile Strength of moisture-conditioned samples specimens and ITS_d is the Indirect Tensile Strength of unconditioned specimens.

4.4.6. Toughness

Fracture toughness represents the ability of resistance towards fracture of any material when there is the existence of initial cracks in the body (Kim and El Hussein 1997). The toughness of the samples is the area under the stress vs strain curve (Figure 7), which is the sum of Fracture Energy (F.E) and Post-cracking Energy (P.E). Fracture energy is the area under the curve until the maximum stress (σ_{max}) is achieved, it represents the cracking resistance of the sample. The post cracking energy represents the ductility of the pavement, and it is the area under the curve from the strain at which maximum stress is achieved until the double of such strain (from ε_{max} to $2\varepsilon_{max}$). To calculate the toughness, for every load level, the displacement incurred is recorded by a data acquisition system. The stress and strain are calculated with Equation 10.

$$\text{Stress } (\sigma) = \frac{2P}{\pi Dt} \qquad \text{Strain } (\varepsilon) = \frac{\Delta D}{D} \quad (10)$$

Where P is the load (kN), D is the diameter of the specimen (mm), t is the thickness of the specimen (mm), ΔD is the deformation and D is the initial diameter of the specimen.

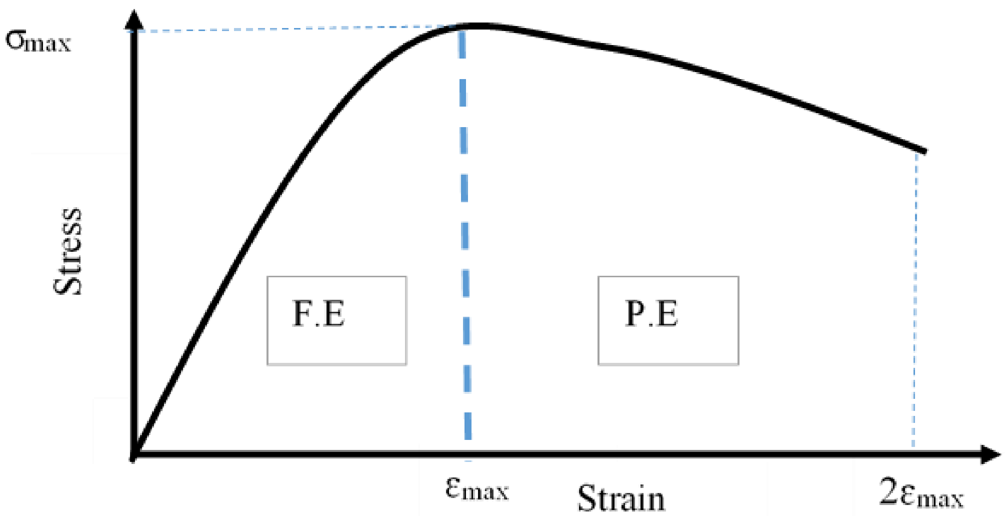

Figure 7. Indirect tensile strength, fracture energy, and post-cracking energy: the curves obtained from the ITS test.

4.4.7. Statistical analysis

The accuracy of the results was confirmed by statistical analysis using the Minitab software. For checking the normality and homoscedasticity of the data, the Anderson–Darling normality test was used. Data that follow normal distribution are analysed by one-way analysis of variance (ANOVA) and two sampled Student tests were performed. For the non-normal data, non-parametric Kruskal Walls and Mann-Whitney U tests were performed. The statistical analysis tests were performed with a confidence level of 95%. That signifies if the p-value is less than 0.05, the null hypothesis is rejected.

4.5. Multi-criteria analysis

Multi-criteria analysis is a technique to select the best alternative based on a set of criteria. The selection of additive for the porous asphalt mixture depends on many factors such as the influence of fibers on the strength of PA mixtures, or the influence on the permeability to not reduce the hydraulic performance of the PA mixtures. Moreover, the effect of fibers on the economy and their associated concerns on the wellbeing of the society. Therefore, in this study, the selection of additives was done by performing a multi-criteria analysis by considering four main criteria: mechanical, hydraulic, economic, and environmental. The impact of the additives was quantified based on the sub-criterion given in Table 8. After the statement of the selected criteria and sub-criteria, there are two stages of multi-criteria analysis: weighting and selection of alternatives.

Table 8. Criteria and parameters for multi-criteria decision-making analysis.

Criteria	Sub criteria
Mechanical	Particle Loss (PL) - dry
	Particle Loss (PL) - wet
	Indirect Tensile Strength (ITS) - dry
	Indirect Tensile Strength (ITS) - wet
Hydraulic	Air void content
Economic	Initial cost
Environmental	Global Warming Potential (GWP)
	Human Toxicity Potential (HTP)
	Marine Aquatic Eco-toxicity Potential (MAETP)

For the allotment of weights, based on the individual importance of the criteria, the weights are allotted. For instance, in the rainy regions where the traffic is low, the importance of hydraulic criteria is higher than the importance of mechanical performance. Therefore, it is fundamental to allot correct weights to all the criteria in each specific case. In this study, three different methods to allot weights were used: CRITIC, DELPHI, and 10 possible case scenarios. CRITIC method is used to compute objective weights, a criterion is normalized based on its being beneficial or non-beneficial. Meanwhile, in the Delphi method, the weights are allotted by aggregating the opinions of the experts in the field. Delphi is an iterative method in which multiple questionnaires are sent to the experts to enhance the accuracy of the weights. The third method used to allot the weights involves assuming 10 possible case scenarios based on experience and literature review. Details about the procedure and equations involved in the CRITIC method are explained in Article 2 of the present study whereas for the DELPHI method the detail of the procedure is explained in Article 3. While the ten possible case scenarios used for the present study are given in Table 9.

For multi-criteria decision-making analysis, three tests were performed to select one alternative. The methods used in the study are: Technique for order of preference by similarity to ideal solution (TOPSIS), weighted aggregated sum product assessment (WASPAS), and evaluation based on distance from average solution (EDAS). TOPSIS method is based on the hypothetical ideal and nadir solutions. The best solution has the minimum distance from the ideal and the maximum from the nadir solution. WASPAS method is a combination of the weighted sum method and weighted product method. While the EDAS method is based on the distance of the criterion from the average solution. More information and procedures of the three methods are detailed in section 2.1 of Article 3.

Table 9. Objective weights according to weighting case scenarios

Case	Air voids	Permeability	Particle Loss		ITS		Explanation
			Dry	Wet	Dry	Wet	
1	0.167	0.167	0.167	0.167	0.167	0.167	Equal importance
2	0.3	0.3	0.1	0.1	0.1	0.1	P = AVC > PL= ITS
3	0.1	0.1	0.3	0.3	0.1	0.1	PL > ITS = AVC = P
4	0.1	0.1	0.1	0.1	0.3	0.3	ITS > AVC = P = PL
5	0.2	0.2	0.2	0.2	0.1	0.1	AVC = P = PL > ITS
6	0.1	0.1	0.2	0.2	0.2	0.2	PL = ITS > AVC = P
7	0.2	0.2	0.1	0.1	0.2	0.2	AVC = ITS > PL
8	0.1	0.1	0.25	0.25	0.15	0.15	PL > ITS > AVC
9	0.1	0.1	0.15	0.15	0.25	0.25	ITS > PL >AVC
10	0.25	0.25	0.15	0.15	0.1	0.1	AVC > PL > ITS

P= permeability, AVC= air void content, PL= Abrasion Loss, ITS= Indirect Tensile Strength

4.6. Environmental analysis

To analyse the additives from the environmental point of view, a life cycle assessment (LCA) was performed considering as a functional unit the production of 1 ton of each asphalt mixture. Based on the ReCiPe midpoint method, evaluating all the impact categories normally included in an LCA would substantially increase the complexity of the MCDM; therefore, the impact categories were selected based on the ease, relevance, and importance in the Delphi questionnaire considering the diverse backgrounds of all the experts. These are the three impact categories (IC) that were considered as the most relevant: Global Warming Potential (GWP) under climate change IC group, Human Toxicity Potential (HTP) under human toxicity IC group, and Marine Aquatic Eco-Toxicity Potential (MAETP) under ecotoxicity IC group. Life cycle assessment is done to calculate the environmental impact of a product throughout its life cycle, following the standards ISO 14040:2005 and 14044:2006. The LCA methodology consists of 4 interrelated stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results.

The goal of this LCA was to determine the environmental impact of PA mixtures, which contain different types of additives to feed the multi-criteria analysis. In the case of Global Warming and Human Toxicity Potential, these receive the highest score in the weighting factors proposed by (Lizasoain-Arteaga et al. 2019), which are an average of those recommended by the EPA, BEES, NOGEPA, and BREE (Abbe and Hamilton 2017)(Huppes and Van Oers 2011). In the case of Aquatic Eco-toxicity Potential, it was the impact that underwent the greatest variation in a previous study, which compares a reference mixture with another containing ARA-POL (one of the additives also used in this study). In addition, the selected impact categories were considered to be wide enough for the bituminous mixture experts answering the survey to understand what they imply. The sources and transportation distances employed to create the inventory can be checked in Table 10.

Regarding fiber, some specific considerations were taken into account. Cellulose fibers used in the study contained 90% of cellulose and 10% of bitumen. According to the provider, cellulose fibers contain recycled wastepaper, its percentage varying depending on its quality. For the analysis, wastepaper fibers were used as the main raw material. FortaFi is composed of 13% of aramid fiber and 87% of polyolefin fiber. As no information regarding the type of polyolefin used was found, polystyrene was assumed for this work. Aramid fiber production process is available in GaBi but aramid pulp is not available. As the manufacturer published the manufacturing process and the GWP impact of both materials, the difference among them was considered to be caused due to an increase in electricity consumption. The CML 2001 (January 2016 update) characterization method was selected for the impact calculation since is the method recommended in the standard EN 15804-2012 regarding the Environmental Product Declaration rules for the construction products.

Table 10. Sources and transportation distances required for inventory.

Material/process	Inventory source	Transport distances (km)	
		Truck	Ship
Coarse and fine aggregates production		30	-
Limestone filler production	Gabi V9.1	30	-
Bitumen production	(Eurobitume 2012)	100	-
VIATOP production	Gabi V9, (Eurobitume 2012)	1,000	-
FortaFi production	Gabi V9.1	-	12,570
Aramid fiber production	Gabi V9.1	1,520	-
Aramid pulp production	Gabi V9.1,	1,520	-
Hydrated lime production	Gabi V9.1	70	-
Asphalt mix production		-	-
Transportation	Gabi V9.1	-	-
Energy production	Gabi V9.1	-	-
Fossil fuel combustion	(NREL 2012)	-	-

5. Published Articles

5.1. Article 1: Selection of fibers to improve porous asphalt mixtures using multi-criteria analysis

5.1.1. Information and impact factor

- Authors: Anik Gupta, Daniel Castro-Fresno, Pedro Lastra-Gonzalez, and Jorge Rodriguez-Hernandez
- Year: 2020
- Journal: Construction and Building materials
- Journal category and position (2021): Engineering, Civil (7/136) – Q1
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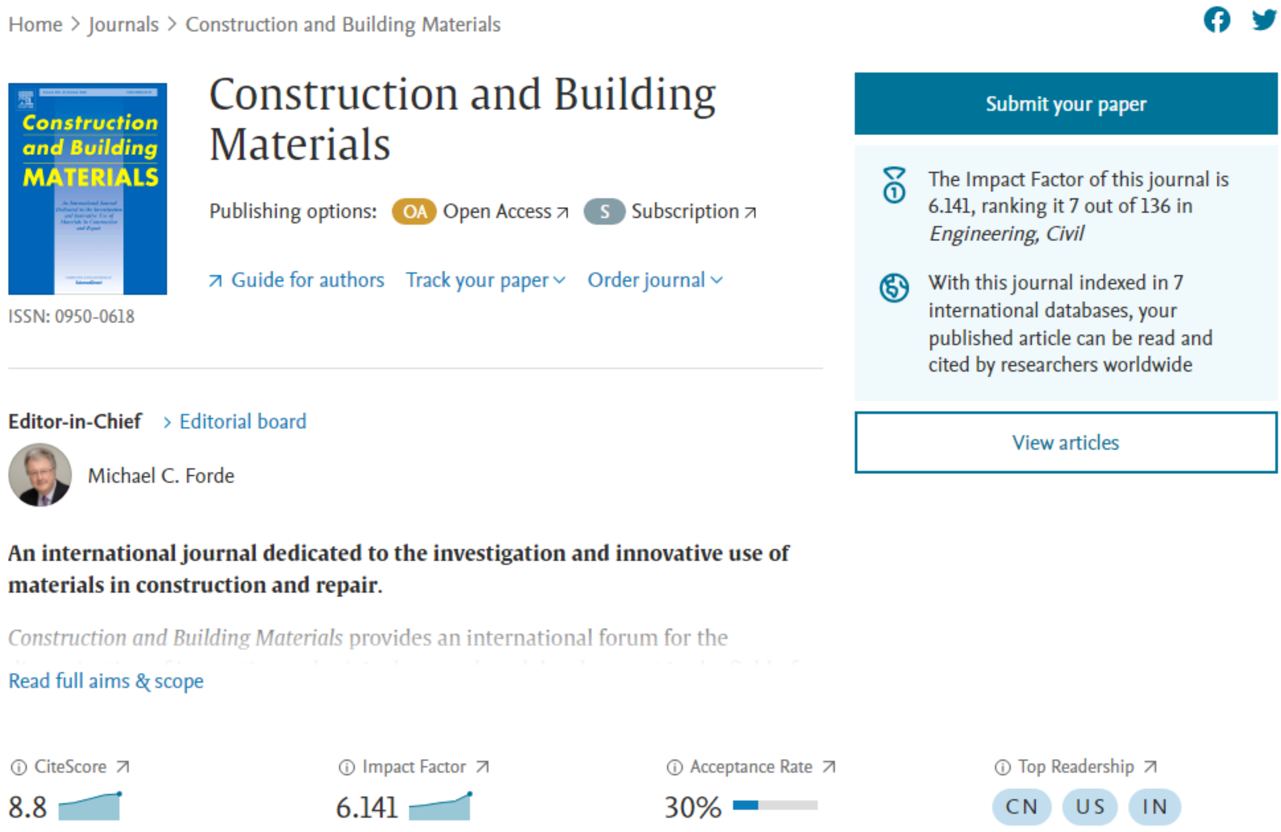

Figure 8. Information of the journal (Article 1)

5.1.2. Transcription of Article 1 (post-print version)

Selection of fibers to improve porous asphalt mixtures using multi-criteria analysis

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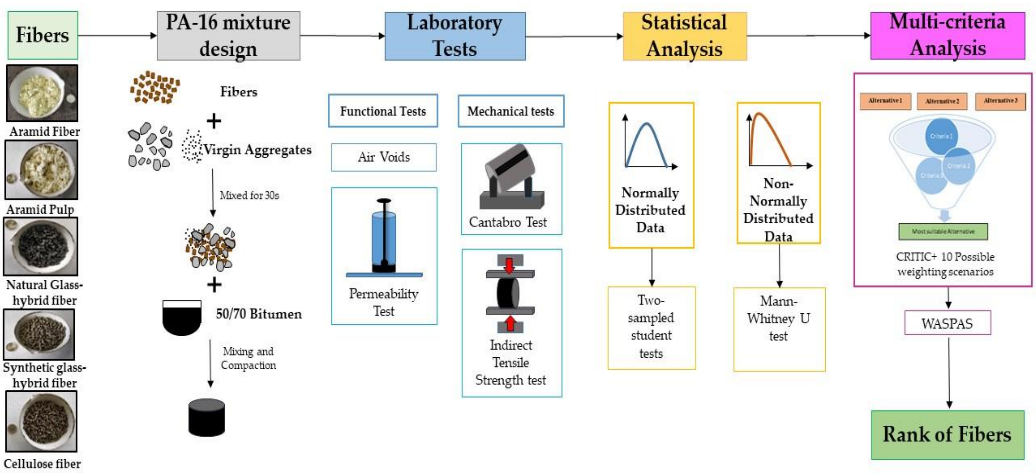
Abstract

Aramid fibers and glass fibers are widely used in dense-graded asphalt mixtures to improve the mechanical characteristics. However, their effect on the characteristics of porous asphalt mixtures has not been widely explored. This study evaluated the influence of aramid fiber, aramid pulp, glass-hybrid fibers and cellulose fibers, to improve the abrasion resistance and strength of the porous asphalt mixtures while maintaining their functional characteristics. The performance of PA-16 mixtures incorporated with fibers was evaluated using Cantabro test, permeability test, indirect tensile strength test (ITS) and moisture susceptibility test. Finally, a multi-criteria decision method (MCDM), weighted aggregated sum product assessment (WASPAS) in combination with criteria importance through inter-criteria correlation (CRITIC) as weighting method, is applied to make a multifaceted decision and select the best option among fiber. Results concluded aramid pulp remarkably enhanced the abrasion resistance while glass-hybrid fibers improved the ITS of the mixtures. Particularly, aramid pulp was selected as the best fiber to improve the mechanical resistance, according to the proposed methodology.

Keywords**:** porous asphalt, Cantabro test, permeability, open-graded mixtures, aramid, glass, synthetic, fibers, multi-criteria, MCDM, WASPAS.

Graphical abstract



1. Introduction

Permeable pavement systems (PPSs) have been accepted worldwide as they are driving the asphalt industry towards more sustainable solutions. In regions of high rainfall, these draining pavements can transfer the rainwater to groundwater level quickly, postponing flash floods and reducing the requirements of the drainage system [1]. Zhu et al. 2018 [2] reported that the use of PPS can lower surface runoff and flood peak by up to 50%. PPSs have been used extensively due to their ease of implementation [3]. The benefits of porous asphalt (PA) mixtures as surface layer are well documented due to their good noise reduction and skid resistance properties [4, 5, 6]. The open-graded structure of porous asphalt mixtures reduces the water splashing and spraying in rainy seasons as well as imparting safety to the pavement [7, 8].

PA mixtures contain higher volumes of air voids as compared to dense-graded mixtures to allow water to pass through their structure. For this reason, these mixtures are designed with gap-graded size distribution, containing a higher percentage of crushed stones [9]. Due to the lower amount of fine aggregates, these porous mixtures may not have enough durability and stability for some applications. The interaction between coarse aggregates lacks consistency as the binder is not able to hold them together. Due to traffic load and environmental factors, the aggregates start loosening and problems like raveling become prevalent. Raveling has been reported as the most serious problem in PA mixtures [10, 11]. Additionally, these kinds of structures are more exposed to oxidation, corresponding to a higher rate of ageing as compared to dense-mixtures. Opara [12] reported that raveling is dependent on the age of the pavement and traffic volume. The incorporation of new generation materials has helped to limit the raveling of porous asphalt layers[10]. For the last three decades, the use of additives has become increasingly more common in PA mixtures.

A number of additives have been used in the PA mixtures like nano-silica, rubber, warm-mix additives, low-density polyethylene, polymer-modified bitumen and fibers [13], [14], [15], [16], [17]. Nano-silica not only improves the durability of PA mixtures but also enhances their resistance towards moisture susceptibility [15, 16]. Cetin, 2013 [6] reported that due to higher void ratios, there is a requirement of highly viscous binder in the case of PA mixtures. Highly viscous binders are more resistant to permanent deformation and have higher strength, whereas modified binders with high polymer content improve indirect tensile strength and resilient modulus [18]. In PA mixtures, the most commonly used fibers are cellulose fibers [19], [20], [21, 22], which retain the binder and reduce binder drainage, enabling an increase in its percentage. In stone mastic asphalt mixtures, it is found that cellulose fiber increases the stiffness [23]. Ma et al. [24] combined hydrated lime, cellulose, mineral and polymer fiber with PA mixtures, and concluded that polyester and mineral fiber had positive effects on the durability of PA mixtures. Haryati [25] studied the effect of natural fibers: coconut shells and fibers in the PA mixtures and found that the natural fibers improve the stability and rutting resistance. Glass fibers are used in the asphalt mixtures as they impart high strength, lesser fatigue cracking and less moisture susceptibility that are primary concerns in the asphalt mixtures [26]. Another study by Luo et al. [27] pointed out that glass fibers have remarkable mechanical properties, and their addition may lead to increases in ductility and high temperature performance as well [27][28]. Slebi-Acevedo [29] analysed the energy parameters such as toughness and fracture energy by incorporating aramid plus polyolefin fiber and homopolymer polyacrylonitrile (PAN) synthetic fiber in PA mixtures. It was concluded that in dry conditions additions of fibers improve the ITS whereas fibers had negative influence as it was observed on the moisture susceptibility. Badeli et al. [30] investigated the use of aramid fiber to reinforce dense-graded asphalt mixtures and found that at high amplitude, the fatigue life is higher than that of the mixtures with no fibers, as their addition results in higher cohesion in the binder. However, their effect on porous asphalt mixtures still needs to be properly analysed.

Nevertheless, it is still not clear which fiber is most suitable for different porous asphalt conditions such as high rainfall areas, where permeability is of utmost importance; regions of heavy traffic where the most important parameter is structural strength; or at intersections where particle loss should be negligible. Moreover, the studies done in the past involve reinforcement of dense-graded asphalt mixtures using aramid fibers; however, no significant literature was found on the use of aramid fibers or use of combinations of different fibers in porous asphalt mixtures. Besides, the comparison among the mentioned fibers when added to PA mixtures should be evaluated in detail.

Comparison of fibers or selecting the most appropriate fiber for a given pavement condition can be done by employing multi-criteria analysis. Multi-criteria decision analysis is widely used to select the best choice among a set of alternatives taking into consideration a number of criteria. Studies have used multi-criteria analysis to evaluate the performance of asphalt mixtures [31, 32, 33, 34]. The criteria are assigned weights according to their relative importance in the outcome. Traditionally, the analytic hierarchy method (AHP) developed by Saaty [35] is commonly used to compute the relative importance of the indicators in the field of infrastructure management [31, 32, 33, 36, 37]. This method transforms subjective assessments into numerical scores based on pairwise combinations. In AHP, experts are asked for their opinion based on their experience in the field. In contrast, the criteria importance through inter-criteria correlation (CRITIC) method is based on an objective statistic approach to assign weights to the criteria. This method omits the necessity of human involvement. Furthermore, it differentiates each criterion based on best and worst value. The normalization of each criterion is done on the basis of whether it is a beneficial or non-beneficial criterion [38].

The WASPAS method is the linear combination of the Weighted Sum Model (WSM) and Weighted Product Model (WPM) methods. WSM and WPM are popular methods, however, they suffer from some disadvantages like high susceptibility to units' ranges and overestimation of definite scores [39]. WASPAS increases the accuracy of WPM by up to 30% and 60% in the case of WSM [40]. Slebi-Acevedo et al. [41] carried out a multi objective optimization using the CRITIC-TOPSIS methodology in porous asphalt mixtures. In another study, a stochastic optimization model was developed by Noori et al. [42] for selecting the most suitable reflective cracking mitigation solution. Jato-Espino [33] used multi-criteria analysis in selection of asphalt wearing courses in roads subjected to heavy traffic. To consider the variability and vagueness of the results, fuzzy logic was also applied. This research utilizes the WASPAS methodology to select the most suitable fiber in different case scenarios, which is done by calculating objective weights using the CRITIC method and ten additional case scenarios that consider real-life pavement conditions.

2. Objective and scope

The objectives of this study are as follows:

- To evaluate the mechanical and functional characteristics of porous asphalt mixtures using five different types of fibers, adopting a laboratory and statistical approach.
- To perform a WASPAS based multi-criteria analysis using 1+10 objective weights (1 CRITIC and 10 hypothetical case scenarios) to rank the fibers based on their performance. The structure of the study is described in Fig. 1.

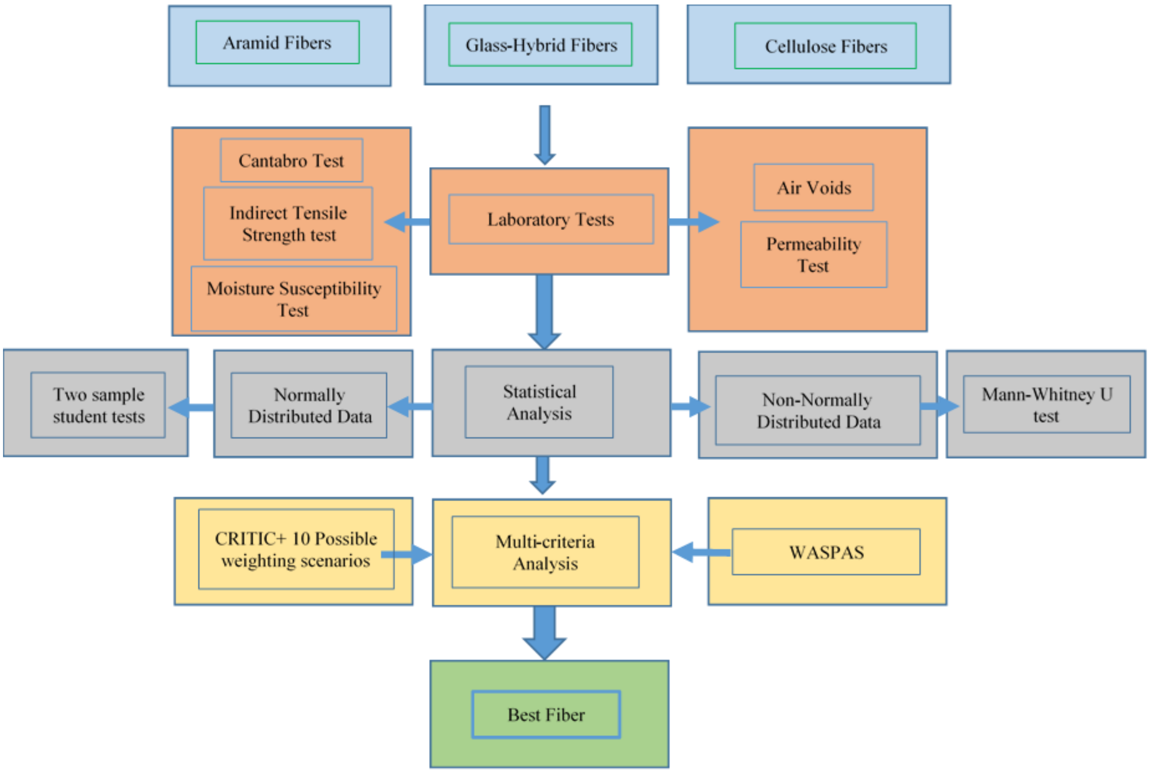


Figure 1. Structure of the study

In this study, aramid fibers were designed with a 4.5% bitumen content whereas glass-hybrid fibers & cellulose fibers were with 5% bitumen content. As aramid fibers were expected to work by strengthening the mortar while glass-hybrid & cellulose fibers are expected to strengthen the mortar as well as retain a certain amount of bitumen, the asphalt mixture required a higher bitumen content in the latter case. It is important to highlight here that in this study we are comparing the 'mixtures with different fibers' mechanically and in conventional conditions instead of 'designing a best mixture'.

Laboratory tests conducted include the Cantabro test for abrasion resistance, permeability test, indirect tensile strength test and moisture susceptibility test. Then statistical analysis was done to compute the effectiveness of using each fiber. In the second part of the study, a combination of CRITIC-WASPAS was proposed to select the best fiber and rank the fibers that can be incorporated into porous asphalt mixtures for maximum improvement in the mechanical resistance and minimum reduction in the permeability of the mixtures. To compute the weights of the criteria, in addition to CRITIC, ten weighting cases were considered to include different scenarios and check the accuracy of the CRITIC method.

3. Experimental work

In this study, a total of 112 samples were prepared. The porous asphalt mixtures were designed to target the PA-16 gradation curve shown in Fig. 2. This gradation will ensure fulfilling the minimum requirement of 20% air voids content. A total of 12 PA mixtures were designed in this study according to European standards for draining bituminous mixtures (EN 13108-7) and the Spanish guidelines "General Technical Requirements for Works of Roads and Bridges" (PG-3).

3.1. Materials

A bitumen with semi-hard penetration grade 50/70 was used for preparing the mixtures, in combination with Ophite as coarse aggregate and limestone as fine aggregate and filler passing a 0.063mm sieve. The properties of the bitumen and aggregates used are given in Table 1. Five different types of fibers were used, whose properties as given by the suppliers are given in Table 2: 2 types of aramid fibers (regular aramid fiber and an aramid pulp), 2 different types of glass-hybrid fibers (one hybrid of glass fiber and cellulose fiber and another hybrid of glass fiber, cellulose fiber and synthetic fiber), and one cellulose fiber. The description of the mixture types is given in Table 3.

Five extra combinations (mixtures with aramid and two glass-hybrid fibers, each with binder contents of 4.5% and 5%; and aramid pulp with cellulose fibers) were also prepared. The mixtures that are prepared by the aramid fibers (AR and ARPL) are prepared with 4.5% bitumen content and the rest of the mixtures (GLCV, GLST, and CF) with 5% bitumen content as the latter retain a part of bitumen that allows increment in bitumen content. A range of bitumen content and fiber content is chosen to compare the fibers on a neutral ground. The range considered was based on the previous experience; and the literature available for the given fibers [28, 32, 43]. These mixtures are explained in detail in the combination of fibers section 5.6. The fibers used in the study are shown in Fig. 3.

3.2. Sample preparation

Firstly, the aggregates were kept for heating at 170°C for 6 hours before mixing. After that, the fibers were added to the aggregates and mixed for approximately 30s. The bitumen was heated at 150°C temperature for two hours and was added to the fiber-aggregate mixture and mixed thoroughly. Next, compaction was done by applying 50 blows on each side with a Marshall hammer according to EN 12697-34 and then specimens were left at room temperature for 24hours before being demolded.

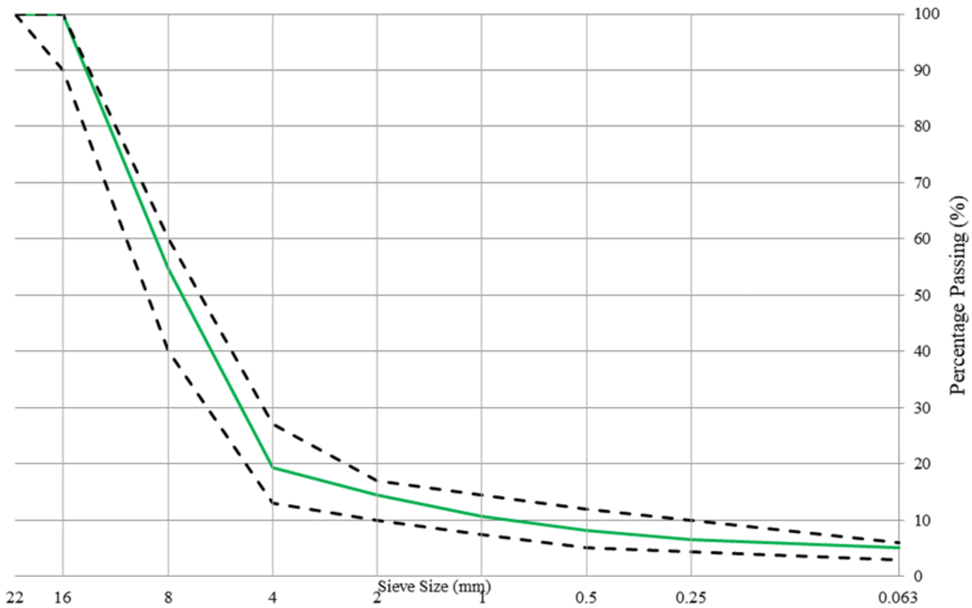


Figure 2. PA-16 design mixtures

Table 1. Properties of materials used for preparation of the sample

Properties	Standards	Value	Specification
	Bitumen 50/70		
Penetration, (0.1mm)	EN-1426	57	50-70
Softening Point (°C)	EN-1427	51.6	46-54
Frass Point (°C)	EN-12593	-13	≤ -8
Specific Weight (g/cc)	EN-15326	1.035	
	Coarse aggregates		
Specific Weight (g/cm^3)	EN 1097-6	2.787	
Los Angeles (%)	EN 1097 - 2	15	≤15%
Flakiness Index (%)	EN 933-3	12	≤20%
	Fine aggregates		
Specific Weight (g/cm^3)	EN 1097-6	2.705	
Sand equivalent (%)	EN 933-8	78	>55

Table 2. Physical properties and composition of the fibers

Fibers	Color	Density	Tensile strength (GPa)	Length (mm)	Material
AR	Yellow	1.44	2.7-3.6	6	Regular aramid fiber
ARPL	Yellow	1.44	2.7-3.6	1-1.5	Aramid pulp
GLCV	Gray to brown	0.55-0.75	2-3	4-10	Hybrid of cellulose fiber & natural glass fiber
GLST	Brown to black	0.35-0.55	>1	5-10	Hybrid of cellulose fiber & glass fiber+ synthetic fibers
CF	-	0.44-0.54	-	1.10	Cellulose fibers

Table 3. Porous asphalt mixtures designed in the study

Short name of the mixture	Bitumen content	Fiber content (% by wt. of mixture)	Explanation
R4.5	4.5	-	No fiber: Reference mixture with 4.5% bitumen content
BC5	5	-	No fiber: 5% bitumen content
AR	4.5	0.05	Regular aramid fiber
ARPL	4.5	0.05	Aramid pulp
GLCV	5	0.5	Hybrid of cellulose fiber & natural glass fiber
GLST	5	0.4	Hybrid of cellulose fiber & glass fiber+ synthetic fibers
CF	5	0.5	Cellulose fibers

3.3. Methods

The laboratory tests performed in this study are detailed in Table 4. Permeability test were performed to understand the hydraulic functionality of the mixtures and their ability to permeate water. In this study, permeability tests were conducted by using a radial flow falling head permeameter. The permeability was measured in terms of the time of discharge which indicates the time taken in seconds for a specified volume of water to pass through a compacted sample. The test is performed at 25°C. Permeability (k) is calculated using Darcy's law shown in Equation 1.

$$k = 2.3\frac{aL}{At}\left[\log\left(\frac{h_1}{h_2}\right)\right] \quad (1)$$

Where a is the area of the tube (cm^2), L is the thickness of the specimen (cm), A is the area of the specimen cross-section (cm^2), t is time for water to flow water from h_1 to h_2 (s), and h_1 and h_2 are the heights of water (cm).

The draindown test was used to check the binder stability at elevated temperatures, according to EN 12697-18. Previous studies recommend binder drainage in porous asphalt mixtures should not exceed 0.3% [8, 44]. The dry Cantabro test is commonly used for evaluating abrasion resistance in porous asphalt mixtures. The Wet Cantabro test is conducted to compute the particle loss under wet conditions according to Spanish NLT 362/92. The procedures are similar, but first, the specimens are kept at 25°C followed by immersion at 60°C for 24 hours and then the samples are kept at 25°C again and allowed to drain before testing. The particle loss is calculated and expressed as the percentage ratio of weight after and before the test. The maximum particle loss under dry and wet conditions should not exceed 20% and 35% respectively.

a. Aramid fiber (AR) a. Aramid Pulp (ARPL) c. Glass-Hybrid Fiber (GLST) d. Cellulose fiber (CF)

Figure 3. Fibers used in the study: (a) Aramid 6mm (AR); (b) Aramid Pulp (ARPL) (c) Glass fibers 6mm (GLST) (d) Cellulose Fiber (CF)

To compute the strength of the specimens with fibers, Indirect Tensile Strength (ITS) tests were performed under dry and wet conditions. Samples were prepared for each mixture type using a Marshall compactor. These samples were divided into two groups of four samples each: an unconditioned subset for computing ITS under dry conditions and a moisture conditioned subset for wet conditions. The dry samples were kept at 15ºC. In the case of the moisture conditioned ones, the samples were kept in a vacuum vessel filled with distilled water for 30 ± 5 min, placing them in a water bath (40 ± 1)°C for a period of 68-72 hours. Later, the samples were placed in a water recipient at 15ºC to break every sample at the same temperature. The samples were then tested for ITS using EN 12697-23. The Indirect Tensile Strength Ratio (ITSR) is calculated by Equation 2.

$$\mathrm{ITSR} = 100 \times \frac{\mathrm{ITS_w}}{\mathrm{ITS_d}} \qquad (2)$$

Where, ITS_w = Indirect Tensile Strength of moisture-conditioned samples specimens; ITS_d = Indirect Tensile Strength of unconditioned specimens.

Table 4. Laboratory tests

Tests conducted	Standard	Permissible Limits (%)	Number of replicates
Bulk density	EN 12697-6	-	3
Total air void	EN 12697-8	20	3
Vertical Permeability	Falling head permeameter	-	4
Dry Cantabro Test	EN 12697-17	20*	3
Wet Cantabro Test	Spanish Spec. NLT-362/92	35*	3
Draindown Test	EN 12697-18	0.3	3
Indirect tensile Strength (ITS)	EN 12697-23	-	4
Tensile Strength Ratio (TSR)	EN 12697-12	85	4

*Limits for most restrictive conditions (these values are for the highest traffic load level)

3.4. Statistical analysis

The statistical analysis was performed to provide the foundation to prove the significance of the results and avoid incorrect analysis due to errors and scattering of experimental data. In this study, statistical analysis was performed by Minitab software. All the data was checked for normality of distribution by performing the Anderson Darling normality test. Regarding the parametric test, two sampled student tests were performed for all mixture types that follow the normal distribution and for the results not following normal distribution, non-parametric, Mann-Whitney U test was performed. For accuracy of results the statistical analysis is performed on three replicates for each condition in case of air voids and Cantabro tests. For permeability and ITS tests, the number of replicates were four for each dry and wet conditions. Null hypothesis is that the difference between the two values is insignificant. A level of significance 95% was considered in this study, which means if the p-value is less than 0.05, the null hypothesis is rejected.

4. Multi-criteria Decision-making analysis

The selection of fibers involves multifaceted scrutiny of diverse factors that can sometimes be in contradiction to each other. For example, to choose between criteria like durability and strength depends on the function anticipated from the pavement. Hence, it is necessary to analyse all the possible choices extensively and take a rational decision. Multi-criteria decision enables unbiased decision to be made. The generalized structure of the MCDM is shown in Fig. 4. In this study, MCDM analysis is adopted to select the best fiber among eleven different scenarios.

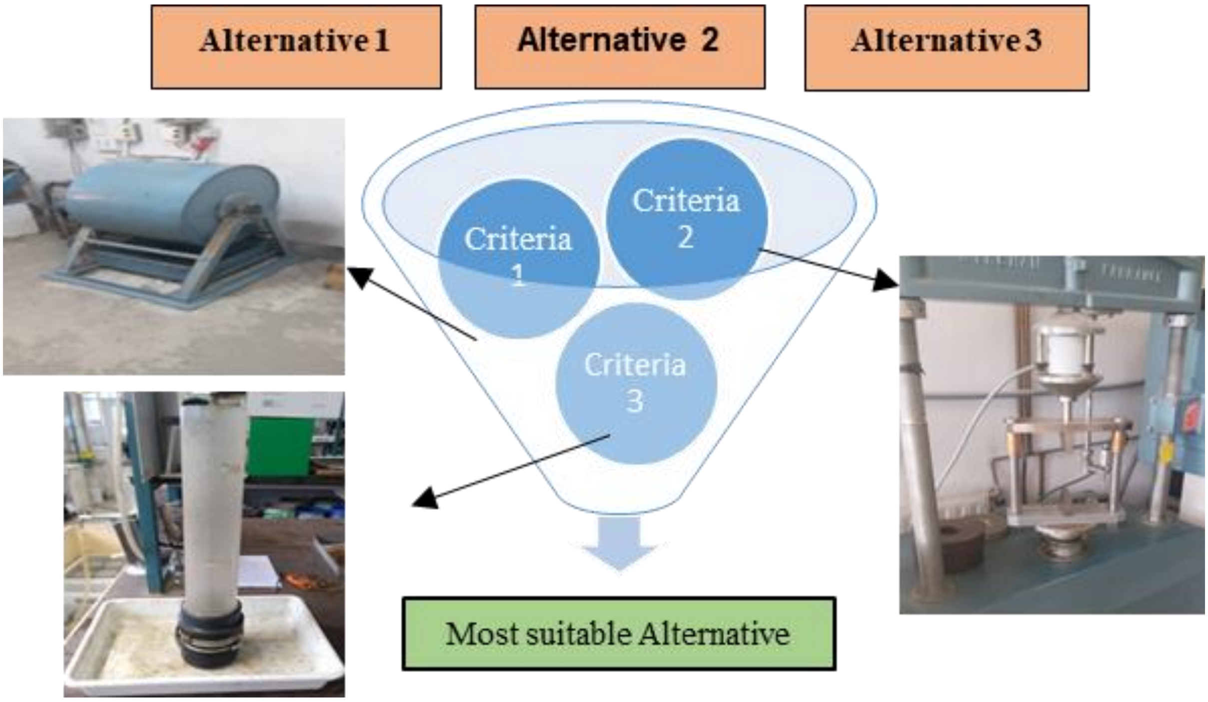


Figure 4. Methodology of Multi-criteria decision-making

WASPAS Method

The weighted Aggregated Sum Product Assessment (WASPAS) method proposed by Zavadskas et. al [40] utilizes two well-known MCDM approaches: Weighted Sum Method (WSM) and Weight Product Method (WPM). WASPAS is known for enhancing the accuracy of these two methods and providing more realistic outcomes [40]. This method has been employed by many researchers in engineering applications [34, 45, 46]. The methodology adopted for multi-criteria analysis in this study is described below [40]:

Step 1: Definition of the problem and preparation of suitable multi-criteria decision-making matrix.

Define the objective and determine all the alternatives. The set of alternatives are represented by A_i (i = 1, 2, 3…. n, n= number of alternatives). Alongside, a set of criteria is decided A_j (j= 1, 2, 3….m, m=

number of criteria). Then, all the alternatives are added in one column of the matrix, and the criteria in a row and the value according to each alternative and criteria is filled in.

Step 2: Normalization of the matrix

Define the comparative importance of the criteria. This step is relevant to remove the abnormalities which may be present in the criteria [47]. Equation 3 and 4 is followed to achieve the normality matrix.

$$\text{Beneficial criteria,}\quad N_{ij} = \frac{A_i}{Max_i(A_{ij})} \tag{3}$$

$$\text{Non-Beneficial Criteria,}\quad N_{ij} = \frac{Min_i\,(Aij)}{Aij} \tag{4}$$

Where N_{ij} is the normalized value of A_{ij}

Step 3: Determine the weights

This step is based on the method adopted, a set of experts can be consulted to provide the weights (w_j) according to their expertise (AHP) or statistical data can be considered (CRITIC). In this case, the CRITIC method was applied to calculate the objective weights of the criteria. In addition, ten different case scenarios were considered in which a wide range of varying weights were adopted.

Step 4: Creation of total relative importance matrices

As mentioned earlier, WASPAS is the linear combination of the WSM and WPM methods. The rank is calculated based on Weighted Sum Model (WSM).

In WSM, the total relative importance is computed by Equation 5.

$$Q_i^{WSM} = \sum_{j=1}^{n} w_j * N_{ij} \tag{5 }$$

In WPM, the total relative importance is computed by Equation 6.

$$Q_i^{WPM} = \prod_{i\equiv1}^{n} N_{ij}^{w_j} \tag{6}$$

Step 5: Determination of total relative importance

A more generalized equation combining the results from WSM and WPM for determining the total relative importance of the i^{th} alternative is as provided by Equation 7:

$$Q_i = \lambda \sum_{j=1}^{n} w_j * N_{ij} + (1\text{-}\lambda) \prod_{i=1}^{n} N_{ij}^{w_j}, \tag{7}$$

Where, λ = 0, 1, 2, 3……n; $\lambda = 0$ means that only WPM is important, 1 means only WSM is important, 0.5 denotes equal importance of both of them.

Step 6: Computation of optimal values of λ

Optimal values of λ are given by Equation 8.

$$\lambda = \frac{\sigma^2\ (Q^{WPM})}{\sigma^2\ (Q^{WSM}) + \sigma^2\ (Q^{WPM})} \quad (8)$$

Compute the variances $\sigma^2 (Q^{WSM})$ and $\sigma^2 (Q^{WPM})$ using the Equations 9 and 10:

$$\sigma^2 (Q^{WSM}) = \sum_{j=1}^{n} w_j^{\,2}\, \sigma^2(N_{ij})\, N_{ij} \quad (9)$$

$$\sigma^2 (Q^{WPM}) = \sum_{j=1}^{n} \left(\frac{\prod_{i\equiv 1}^{n} N_{ij}^{w_j}\, N_j}{(N_{ij})^{w_j} (N_{ij})^{(1-w_j)}} \right)^2 \sigma^2\,(N_{ij}) \quad (10)$$

Step 7: Compute the estimates of variances of normalized initial criteria values as in Equation 11:

$$\sigma^2 (N_{ij}) = (0.05 N_{ij})^{\,2} \quad (11)$$

CRITIC Method

For any multi-criteria decision-making method, computation of relative weights is a critical stage that determines the degree of accuracy achieved in the result. The CRITIC method provided by Diakoulaki et. al [46] is a widely used method to obtain the objective weights of importance for all criteria. This method reflects the relative importance based on the intrinsic information contained by each criterion [48]. In this method, the criteria are normalized based on whether they are beneficial or non-beneficial criteria [38]. This method omits the requirement of human intervention or pairwise comparisons as in the case of other weighting methods. The procedure to compute the weights of the criteria by CRITIC is given as follows:

Step 1: Formulation of decision matrix

A decision matrix is formed for all alternatives with respect to the criteria (Equation 12)

$$X = [x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{11} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (i=1, 2, 3\ldots m \text{ and } j= 1, 2, 3\ldots.n) \quad (12)$$

X_{ij} gives the value of the i^{th} alternative with respect to the j^{th} criteria

Step 2: Normalization of Decision matrix (Equation 13 and 14)

For beneficial criteria, $$x_{ij}^{*} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (13)$$

For Non-beneficial criteria, $$x_{ij}^{*} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (14)$$

Where x_{ij}^{*} represents the normalized vector of criterion i with respect to response j, $\max(x_{ij})$ represents the maximum value of criterion corresponding to j, and $\min(x_{ij})$ represents the minimum value of a criterion with respect to response j,

Step 3: Calculate the standard deviation σ_j of each criterion using the corresponding vector (Equation 15).

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m}(x_{ij} - \bar{x}_i)^2}{m}} \quad (15)$$

where $\bar{x}_j$ is the mean of the criterion j.

Step 4: Construct a symmetric n × n matrix with generic element rjk, which represents the Pearson correlation coefficient between x_j and x_k as given in Equation 16.

$$R = [r_{jk}]_{nxn} \quad (16)$$

Step 5: Determine H_j by combining the standard deviation with the symmetric matrix to measure the information of the criteria in the decision matrix provided by Equation 17.

$$H_j = \sigma_j \sum_{k=1}^{m}(1 - r_{jk}) \quad (17)$$

Step 6: Determination of objective weights of the criteria according to Equation 18.

$$W_j = \frac{H_j}{\sum_{j=1}^{m} H_j} \quad (18)$$

5. Results and discussion

5.1. Draindown Test

The result of the draindown test shown in Fig. 5 demonstrates that all mixtures pass the requirement except for BC5. The reference mixture, R4.5, showed negligible draindown and at this binder content, addition of aramid fibers did not change the draindown. In contrast, BC5 was found to be unacceptable, as it was not able to accommodate the high binder content of 5%. Only for statistical comparison of glass and cellulose fibers, this mixture is considered in air voids and particle loss tests.

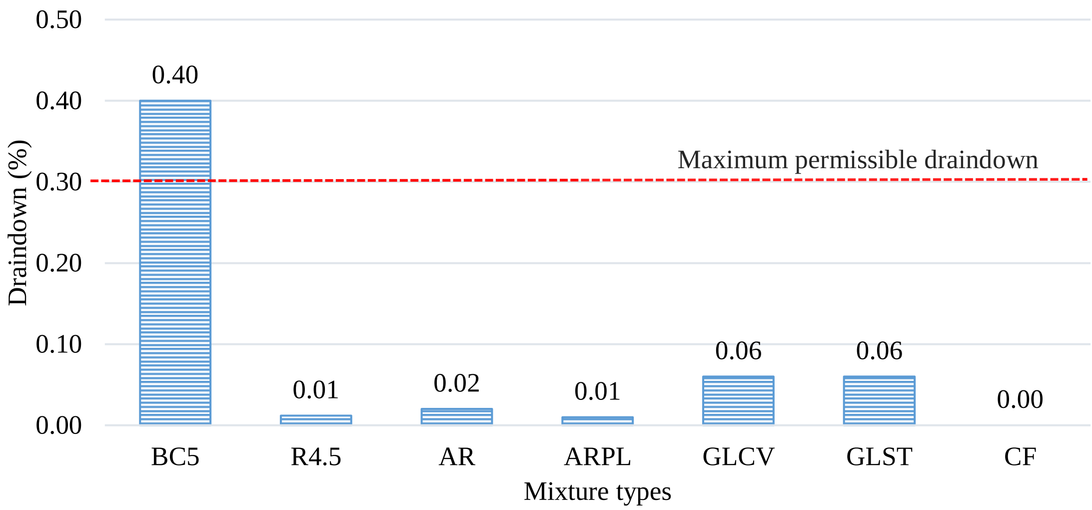


Figure 5. Draindown results

This is done to understand the influence of fiber when added at binder content of 5%. Interestingly, addition of GLCV, GLST, CF fibers to the 5% binder content mixtures have greatly reduced draindown passing the desired requirement (< 0.3%). It is in agreement to the hypothesis that glass-hybrid and cellulose fibers retain bitumen and a higher bitumen content is required in this type of porous asphalt mixtures.

5.2. Air voids and permeability

Higher air void contents is an important requirement for porous asphalt (PA) mixtures in order to maintain the flow of water, and therefore it is essential that the addition of fibers does not result in excessive reduction of their air voids. The air void content for all the mixtures with fibers is in the range of 19-22%. A statistical analysis for air voids as compared to R4.5 is presented in Table 5. The results of volumetric analysis and permeability test are shown in Fig. 6. As can be observed, BC5 has the lowest air void contents because of its higher bitumen content. Addition of glass-hybrid fiber GLST and cellulose fibers CF did not significantly affect the air voids (p-value = 0.3 and 0.149 respectively with respect to BC5) whereas GLCV fiber increases the air void content significantly (p-value= 0.044 with respect to BC5), which may be due to even higher absorption of bitumen.

Table 5. Statistical analysis of effect of fibers on air voids as compared to R4.5

Air voids					
Mixture	p-value	Significance	Mixture	p-value	Significance
AR	0.158	No	GLST	0.002	Yes
ARPL	0.065	No	CF	0.003	Yes
GLCV	0.037	Yes			

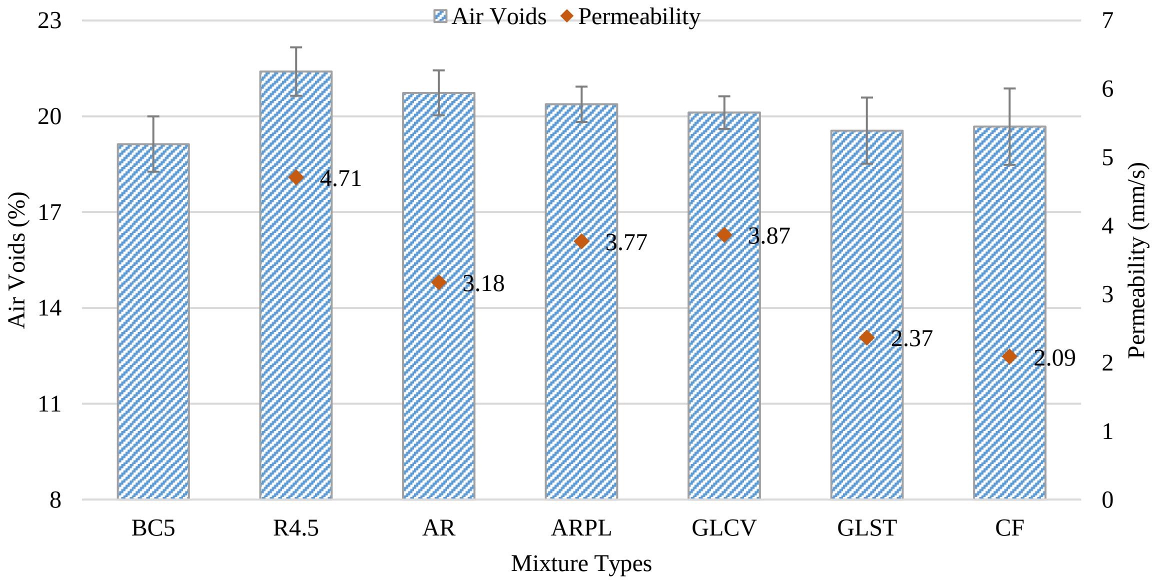


Figure 6. Results of air void content and permeability test, error bars represent standard deviation from the mean

Table 5. Statistical analysis of effect of fibers on permeability as compared to R4.5

Permeability					
Mixture	p-value	Significance	Mixture	p-value	Significance
AR	0	Yes	GLST	0	Yes
ARPL	0.014	Yes	CF	0	Yes
GLCV	0.194	No			

Aramid fibers did not show a significant impact in the voids of R4.5. It is worth noting here that the addition of fibers does not reduce the voids in the mixtures substantially. This might be due to absorption of bitumen by the fibers. As for mixtures with two types of aramid fibers, they show high air void contents as the reductions were insignificant (p-value> 0.05).

Concerning the permeability results, good correlation was expected between the air voids and permeability of the samples; however, in this study no correlation was observed among the two (R2 = 0.269). This may be due to the fact that air voids do not necessarily represent the interconnected air void content. The statistical analysis indicates maximum reduction in permeability for cellulose fibers (55.6%), GLST (44.9%) and aramid fiber (32.5%) as compared to R4.5 The p-value and corresponding significance is given in Table 6. Surprisingly, air voids of all the mixtures were in the same range as shown by the error bars. The only fiber that has insignificant effect on permeability is GLCV which may be due to binder absorption as was also observed in air voids. However, it should be kept in mind that all mixtures containing fibers have lower permeability as compared to the reference mixture.

5.3. Cantabro test

The Cantabro test results for all the mixtures are given in Fig. 7. Mixtures with glass-hybrid and cellulose fibers improve the performance of R4.5, but as they are expected to strengthen the mortar as well as to retain a certain amount of bitumen, they have been compared with BC5 which has better behavior. The mixture with GLST fibers has high impact on the abrasion loss, it reaches the best performance of this type of fibers. The particle loss is reduced by 8.8% in dry conditions, while in wet conditions it is reduced by 31.3%. Presence of synthetic material in GLST may be strengthening the mortar that resulted in higher adhesion and lower abrasion loss. This result is in contrast to a previous study [13], in which it is reported that the glass-synthetic fibers increase the abrasion loss. This study was made at 5% binder content of 60/70 penetration; however, the fiber content used in that study was only 0.2%. This content of synthetic glass-hybrid fiber might not be sufficient to form a strong matrix due to use of different aggregates, which may be a reason for increased abrasion loss. With increasing fiber content, the fiber-to-fiber contact makes the binder matrix stronger resulting in high adhesion. GLCVs do not contain synthetic material and they reduce the particle loss by only 17% in wet conditions, while the difference is negligible in dry conditions. When compared to cellulose fibers, GLCV has shown similar behavior in wet conditions while in dry conditions, higher abrasion resistance was observed.

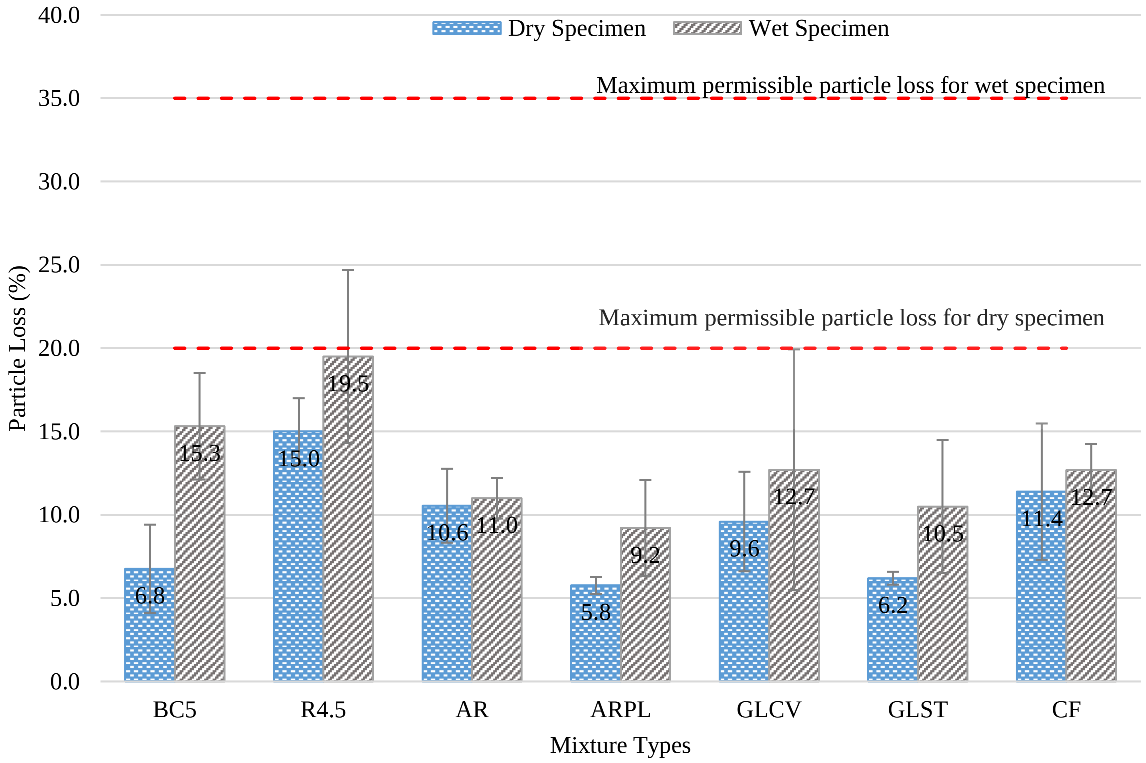


Figure 7. Average of abrasion resistance in dry and wet conditions, standard deviation about mean is represented by the bars

Table 7. Results of statistical analysis of Abrasion resistance as compared to R4.5

Mixture	p-value	Significance	Mixture	p-value	Significance
		Dry abrasion resistance			
AR	0.053	no	GLST	0.003	yes
ARPL	0.003	yes	CF	0.298	no
GLCV	0.074	no			
		Wet abrasion resistance			
AR	0.005	yes	GLST	0.111	no
ARPL	0.046	yes	CF	0.051	no
GLCV	0.425	no			

Concerning aramid fibers, aramid fiber AR significantly reduces the particle loss in dry and wet conditions (29.7% and 43.5%) with respect to R4.5, although it is significant only under wet conditions (p-values are presented in Table 7). Aramid pulp (ARPL) has shown the highest reduction of 61.5% and 61.3% in dry and wet particle loss respectively, and it is the only one with significant improvement in dry and wet conditions. This indicates that with a fiber content of only 0.05% of aramid pulp, particle loss of porous asphalt mixtures has been reduced by more than half. Abrasion resistance is the most important concern in porous asphalt mixtures, a small quantity of aramid pulp has remarkable improvement on the durability of PA mixtures by enhancing the abrasion resistance. This phenomenon may be due to fibrillation of aramid pulp in bitumen, which resulted in a stronger adhesive mortar that links the coarse aggregates.

5.4. Indirect tensile strength and moisture susceptibility

The Indirect Tensile Strength (ITS) test was performed on all the samples with the fibers under dry and wet conditions. The ITS test results are illustrated in Fig. 8 and the statistical analysis is given in Table 8. For ITS under dry conditions, the mixtures with GLCV, GLST, and CF fibers have shown higher values, which was expected due to higher bitumen content. The increment in ITS value is not statistically significant for CF (4.46% with p-value >0.05) or GLST as well (5.28% with p-value >0.05). This behavior is in agreement with the studies [13, 49], where it was concluded that glass fibers improve the tensile strength of porous asphalt mixtures.

Table 8. Results of statistical analysis of ITS as compared to R4.5

Mixture	p-value	Significance	Mixture	p-value	Significance
		Dry abrasion resistance			
AR	0.423	no	GLST	0.293	no
ARPL	0.984	no	CF	0.229	no
GLCV	0.332	no			
		Wet abrasion resistance			
AR	0.023	yes	GLST	0.666	no
ARPL	0.044	yes	CF	0.957	no
GLCV	0.293	no			

High moisture susceptibility can lead to various failure mechanisms in porous asphalt mixtures, it is due to loss of adhesion between bitumen and aggregates [50]. Aramid fibers (AR) do not greatly affect the ITS results under dry conditions, for p-values of AR and ARPL are 0.423 and 0.984, respectively. Under wet conditions, the reduction in the case of aramid pulp (ARPL) is 10.7%, the variation is significant (p-value= 0.044) at a 95% level of significance. Extreme reductions were observed in ordinary aramid fiber as well with a 16.3% reduction in ITS. This phenomenon is explained by the negative influence of aramid fibers on the moisture susceptibility of porous asphalt mixtures, even when they were added at the small fiber content of 0.05%. On the other hand, for CF, GLCV, GLST, the difference is negligible (p-value<0.05). Based on these results, it can be inferred that the glass fibers do not increase the moisture susceptibility whereas the same may not be the case for aramid fibers. Among the two aramid fibers included in the study only ARPL; i.e. aramid pulp satisfies the minimum requirement of 85% ITSR.

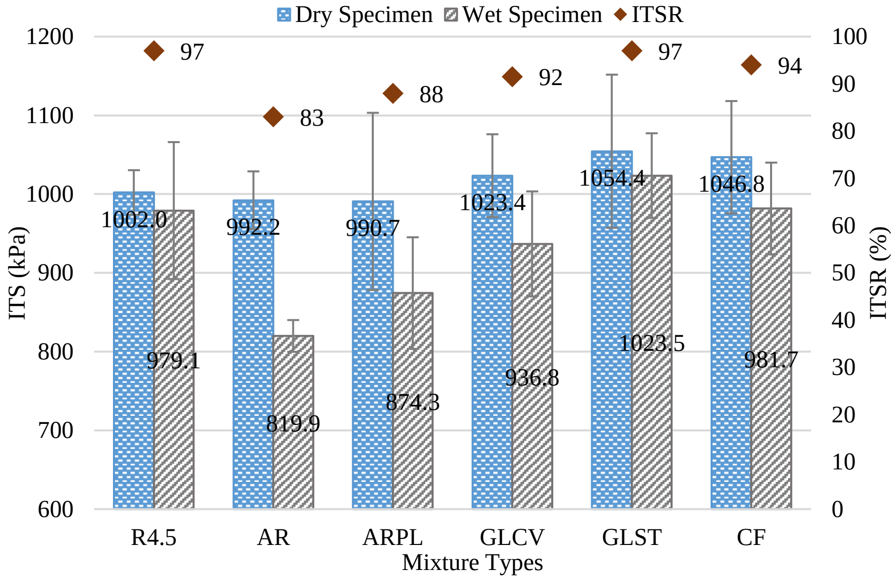


Figure 8. Indirect tensile strength of the mixture types, standard deviation about mean is represented by the bars

5.5. Optimization of aramid fiber mixtures

An investigation was made to analyse the impact of fiber content and bitumen content. In this part, only the regular aramid fiber AR was considered. Fig. 9 shows results of air voids and Cantabro test on the primary vertical axis and draindown on the secondary vertical axis for three different contents of fiber: aramid fiber 0.03 & 0.05 in 4.5, 5.0, and 5.5% bitumen content and 0.08% fiber content with 5% bitumen content.

It can be observed that the air voids decrease due to the increment in bitumen content and fiber content, which was expected as the bitumen and fibers fill the spaces among the aggregates, resulting in lower air void contents. The peak of binder draindown is observed at 5.5% bitumen content, independently of the fiber content (0.03 or 0.05%). The increase in the binder draindown when 5.5% bitumen is used was not found to be proportional, so a lower percentage of bitumen is recommended. Meanwhile, the high value of draindown is the reason for the instability of the binder in the mixture.

Abrasion resistance increases with an increase in fiber content. At 4.5% and 5% bitumen content, on increasing the fiber content, the abrasion resistance increases except in the case of 0.08% fibers where the particle loss under wet conditions is higher at 5%; this may be due to the formation of clusters owing to a large amount of fibers. Moreover, this trend is not apparent in 0.05% fiber content at 5.5% binder content, where the particle loss is greater when fiber content is increased. This may be due to higher bitumen content leading to slipping action or inefficient coating of fibers.

Overall, it was concluded that the 4.5% and 5% bitumen content with 0.05% fiber content were two optimum combinations. However, 4.5% higher air void contents and lower draindown were observed. Additionally, the abrasion resistance under dry and wet conditions is higher than the rest of the tested alternatives at a comparatively lower binder content of 4.5%.

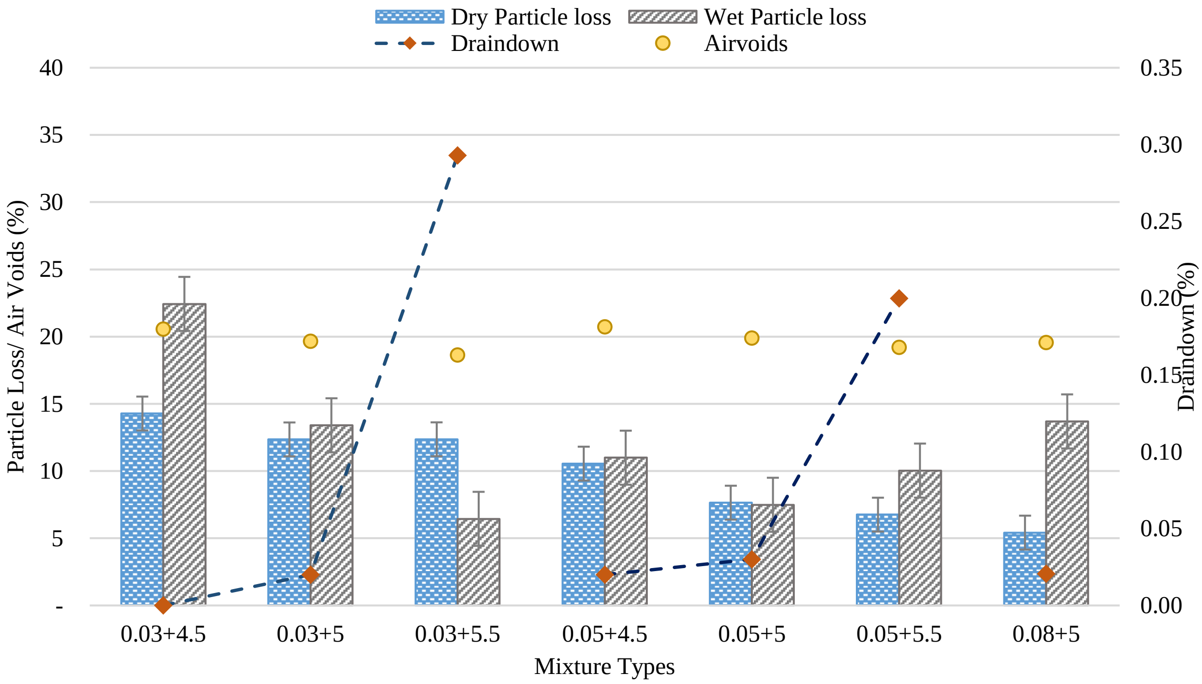


Figure 9. Effect of fiber content and bitumen content in case of regular aramid (AR) fibers. Fiber content varies from 0.03% and 0.05% content with 4.5%- 5.5% bitumen content and 0.08%+5%

5.6. Combination of fibers

It has been observed in the previous section that although aramid pulp enhances the abrasion resistance of the mixture, it does not improve the strength of the mixtures in the water sensitivity test. However, this is not the case for glass-hybrid fibers. In terms of ITS under dry and wet conditions, mixtures with both kinds of glass-hybrid fibers (GLST and GLCV) result in higher strength than mixtures without fibers (R4.5). Therefore, an experiment was performed to check for any synergistic benefits of using the combination of aramid pulp and glass-hybrid fibers.

Table 9. Combination of fibers

Mixture	Bitumen content	ARPL	Fiber content
ARPL+GLCV 4.5	4.5		0.5
ARPL+GLST 4.5	4.5		0.4
ARPL + GLCV	5	0.05	0.5
ARPL + GLST	5		0.4
ARPL + CF	4.5		0.5

The bitumen content and the fiber content of the 5 combinations studied are given in Table 9, the content of aramid pulp was 0.05% whereas the content of GLCV and CF was 0.5% and GLST was 0.4% by the weight of mixture. The comparison of the outcome is shown in Fig. 10. As can be observed from the figure, particle loss is higher compared to when the fibers were added alone in the mixtures. In the case of a bitumen content of 4.5%, the results were worsened by the combination to a great extent. With only aramid pulp the particle loss was only 5.77% but in combination with glass-hybrid fibers, GLCV (9.6%) and GLST (6.2%), the particle loss is even more than double (20.4% and 12.5% respectively under dry conditions). The same pattern was observed in the case of wet conditions as well. In the case of 5% bitumen content, the reduction in particle loss was lesser, which may be attributable to formation of better matrix with ARPL and GLCV & ARPL and GLST fibers at higher binder content; however, particle loss is still higher. This pattern is prominent with cellulose fibers as well.

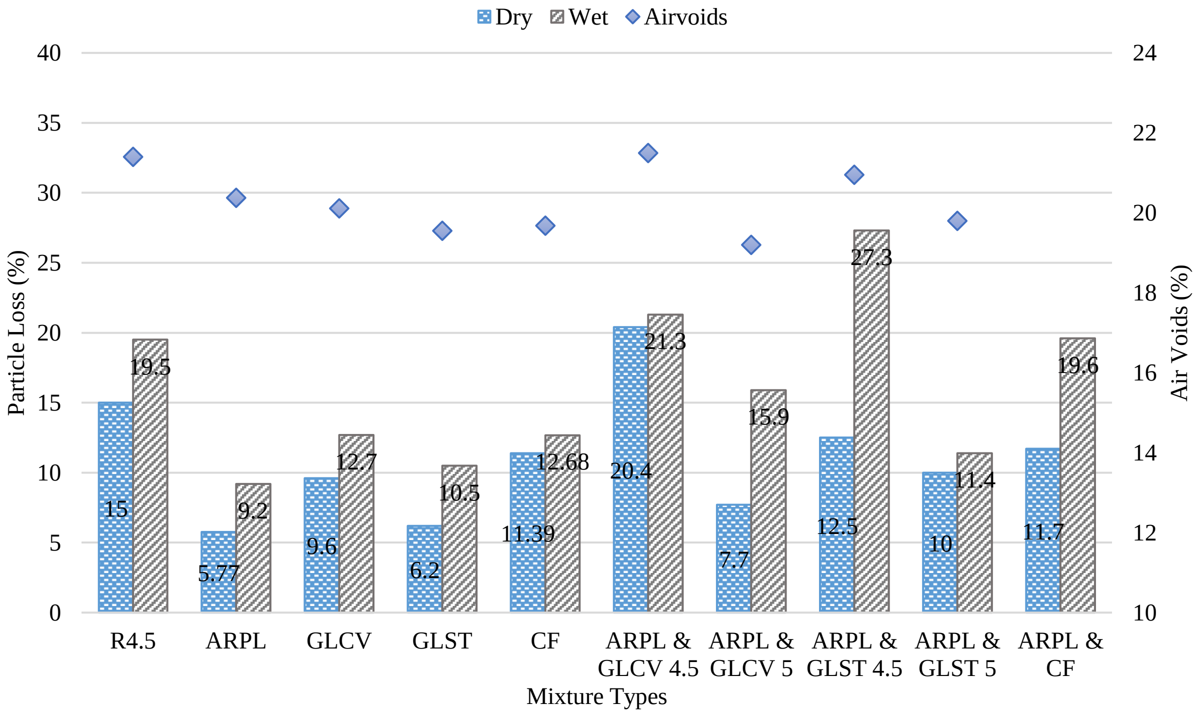


Figure 10. Results of abrasion resistance and air voids for combinations of fibers

Combination of fibers in the case of 4.5% bitumen content has a negligible effect on air voids as compared to when single fibers were added. While in the case of 5% bitumen content, the air voids were reduced. Therefore, in this study it can be inferred that combination of fibers led to development of a non-homogeneous mixture which led to the evolution of a weakened matrix of the fibers. This was responsible for low integrity of the mixture and higher particle loss. This pattern was observed with all the 5 combinations tested. However, the combination of fibers is a complex topic that requires further attention due to many factors such as particle size distribution, optimization of bitumen contents and fiber contents.

6. Multi-criteria Decision Making (MCDM)

To select the most suitable fibers among the variety of aramid, glass and cellulose fibers, multi-criteria analysis is done. The criteria for the selection were chosen carefully as they determine the accuracy of the results. The criteria chosen were as follows: air void content, permeability, abrasion loss (under dry and wet conditions) and ITS (under dry and wet conditions). The normalized matrix is given below in Table 10, prepared in accordance with beneficial or non-beneficial criteria as given in Equation 3.

The weighting case scenarios are given in Table 11. Weights according to the CRITIC method are given as 1C weighing case scenario. As it can be seen, CRITIC method gives the highest weightage to air void content followed by dry ITS and permeability; however, the difference among all the criteria weights is not very high. Under realistic conditions, this result is not 100% correct as the most important criteria may be abrasion resistance in porous asphalt mixtures and raveling is the most common degradation mechanism. That suggests abrasion resistance should be given higher weights than air void content. Therefore, ten additional weighting case scenarios were designed according to the different possible requirements of the roads. For instance, generally, the most apparent problem in porous asphalt pavements is raveling; therefore, abrasion resistance is the most important criterion (scenario 3); for roads subjected to a high volume of traffic, ITS is the most important criterion (scenario 4); if a road is located in high rainfall regions, permeability and air void content are most important requirements (case scenario 2).

Table 10. Normalized multi-criteria decision matrix

			Cantabro test		ITS (KPa)	
	Air Voids	Permeability	Dry	Wet	Dry	Wet
R 4.5	1.00	1.00	0.38	0.47	0.94	0.96
GLCV	0.94	0.82	0.60	0.72	0.97	0.92
GLST	0.91	0.50	0.93	0.88	1.00	1.00
CF	0.92	0.44	0.51	0.73	0.99	0.96
AR	0.97	0.68	0.55	0.84	0.94	0.80
ARPL	0.95	0.80	1.00	1.00	0.94	0.85

As can be observed from Fig. 11, aramid pulp (ARPL) is ranked first for 10 out of 11 scenarios. The reason is that ARPL reduces the particle loss considerably and does not have a significant effect on the air voids, permeability, and ITS of the mixtures. In scenario 4, where ITS is the most important criteria, the best performing fiber is GLST, due to its higher value of ITS, although the difference in the factors is less (0.81%). In most case scenarios, aramid pulp (ARPL) is followed by glass-hybrid fiber (GLST) due to the positive effect on the ITS of the mixtures obtained from the synthetic content. On the contrary, in scenario 2, where permeability is the most important, GLST has the second-lowest position.

R4.5 has a higher rank than cellulose fibers in 7 out of 11 scenarios. This is due to the limited improvement of abrasion resistance when adding cellulose fiber, at the same time the effect of cellulose fiber on permeability is negative. When more importance is given to abrasion loss, which is a principal problem observed in PA mixtures, aramid pulp (ARPL) is the most suitable fiber because it shows the highest improvement compared to reference mixture.

Table 11. Objective weights according to weighting case scenarios.

Case	Air voids	Permeability	Abrasion Loss dry	Abrasion Loss wet	ITS dry	ITS wet	Explanation
			CRITIC				
1C	0.19	0.17	0.15	0.16	0.18	0.15	CRITIC
			Ten case scenarios				
1	0.167	0.167	0.167	0.167	0.167	0.167	Equal importance
2	0.3	0.3	0.1	0.1	0.1	0.1	P = AVC > AL= ITS
3	0.1	0.1	0.3	0.3	0.1	0.1	AL > ITS = AVC = P
4	0.1	0.1	0.1	0.1	0.3	0.3	ITS > AVC = P = AL
5	0.2	0.2	0.2	0.2	0.1	0.1	AVC = P = AL > ITS
6	0.1	0.1	0.2	0.2	0.2	0.2	AL = ITS > AVC = P
7	0.2	0.2	0.1	0.1	0.2	0.2	AVC = ITS > AL
8	0.1	0.1	0.25	0.25	0.15	0.15	AL > ITS > AVC
9	0.1	0.1	0.15	0.15	0.25	0.25	ITS > AL >AVC
10	0.25	0.25	0.15	0.15	0.1	0.1	AVC > AL > ITS

P= permeability, AVC= air void content, AL= Abrasion Loss, ITS= Indirect Tensile Strength

In summary, aramid pulp, ARPL improves the cohesion of the mortar. Glass-hybrid fibers GLST and GLCV were next in rank to ARPL, due to their high ITS value and lower moisture susceptibility. Glass-hybrid fiber reinforces the mortar due to its uniform distribution and high strength, in a similar way as a binder with a high viscosity bitumen. The ordinary aramid fiber AR reduces the ITS significantly. In addition, they have lower permeability due to the lower amount of interconnected air voids. Mixtures with cellulose fiber, CF, were the worst-performing mixtures even when compared with mixtures without any fiber (R4.5). Cellulose fibers reduce the permeability of the mixture prominently, while the improvement in abrasion resistance due to their presence is negligible.

For every case scenario, the values of λ were different, based on different standard deviations of WSM and WPM according to Equation 8. The results for total relative importance (Qi) based on the WASPAS method explained in Equation 6 vs weighting case scenarios are given in Fig. 12. It is shown that ARPL has distinctly higher performance, and even after changing the values of the weights, the rank does not change greatly. For all the values of λ, the poorest performing fiber is cellulose fiber. In order of preference (best to worst) the results are: ARPL> GLST> GLCV> AR> R4.5> CF.

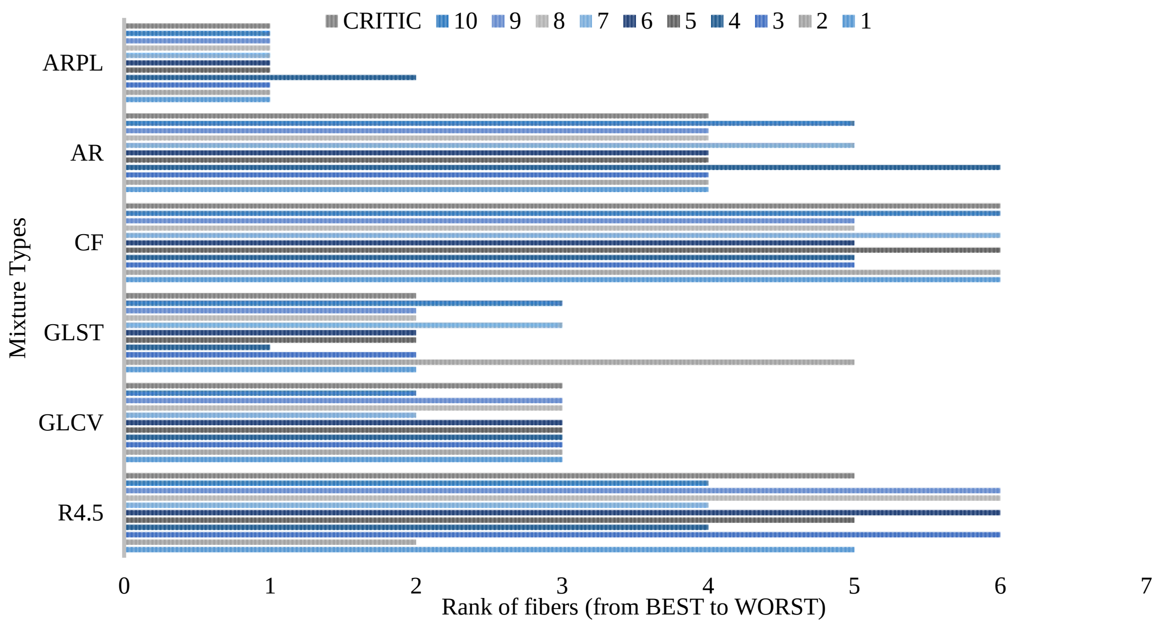


Figure 11. Rank of fibers based on 10 (hypothetical) +1 (CRITIC) weighting criteria

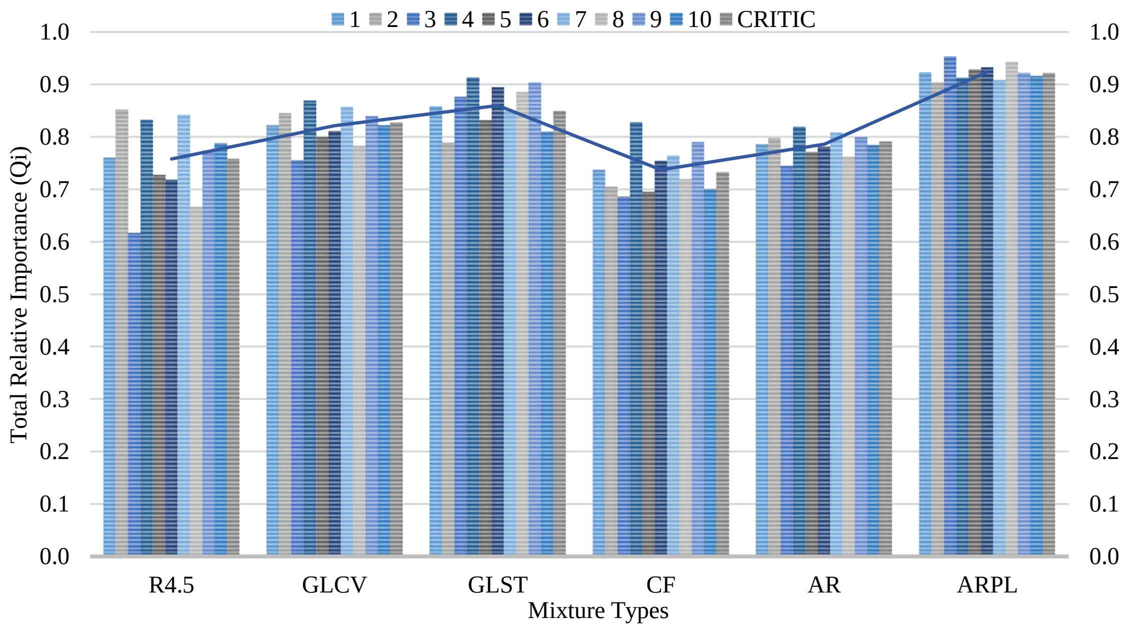


Figure 12. The total relative importance of the fibers

7. Conclusions

This study was performed to evaluate the performance of a set of fibers added to porous asphalt mixtures: namely aramid fibers, glass-hybrid fibers, and cellulose fibers. It was based on laboratory assessment and statistical and multi-criteria analysis. The mixtures were evaluated using the Cantabro test, indirect tensile strength test, and permeability test. This was followed by statistical analysis and a

CRITIC-WASPAS multi-criteria decision-making method to select the best alternative based on the laboratory test results. The following conclusions can be drawn from this study:

- Fibers in porous asphalt mixtures slightly reduce the air voids content, as well as the permeability. However, all mixtures containing fibers surpass the minimum requirement of 20% of voids. Meanwhile, a higher reduction is observed in the permeability test compared to air void content.
- For the Cantabro test, even a small amount of 0.05% of aramid pulp reduces the particle loss to less than half of the reference mixture's, both under dry as well as wet conditions. Ordinary aramid fibers, glass-hybrid fibers GLST and GLCV also have a positive influence on the abrasion resistance both in dry and wet conditions. On the contrary, cellulose fibers have a negligible effect on the abrasion resistance of the mixtures.
- Concerning the results of indirect tensile strength tests of the mixtures, glass-hybrid fibers had a positive effect, while a significant reduction in ITS is observed in mixtures incorporating aramid fibers. Likewise, moisture susceptibility is observed to be lower in the case of glass-hybrid fibers than aramid fibers. Aramid pulp is the only aramid fiber to satisfy the minimum required ITSR.
- Incorporation of a combination of aramid pulp and glass-hybrid fibers is not found to be very promising as it has reduced the air void content and abrasion resistance, while their addition individually to the mixtures led to superior performances, especially with the production process applied.

For multi-criteria decision-making analysis, the CRITIC method was utilized to find the weights along with ten other weighting case scenarios considering all suitable requirements. The weights from the CRITIC method were not found to be very realistic as this method gave higher weighting to the air void content (19%) followed by dry ITS (18%), and then abrasion resistance (15%).

- The WASPAS multi-criteria approach confirms the results inferred from the laboratory analysis. Therefore, it can be concluded that multi-criteria analysis is a viable approach for the selection of materials for asphalt mixtures. According to multi-criteria analysis, the ranking of fibers is (best performance to worst performance): aramid pulp> synthetic glass-hybrid fiber> natural glass-hybrid fiber> ordinary aramid fiber> reference mixture> cellulose fiber i.e. ARPL> GLST> GLCV> AR> R4.5> CF.

In the future line of research, it is recommended to check these fibers based on their influence on the packing of the aggregates, energy parameters, low temperature cracking resistance, high-temperature stability, etc. It is also important to check the effect of fibers on the aging of the bitumen mastic as aging is a very important concern in porous asphalt mixtures. Moreover, it was found that the combination of fibers is an important research line in itself and requires directed attention, it is recommended to study the effect of combining the fibers on the porous asphalt mixtures.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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5.2. Article 2: Multi-criteria selection of additives in porous asphalt mixtures using mechanical, hydraulic, economic, and environmental indicators

5.2.1. Information and impact factor

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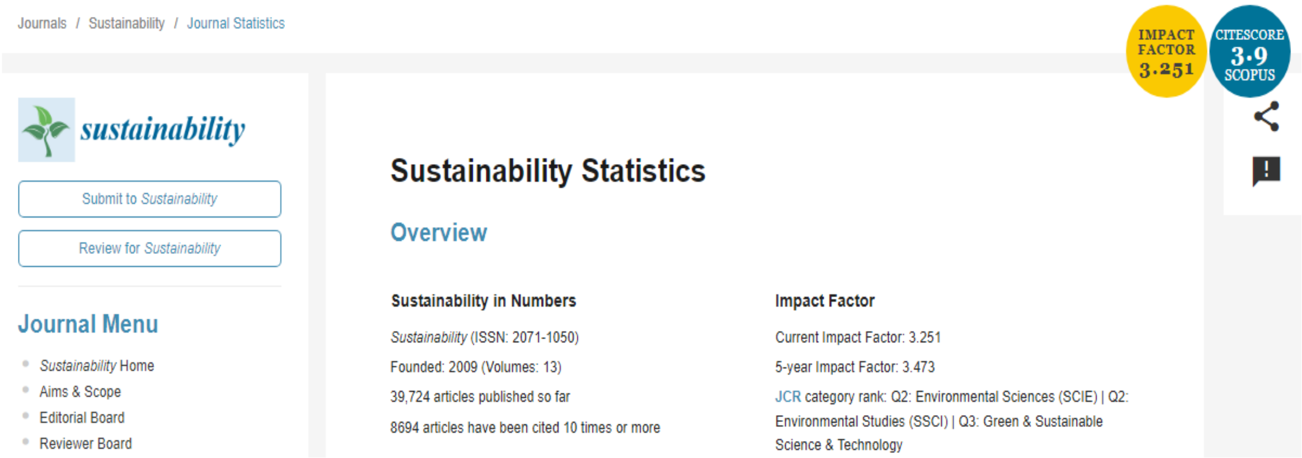

Figure 9. Information of the journal (Article 2).

5.2.2. Transcription of Article 3 (post-print version)

Multi-criteria selection of additives in porous asphalt mixtures using mechanical, hydraulic, economic, and environmental indicators

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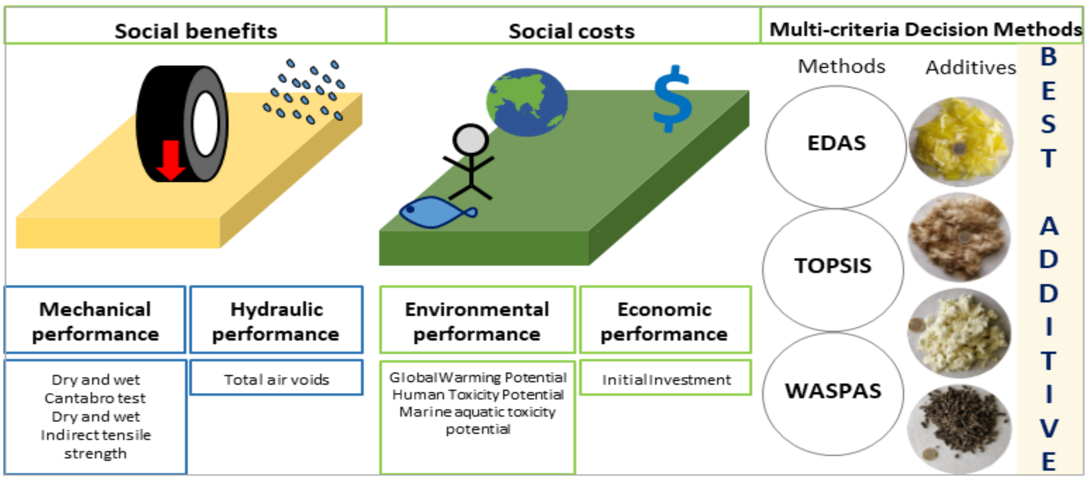
Abstract:

Porous asphalt (PA) mixtures are more environmentally friendly but have lower durability than dense-graded mixtures. Additives can be incorporated into PA mixtures to enhance their mechanical strength, however, they may compromise the hydraulic characteristics, increase the total cost of pavement, and negatively affect the environment. In this paper, PA mixtures were produced with 5 different types of additives including 4 fibers and 1 filler. Their performances were compared with the reference mixtures containing virgin bitumen and polymer-modified bitumen. The performance of all mixes was assessed using: mechanical, hydraulic, economic, and environmental indicators. Then, the Delphi method was applied to compute the relative weights for the parameters in multi-criteria decision-making methods. EDAS, TOPSIS, and WASPAS were employed to rank the additives. According to the results obtained, aramid pulp displayed comparable and, for some parameters such as abrasion resistance, even better performance than polymer-modified bitumen, while cellulose fiber demonstrated the best performance regarding sustainability, due to economic and environmental benefits.

Keywords: porous asphalt, aramid fiber, multi-criteria decision making, life cycle assessment.

Graphical abstract:



Highlights:

- Results show that mechanical, hydraulic, economic, and environmental indicators are vital in the selection of porous asphalt additives.
- Mixtures with aramid pulp have shown better mechanical resistance than polymer-modified bitumen.
- Cellulose fiber has the least impact on the environment based on the parameters considered in the study.
- Aramid pulp and cellulose fibers are recommended additives for porous asphalt mixtures.

1. Introduction

The idea of sustainability has three essential components: engineering for society, economic development, and respect for the environment [1]. The construction sector causes significant environmental impacts, with a substantial release of emissions into the environment, as well as consuming energy and natural resources [2].

Porous asphalt (PA) is a step forward towards sustainability [3]. However, the additives are additional constituents that can have a significant influence on the environmental and economic impacts. Over the last 30 years, several types of additives, fibers, and fillers have been used in PA mixtures. Additives like nano-silica, warm mix additives, etc.; fibers such as glass fibers, nylon fibers, steel, aramid etc.; and fillers, such as hydrated lime, diatomite, etc. are added to PA mixtures [4-11].

Fibers exhibit various mechanisms, four of which are explained next. Firstly, the formation of a network as reported by Chen and Lin [12], cellulose fibers increase the viscosity of the bitumen mastic if added at 0.3% fiber content, these fibers create a 'localized network structure'; and at 0.4% fiber content, they form a continuous network which reinforces the bitumen. Due to the formation of this network, fibers retain bitumen, which assists in the formation of thicker coating around the aggregates without the risk of draindown. Secondly, some fibers such as steel fibers resist the fatigue-induced cracking damage; therefore, the micro-cracks do not transform into macro cracks [13]. In addition to this steel wool fibers also improve the healing of PA mixtures by induction heating [14]. Thirdly, synthetic fibers carry a proportion of tensile loads and improve the tensile strength of the mixtures [12]. Fourthly, fibers such as glass fibers enhance the performance of asphalt mixtures at high temperatures as they have very high-temperature resistance, and when the softening point of bitumen is exceeded, they support the bitumen and resist binder stripping and drainage [15].

Concerning the fillers, amount and type are decisive when estimating the cohesion among the constituents of PA mixtures [6]. According to Mohd Shukry et al., 2018 [16], fillers work by stiffening and improving the adhesion of the binder-aggregate matrix. Hydrated lime enhances the chemical bonds between aggregates and binders and reduces particle loss and improves moisture resistance so it can be used in rainy areas [17]. Meanwhile, Hu et. al [18] reported that the activated carbon filler has a higher surface area than limestone filler and due to this property, activated carbon retains bitumen that facilitates higher bitumen content.

However, these additives may block a part of the air pockets present in the bitumen-aggregate matrix [19]. They reduce the permeability of the PA mixtures, which may render the PA mixture useless [20]. It is important to consider the impacts of additives on hydraulic, economic, and environmental factors at an early stage by performing a life cycle assessment. In a study by Marzouk et. al [21], the environmental impact of road construction projects was quantified before starting by utilizing by Building information modelling (BIM). The study included seven different stages of a road construction project from manufacturing phase to deconstruction phase. Rodriguez-Fernandez, 2020 [22] analysed the influence of PA mixtures with warm mix additives on the environment and found that warm-mix additives with polymer modified bitumen (PMB) reduce the impacts on human health, ecosystem diversity, and resource availability. In another study [2], ReCiPe indicators were used for life cycle assessment of end-of-life tires and cellulose fiber-reinforced PA mixture. It was concluded that the use of cellulose fibers reduces the impact on human health and the ecosystem; however, the energy consumption of cellulose fibers was 25% higher than end-of-life tire fibers. In another study on the recyclability potential of PA mixtures with steel wool fibers, it was found that the mixtures with 40% recycled material displayed better performance than a control mixture [14].

Therefore, it is vital to find a balance among the mechanical, hydraulic, economic, and environmental constraints to optimize the performance of these mixtures. The same additive that performs well in one aspect may not necessarily perform well in others; therefore, to assess the net influence, multi-criteria analysis can be applied.

In multi-criteria analysis, an alternative is selected according to the criteria which comprise different parameters. These criteria are allotted relative importance which may be based on the expertise of the researchers in the field [23]. However, there are many methods to compute the relative importance of the various criteria. Analytic hierarchy process (AHP) is the most commonly used method in the road construction sector [24-28]. The scores in this method are computed by pairwise comparisons and opinions of experts [29]. Another method of great relevance is the Delphi method. Shrestha and Shrestha 2019 [30] employed the Delphi method to analyse road maintenance routines. In this method, the opinions of experts are asked for more than one time to achieve a general consensus with the aim of minimizing uncertainty and improving accuracy. Although, there are methods such as Criteria Importance Through Inter-criteria Correlation (CRITIC) that do not require human intervention, which can be useful to obtain the scores quickly or avoid human errors. Ariza et al. [31], employed multi-criteria analysis for the selection of sustainable urban drainage systems (SUDS) on the basis of environmental, social, and economic aspects using CRITIC.

After the allotment of scores, the multi-criteria decision methodology is applied to select the best alternative. MCDMs that can be utilized include: integrated value model for structural assessment (MIVES), weighted aggregated sum product assessment (WASPAS), elimination et choix traduisant la realité (ELECTRE) (elimination and choice translating reality in original French), technique for order of the preference by similarity to ideal solution (TOPSIS), evaluation based on distance from average solution (EDAS), preference ranking organization method for enrichment evaluation (PROMETHEE). Jato-Espino et al., 2018 [28] employed TOPSIS for the selection of asphalt wearing courses in highly trafficked roads. In another study [32], the optimization of asphalt mixtures incorporating nylon fibers was done using the WASPAS method, where different bitumen, and fiber contents were considered for optimization of an open-graded asphalt mixture. However, there was a lack of literature assessing the 'complete' performance of additives in PA mixtures in terms of mechanical, hydraulic, economical and environmental indicators based on multi-criteria analysis.

In this paper, a multi-criteria decision-making method is employed to select the best additive among the six different types of additives in the PA mixtures based on its effect on mechanical, hydraulic, economic and environmental factors. The hypothesis is that although the additives improve the mechanical performance of PA mixtures they may not improve other aspects proportionally; this study investigates whether this improvement is in overall performance based on hydraulic, economic, and environmental indicators. Figure 1 shows the structure of the study.

The sections are divided as follows; after this first section dedicated to the introduction, the second section discusses the selected methodology describing the multi-criteria decision-making methods: EDAS, TOPSIS, and WASPAS. Then, materials and alternatives and the properties of the materials used are discussed. Next, the selection of indicators that quantify the performance of the additives are explained: mechanical (dry and wet abrasion loss, dry and wet indirect tensile strength test), hydraulic (air voids), economic (initial investment) and environmental indicators (global warming potential, human toxicity potential, marine aquatic eco-toxicity potential). Finally, the criteria of calculation of relative weights is explained. The third section presents the results and discussion of the multi-criteria decision methods. The final section presents the main conclusions drawn from this study.

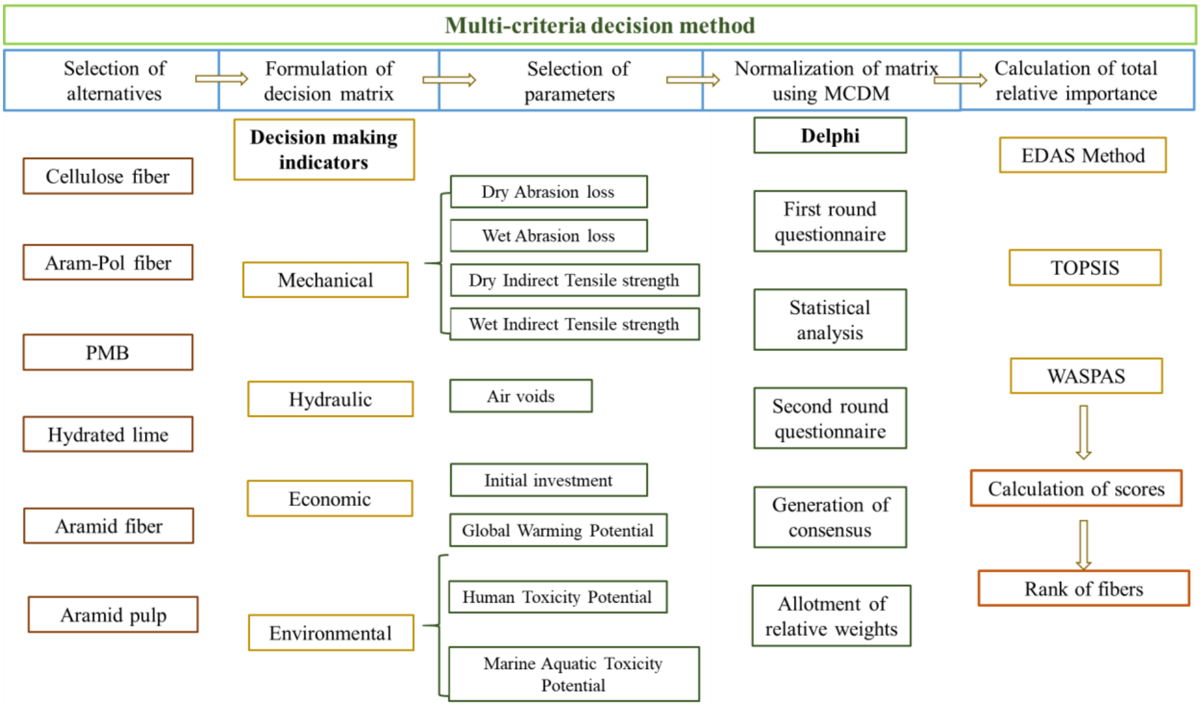


Figure 1. Structure of the study

2. Methodology

2.1. Multi-criteria Decision-making methods (MCDMs)

The three MCDMs used in the study are the EDAS, TOPSIS, and WASPAS methods. They were selected as their approaches were the most interesting ones for this paper.

WASPAS, developed by Chakraborty and Zavadskas [33] is the combination of two individual MCDMs, namely the weighted sum method (WSM) and weighted product model (WPM). WSM is based on the simple weighted addition of the criteria whereas the WPM is an improvement of WPM as its structure eradicates units of measure. It was found that the WASPAS method improves the accuracy of the other two methods [34].

TOPSIS, proposed by Hwang and Yoon, 1981 [35] is among the conventional methods [36, 37]. The principle of TOPSIS is based on the assumption that each criterion tends to increase or decrease the utility [38]. TOPSIS ranks the alternatives based on the ideal and nadir hypothetical solutions, respectively. The best alternative is the one that has the least distance from the ideal solution and the greatest from the nadir solution. This method is a ‘compensatory aggregation method’ which indicates that a reduction in one criterion corresponds to an increment in another [25].

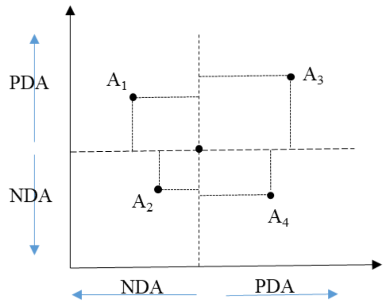
Finally, the EDAS method, developed by Mehdi Ghorabaee [39], utilizes the average solution for evaluating all alternatives with regards to their PDA (positive distance from average) and NDA (negative distance from average). This depends on each criterion being beneficial and non-beneficial.

In this method, there is no necessity to calculate the ideal and nadir solution as it is based on the distance from the average solution [39].

MCDMs were performed to rank the additives selected for this study based on four criteria: mechanical, hydraulic, environmental, and economic. A short description of each can be seen in Table 1 [33, 35, 39]. However, as the results could change depending on the method employed, these three methods were selected to compare the results and to evaluate the accuracy and suitability for porous asphalt (PA) pavements.

Table 1. EDAS, TOPSIS, WASPAS method

<table>
<tr><th>EDAS</th><th>TOPSIS</th><th>WASPAS</th></tr>
<tr><td colspan="3">Full form</td></tr>
<tr><td>Evaluation Distance from Average Solution</td><td>Technique for Order Preference by Similarity to Ideal Solution</td><td>Weighted aggregated sum product assessment</td></tr>
<tr><td colspan="3">Construct the decision-making matrix</td></tr>
<tr><td colspan="3">$X = [x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$ (i=1, 2, 3…m and j= 1, 2, 3….n)
X_{ij} gives the performance of the i^{th} alternative with respect to the j^{th} criterion</td></tr>
<tr><td>PDA and NDA</td><td colspan="2">2. Normalize the decision matrix</td></tr>
<tr><td>Beneficial criteria
The positive distance from average (PDA_{ij}) and negative distance from average (NDA_{ij}) is calculated as:
$PDA_{ij}= \frac{\max(0,\ (x_{ij}-AV_j))}{AV_j}$,
$NDA_{ij}= \frac{\max(0,\ (AV_j-x_{ij}))}{AV_j}$
Non-beneficial criteria
$PDA_{ij}= \frac{\max(0,\ (AV_j-x_{ij}))}{AV_j}$,
$NDA_{ij}= \frac{\max(0,\ (x_{ij}-AV_j))}{AV_j}$
AV_j is the average solution according to all criteria j.</td><td>$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$</td><td>Beneficial criteria
$\bar{x}_{ij} = \frac{x_{ij}}{Max_i(x_{ij})}$
Non-beneficial criteria
$\bar{x}_{ij} = \frac{Min_i\ (xij)}{x_{ij}}$</td></tr>
</table>



Weighted normalized decision matrix		
$SP_i = \sum_{i=1}^{n} w_j * PDA_{ij}$, $SN_i = \sum_{i=1}^{n} w_j * PDA_{ij}$	$Q_i = \sum_{i=1}^{n} w_j * \bar{x}_{ij}$ Where w_j refers to the weight of j[th] criterion.	WASPAS is a combination of two methods WSM and WPM For WSM For WPM $Q_i^1 = \sum_{i=1}^{n} w_j * \bar{x}_{ij}$ $Q_i^2 = \prod_{j=1}^{n} x_{ij}^{-w_j}$
Normalize the Matrix	4. Positive and negative ideal solutions	
$NSP_i = \frac{SP_i}{\max(SP_i)}$, $NSN_i = 1 - \frac{SN_i}{\max(SN_i)}$	Positive ideal solutions (Q^+) $Q^+ = (Q_1^+, Q_2^+, Q_3^+ \ldots Q_n^+) = \{(\max v_{ij} \mid j \in I), (\min v_{ij} \mid j \in J)\}$ Negative ideal solutions (Q^-) $Q^- = (Q_1^-, Q_2^-, Q_3^-, \ldots Q_n^-) = \{(\min v_{ij} \mid j \in I), (\max v_{ij} \mid j \in J)\}$ Where I relates to beneficial criteria; i= 1, 2, 3…m and J related to non-beneficial criteria j= 1, 2, 3,.. n. Positive solutions (d_i^+) and negative solutions distance $d_i^+ = \sqrt{\sum_{j=1}^{n}(Q_{ij} - Q_j^+)^2}$ $d_i^- = \sqrt{\sum_{j=1}^{n}(Q_{ij} - Q_j^-)^2}$	
Calculate the relative scores		
Appraisal score (AS_i) $AS_i = \frac{1}{2}(NSP_i + NSN_i)$ Where $0 \leq AS_i \geq$	Relative closeness (RC_i) $RC_i = \frac{d_i^-}{d_i^+ + d_i^-}$	Joint Performance score (Q_i) $Q_i = \lambda Q_i^1 + (1-\lambda) Q_i^2$ Where, $\lambda = \frac{\sigma^2 (Q_i^2)}{\sigma^2 (Q_i^1) + \sigma^2 (Q_i^2)}$

2.2. Materials and alternatives

The study aims to compare the performance of novel additives that are used to improve the performance of PA mixtures. A variety of additives were considered, and their performance was assessed based on mechanical, hydraulic, economic, and environmental indicators. The additives used in the study were one filler (hydrated lime) and four fibers (regular aramid fiber, aramid-polyolefin fibers, aramid pulp and cellulose fibers). Two additional mixtures were prepared without any additive: one with virgin bitumen (penetration 50/70) and another with PMB 45/80-65.

The PA mixtures were designed according to the Spanish guidelines PG-3 for PA mixtures (Table 2) with the 16mm maximum aggregate size, 4.5% bitumen content, 0.05% fiber content, and 20% minimum air void content. The cylindrical specimens were prepared according to European standard EN 12697-30, applying 50 blows per side using Marshall Compactor.

The aggregates were first heated at 170°C for 6h after that the fibers along with the aggregates were added by dry process along with the aggregates and mixed for approximately 30 seconds to obtain a homogeneous mix. Then, the virgin binder was added at 150°C (whereas PMB at 175°C) and blended thoroughly in this fiber-aggregate mixture for proper coating. The compaction was done with 50 blows on each face of a Marshall specimen and then the specimens were left for 24 hours at room temperature before demolding. The properties of fibers are detailed in Table 3 and those of bitumen & aggregates in Table 4. All the mixtures used in the study are shown in Table 5 and the fibers are shown in Figure 2. The control mixture was prepared with a virgin bitumen content 4.5% and limestone filler without fibers. The gradation, bitumen and fiber content were kept constant for mixtures with aramid fiber, pulp, and polyolefin fibers to ensure that any variation in the performances is due to use of additives.

Table 2. PA mixture gradation (PG-3)

Sieve size (mm)	22	16	8	4	2	1	0.5	0.25	0.063
Passing (%)	100	100	54.5	19.0	14.1	10.3	7.8	6.3	5.0

Table 3. Physical properties of the fibers.

Fiber	Aramid-Polyolefin fiber		Aramid Pulp	Aramid fiber	Cellulose
	Aramid	Polyolefin			
Form	Monofilament	Serrated			
Color	Yellow	Yellow	Yellow	Yellow	Brown
Density (g/cm3)	1.44	0.91	1.44	1.39	0.48
Length (mm)	19	19	1-1.5	6	1.1
Tensile Strength (MPa)	2758	483		3200	
Decomposition temperature (°C)	> 450	157	> 450	500	
Acid/Alkali Resistance	Inert	Inert			

Table 4. Properties of materials used for the preparation of the sample

Properties	Standards	Value		Specification
Bitumen				
		Virgin bitumen	PMB	
Penetration, (0.1mm)	EN-1426	57	55	50-70
Softening Point (°C)	EN-1427	51.6	74.1	46-54
Frass Point (°C)	EN-12593	-13		≤ -8
Specific Weight (g/cc)	EN-15326	1.035	1.028	
Coarse aggregates				
Specific Weight (g/cm^3)	EN 1097-6	2.787	8 / 4	
Los Angeles (%)	EN 1097 - 2	15	14 / 10	≤15%
Flakiness Index (%)	EN 933-3	12	12 / 6	≤20%
Flakiness Index (%)	EN 933-4	20	18 / 12	
Fine aggregates				
Specific Weight (g./cm^3)	EN 1097-6	2.705		
Sand equivalent (%)	EN 933-8	78		>55
Hydrated Lime				
Density (g/cm3)		1.959		
CaO content (%)		≥ 90		
MgO content (%)		≤ 5		
CO_2 content (%)		≤ 4		
Remained on sieve 0.2 mm (%)		≤ 2		

Table 5. Mixture types

Mixture types	BITU	PMB	HYDLIM	ARA-POL	PULP	ARA	CELLU
Type of Bitumen	Virgin bitumen;	PMB bitumen;	Virgin bitumen	Virgin bitumen	Virgin bitumen	Virgin bitumen	Virgin bitumen
Bitumen Content	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	5%
Fiber; fiber Content	None	None	None	Aramid-Polyolefin fiber; 0.05%	Aramid Pulp; 0.05%	Aramid fiber; 0.05%	Cellulose fiber; 0.5%
Filler	Limestone	Limestone	Hydrated lime	Limestone	Limestone	Limestone	Limestone

However, mixtures with cellulose fibers were designed with 5% bitumen content and higher fiber content of 0.5% as they are expected to stabilize the binder as they retain a part of the binder [40, 41]. For mixtures prepared with HYDLIM additive, the limestone filler was completely replaced by the hydrated lime and no other additive was used.

Figure 2. Fibers used in the study: (a) Aramid fiber (ARA); (b) Aramid-Polyolefin fiber (ARA-POL); (c) Aramid Pulp (PULP); (d) Cellulose fiber (CELLU).

2.3. Selection of indicator

2.3.1. Mechanical indicators

Mechanical resistance of the specimens was evaluated by draindown tests, Cantabro tests, and indirect tensile strength tests. The draindown test of the mixtures was performed according to the European standard EN 12697–18. This test assesses the stabilizing ability of PA mixtures. The mixture design used in the study ensured that the draindown was less than 0.3% as recommended by various researchers [42- 45]. The draindown of the mixture types were well below the limit; in the range of 0.01%. Therefore, the results were not included in the multi-criteria analysis.

The Cantabro test evaluates the ability of the mixture to resist disintegration by impact or abrasion caused by vehicles [46]. The adhesion between the constituents of the PA mixtures is strongly affected by the water and high temperature [47, 48]. These tests in dry and wet conditions were performed according to EN 12697-17 and Spanish guidelines NLT-362/92, respectively. In the latter, specimens were submerged in water at 60°C for 24h and then kept at 25°C before testing for one day.

The indirect tensile strength (ITS) is an indicator of the ability of a mixture to absorb energy without fracture. It is the maximum load a specimen can sustain without fracture. The ITS tests were performed to assess the integrity of the mixture against moisture damage and confirm whether the coating of the binder around the fiber-aggregate mixture is uniform. The tests were done according to European standards EN 12697-23 and EN 12697-12 for dry and wet conditions, respectively.

A total of 98 specimens were manufactured with at least three replicates per test to ensure the accuracy of tests. The percentage reductions in abrasion loss and percentage increments in indirect tensile strength in comparison to reference mixture BITU induced by the incorporation of fibers are shown in Table 6. The upward arrow indicates an improvement in abrasion resistance (or reduction in particle loss) due to additives. However, in the case of indirect tensile strength, it indicates the increment in strength. These were further converted into scores to evaluate the rank of additives.

Table 6. Parameters considered for mechanical indicator

Mixtures/criteria	**CELLU**	**ARA-POL**	**PMB**	**HYDLIM**	**ARA**	**PULP**
PL - dry (% reduction)	↑18.73	↑10.65	↑24.56	↓6.46	↑0.69	↑58.82
PL - wet (% reduction)	↑ 38.05	↓94.68	↑47.17	↑30.21	↑24.84	↑55.04
ITS - dry (% rise)	↑6.58	↑10.52	↑8.27	↑18.98	↑10.32	↑0.87
ITS - wet (% rise)	↑27.32	↑21.71	↑27.03	↑11.41	↓7.27	↑13.39

Note: PL-dry & PL-wet refers to particle loss in dry & wet conditions; ITS-dry & ITS-wet refers to the indirect tensile strength test in dry & wet conditions.
For reference mixture BITU, the values for PL-dry & PL-wet were 14% & 20.5% respectively; for ITS-dry & ITS-wet, there were 982.2 kPa & 771.1 kPa respectively.

2.3.2. Hydraulic indicators

The hydraulic performance of the PA mixtures is highly dependent on the voids present in the structure as they act as a path through which the water flows. However, when the additives are added in the PA mixtures, they block a part of the air voids and, hence, it can be expected that the air voids will reduce due to additives. It is important to design the gradation carefully to not compromise the hydraulic performance of the mixture. Many researchers have recommended that the air voids in PA mixtures should be 20% [49-52]. The air voids were calculated according to the European standard EN 12697-8.

The percent variation in air void content of the mixture types regarding the control mixture is given in Table 7. As can be observed, the percentage variation among the air void content of all the mixture types was negligible. The highest difference was observed in the case of cellulose fibers (air void content: 19.7%), which makes sense as the binder content (5%) and fiber content (0.5%) were higher in that case. Similar to mechanical performance, the hydraulic performance of fibers was converted in scores to take a multi-criteria decision.

Table 7. The hydraulic performance indicator for alternatives

Mixtures/criteria	CELLU	ARA-POL	PMB	HYDLIM	ARA	PULP
Percentage variation (%)	↓ 8.19	↓1.64	↓0.09	↑0.16	↑0.51	↓4.92
Note: The air void content of the reference mixture BITU = 21.4%						

2.3.3. Economic indicators

The additives were evaluated based on the capital invested at the beginning of the construction of a pavement. The total cost of asphalt (in euro/tonne) was computed for each type of mixture by summation of individual cost of bitumen, aggregates, fillers and additives. The economic indicator is shown in Figure 3.

It is worth mentioning here, the PULP fibers used were the waste products obtained from the production of aramid fibers (ARA); therefore, their use can result in additional savings. Furthermore, it was found that the addition of fibers and fillers did not increase the cost of the manufacturing process as they were incorporated by the dry method, i.e., they were added with the aggregates in the mixture. However, the use of PMB implies a higher cost in the manufacturing process since an increment of manufacturing temperature is required to reduce its viscosity. Therefore, an increase of 20°C (160° C to 180°C) requires an increment of 6-9% in total energy, which includes the energy required for heating and drying of aggregates (which also depends on the moisture content). Therefore, a value of 7.5% increment was considered due to the use of PMB bitumen.

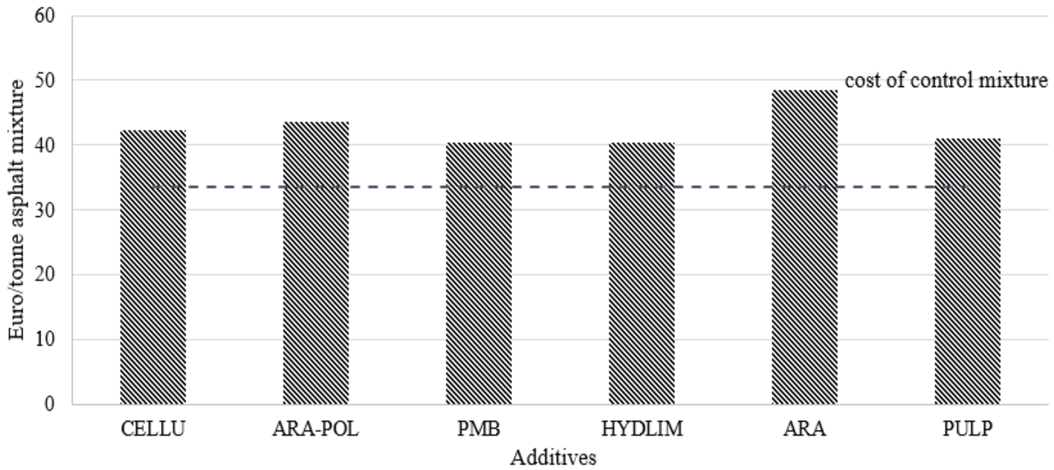


Figure 3. Cost of the asphalt mixtures (euro/tonne)

2.3.4. Environmental indicator

Life cycle assessment is done to calculate the environmental impact of a structure. To analyse the additives from the environmental point of view, a life cycle assessment (LCA) was performed following the standards ISO 14040:2005 and 14044:2006. The environmental analysis is done based on the ReCiPe method and the production of 1 ton for each asphalt mixture was considered as a functional unit. LCA included the production of materials, transportation to the asphalt plant and production of the asphalt mixture. Only three impact categories were selected as evaluating all the impact categories that are normally included in an LCA would substantially increase the complexity of the MCDM. In a study done by Lizasoain-Arteaga et al. 2019 [53], global warming potential and human toxicity potential received the highest score in the weighting factors, these are also among those recommended by the EPA, BEES, NOGEPA, and BREE [54, 55]. Moreover, marine aquatic eco-toxicity potential underwent the greatest variation in a previous study [56] which compared a reference asphalt mixture with no fibers to another containing FortaFi additive (one of the additives also used in this study). Therefore, these three categories were selected as the most relevant parameters to analyse the impacts on the environment: Global Warming Potential (GWP), Human Toxicity Potential (HTP), and Marine Aquatic Eco-toxicity Potential (MAETP). The CML 2001 (January 2016 update) characterization method was selected for the impact calculation since this method is recommended in the standard EN 15804-2012 regarding the Environmental Product Declaration rules for construction products. It should be mentioned that:

1. CELLU fibers contain 90% cellulose fiber and 10% bitumen. According to the provider, cellulose fibers contain recycled wastepaper, its percentage varying depending on its quality. For the analysis, waste paper fibers were used as the main raw material.
2. ARA-POL is composed of 13% aramid fiber and 87% polyolefin fiber. As no information regarding the type of polyolefin used was found, polystyrene was assumed for this work.
3. The production process for aramid fiber (ARA) is available in GaBi but for aramid pulp (PULP) it is not available. As the manufacturer published the manufacturing process and the GWP impact of both materials, the difference among them was solely due to an increase in electricity consumption while manufacturing PULP.

The percentage increase in the impact on GWP, HTP, and MAETP for all additives compared to the control mixture is showing in Figure 4. The use of additives has a higher impact on the environment than using the control mixture with virgin bitumen and no fibers. Cellulose fiber and ARA-POL fibers are among the additives that caused the least increment in global warming potential and are least toxic to human and marine aquatic life.

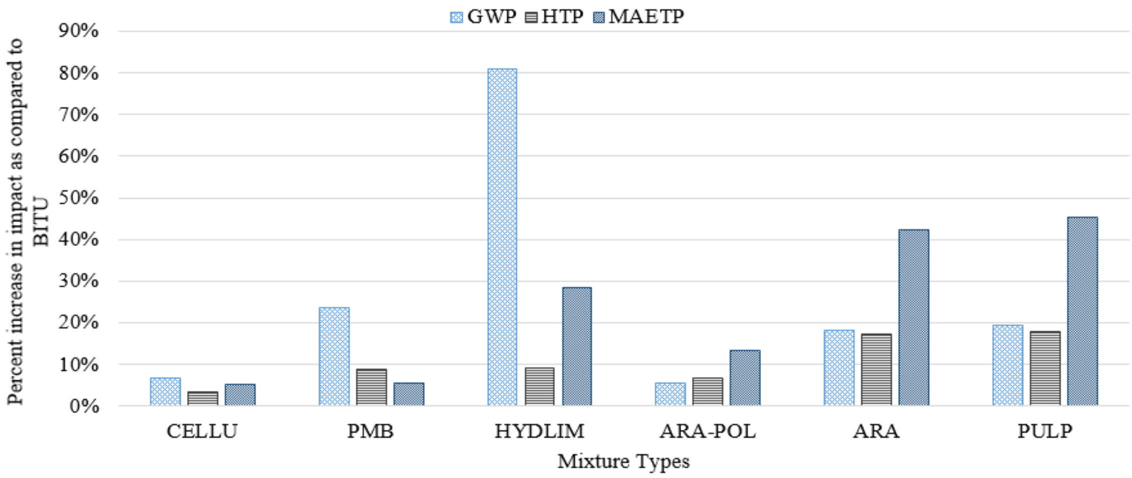


Figure 4. The percentage increment in impact on the environment with respect to control mixture (BITU)

4. Computation of relative weights

Once the parameters are chosen, it is crucial to evaluate the relative importance of each of them in the selection of alternatives. The Delphi method was used for this purpose. This method is based on the idea of aggregating the judgments of a group of experts to enhance the accuracy of decision-making without bringing them together physically. In this iterative method, questionnaires are prepared one after the other and each subsequent questionnaire is prepared based on the results obtained during the previous one. The process is stopped when a consensus or sufficient information is obtained. According to the judgments, the relative weights or scores are computed indicating the range of importance from high to low. In contrast to other methods, the accuracy of this method is not determined by the number of participants but by their expertise. This method does not necessitate the complexity of pairwise comparison as other methods such as the analytic hierarchy process (AHP). For example, if the scores are allotted as shown in the illustrative example in Figure 5, the different levels of scores can be estimated instead of a comparison between one pair, and consequently, the comparative rating can be added to more than two parameters at the same time. Additionally, in the Delphi method, error due to the human mind is reduced as the experts are given multiple chances to reconsider their answers.

In this study, a group of 5 experts based on their experience chose the criteria that can determine the performance of each additive. Then a questionnaire with the defined criteria and indicators (sample of questionnaire is provided in Appendix 1) was sent to a diverse group of 32 experts in the field of asphalt pavement engineering to provide weights for the parameters based on their expertise. Around 65% of experts are working in the university, 15% in the research centers, and 20% work in construction companies or national road authorities. Many researchers work as senior researchers or scientists in reputed research organizations, while others are working as professors in recognized universities. The experience of more than 90% of the experts are directly related to asphalt pavements and road engineering. In terms of geographical diversity, the experts work in 11 countries including India, Chile, Colombia, Spain, Italy, the United Kingdom, and Switzerland.

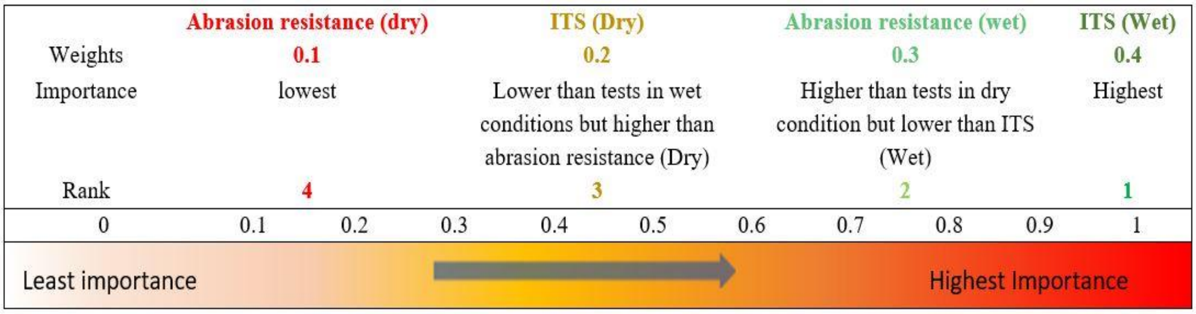


Figure 5. Explanation of the scoring system.

The questionnaires were presented in the form of numerical values from 0 to 1 where 0 indicated minimum importance whereas 1 indicated the highest importance (see Figure 5). The experts were asked to fill in their responses on parameters so that the sum was 1 for each indicator. The indicators chosen include mechanical, hydraulic, environmental, and economic parameters.

After the analysis of results obtained in the first questionnaire, a statistical analysis was performed to evaluate the coefficient of variation and confidence interval among the opinions of the experts. In the second questionnaire, the mean and standard deviation for each parameter was also mentioned, so that the experts have the choice to change their answers to minimize the standard deviation about the mean. After the second questionnaire, a consensus was obtained with a significant reduction in the coefficient of variation, suggesting that the two rounds were sufficient. In the second questionnaire, 24 responses were received out of 32; the remaining 8 responses were maintained as they were in the previous round.

4.1. The relative weight of Mechanical indicators

The results obtained after the final round are shown in Figure 6a. It was found that relatively higher weights were allotted to the performance in the wet conditions; both for the Cantabro test and indirect tensile strength test. This makes sense as the moisture susceptibility in PA mixtures is a great concern due to the higher porosity that makes the mixture very exposed to aging and oxidation in comparison to dense-graded mixtures. In both dry and wet conditions, the abrasion resistance is given higher priority than the indirect tensile strength test. This can be explained because that the raveling is the biggest concern in PA mixtures due to high air void content in their structure [46, 57- 59]. Also, in wet conditions, the test for abrasion resistance is performed under harsher conditions as the samples are submerged at a high temperature of 60°C (in comparison to 40°C in ITS test) which may be higher than the softening point of the bitumen resulting in more binder stripping and a higher abrasion loss.

4.2. Relative weights of Environmental indicators

The relative weights are given in Figure 6b. The results show that the experts consulted assigned a similar weight to all the proposed impacts with the weight of GWP being slightly higher. This may be because nowadays, this impact is considered as the most prominent in environmental analysis and although changing, it is still the main impact referred to in international forums and agreements. Human toxicity received greater weight than aquatic ecotoxicity, which may be the result of the great social concern about diseases such as cancer which can be the result of fumes generated in the construction industry. Economic and hydraulic indicators do not need relative weighting because there is only one indicator per criterion.

4.3. Comparison of Indicators

The relative weights for each indicator are shown in Figure 6c. The weights are given in highest to lowest in the order hydraulic > mechanical > environmental > economic. The hydraulic indicator includes the total air void content of the PA mixture. Among mechanical and hydraulic indicator, the latter were given more importance by the experts.

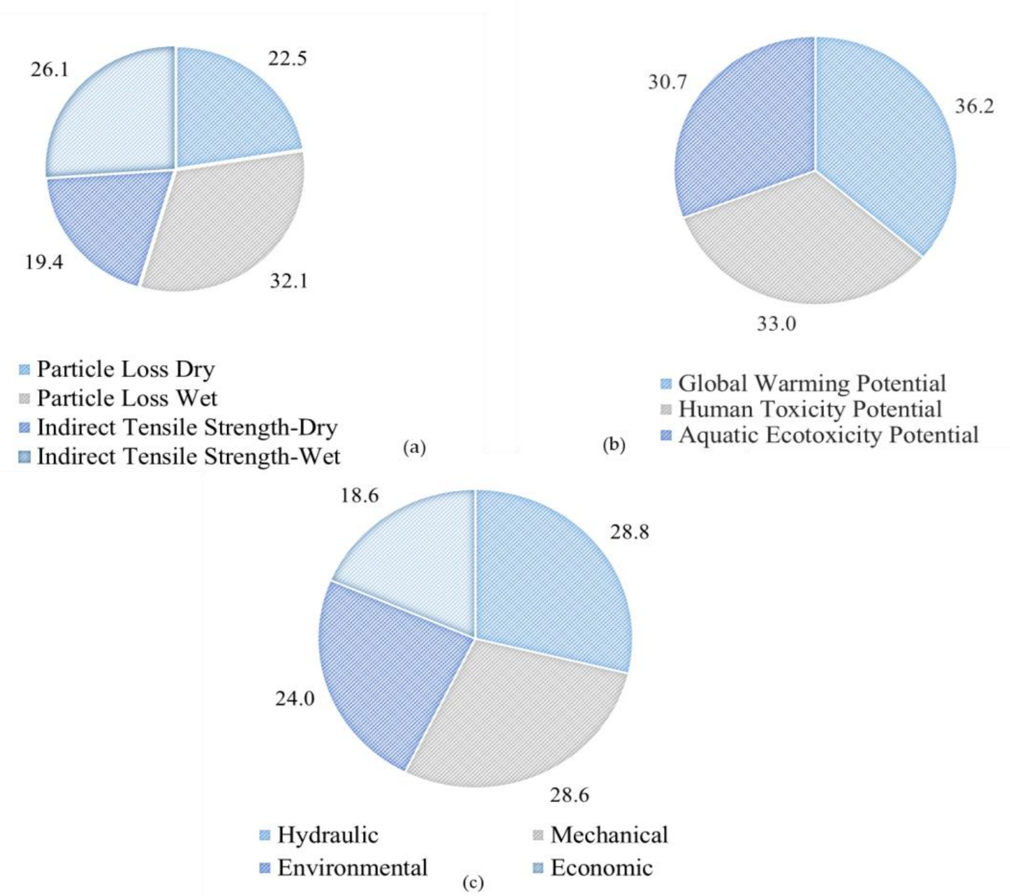


Figure 6. Relative weights according to Delphi method for (a) mechanical indicator; (b) environmental indicator; (c) indicators

It makes sense as the air voids indicate the efficiency in passing the water, absorbing noise, and reducing skid risk. Especially when additives are used in the mixture, the amount of air voids is affected. Therefore, it is important to maintain hydraulic performance along with mechanical performance. The environmental indicator is given higher importance than the economic one as the environmental impact is high; thus, it will overshadow other economic advantages of PA mixtures.

5. Results and discussions

5.1. Mechanical Indicators

Figure 7 presents that the score given for each type of mixtures using the EDAS, TOPSIS, and WASPAS methods. It can be observed that the three methods have shown very good agreement with each other in the evaluation of the mechanical indicators, as for every MCDM the ranks of mixture types are as follows from best to worst: PULP> PMB> CELLU> HYDLIM> ARA> BITU> ARA-POL. Using multi-criteria decision-making methodologies, the performance of fiber varied greatly depending on the material of the additive.

The PULP fiber was shown to have the best performance as the AS (EDAS), RC (TOPSIS), Q (WASPAS) were highest for PULP. This is probably because PULP fibers improved the abrasion resistance significantly (+58.82% and +55.04 in dry and wet conditions with respect to BITU), which was selected as the most important mechanical indicator by the experts. The reason for this phenomenon may be the defibrillation of pulp fibers into small-sized of fibers (1-1.5mm) which may strengthen the bitumen-aggregate matrix. It is worth mentioning here, that the mechanisms of fibers has been explained by the authors in previous articles [7, 60]. The mechanical resistance of the PULP fiber not only matched the performance of PMB but was even found to be better. Moreover, PULP fibers improved the strength in wet conditions.

Other additives CELLU, HYDLIM, and ARA additives also performed better than the control mixture but worse than PMB indicating that the additives improve the mechanical resistance of the conventional PA mixture with virgin bitumen, which is confirmed by many researchers [5, 61-63]. Especially in the case of the ITS and Cantabro tests in wet conditions, the samples were kept at a higher temperature of 40°C and 60°C, at which the viscosity of bitumen reduces. However, due to the use of additives the viscosity increases which helps in maintaining a similar value. However, there is one exception, ARA-POL had the worst performance as the abrasion losses were very high, particularly under wet conditions (-94.7%). This may be because of the unsuitability of polyolefin in improving the viscosity of the binder in the asphalt mixture.

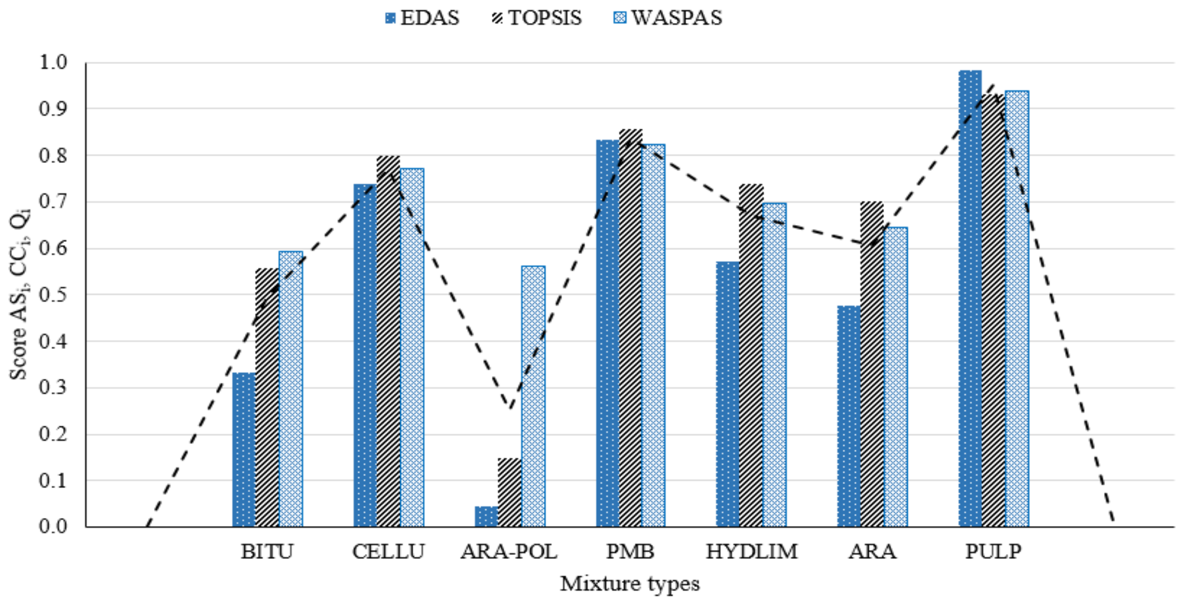


Figure 7. Mechanical indicators: relative scores AS (EDAS), CC (TOPSIS), Q (WASPAS). The dotted line indicates the average of the AS, CC, Q.

5.2. Hydraulic and economic indicators

For the hydraulic indicators, where the air void content was considered, the best additive for this case was the one that displayed the highest air void content. The rank of the additives was based on the hydraulic performance of the additives in the order from highest to lowest: ARA> HYDLIM> PMB> ARA-POL> PULP> CELLU. It is worth mentioning here that the CELLU fibers were prepared with a bitumen content of 5% which was higher than the rest of the mixture types. However, the reduction in the case of CELLU was not proportionate to the increase in the bitumen content, due to high absorption of bitumen by fibers. The variation in the values was not found to be significant (p-value> 0.05) for all other fibers. Hence, it can be safely said that the additives did not reduce hydraulic performance. The reason for this may be the small quantity of additives and no significant changes in the gradation. If we characterize the mechanical and hydraulic indicators as physical characteristics, the best performance will be of PMB mixtures as it was ranked higher in both indicators.

Based on the economic indicator the ranks of fibers from best to worst are BITU> HYDLIM> PMB> PULP> CELLU> ARA-POL> ARA. It is obvious that the reference mixture BITU will present the lowest cost as no fibers were added. HYDLIM is next in line as in these mixtures, limestone filler is replaced by hydrated lime that resulted in a minimum increase in the cost. Aramid fibers are the most expensive fiber and even with a fiber content of just 0.05% the cost of these mixtures is highest.

5.3. Environmental indicators

The rank according to Figure 8 for the asphalt mixtures is as follows: BITU> CELLU> ARAPOL> PMB> ARA> PULP> HYDLIM. The burning of fossil fuels, drying, and heating the aggregates represent around 85% of the energy consumption of an asphalt plant. In HYDLIM mixtures, the limestone filler was replaced by hydrated lime that led to a very high impact on the environment. Hydrated lime has a very high global warming potential (GWP) which results in its lowest rank. For parameters HTP and MAETP, the impacts of HYDLIM are comparable to other mixtures. Binder is an additional major source of GHG emissions during the production of the asphalt mixture.

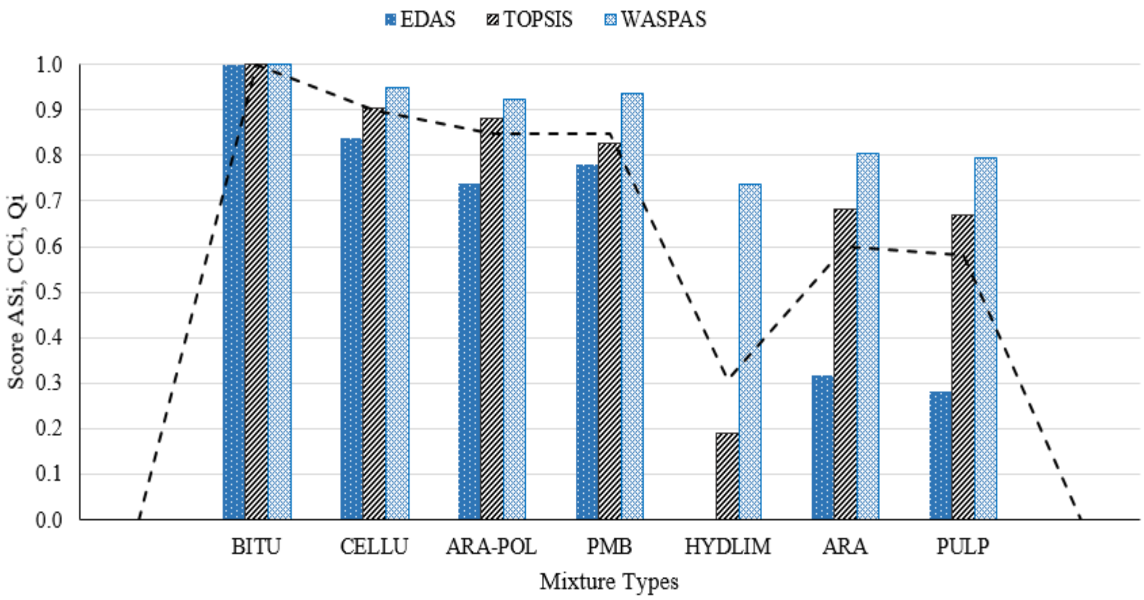


Figure 8. Environmental indicator: AS, CC, and JPS scores using EDAS, TOPSIS, and WASPAS methods respectively. The dotted line indicates the average of the AS_i, CC_i, Q_i

While using the PMB due to higher manufacturing temperature, any increase or decrease in the product temperature has a direct impact on the amount of fuel consumed, and environmental impact [64]. The PMB has a lower rank despite the absence of fibers. It is also important to keep in mind that the recyclability of PMB has been questioned many times by researchers due to the presence of polymers. A lot of research is ongoing on the replacement of the polymer-modified bitumen without compromising the mechanical performance thanks to the addition of fibers.

5.4. Ranking of Indicators

If all the indicators were given the values as proposed by the group of experts shown in Figure 6c, then the resulting ranking using EDAS, TOPSIS, and WASPAS would be as shown in Figure 9; in order of rank: PMB> PULP> CELLU> BITU > HYDLIM> ARA > ARA-POL.

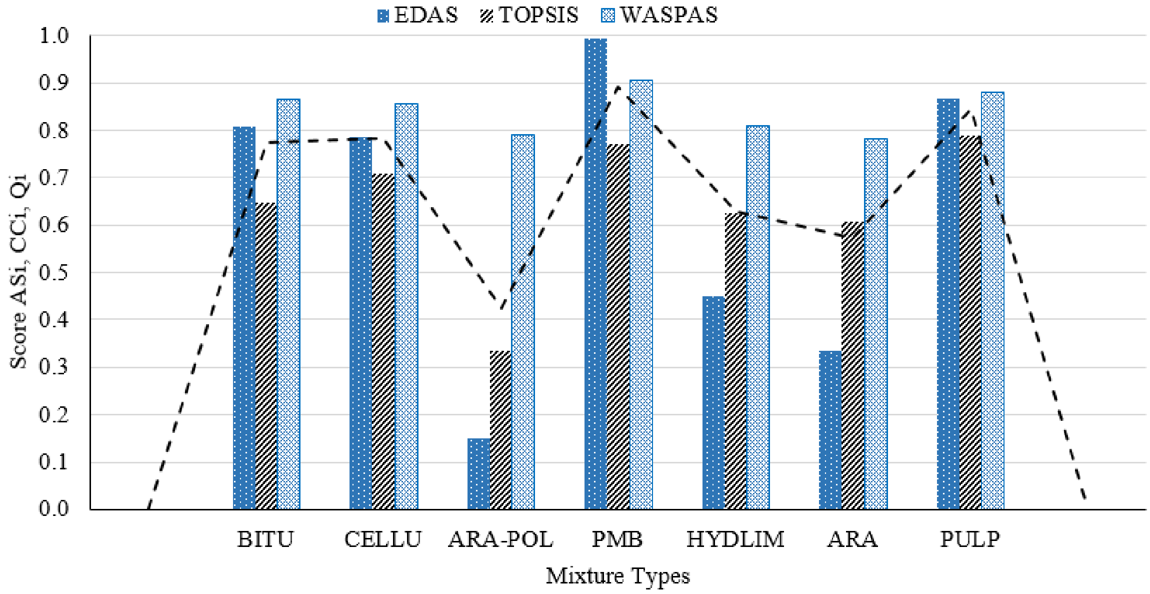


Figure 9. Mechanical, hydraulic, and economic and environmental indicators: AS, CC, and JPS scores using EDAS, TOPSIS, and WASPAS methods, respectively. The dotted line indicates the average of the AS_i, CC_i, Q_i

All parameters involved were given a priority by multiplying the relative weights allotted to the indicators and then to the individual parameter. For example, environmental indicators were given a relative weight of 0.24, and for GWP a relative weight of 0.36, then the cumulative weight of GWP will be the multiplication of 0.24 and 0.36 i.e., 0.087 (8.7%). It can be seen from that considering the influence of mechanical, hydraulic, economic, and environmental indicators, and their corresponding parameters, PMB and PULP were the best performing mixtures.

EDAS and WASPAS attributed the highest score to PMB while according to TOPSIS, PULP showed the best performance. Overall, PMB and PULP both improve the mechanical performance of the mixtures without significant differences among them. It is important to note that the CELLU fibers have good mechanical performance and lower impact on the environment which explains their widespread use. In turn, HYDLIM mixtures were among the highest-ranked in terms of hydraulic and economic parameters; however, due to the high impact on the environment and low improvement of mechanical resistance, its use can be questioned.

5.5. Discussion of Multi-criteria decision-making methods

As an additional contribution of this research, a comparison among the three multi-criteria decision-making methods is illustrated in graphical form, as shown in Figure 10.

In the same way, different linear regression models were developed based on the scores attained by each multi-criteria method. Accordingly, EDAS vs. WASPAS displayed the best agreement with an R^2 value of 0.94 (See Figure 10b), followed by the EDAS Vs. TOPSIS regression model with an R^2 value of 0.78. Finally, TOPSIS vs. WASPAS displayed the lowest agreement with an R^2 value of 0.59. Regarding the preference rankings, it was observed that EDAS had the largest gaps among the scores whereas, in the WASPAS method, all designs exhibited closer values in the scores. Accordingly, in this research, although the ranking was similar among the three methods, in EDAS the differences in the scores were more noticeable. In any case, PMB and PULP were ranked in the first positions whereas ARA-POL was in the last position.

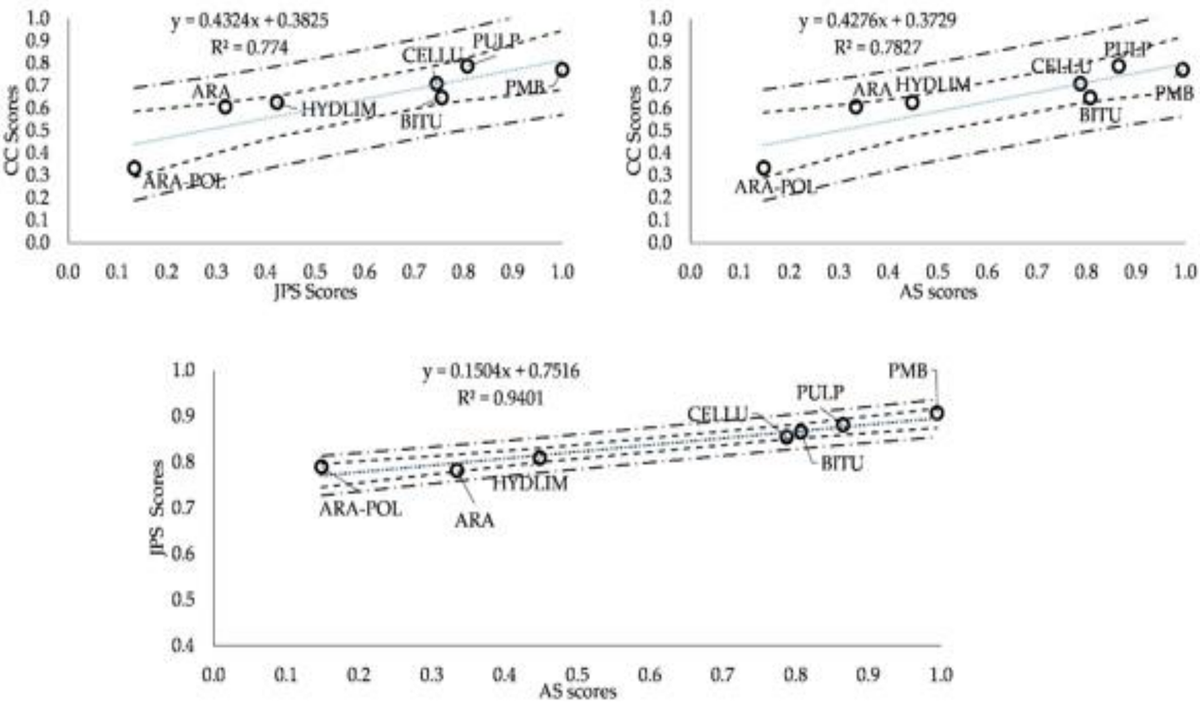


Figure 10. Comparison of multi-criteria methods (a) TOPSIS Vs. WASPAS (b) TOPSIS Vs. EDAS (c) WASPAS Vs. EDAS

6. Conclusions

In this study, a multi-criteria decision-making method was applied to rank the performance of various additives in PA mixtures- three types of fibers: aramid fiber, aramid pulp and aramid-polyolefin fibers; two types of fillers: limestone (standard) & hydrated lime; and two types of bitumen: virgin bitumen 50/70 & polymer modified bitumen. Their performance was analysed based on four indicators, namely: mechanical indicators (abrasion resistance in dry conditions and wet conditions and indirect tensile strength in dry conditions and wet conditions); hydraulic indicator (air voids); economic indicator (initial investment) and environmental indicators (global warming potential, human toxicity potential, and marine aquatic eco-toxicity potential). The relative weights were calculated using the Delphi method and the alternatives were ranked using the multi-criteria methods EDAS, TOPSIS, and WASPAS. The following conclusions can be drawn from the study:

- According to the Delphi method, experts gave the highest relative weights to abrasion loss in wet conditions in mechanical resistance as it poses a serious concern for porous asphalt mixtures due to their open-graded structure. Meanwhile, for the environmental indicator, the highest relative weight was allotted to global warming potential.
- The additives improved the mechanical performance of the PA mixtures. The highest scores were observed for the porous asphalt mixtures with PULP fibers according to all three methods. Additionally, mixtures with aramid pulp exhibited the highest abrasion resistance, whereas aramid-polyolefin fibers showed the lowest abrasion resistance.
- The additives did not compromise the hydraulic characteristics of the PA mixtures severely. The scores were given in the order (best to worst): ARA> HYDLIM> PMB> ARA-POL> PULP> CELLU. Although cellulose fiber displayed the lowest air voids content, no significant reduction was observed compared to the reference mixture. Overall, it was found that
- Concerning the economic indicator, the highest score was given to mixtures with hydrated lime. This was closely followed by the aramid pulp, which was a waste product during the manufacturing of the aramid fibers, requiring the least initial investment among all the fibers included in the study.
- The environmental indicator suggested that the additives had a higher impact on the environment. However, the addition of cellulose fiber (the only natural fiber tested) had the least impact on the environment, whereas the hydrated lime had the highest impact on global warming potential.
- The three multi-criteria decision-making methods used (EDAS, TOPSIS, and WASPAS) have shown very good agreement, especially for the mechanical indicators. EDAS and WASPAS have shown higher agreement compared to EDAS and TOPSIS or TOPSIS and WASPAS.
- Overall, the use of aramid pulp and cellulose fibers is recommended in PA mixtures based on mechanical, hydraulic, economic, and environmental indicators. On the one hand, aramid pulp (a waste product) had been shown to have enhanced the mechanical characteristics considerably, while on the other hand, cellulose fibers had the lowest impact on the environment.

In the future, the influence of fibers on the rate of aging should be analysed using short and long-term aging procedures as well as fiber's behavior in PA mixtures at low and high temperatures. Another interesting line of research could be to evaluate the recyclability of the PA mixtures incorporated with additives. It is also important to assess the impact of the increment in temperature on the environmental indicator by using polymer-modified bitumen. Increase in temperature results in higher emissions, and high environmental impact.

Author Contributions:

Conceptualization, A.G., J.R-H., and C.J.S.-A.; methodology, A.G.; investigation, A.G. C.J.S.-A, and E.L-A.; writing—original draft preparation, A.G.; review and editing, C.J.S.-A., J.R-H, D.C-F. and E.L-A; supervision, D.C-F.; Resources, D. C-F., J.R-H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest:

No potential conflict of interest was reported by the authors.

Annex

URBAN ROADS

ULTICRITERIA QUESTIONNAIRE FOR THE SELECTION OF THE BEST ADDITIVE IN POROUS ASPHALT MIXTUR

For the selection of the best additive in porous asphalt mixtures used in urban areas, a multi-criteria decision tool is being developed. For this reason, the performance of different additives in this type of mixtures are studied and compared using a series of indicators and criteria related to their mechanical, hydraulic, environmental and economic impact.

A crucial issue within this procedure is to establish the relative importance between the elements that comprise the proposed decision-making tree. Gathering the opinions of a group of people with great expertise in the assessed subject strengthens the quality of such judgments making them more robust in nature.

The experts are requested to assign the relative weight (upto two decimal points) of the following indicators according to their knowledge and expertise in the matter.

The values can be any decimal from 0 to 1 based on the relative importance 0 being with the lowest importance and 1 being with the highest importance	**0≤ value ≤1**

The assessments contained in each of the spreadsheets submitted by the experts will be synthesized to obtain a common mean and standard deviation and will be **sent back once again** to the experts to make changes to their initial opinions so as to minimize the standard deviation and obtain an overall value that reflects a consensual solution.

ILLUSTRATIVE EXAMPLE

Indicator I

Assign the proper relative weight to you

	Parameter A	Parameter B	Parameter C	Parameter D
Add weights	0.3	0.3	0.2	0.2

**** The sum of the relative weights of the parameters must be equal to 1.***

The sum of the weights is equal to 1

INDICATORS

Mechanical

	Particle loss - dry	Particle loss - wet	ITS - dry	ITS - wet conditions
	(it is conducted to assess	(it is conducted to assess	(Indirect tensile	(In wet conditions, ITS signifies
Add weights	?	?	?	?

**** The sum of the relative weights of the parameters must be equal to 1.***

Environmental

	Global Warming Potential	Human Toxicity Potential	Aquatic Ecotoxicity Pot.
	(change in global temperature caused by the greenhouse effect that the release of "greenhouse gases" by human activity creates)	(It calculates the potential harm of a chemical released based on both the inherent toxicity of a compound and its potential dose)	(Toxicological responses of different species considering maximum tolerable concentrations in water.)
Add weights	?	?	?

**** The sum of the relative weights of the parameters must be equal to 1.***

CRITERIA

	Hydraulic	Mechanical	Environmental	Economic
	(Hydraulic criteria includes the total air voids, signifies the ability of mixtures to let water pass through their	(includes particle loss and ITS both in dry and wet conditions, signifies the mechanical	(Includes global warming potential and human toxicity potential,	(includes initial investment, signifies the initial cost incurred while implementing the porous asphalt mixtures)
Add weights	?	?	?	?

**** The sum of the relative weights of the parameters must be equal to 1.***

Optional remarks. This space is designed for the expert to give the reasons you deem appropriate to justify the weights assigned to each of the criteria and indicators.

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5.3. Article 3: Critical assessment of new polymer-modified bitumen for porous asphalt mixtures

5.3.1. Information and impact factor

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Critical assessment of new polymer-modified bitumen for porous asphalt mixtures

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Abstract

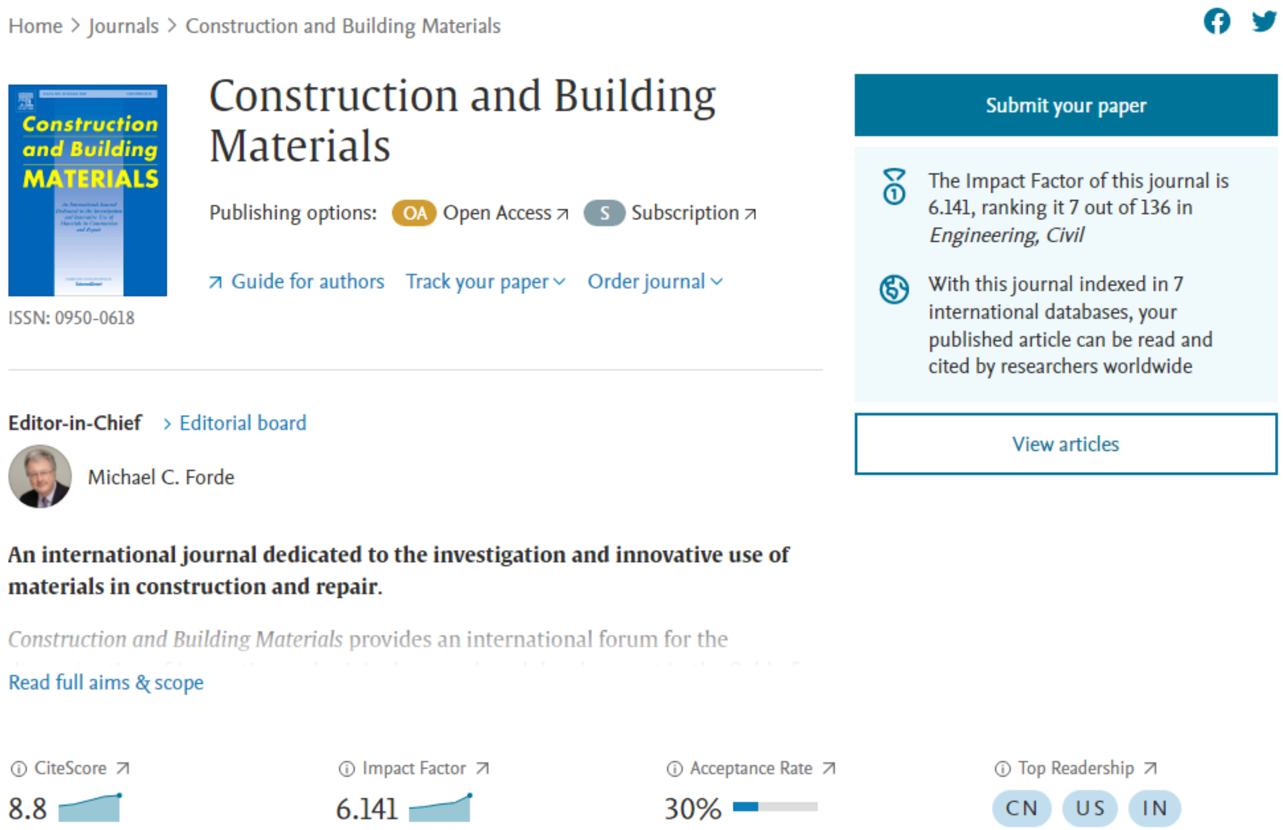

Figure 10. Information of the journal (Article 3).

5.3.2. Transcription of Article 3 (post-print version)

Critical assessment of new polymer-modified bitumen for porous asphalt mixtures

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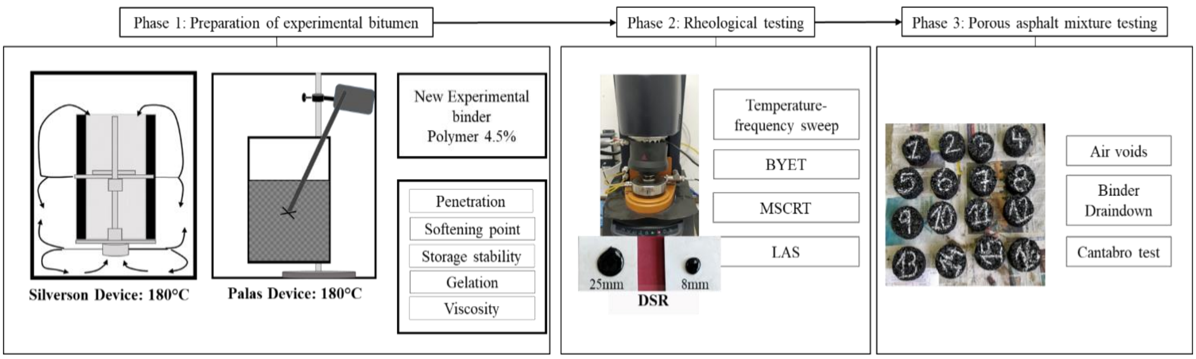
Abstract

New experimental polymer-modified bitumen with a high-vinyl content polymer was fabricated for porous asphalt (PA) mixtures. The bitumen with maximum stability was achieved using storage stability, gelation criteria and physical bitumen tests. A dynamic shear rheometer was used to compare the complex modulus, number of fatigue cycles, yield stress, and non-recoverable creep compliance of the experimental bitumen with a reference virgin bitumen 50/70 and a PMB 45/80-65 binder. PA mixtures were also designed to analyse the abrasion resistance and binder drainage characteristics. It was concluded that the experimental bitumen with 4.5% polymer content showed higher elastic response, better fatigue resistance, and improved rutting behavior than the reference PMB. PA mixtures with the new experimental bitumen exhibited higher abrasion resistance, but underwent higher binder drainage, which was addressed by the incorporation of aramid pulp and glass-hybrid fibers.

Keywords: bitumen fabrication; polymer-modified bitumen; DSR; LAS; BYET; MSCRT; porous asphalt mixtures; aramid fibers; durability

Graphical abstract:



Highlights

- The experimental binder was prepared with high-vinyl content polymer.
- The experimental bitumen showed adaptation to variation in temperature.

- The experimental binder exhibited low creep compliance and high percentage recovery.
- The addition of fibers addressed the draindown problem of experimental bitumen mixtures.

1. Introduction

Increasing traffic load has led to requirements of more durable asphalt mixtures. In addition to traffic, adverse weather conditions reduce the serviceability of the pavement. These problems worsen in porous asphalt (PA) mixtures, due to their exposed structure that facilitates excessive oxidation of bitumen [1, 2]. Due to combined effects of oxidation, climatic conditions, and vehicle loading, raveling constitutes the predominant distress in PA pavements [3, 4, 5]. To improve raveling resistance, polymer-modified bitumen (PMB) can be used to enhance the interaction between binder and aggregates without causing segregation of material [6, 7, 8]. Therefore, PA mixtures with PMB are less susceptible to abrasion due to their greater adhesion and having fewer fissures in binder [9, 10]. PMB has very high temperature stability so there is noticeable reduction in the rut depth [11,12]. Additionally, PA mixtures with PMB binder have more elasticity, which improves the low temperature crack resistance [10, 13].

According to Shell bitumen handbook (sixth edition) [14], plasticity interval is “the temperature range between the measure of high temperature performance (e.g. the softening point or criteria based on the complex modulus in the SHRP PG grading approach) and the low temperature measure of performance (e.g. a brittleness point or limiting stiffness value determined by the BBR)”. The polymer modification enhances the plasticity interval based on the polymer properties, polymer content, nature of base bitumen and degree of modification [14]. According to studies, if the polymer content is less than 2.5% then the properties of base bitumen dominates the resultant binder properties with higher viscous components. If polymer content is 5%, then the resultant bitumen exhibits an equal contribution from polymer and bitumen. At polymer content higher than 7.5%, polymer phase is more dominant and the bitumen acts like rubber [15, 16].

Bitumen is most commonly modified with elastomers [17]. Elastomers resist deformation by stretching and then recover the original shape (shell). Styrene-Butadiene-Styrene copolymers (SBS) are among the elastomers frequently used to modify bitumen [7, 17-23]. They form a three-dimensional network by physical crosslinking of molecules [14]. The butadiene block is highly elastic while the styrene block is stiff and shows good compatibility with the aromatic fraction of bitumen [24]. SBS polymers provide high elasticity, low temperature cracking [25], better rutting behavior at high temperatures [26], high viscosity [15], high softening point and a low penetration value [13, 27]. However, use of this polymer is critical, with some drawbacks such as lack of storage stability because of low thermodynamic compatibility with bitumen, and high rate of polymer ageing due to ruptures in polymer chains caused by UV radiation (CH bonds) [15, 21]. Styrene is easily dissolved in bitumen due to the presence of aromatic rings whereas butadiene has simple carbon hydrogen bonds (CH bonds). The presence of aromatic rings in bitumen enables swelling to up to nine times its initial volume [24, 28]. High-vinyl content SBS (>35%) improves the viscosity and improves the bond between polymer and bitumen [16] and has a lower rate of ageing. According to Singh et al., 2018 [21], it was found from gel permeation chromatography (GPC) the high-vinyl SBS polymer reduces the rate of erosion compared to that with lower vinyl content. High-vinyl SBS polymer may reduce the issues relating to storage stability, high viscosity, and degradation of SBS polymers [16, 21].

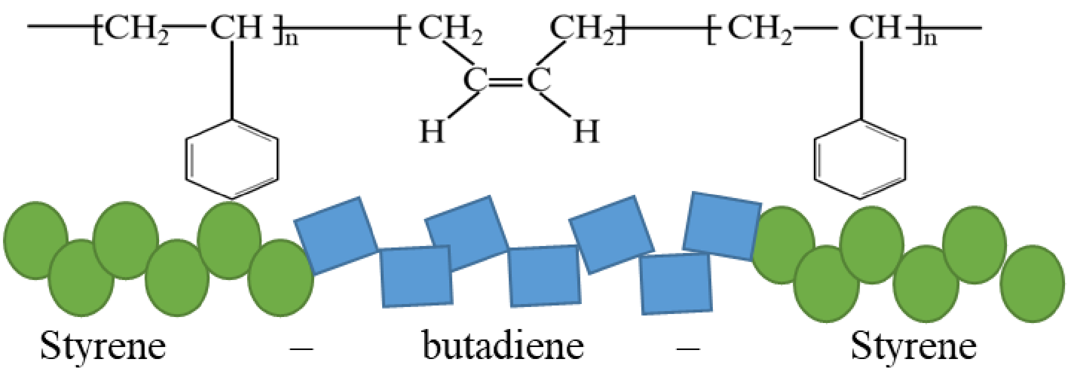


Figure 1. Structure of SBS polymer

To characterize a new bitumen and analyse the rheological parameters of modified bitumen, the dynamic shear rheometer (DSR) is most commonly used [12, 29- 33]. The time sweep test is used to analyse fatigue characteristics in asphalt material [34]. However, this test is time consuming and so shear stress tests and amplitude sweep tests, such as the Linear Amplitude Sweep test (LAS), can be used. The LAS test has gained popularity as many studies state that its results can estimate the fatigue characteristics of the binder that pavement in the field [35, 36]. The LAS test involves complex mathematical modeling, and it is difficult to account for non-linear viscoelastic properties [31, 35]. The BYET (Binder Yield Energy Test) with monotonic loading has shown good correlations with LAS test results and fatigue of the asphalt mixtures [31]. Nevertheless, many researchers have questioned the validity of BYET because of multi-peak behavior [36, 37]. For the analysis of rheological performance of bitumen at high temperatures, Multi-Stress Creep and Recovery Test (MSCRT) has been widely performed by many researchers [31, 38-42]. Vischer et al. [43] found in their study that this test accurately simulates the realistic rutting in the asphalt mixtures and the non-recoverable creep compliance (J_{nr}) parameter indicates the sensitivity to rutting.

1.1. Objectives and methodology

The main objective of this research is to develop a new bitumen using high-vinyl content SBS polymer, catering to the requirements of PA mixtures. The bitumen developed was analysed using conventional physical tests such as penetration, softening, viscosity, storage stability, gelation; and rheological tests such as DSR, LAS, BYET, and MSCRT. The second objective is to investigate the laboratory performance of PA mixtures manufactured with the new experimental bitumen, comparing it with conventional virgin bitumen and a commercial polymer-modified bitumen. Finally, the suitability of the new bitumen combined with aramid and glass fibers was also assessed.

This study was conducted in three phases:

Phase 1. *Preparation of the new experimental bitumen:* Tests were carried out and the experimental procedure was adopted for the fabrication of new experimental bitumen.

Phase 2. *Rheological testing:* Tests were carried out to assess the rheological characteristics of the new experimental bitumen performance compared to virgin bitumen 50/70 and a commercial PMB 45/60-85.

Phase 3. *PA mixture testing:* Comparison of PA mixtures prepared with the new experimental bitumen with the commercial PMB 45/60-85 and virgin bitumen 50/70, including the study of the effect of fibers in PA mixtures combined with the new experimental binder.

2. Materials and Methods

2.1. Preparation of the new experimental bitumen

The fabrication of experimental bitumen is done based on conventional tests i.e. penetration (EN 1426:2015), softening point (EN 1427:2015) and viscosity tests (EN 13302 at temperatures 135°C, 150°C and 175°C); and tests specifically used with PMB i.e. storage stability (ASTM D7173 or EN 13399) and gelation tests (laboratory procedure).

2.1.1. Storage stability and gelation tests

The thermodynamic compatibility between polymer and bitumen is limited, due to their chemical structure. When polymer-modified bitumen is prepared by physical mixing, the polymer tends to separate during storage at high temperatures, giving rise to coarse phase dispersion on cooling, which results in the formation of a polymer-rich phase swollen by the aromatic compounds of the bitumen at the top, and asphaltene-rich phase with no polymer at the bottom. These phenomena can be controlled by using chemical cross-linkers, like Sulphur or other reactive components [14, 21, 44]. In storage stability test, the bitumen fabricated is poured carefully to avoid incorporation of air bubbles in the tubes of height 100 mm to 120 mm. The tubes are kept in the oven at a temperature 180°C for 3 days, and then cut into three equal parts. Later, the samples from the top and the bottom of the tube are tested for their penetration and softening point [45]. New experimental bitumen was fabricated using the raw materials– virgin binder (70/100), high-vinyl content styrene-butadiene copolymer (Table 1) and Sulphur as a cross linker.

Chemical crosslinking as a strategy to attain storage stability must be carefully controlled, since overdosing of Sulphur may lead to gelation of the modified bitumen which may result in serious problems in the bitumen plants. During laboratory small scale PMB manufacture, the Weissenberg effect (phenomenon occurring when an elastic liquid climbs up during stirring and wraps itself completely around the rotating rod) [24] has been interpreted as the first indicator of gelation risk. In gelation test, the modified bitumen is kept in an oven at 180°C for 7 days and visual inspection is done every 24 hours for any signs of gelation.

2.1.2. New experimental bitumen fabrication procedure

New experimental bitumen was fabricated using the raw materials– virgin binder (70/100), high-vinyl content styrene-butadiene copolymer (Table 1) and Sulphur as a cross linker. The objective was to attain a stable new experimental bitumen with the highest polymer content, and an iterative process divided into trials involving different procedures and polymer dilutions. The process consisted of manufacturing a high concentration masterbatch (7.5% SBS) and then creating dilutions to reach different polymer concentrations in the range from 3% to 7%. The experimental procedure adopted for the fabrication of bitumen is given in Figure 2. Dispersion of the polymer was carried out using the Silverson high shear device and further dilution was done at low shear using a Palas device (Figure 3). The dilutions were prepared to find out the phase inversion point from being bitumen dominant to being polymer dominant. Dispersion, chemical reaction, and dilutions of the masterbatch were carried out at the high temperature of 180ºC. After fabrication, the storage stability & gelation tests were performed both on the masterbatches and dilutions and the results are shown in Table 2. As can be seen, with higher polymer contents (higher than 4.5%), the resulting bitumen failed the gelation and storage stability tests and so were not stable. However, the dilutions passed the two tests, which suggests the bitumen was stable at lower polymer contents. Stability was achieved due to an adequate ratio of polymer/chemical crosslinker. Another explanation may be the phase conversion: at low polymer contents, the binder is bitumen dominated, however on increasing the polymer content, the bitumen becomes polymer dominated. In addition to this phenomenon, polymer content and source of bitumen can also affect the stability of the bitumen.

The optimum properties were obtained for 4.5% polymer concentration, hereafter named experimental bitumen (abbreviated as EXPBIT). Table 3 presents the results of the test performed on the experimental bitumen according to the EN: 14023 guidelines (for polymer modified bitumen) and it passed the requirements for PMB 45/80-65 bitumen.

Table 1. Typical values of polymer used in the study (Kraton D0243).

Test	Standard	Typical Value
Tensile strength (MPa)	ISO37	2
Specific gravity	ISO 2781	0.94
Vinyl content (%)	KM03	>35
Hardness (shore A, 10sec)	ISO 868	70
Volatile matter (%m)	KM 04	≤0.3
Ash (%m)	ISO 247	0.2-0.5

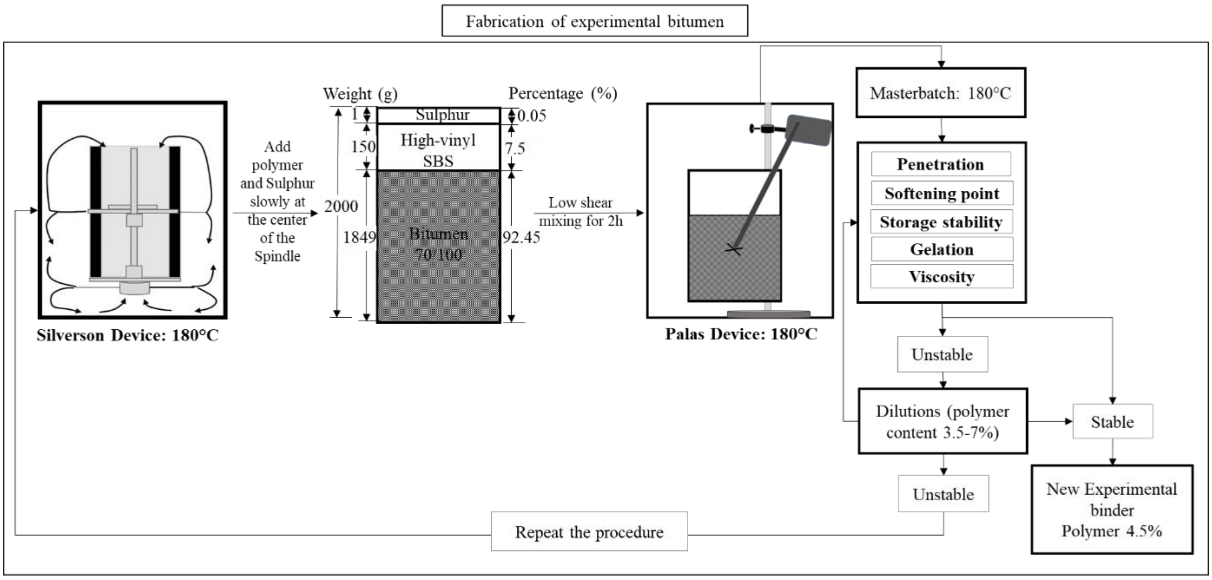


Figure 2. Preparation of experimental binder

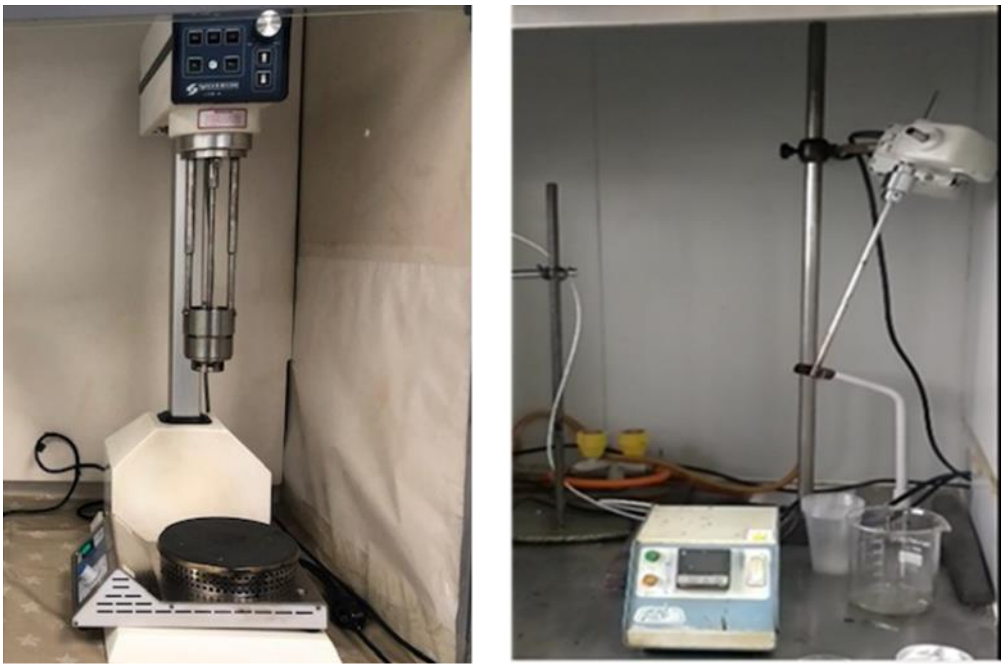


Figure 3. a. Silverson machine for high shear mixing; b. Palas device for low shear mixing

Table 2. Properties of bitumen obtained in Trials 1, 2 and 3.

Trials	Polymer Content (%)	Penetration point (0.1 mm)	Softening Point (ºC)	Penetration index	Storage Stability	Gelation
Masterbatch 1	7.5	47	83.1	4.57	Failed	Failed
Masterbatch 2	7.5	48	83.4	4.66	Failed	Passed
Masterbatch 3	7.5	45	84.2	4.6	Failed	Failed
Dilution	7	50	87.6	5.3	Failed	Failed
Dilution	6	48	76.8	3.77	Failed	Failed
Dilution	4.5	54	68.4	2.77	Passed	Passed
Dilution	4.5	49	69.3	2.66	Passed	Passed
Dilution	4.3	55	68.3	2.81	Passed	Passed
Dilution	4.2	51	64.6	1.95	Passed	Passed
Dilution	4	50	62.8	1.57	Passed	Passed

2.2. Rheological characteristics of experimental bitumen

In the second phase of the study, the rheological properties of the new experimental bitumen were analysed in comparison to conventionally used binders in PA mixtures: virgin bitumen 50/70 (abbreviated as VIRBIT) and commercial polymer-modified bitumen PMB 45/80-65 (abbreviated as PMB). Table 3 shows the properties of the three binders used in the study.

Table 3. Properties of the reference binders for PA mixtures: VIRBIT and PMB

Properties	Standards	Virgin bitumen 50/70 (VIRBIT)	PMB 45/80-65 (PMB)	Experimental bitumen (EXPBIT)
Polymer content (%)		-	-	4.5
Penetration, (0.1mm)	EN 1426	57	55	52
Softening Point (°C)	EN 1427	51.6	74.1	67.6
Penetration Index	EN 12591-Annex	-0.50	3.74	3.63
Cohesion (J/cm2) 5ºC	EN 13588			6.27
Density (g/cm3)		1.035	1,028	
Elastic Recovery at 25ºC (%)	EN 13398	-	92	73
Frass Point (°C)		-13	-	-
Viscosity at 100ºC (MPa)		-	23099	-
Viscosity at 135ºC (MPa)		-	1951	1471
Viscosity at 150ºC (MPa)	EN 13302	-	924	737
Viscosity at 175ºC (MPa)		-	-	247
Storage stability	EN 13399	-	-	Passed
Gelation	-	-	-	Passed

2.2.1. Temperature and frequency sweep test

Dynamic shear rheometer can be used to determine the stiffness and the phase angle of the bitumen. The rheological parameters such as complex modulus, phase angle, and storage modulus were computed by using temperature frequency sweep tests. The specimen is subjected to a strain of 1% to maintain the specimen within the linear visco-elastic range. In this study, the stiffness and phase angle were determined at every temperature in increments of 10°C from 10°C to 80°C, to compute the stiffness at a wide range of frequencies. The distance between the two plates was maintained at 2 mm with the 8 mm spindle, which was used for temperatures 10°C to 40°C. For higher temperatures of 40°C to 80°C, a 1 mm gap and spindle of diameter 25 mm was used. The tests were performed at eight frequencies from 0.1 Hz to 10 Hz. The mastercurves of complex modulus and phase angles can be plotted using the time-temperature superposition principle. Some researchers have questioned the applicability of the time-temperature superposition principle (TTP) on polymer-modified bitumen [17, 46, 47, 48]. While others have applied TTP for the analysis of PMBs [49-52]. In a study [17], it was found that for unaged PMB, at low polymer contents and low temperatures the TTP is valid as the bitumen phase dominates. However, at high temperatures, the polymer phase dominates and due to loss of its structure, the applicability of TTP can be questioned. Therefore, in this study, considering that polymer content is low to medium (lower than 5%), it is assumed that TTP is valid. The mastercurves were prepared by shifting the data to a reference temperature of 20°C. Equation 1 shows the sigmoidal function used to fit the data.

$$\text{Log } G' = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log a_T + \log g)}} \tag{1}$$

Where, a_T is a shifting factor, and δ, α a, β, γ are fitting parameters determined using the least square method.

2.2.2. Linear Amplitude Sweep (LAS) test

The Linear Amplitude Sweep (LAS) test, proposed by Hintz et.al 2011, is an accelerated damage test performed at 25°C to assess the resistance to deformation of binder. This test method employs cyclic loading, increasing the load amplitudes linearly. The gap was kept 2 mm and spindle of 8 mm diameter is used. This test was performed according to AASHTO TP-101. The temperature of 25°C eliminates the flow behavior [38]. The two main steps of this test are:

Frequency sweep: The frequency is increased from 0.2-30 Hz at 0.1% shear strain amplitude, this is done to obtain rheological properties within the linear visco-elastic range. A graph is plotted of storage modulus versus frequency. Then, the parameter B is computed from the slope of the graph (Equation 2)

$$\alpha = \frac{1}{m} \tag{2}$$

Amplitude sweep: The amplitude of shear stain is increased from 0.1 to 30%. This is done to assess the damage to the specimen. The parameter A (Equation 8) is computed by visco-elastic continuum damage (VECD) theory. The damage accumulation and integrity parameter are computed as given in Equation 3 and 4 respectively.

$$D(t) \approx \sum_{i=1}^{N} [\pi \gamma_0^2 (C_{i-1} - C_i)]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \tag{3}$$

Where, γ_o = applied strain for a given data point, percent

$|G^*|$ = Complex shear modulus, MPa

$\alpha = \frac{1}{m}$ (m is the slope of the graph of storage modulus versus frequency)

t = testing time, second

$$C(t) = \frac{|G^*|(t)}{|G^*|_{initial}} \tag{4}$$

Where, $|G^*|$ (t) is the initial value of $|G^*|$ at time (t) and $|G^*|_{initial}$ is the initial value of $|G^*|$.

The relationship between C(t) and D(t) is calculated using Equation 5.

$$C_{(t)} = C_0 - C_1 D^{C_2} \tag{5}$$

With $C_0 = 1$, the initial value of C and C_1 and C_2 = curve-fit coefficients calculated through the power law adapted from Hintz, et al., in the form shown in Equation 6:

$$\log(C_O - C(t)) = \log(C_1) + C_2 \cdot \log(D(t)) \tag{6}$$

A, B parameters are used to compute the total number of the cycles to failure (N_f) using Equation 7.

$$N_f = A. (\gamma_{max})^{-B} \tag{7}$$

Where, $A = \frac{f\,(D_f)}{(1+(1-C_2)\alpha)\,(\pi C_1 C_2)^{\alpha}}$

$D_f = \frac{(C_0 - C_{at\ peak\ stress})^{\frac{1}{C_2}}}{C_1}$

f = loading frequency,

k = 1 + (1 – C2)α,

B = 2α

γ_{max} = the maximum expected binder strain for a given pavement structure.

2.2.3. Binder Yield Energy Test (BYET)

In the binder yield energy test (BYET), a constant monotonic shear loading of the specimen at constant shear rate is used to compute the fracture cracking. The main objective is to test the sample using a constant shear rate until the sample yields and peak shear strength is obtained. This test is conducted according to AASHTO TP 123 using the dynamic shear rheometer device with a 2 mm gap and 8 mm spindle at 25°C temperature. The constant strain rate of 2.315% s^{-1} is applied for 30 minutes until 4167% strain is achieved by the specimen. A stress-strain graph is plotted where the peak indicates the maximum yield stress and the area under the curve up to the strain corresponding to maximum yield point indicates the binder yield energy.

2.2.4. Multi Stress Creep and Recovery Test (MSCRT)

The multi stress creep and recovery test (MSCRT) is performed to compute the stress sensitivity of a bitumen at the selected temperature. This test was performed according to EN: 16659 with a 1 mm gap using a 25 mm spindle at 60°C. In this test, specimens were subjected to a constant stress of 0.1 kPa for 1s followed by 9 s rest, the process was terminated after 10 cycles. The percent recovery and non-recoverable creep compliance of the bitumen were computed and were averaged for the ten cycles to obtain the non-recoverable creep compliance (J_{nr}) and the percentage of recovery (%R) at the stress levels 0.1 kPa and 3.2 kPa. The parameter J_{nr} indicates the sensitivity of bitumen towards permanent deformation under repetition of applied stress (Equation 8). The parameter %R (Equation 9) indicates the ability of bitumen to recover from deformation. It also estimates the degree of polymer modification in a binder. Equation 10 enables the calculation of the stress sensitivity of the binder.

$$\text{Non-recoverable creep compliance (Jnr)} = \frac{\text{non-recovered strain}}{\text{applied stress}} \quad (8)$$

$$\%R = \frac{\text{recovered strain}}{\text{Total strain}} \quad (9)$$

$$Jnr_{\text{-diff}}\ (\%) = \frac{J_{nr3.2} - J_{nr0.1}}{J_{nr0.1}} * 100 \quad (10)$$

Where, %R is the percentage recovery, $J_{nr\text{-}diff}$ is the percentage of variation of the non-recoverable creep compliance value corresponding to stress level 3.2 ($J_{nr3.2}$) compared with the non-recoverable creep compliance value corresponding to stress of 0.1 kPa ($J_{nr0.1}$).

2.3. Porous asphalt mixtures

2.3.1. Sample preparation

The mixtures were prepared according to the PG-3 Spanish technical guidelines [53], with the gradation given in Table 4. The samples prepared in this study are described in Table 5. The density of fiber and its tensile strength are included in Table 5, the rest of the properties of fibers being detailed in previous studies on aramid pulp and glass hybrid fibers [54]. The aggregates were pre-heated at 180°C for 6 h and bitumen is heated for 2 h (virgin bitumen at 155°C and polymer-modified bitumen and experimental bitumen at 165 ºC).

Table 4. Aggregate gradation of PA mixtures

Sieve size (mm)	22	16	8	4	2	1	0.5	0.25	0.063
Passing (%)	100	100	54.5	19.1	14.1	10.3	7.8	6.3	5.0

Table 5. Properties of mixtures prepared in the study

Mixture types	Composition	Density of fiber (g/cc)	Tensile strength (GPa)	Fiber content (% by wt. of mix)
VB4.5	Virgin bitumen 50/70	-	-	-
PMB4.5	PMB45/80-65	-	-	-
EXP4.5	Experimental binder	-	-	-
EXPST0.3	Experimental binder and glass-cellulose hybrid fiber	0.35–0.55	>1	0.30
EXPST0.5	Experimental binder and glass-cellulose hybrid fiber	0.35–0.55	>1	0.50
EXPPULP0.03	Experimental binder and aramid fiber	1.44	2.7–3.6	0.03
EXPPULP0.05	Experimental binder and aramid pulp fiber	1.44	2.7–3.6	0.05

The fibers are commonly used as additives in the asphalt mixtures [55-58]. The fibers were added as received from the manufacturers in aggregates, mixed thoroughly for approximately 30 s, and then the bitumen was mixed thoroughly with the fiber-aggregate mixture. The specimens were compacted in Marshall mould at 50 blows on each face (EN 12697-34) and conditioned at room temperature for one day prior to testing.

2.3.2. Porous asphalt mixture tests and statistical analysis

Air voids refer the total air void content, however there is a portion of voids filled with bitumen that do not participate in the transmissibility of the water. The PA mixtures allow water through their structure due to the presence of high number of interconnected air voids. The total air void content was computed based on EN 12697-8 and the interconnected air void content were estimated from permeability of the mixtures.

The Cantabro test measures the abrasion resistance of the PA mixtures. In this study, the test was conducted under dry conditions (according to EN 12697-17) as well as wet conditions (according to NLT 362/92). In this second scenario, the samples are kept in water for 24 h at 60°C, and after that, they are kept for 24 h at 25°C before performing the test. The permissible limits for abrasion resistance for the highest traffic category according to PG-3, article 543 are 20% and 35% for dry and wet conditions respectively. The particle loss is calculated according to Equation 11.

$$\text{Particle loss (\%)} = \frac{\text{initial mass (g)} - \text{final mass (g)}}{\text{initial mass (g)}} * 100 \quad (11)$$

Pertaining to high air voids, the binder in the PA mix may drain downwards due to the action of gravity. Therefore, draindown tests were performed. According to EN 12697-18:2017, the binder drainage was computed by keeping uncompacted PA mixtures at 180°C for three hours in a wire mesh basket and calculating the change in weight. The recommended binder draindown in PA mixtures should be less than 0.3% [59, 60].

The statistical analysis is important to assess the significance of the difference among the various samples. The results of porous asphalt mixture tests were first checked for normality by performing the Anderson Normality test. Afterwards, the results following normal distribution were compared based on two-sample student's parametric tests. While the non-parametric Mann-Whitney tests were performed on test results that did not follow normal distribution. A level of significance (α) of 0.05 was used which indicates a 5% risk of concluding that a difference exists when there is no actual difference. If the mixtures share a common group letter, this indicates that their means are not statistically different from each other.

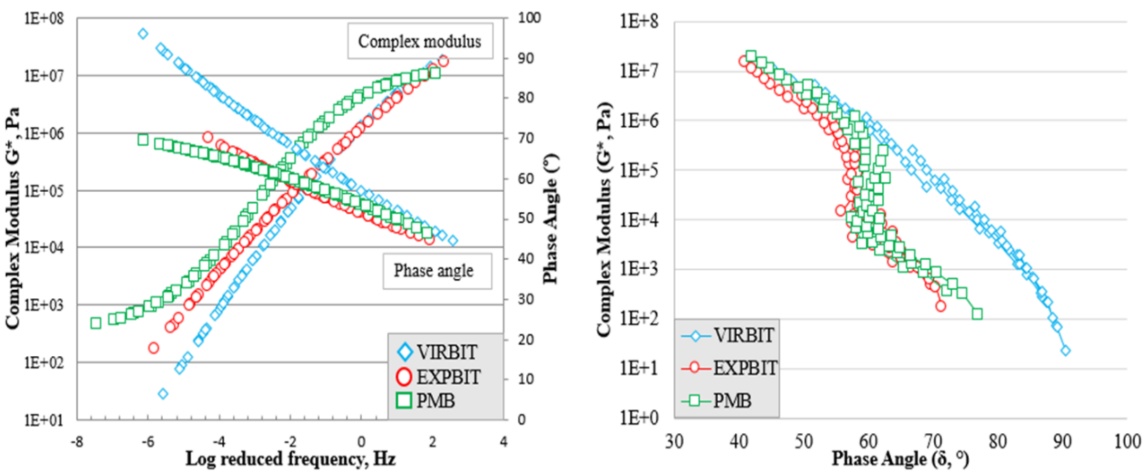
3. Results and discussion

3.1. Rheological testing

3.1.1. Dynamic Shear Rheometer

The data obtained from temperature and frequency sweep tests was used for the calculating the complex modulus and phase angle of the three binders (experimental, virgin, and reference PMB 45/80-65). Mastercurves of complex modulus and phase angle are provided in Figure 4a and a black diagram in Figure 4b, respectively. At low frequencies, a clear difference between the complex modulus and phase angle of three binders can be observed. The PMB showed the highest complex modulus that means that it is stiffer at lower frequencies as compared to the other two bitumen. EXPBIT showed higher complex modulus than VIRBIT indicating greater stiffness, however at intermediate frequency range both mastercurves indicated similar stiffness of bitumen. Eventually, at higher frequencies, the complex modulus of PMB also coincided with the other two bitumens which signifies that at higher frequencies there was no significant difference in the stiffness among the three bitumens. However, concerning phase angle, the mastercurves of VIRBIT exhibited higher phase angle that indicated lower elasticity and high deformation ability. On the other hand, the phase angle mastercurves of both the modified bitumens (PMB and EXPBIT) were overlapping, which suggests a similar elastic response. In both mastercurves, PMB exhibited a plateau at intermediate loading frequency, which is an indication of an elastic polymer network, as observed in past studies [3, 15].

As shown in Figure 4b, PMB and EXPBIT exhibited similar behavior, which was significantly different to the black diagram of the VIRBIT. At higher complex modulus (>10^5 Pa), insignificant differences were observed among the three bitumens while at lower complex modulus (<10^5 Pa), EXPBIT appears to show the lowest phase angle and VIRBIT exhibited the highest phase angle, indicating a greater viscous response than elastic response for the virgin binder.



a. b.

Figure 4. DSR results of the binders: a. Master curves (Tref =20°C); b. Black diagram (Temperatures 10-80°C).

Figure 5 shows the values of complex modulus and phase angle at temperatures 10°C, 40°C, 80°C with frequency of 1.59Hz (10 rad/s) which is usually considered as a reference frequency corresponding to the shearing action at traffic speed of 90 kmph (50 mph) according to Superpave specifications.

VIRBIT exhibited the highest phase angle, which indicates its lower elastic response. At lower temperatures, VIRBIT exhibited high complex modulus whereas the stiffness was reduced on increasing the temperature suggesting an increment in proportion of viscous component when increasing the temperature. Among modified bitumens (PMB and EXPBIT), it is clear that the EXPBIT adapted the best to variation in temperature, because when the temperature was low, which can induce cracking problems, the EXPBIT exhibited a lower modulus. However, when the temperature was high, which leads to deformation problems, it displayed higher modulus than PMB. The high-vinyl SBS content may have a softening effect due to which the stiffness was lower, however the elasticity was higher as compared to PMB. Since phase angle is an indicator of recovery and non-recoverable deformation, due to lower value, EXPBIT exhibited greater elasticity than PMB over the entire range of temperature. This indicates that the viscous component is lesser in EXPBIT than in PMB.

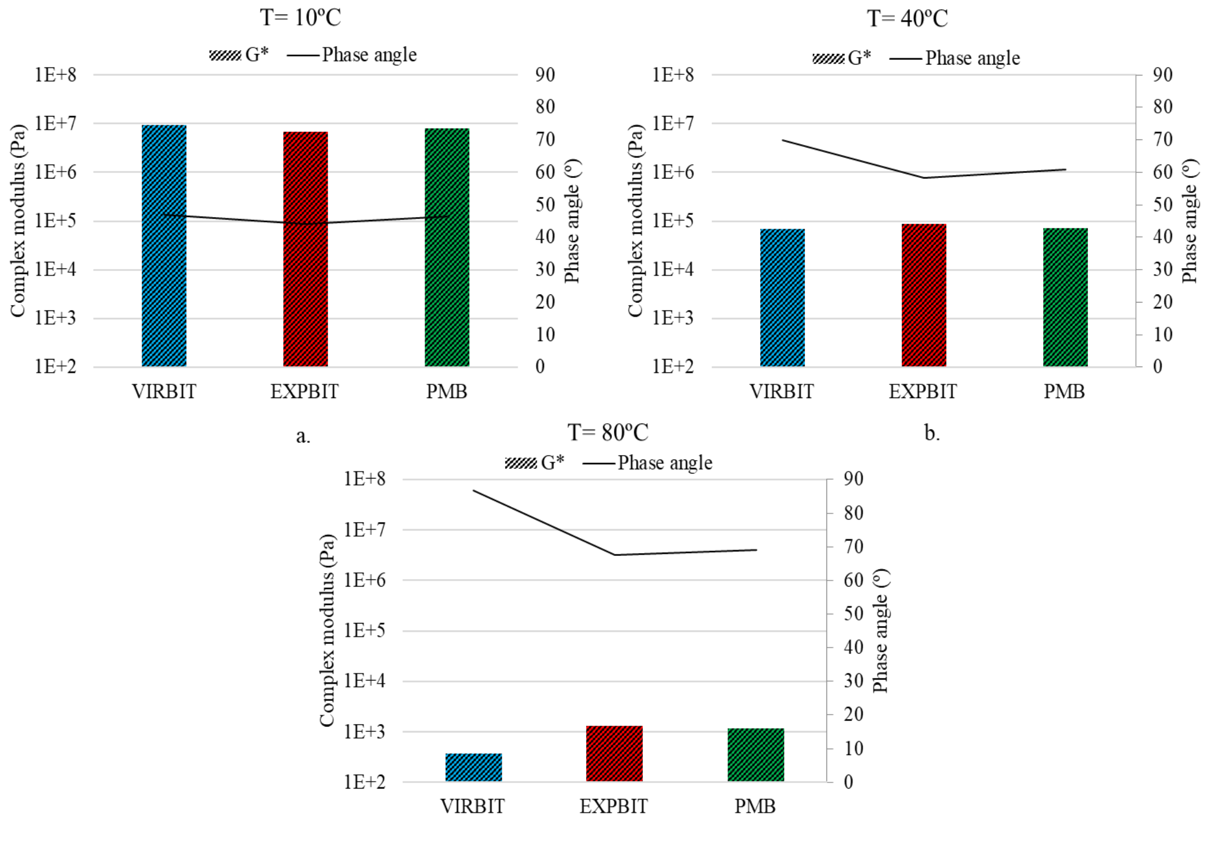
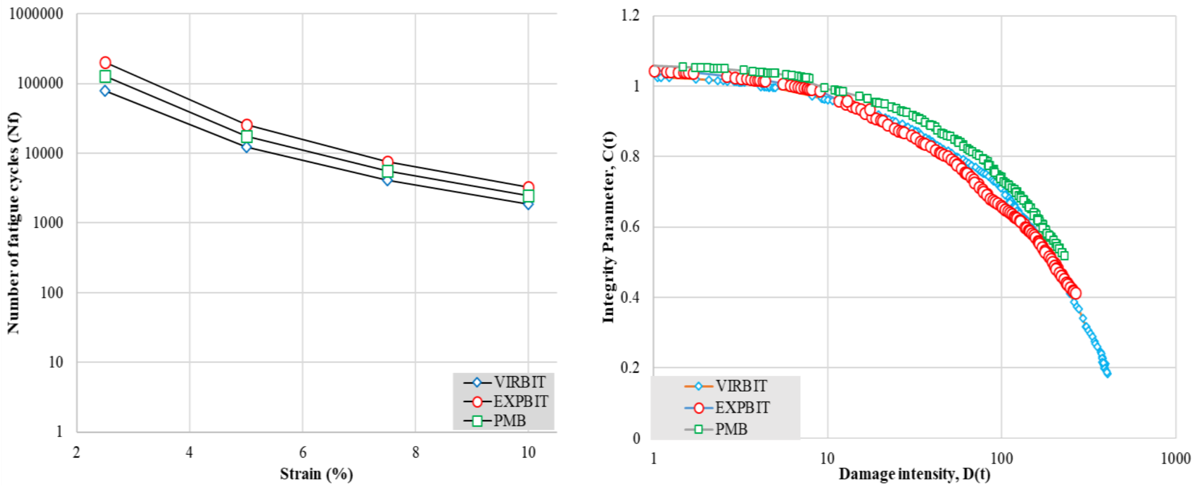


Figure 5. Stiffness and phase angle parameters for each binder type at temperature a. 10°C; b. 40°C; c. 80°C

3.1.2. LAS results

The cycles until fatigue failure from the LAS test performed at 25°C are shown in Figure 6a and the plot of integrity parameter vs damage intensity is given in Figure 6b. The fatigue behavior was analysed using the VECD theory, next parameters A and B were computed and then the number of fatigue cycles (N_f) at various strain levels were computed. For each applied strain level, the pattern was similar: the highest number of cycles to failure is exhibited by the experimental bitumen, followed by PMB and then virgin bitumen. The virgin bitumen and experimental bitumen showed similar integrity parameters, however, VIRBIT has the lowest fatigue life. PMB showed a higher value of the integrity parameter than EXPBIT, however, the number of cycles to fatigue failure for PMB was lower than EXPBIT. This indicates that the presence of high-vinyl SBS in EXPBIT had a positive influence on the elasticity that may enable mixtures with EXPBIT to undergo more cycles before fatigue failure. The increased elasticity may be attributed to the addition of high-vinyl SBS. The fatigue life of EXPBIT was significantly greater than PMB (36.5%) and VIRBIT (63.9%) at low strain level (2.5%) whereas this increment was lower at high strain level (10%) compared to PMB (23.5%) and VIRBIT (48.24%). For thick pavements or low-traffic roads, the strain levels are lower and thus it can be concluded that EXPBIT may exhibit better fatigue performance than PMB and VIRBIT binder in this case compared to thin pavements or high traffic roads.



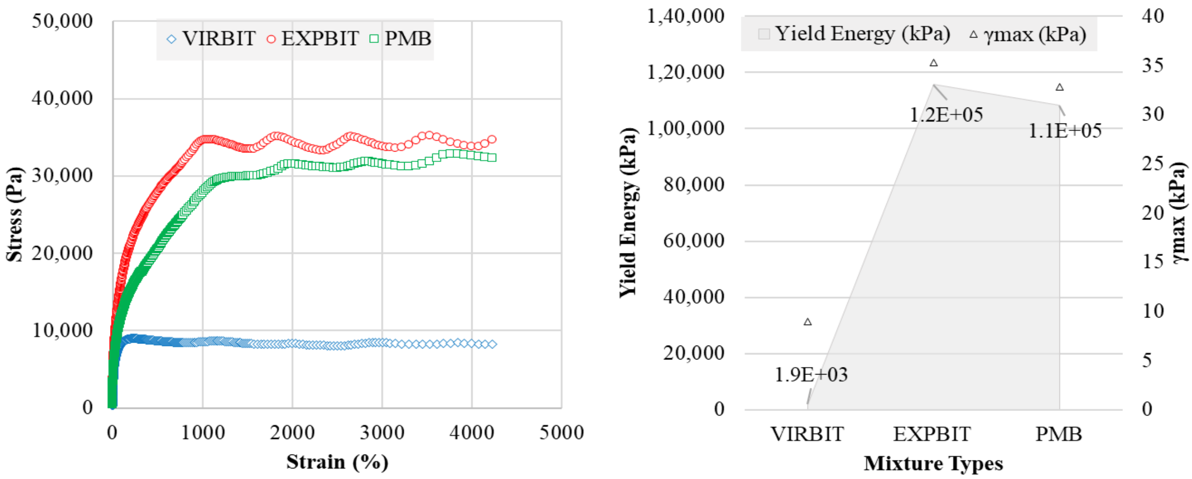
a. b.

Figure 6. Results from N_f from LAS tests

3.1.3. BYET results

The BYET test was performed at 25°C temperature. The stress-strain plot for the asphalt binders are shown in Figure 7a and the yield stress and the area under the curve are shown in Figure 7b. The yield stress was highest for EXPBIT, therefore the addition of high-vinyl SBS may improve the fatigue life and may reduce fatigue cracking. The virgin binder displayed the lowest yield stress as well as the area under the curve. Greater area under the curve means higher yield energy, therefore, the modified binders can withstand a higher load before yielding compared to virgin binder.

Multi-peak phenomena were observed in the case of modified binders PMB and EXPBIT, this phenomenon was also previously noted by other researchers [34, 61]. This may be due to the high elasticity and good recovery because of the presence of polymer. According to Johnson [34], the first peak indicates the asphaltene-maltene relationship whereas the secondary peak is an indicator of the strength of polymer cross-linking. The results in this study were computed from the first peak of the graph. It is very interesting to note that the results were in agreement with LAS results that indicated that the experimental bitumen exhibits the largest number of cycles before failure.



a. b.

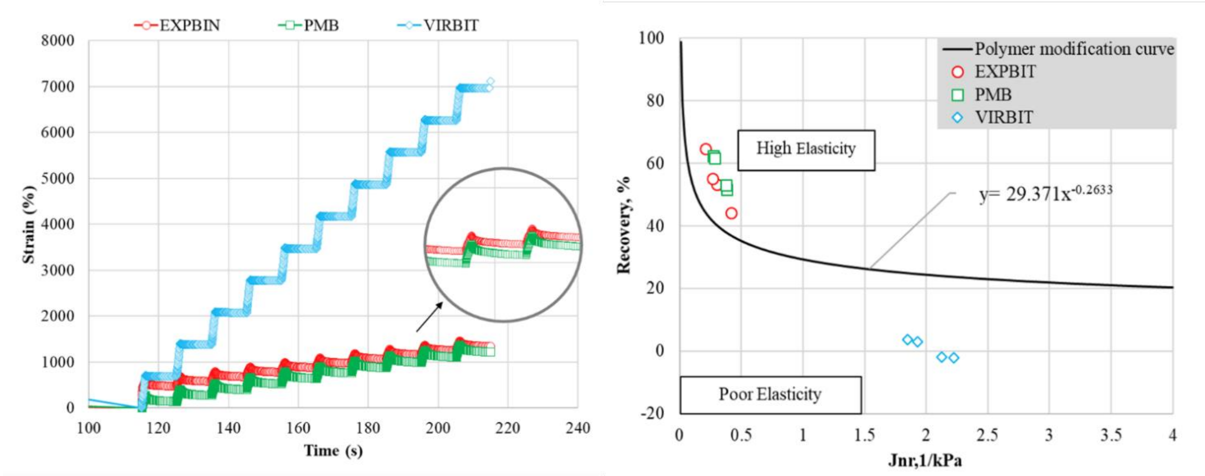
Figure 7. BYET results, a. yield stress and yield energy plots; b. stress and strain plots

3.1.4. MSCRT results

MSCRT shows the bitumen performance at high temperature that is an indicator of rutting characteristics of the asphalt pavement. As observed from Figure 8a, VIRBIT showed higher strain compared to other binders. This means that under the same loading and time, the strain produced in the virgin bitumen was much higher, which is due to the low stiffness of this bitumen at high temperatures. During the loading and unloading of the curve, the virgin bitumen exhibited less viscoelastic behavior as negligible reshaping of sample was observed. Meanwhile, for modified binders (PMB and EXPBIT), high recovery was observed. The EXPBIT and the PMB exhibited very similar properties, with a slightly higher strain observed in the case of experimental binder due to the lower stiffness of EXPBIT.

The plots for recovery (%R) vs creep compliance (J_{nr}) along with polymer modification curve are shown in Figure 8b. The polymer modification curve is an indicator of elasticity according to AASHTO M 332. If the recovery (%R) of bitumen lies above this curve, this means that the bitumen has good elastomeric behavior and vice-versa [62]. The %R of the two modified bitumens (EXPBIT and PMB) was located above this curve, therefore they showed high elasticity while %R for VIRBIT was located below the modification curve and thus exhibits poor elasticity. The virgin bitumen showed negative percent recovery at 3.2kPa stress level. Negative recovery indicates that the strain increases even in the unloading phase; which is common in soft bitumen [63].

At a stress level of 3.2 kPa, J_{nr} indicates the rutting performance of the binder. For extreme, very heavy, heavy and standard traffic, J_{nr} should be less than 0.5, 1, 2, and 4 kPa^{-1} respectively [64]. The two modified bitumens were within the limit for extreme traffic, whereas the value of J_{nr} for virgin bitumen was higher than 2 kPa^{-1}, which suggests that this bitumen was suitable for standard traffic level according to Superpave. $J_{nr\text{-}diff}$ should not be higher than 75% for 0.1 and 3.2kPa stress levels. All three bitumen samples were well within this limit. Moreover, it should be noted that the J_{nr} value for experimental binder was less than PMB, which suggests that the rutting performance of EXPBIT is better than PMB.



a. b.

Figure 8. MSCRT results: a. strain vs time plot, b. Percentage recovery and J_{nr} values.

3.2. Porous asphalt mixtures testing

Rheological tests have shown that the EXPBIT performs better than both PMB and VIRBIT in fatigue and rutting criteria. However, the PA mixtures suffer the problem of raveling that poses a great concern. Therefore, PA mixtures were prepared to analyse the performance of the EXPBIT towards air void content, raveling, binder drainage. In addition to this, additional mixtures were prepared to assess the suitability of using the new binder with aramid and glass fibers, which have been proved to improve the mechanical resistance of PA mixtures [54].

3.2.1. Air voids content

Figure 9 shows the air void content and the interconnected air void content of the different mixture types. For the three binders the air void content was very similar. However, on addition of fibers, the air void content was slightly reduced. The presence of fibers may block part of the air voids and compromise the permeability of the mixtures if the amount of fibers is not correctly designed. As can be observed all mixture types displayed air void contents higher than 20%. Significant differences were observed only in the case of glass-hybrid fibers (EXPST0.3 and EXPST0.5). Considering the interconnected air voids, indicated by the permeability of the mixture types, the highest reduction was observed in the EXPST0.3 case, which may be due to development of a stronger matrix.

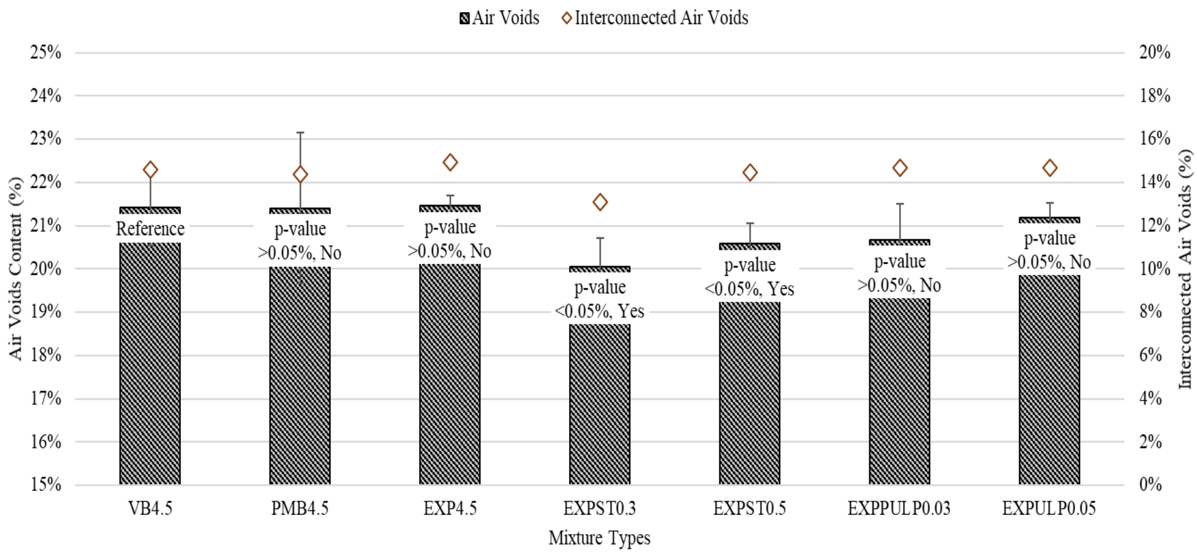


Figure 9. Air void content for mixture types, error bars represent the standard deviation about the mean and the labels represent the p-value and significant difference from VB4.5 using the two-sample student's test.

3.2.2. Draindown test

Binder drainage is an important concern in PA mixtures due to the low percentage of fine aggregates. When the asphalt mix is subjected to high temperatures, the binder tends to drain down the structure of the air voids. As observed in Figure 10, for the same bitumen content of 4.5%, the experimental bitumen displayed higher draindown than virgin binder and PMB. The reason for this result may be the different manufacturing temperature of the three bitumens. In this study the manufacturing temperature of PA mixtures with EXPBIT is 165°C. For lower binder draindown, it is recommended to reduce the manufacturing temperature in the future. The binder drainage of EXP4.5 was close to the maximum recommended limit of 0.3%, however, it did not surpass the permissible limit considerably.

When the fibers were added at 4.5% binder content, it was found that the binder drainage was reduced considerably, as both glass fibers and aramid pulp (EXPST0.3, EXPST0.5, EXPULP0.03 and EXPULP0.05) improved the binder stability. The possible explanation for this phenomenon may be the high bitumen absorption by the fibers or the development of a strong 3-D network on addition of fibers which is in agreement with studies that suggest that fibers improve the binder stability of PA mixtures [54, 56-58].

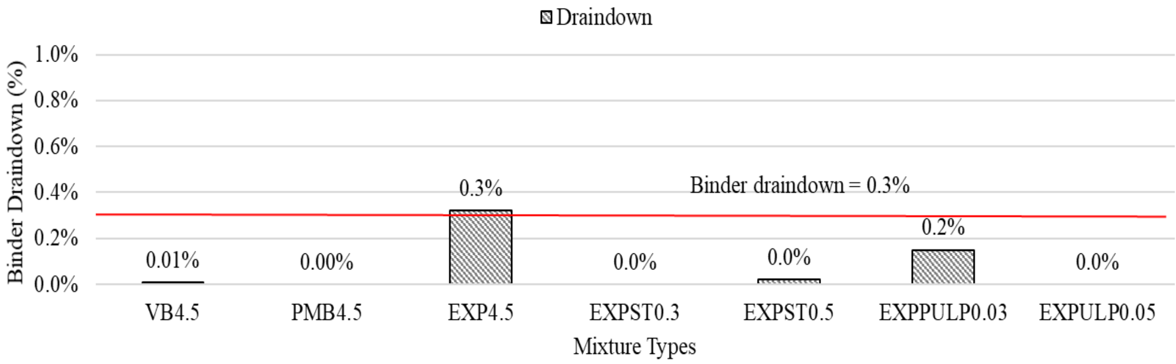


Figure 10. Draindown of the mixtures

3.2.3. Cantabro test

Figure 11 represents the abrasion loss of all mixture types. The highest abrasion loss both in dry and wet conditions corresponded to the mixtures with VIRBIT. According to statistical analysis, significant differences were observed among the different mixture types as shown in Table 6. Comparing with VB4.5, experimental binder with and without the fibers has shown significant differences as the p-value is less than 0.05 both under dry and wet conditions. However, the experimental binder showed very similar abrasion loss to PMB. This can be attributed to high viscosity due to presence of polymers in the binder, which improves adhesion and raveling resistance. In dry conditions, the EXPBIT performs better than the PMB binder, but, in wet conditions, the particle loss is higher. However, the error bar suggests negligible difference in particle loss among the two modified bitumens.

Table 6. Statistical analysis of abrasion resistance under dry and wet conditions (two-sample t test)

	VB4.5	PMB4.5	EXP4.5	EXPST0.3	EXPST0.5	EXPPULP0.03	EXPPULP0.05
Dry Conditions							
Normal	yes	yes	yes	yes	yes	yes	yes
p-value		0.152	0.001	0	0	0.003	0.001
Significance		no	yes	yes	yes	yes	yes
Wet conditions							
Normal	yes	yes	yes	yes	yes	yes	yes
p-value		0.043	0.002	0	0.002	0.001	0.007
Significance		yes	yes	yes	yes	yes	yes

On addition of fibers, the particle loss was further reduced as the mixtures with fibers EXPST0.3, EXPST0.5, EXPPULP0.03, and EXPPULP0.05 have lower particle loss compared to the EXP4.5 mixture in dry conditions (see Table 6). The difference is more prominent under wet conditions. The combination of glass fibers at 0.3% with experimental binder has the lowest abrasion loss both in dry and wet conditions (particle loss 5% and 5.9% in dry and wet conditions respectively). EXPST0.5% has higher abrasion loss than the EXP4.5 mixture, which may be due to the high amount of fiber that may have resulted in cluster formation. However, the difference between the mixtures with the two fiber contents is not significant. The addition of aramid pulp fibers has also reduced the particle loss of mixtures with fibers and the change in their fiber content had negligible influence.

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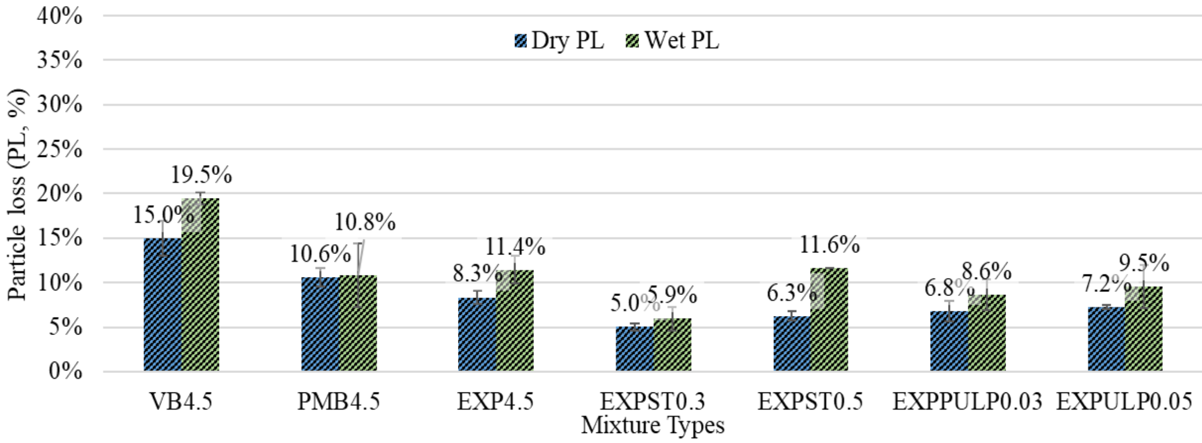

Figure 11. Particle loss (PL) under dry and wet conditions, error bars represent the standard deviation about the mean.

Figure 12 shows the plot of particle loss vs. air voids. A general trend under dry and wet conditions can be observed that on increasing in air voids, the particle loss increases as well. EXP4.5 mixtures have shown good abrasion resistance as well as high air void content followed by PMB4.5, which exhibits same particle loss in dry and wet conditions indicating less moisture damage. It is interesting to note that the EXPST0.3 has the highest abrasion resistance, both in dry and wet conditions, but its air void content is lowest (20.1%), although, still higher than the minimum permissible limit of 20%.

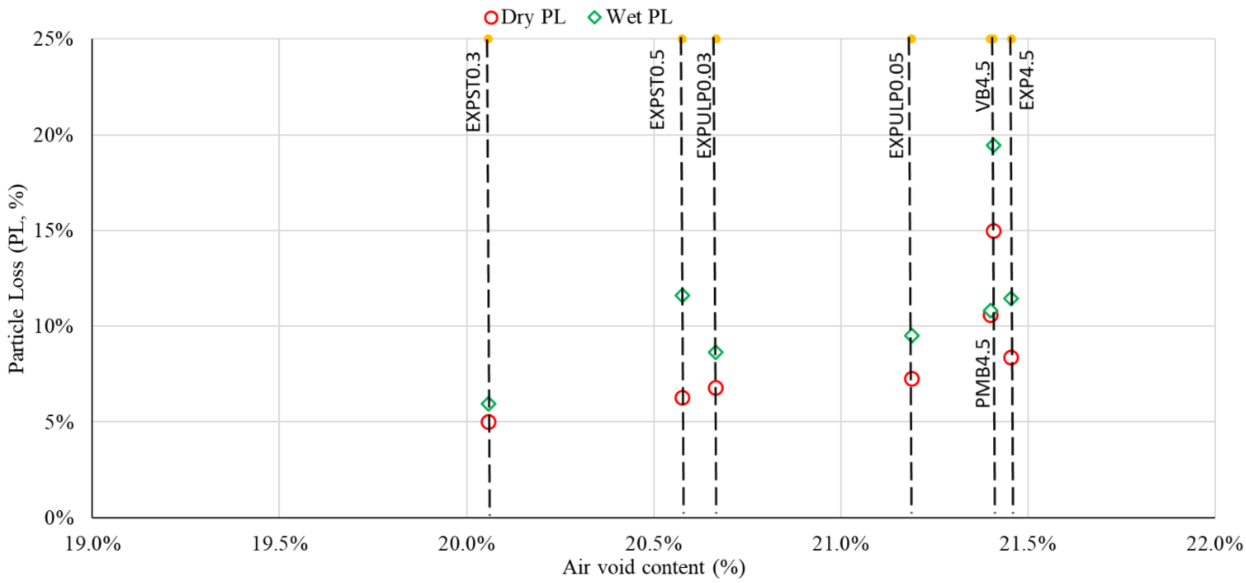

Figure 12. Particle loss Vs. Air void content.

4. Conclusions

In this study, a new modified bitumen using SBS polymer with high-vinyl content was developed to improve the mechanical resistance of porous asphalt (PA) mixtures. Experimental bitumen was compared with commercially available PMB45/80-65 and virgin bitumen 50/70 as these binders have a very similar penetration values. The rheological tests include temperature and frequency sweep tests, linear amplitude sweep test, binder yield energy test, and multiple stress creep recovery test. Moreover, PA mixtures were prepared with these three asphalt binders to assess the behavior of the experimental bitumen in comparison to others. The synergistic benefits of fibers with the experimental bitumen were also investigated using two different fibers: glass-hybrid fibers and aramid pulp fibers. The following conclusions were drawn:

- After several trials, a polymer content of 4.5% was found to be stable as it conformed to the requirements of existing PMB based on conventional tests. An increase in the polymer content resulted in storage stability failure and gelation during fabrication of binder.
- PMB showed the highest stiffness while virgin bitumen exhibited the highest phase angle over a wide range of frequencies. At 1.59 Hz frequency, experimental bitumen showed best adaptation to variation in temperature. At low temperature, the experimental bitumen exhibited lower complex modulus that indicated higher cracking resistance. At high temperatures, experimental bitumen exhibited higher complex modulus, which indicates high stiffness under deformation. The high vinyl SBS content may have softened the bitumen leading to lower complex modulus but higher elasticity.

- Linear amplitude sweep tests highlighted that the number of fatigue cycles to failure is greater for the experimental bitumen in comparison with commercial PMB and virgin bitumen at any given strain level. Therefore, addition of SBS in experimental bitumen may have a positive influence on the fatigue performance.
- Binder yield energy test results showed the multi-peak phenomena for PMB and experimental bitumen. The results were in agreement with the linear amplitude sweep tests, the highest yield stress and yield energy were observed for the new experimental binder.
- At high temperatures, according to multi-stress creep and recovery test results, the experimental bitumen showed very similar high temperature characteristics to PMB. Experimental bitumen exhibited lowest creep compliance and highest percentage of recovery, indicating better elastomeric behavior and superior rutting performance compared to PMB and virgin bitumen.
- Porous asphalt mixtures prepared with experimental bitumen showed similar air voids compared to the reference mixtures with virgin bitumen and PMB. However, the draindown results indicated lower stability of experimental binder. The incorporation of fibers which remarkably improved the binder stability.
- Concerning the influence of experimental bitumen on the abrasion resistance of PA mixtures, the particle loss was found to be similar to PMB mixtures and lower than virgin bitumen under both dry and wet conditions.
- On addition of fibers, synergistic benefits can be observed as the abrasion resistance is greatest for the experimental bitumen with a fiber content of 0.3% glass hybrid fibers mixtures, followed by fiber content of 0.03% aramid pulp fibers.

Consequently, it can be concluded that the new experimental bitumen combined with fibers showed a better performance in this study than PMB for PA mixtures. For future research, an important aspect will be to investigate the effect of aging on the physical, chemical, and rheological properties of the experimental bitumen and evaluate the performance of PA mixtures by simulating the field aging in the laboratory.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. Summary of results and discussion

6.1. Porous asphalt mixtures

6.1.1. Hydraulic performance

In this study, the fibers were added at 0.05% by weight of the mixtures for aramid fibers and at 0.50% for the glass-hybrid fibers and cellulose fibers, following the commercial recommendations and previous experiences. The results of the air voids in the porous asphalt mixtures according to the additives are shown in Figure 11. Due to the small fraction of fibers added in the mixtures, the reduction of the voids in the mixtures was low, almost negligible with aramid fibers and a little higher with the glass fibers and cellulose fibers, but always with the air void content higher than 19%. The difference was not significant, and it was concluded that the reduction of air voids content by adding fibers is negligible. For some fibers, the permeability results were performed based on the availability, concluding that the permeability is not reduced significantly by the addition of fibers (the results of the permeability are available in Article 1).

6.1.2. Mechanical performance

The Cantabro test is an indicator of the resistance of the mixture towards wear and disintegration caused by vehicles. The disintegration can be either caused due to cohesion failure or adhesive failure. In cohesion failure, the mastic is weaker than the binder-aggregate interface, while in adhesion failure, the binder-aggregate interface is the weaker one. In PA mixtures, due to the lower number of fines, the mastic is not strong, and the binder does not effectively coat the aggregates, which leads to high raveling. The use of additives in PA mixtures improved abrasion resistance.

The dry and wet particle loss according to the additives in Figure 12. While for fibers, particle loss in dry conditions is lowest for aramid pulp fibers followed by GLST fibers. Aramid pulp reduced the particle loss up to 60%. This may be due to defibrillation of fibers which leads to the formation of strong mastic and reduces the susceptibility towards abrasion resistance. Meanwhile, the highest particle loss was observed for the mixtures with hydrated lime and aramid ARA2 fibers. In wet conditions, ARA-POL fibers have maximum particle loss.

Regarding the tensile strength of the PA mixtures, the results are shown in Figure 13. Aramid fibers have shown higher moisture susceptibility. All aramid fibers have either lowered or did not influence the moisture susceptibility. The reduction in the case of aramid pulp was 10.7%, which is significant (p-value < 0.05). However, glass hybrid fibers have shown higher tensile strength as compared to the reference mixtures. This can be due to higher binder content of 5% instead of 4.5% in the case of glass hybrid fibers and cellulose fibers. In wet conditions, ARA2 fibers have reduced the tensile strength significantly. In wet conditions, the results have shown the adverse effect of fibers what may be due to the high susceptibility of fibers towards moisture which may be the reason for binder stripping and reduction in tensile strength. The energy parameters (shown in Figure 14) were also computed for the additives in PA mixtures, concluding that the aramid fibers have adverse effects on the energy parameters of porous asphalt mixtures, more information is available in Gupta et al. 2021.

One interesting thing to note is that aramid pulp fibers were found to have a positive influence on the abrasion resistance while it lowered the tensile strength of the PA mixtures. Meanwhile, glass-hybrid fibers have improved the indirect tensile strength. Therefore, it was proposed in the study to assess the performance of PA mixtures prepared with the combination of these fibers. However, it was found that on combining different fibers, the particle loss increased due to the development of a non-homogeneous mixture (the whole detail of the results and findings can be found in section 5.6 of Article 1).

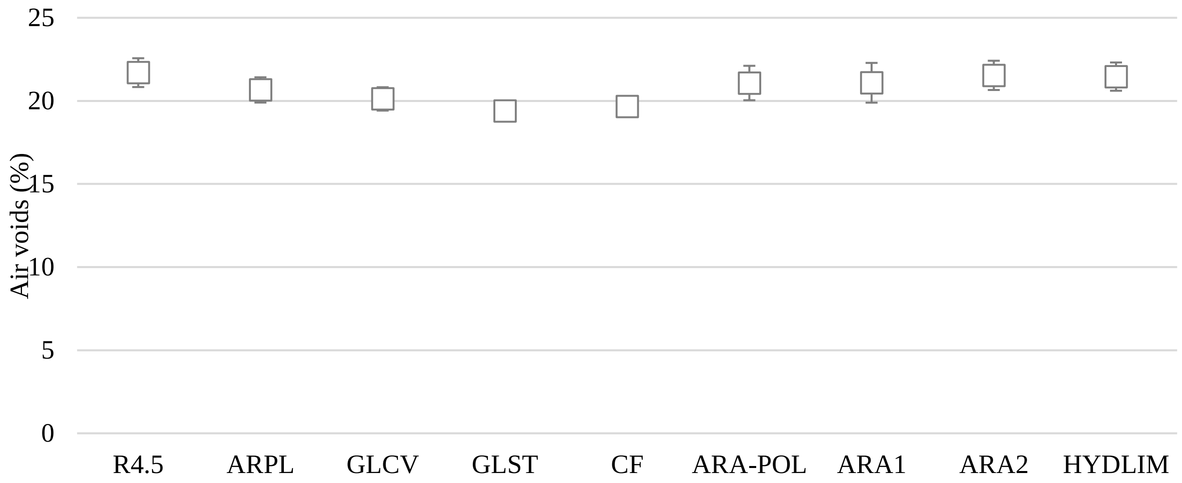


Figure 11. Air void characteristics of mixtures with additives.

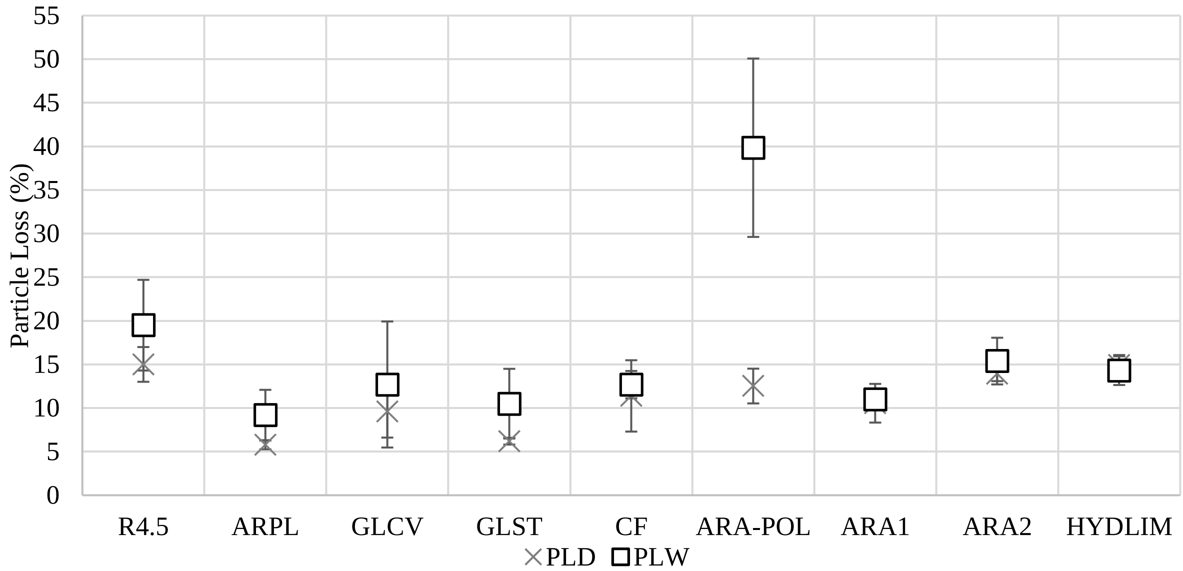


Figure 12. Abrasion loss of the mixtures with additives.

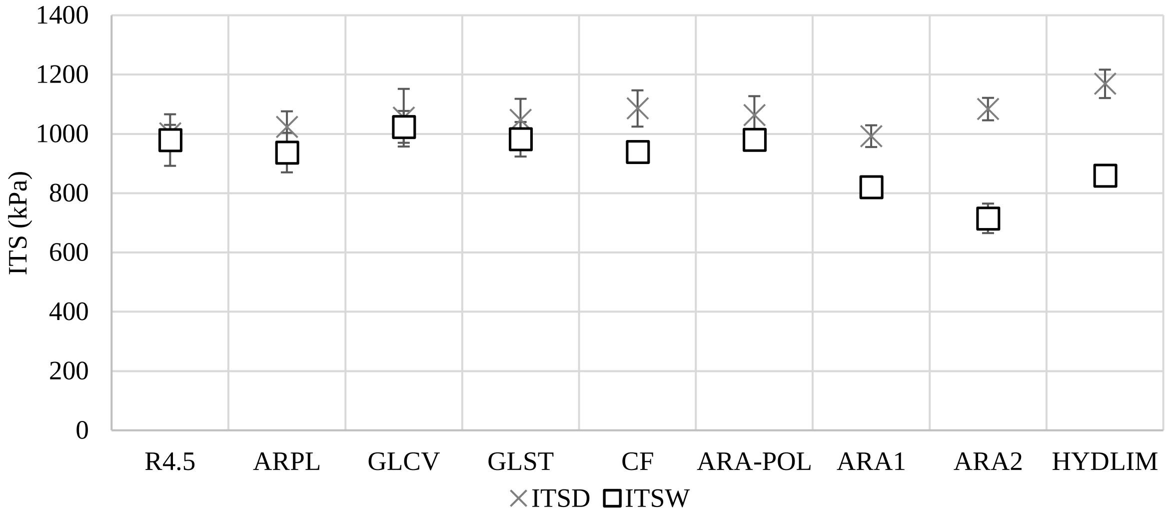
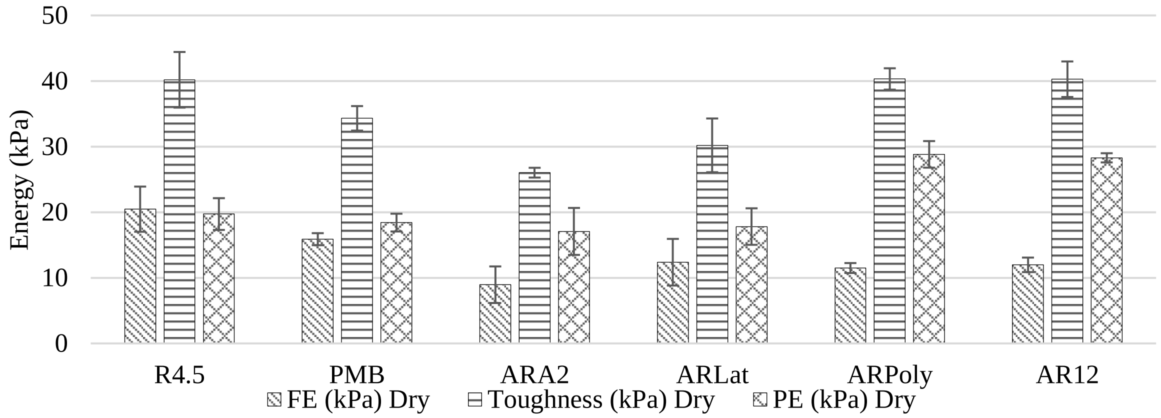


Figure 13. Indirect tensile strength test results of mixtures with additives.



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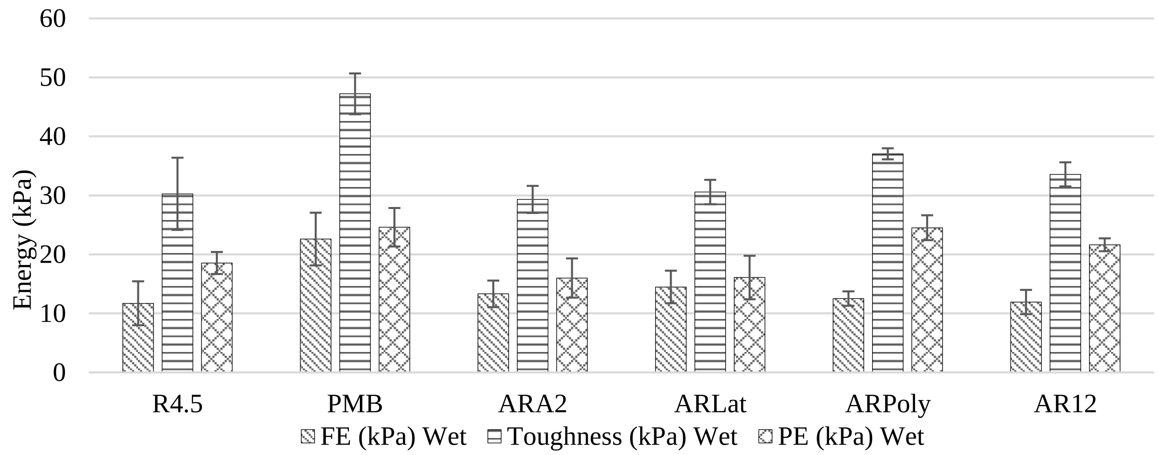


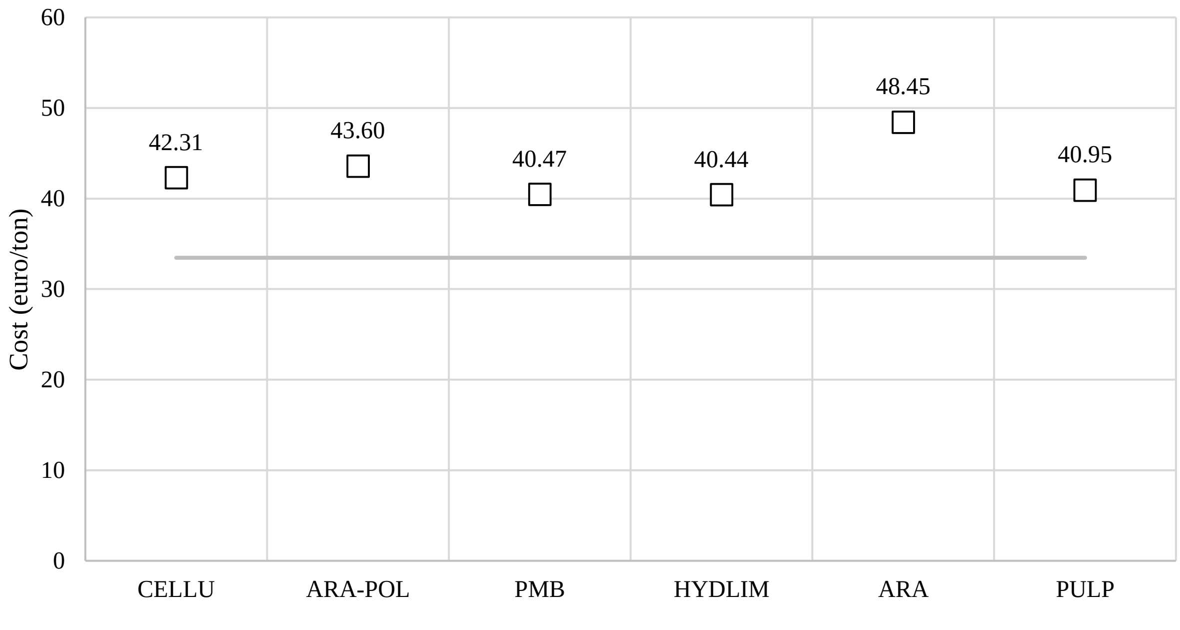
(b)

Figure 14. Energy parameters of mixture types in (a) Dry and (b) Wet conditions.

6.1.3. Economic and environmental impacts of additives

It is vital to address the impact of additives on budgetary planning, not only in terms of the economy but also on the wellbeing of society and sustainability. It is important to check the resilience of the asphalt mixtures towards their impact on climate change. In this study, the economic impact was computed based on the initial investment required for asphalt mixture in terms of euro/ton. The results are given in Figure 15. The minimum increase can be observed when the virgin bitumen is replaced by the polymer-modified bitumen. However, it is important to note that the asphalt mixtures prepared with the polymer modified bitumen require a higher mixing temperature that also contributes towards the costs incurred. According to the consulted asphalt plant managers, an increase of 20℃ that is required for PMB increases the total energy by 6-9% (for heating and drying of aggregates). In this study, an average increment of 7.5% in the total energy needed for production was considered due to the use of PMB bitumen.

Regarding the impacts of additives on the environment, the selected indicators were global warming potential, human toxicity potential, and marine aqua toxicity potential. The results are given in Figure 15 (b), (c), and (d). The impacts are computed based on the acquisition of the raw materials before the pavement construction, per kg in the material processes, and per kg*km in transportation processes. For global warming potential, it can be observed that the hydrated lime has the maximum impact. Aramid fibers ARA1 and PULP have also high impacts on the global warming potential. For human toxicity potential, aramid fibers ARA1 and PULP fibers have higher impacts as compared to other additives. While regarding marine aqua eco-toxicity potential, hydrated lime has exhibited the highest impact.



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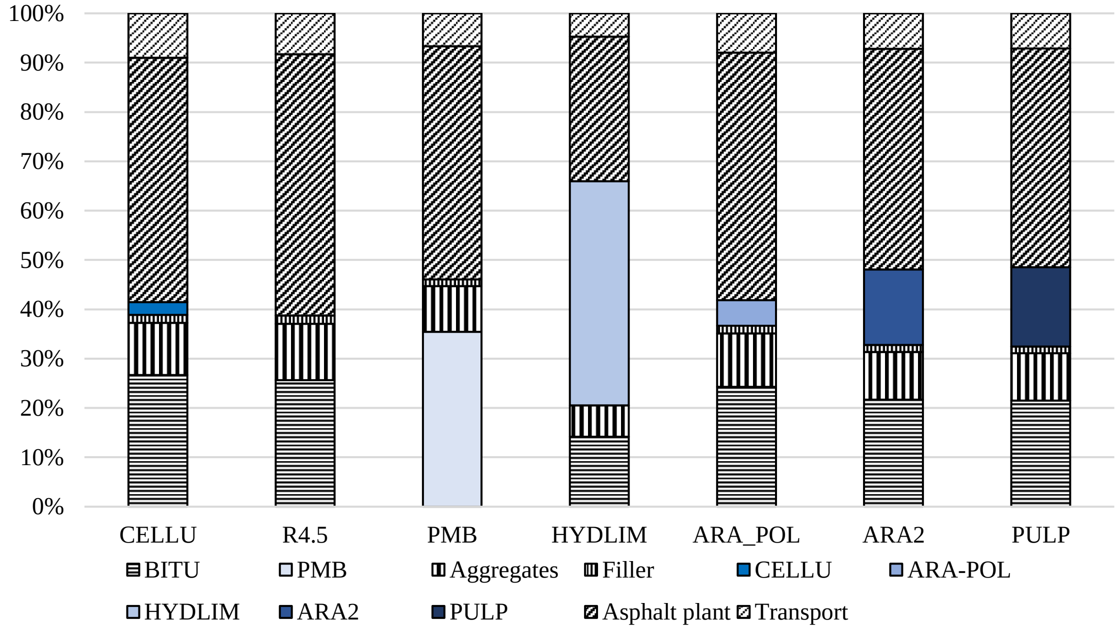
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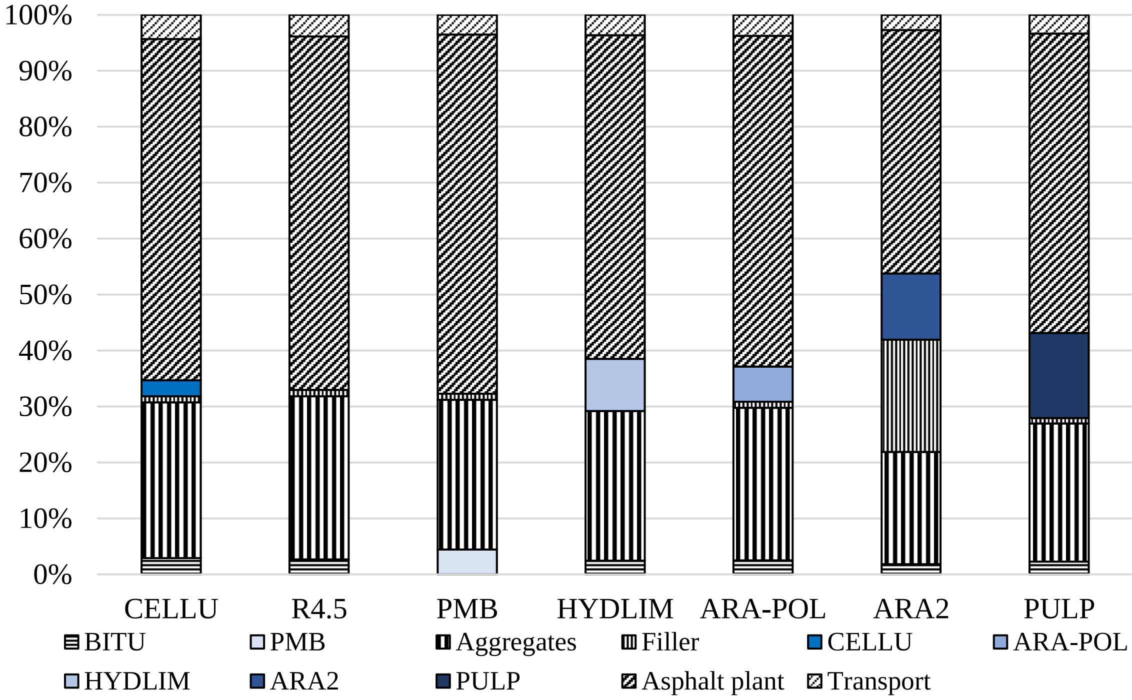
(b)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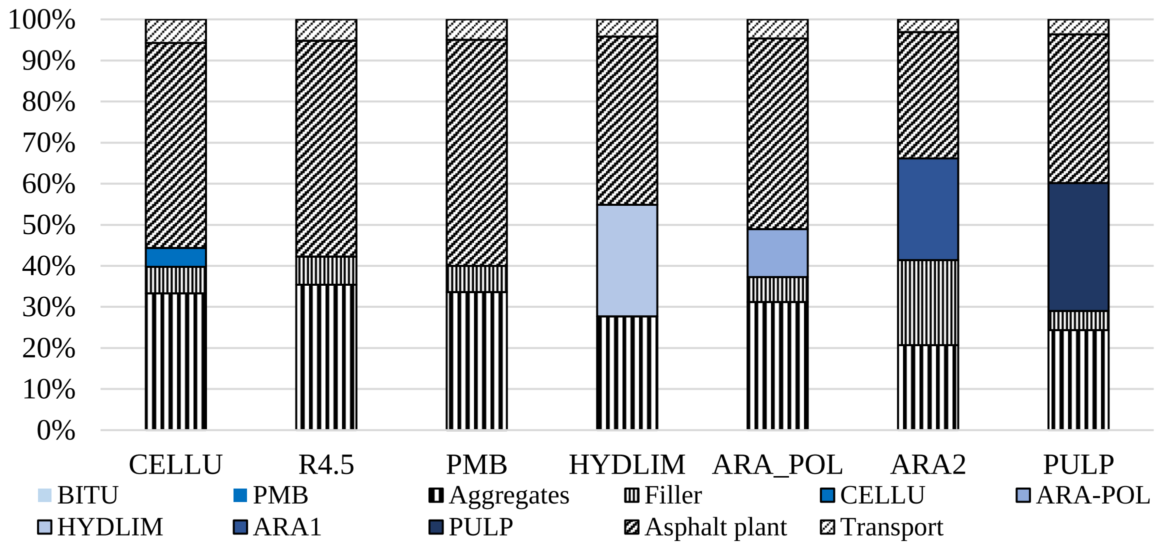
(c)



(d)

Figure 15. Performance of additives on PA mixtures. (a) Economic indicator; (b) Environmental indicator: Global Warming Potential (GWP); (c) Environmental indicator: Human Toxicity Potential (HTP); (d) Environmental indicator: Marine aqua-toxicity potential (MAETP).

Consequently, hydrated lime and aramid fibers (ARA2 and PULP) are among the additives used in the study that are posing the highest impacts on the environment. However, these additives are enhancing the mechanical performance significantly, resulting in a more resilient and sustainable pavement. Therefore, it is required to perform cradle-to-grave analysis that includes the cost incurred from pavement construction to end of life, including maintenance of the built pavement to take a decision.

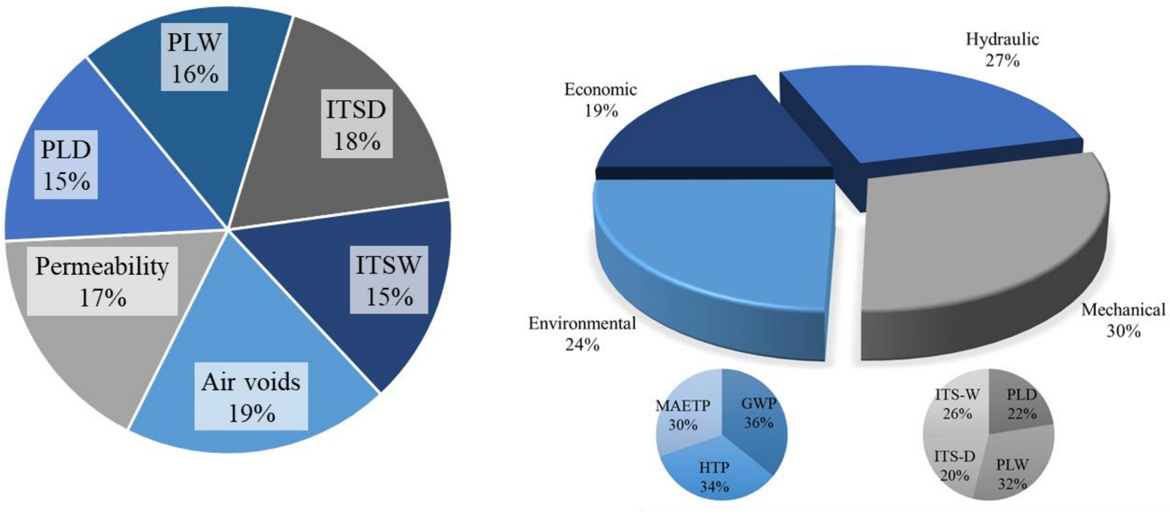
6.2. Multi-criteria selection of additives

6.2.1. Allotment of weights

The weights were allotted by three methods: CRITIC, Delphi, and 10 possible criteria chosen based on 10 case scenarios that can be possible in realistic situations. The results obtained by CRITIC and Delphi methods are given in Figure 16 (a) and (b), respectively. The figures suggest that according to the CRITIC method, the highest weights are allotted to the air voids followed by the indirect tensile strength in dry conditions.

In the Delphi method, the weights were allotted by a group of 32 experts working in esteemed institutions and expertise in asphalt pavement engineering with diverse backgrounds (India, Chile, Columbia, Spain, Italy, the United Kingdom, and Switzerland). More information about the use of the

Delphi method is given in Section 2.4 of Article 2. The highest priority in the case of the mechanical parameter was given by experts to the particle loss in wet conditions as abrasion resistance is the main concern in PA mixtures and combination with susceptibility of water may be detrimental to the PA mixtures. Therefore, any additive that enhances the particle loss in wet conditions (PLW) of the PA mixtures can be very advantageous. Regarding the environmental impacts, the highest weights were allotted to the global warming potential, this impact is usually the most prominent parameter in environmental analysis nowadays because of its importance in international forums and agreements. Comparison of indicators suggests that the experts allotted the highest weight to the mechanical performance followed by hydraulic, environmental, and then economic performance. This makes sense as the additives have the maximum influence on the mechanical resistance of the PA mixtures. However, they may have a negative influence on the hydraulic characteristics of the PA mixtures, and it is important to keep in check the impacts on the hydraulic performance.



(a) (b)

Note: PLD/W: particle loss in dry/wet conditions; ITS-D/W: Indirect tensile strength in dry/wet conditions
GWP: Global warming potential; MAETP: Marine aqua-eco-toxicity toxicity potential; HTTP: Human toxicity potential

Figure 16. Weights allotted to the parameters using method: (a) CRITIC; (b) Delphi.

The 10 possible scenarios were based on previous experiences and realistic situations based on the relative importance and type of roads. For instance, in case scenario 2, the highest importance was given to the functional performance of the road, this scenario is most useful for sidewalks or low traffic roads in rainy regions. In case scenario 6, the maximum importance is given to the mechanical performance of the asphalt roads, which is the case for high traffic roads. The rankings were given based on the response obtained from the majority of the scenarios. All the weighting methods were considered while performing the multi-criteria decision-making analysis.

6.2.2. Multi-criteria analysis

A variety of fibers were considered at different stages of the study. For the individual mechanical indicator, the fibers considered were ARA1, PULP, GLCV, GLST, CELLU given in Figure 17; and for the overall study (including mechanical, hydraulic, economical, and environmental indicators), fibers considered were: ARA, PULP, CELLU, ARA-POL, and HYDLIM shown in Table 11. The mechanical performance of the additives suggested that the aramid pulp had the best rank based on all the three methods used in the study (WASPAS, EDAS, and TOPSIS This may be since they reduce the abrasion loss by up to 60%. That is significant considering the main concern in this type of mixture is raveling. Based on the results of WASPAS including the hydraulic performance as well, glass hybrid fibers with synthetic components had the second-highest rank. They improved the raveling resistance as well as the indirect tensile strength of the PA mixtures.

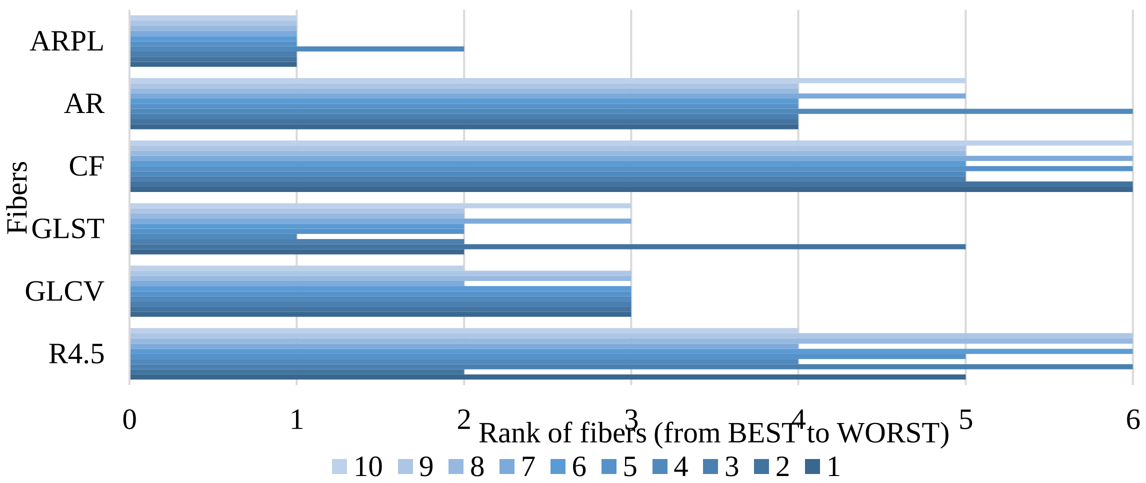


Figure 17. WASPAS results for the 10 possible criteria and CRITIC.

Almost all additives improved the performance of the PA mixtures as the rank of the mixtures of fibers is higher than the reference mixtures. Therefore, it is safe to say that the additives used in the study improve the mechanical resistance of the PA mixtures. However, considering only the hydraulic performance, the mixtures with fibers have lower ranks than the reference mixtures as the fibers block a part of air voids. As hydrated lime and PMB were additives that were used to replace the limestone filler and reference bitumen respectively, they do not influence the hydraulic performance of the PA mixtures. Due to the same reason, the mixtures with hydrated lime and PMB had the lowest impacts on the economic costs. The economic costs of PULP fibers were also low as they are the end products of aramid fibers and therefore, their cost is very low.

The environmental indicator suggests that the PA mixtures prepared with cellulose fibers are the most preferred mixture. It makes sense as it has very low impacts on the global warming potential

(GWP), marine aqua-eco-toxicity toxicity potential (MAETP), and human toxicity potential (HTP). These fibers are natural and do not pose a danger to the environment. ARA-POL was also considered to have low impacts on the environment. Meanwhile, the PULP fibers that were most preferred in terms of mechanical indicators ranked 6th due to their high impacts on the environment. However, hydrated lime had shown severe impacts on the environment.

If all the indicators are considered then the ranking of the alternatives using EDAS, TOPSIS and WASPAS will be in the order: PMB > PULP > CELLU > BITU > HYDLIM > ARA > ARA-POL. However, it is worth mentioning here that the priority is calculated by combining the weights allotted to the indicators and then to the individual parameter. More directed research is required on the analysis of the combined impact of any additive on the performance of porous asphalt mixture. In the present study, based on the influence of additives on mechanical, hydraulic, economic, and environmental indicators, the most preferred alternative was PMB followed by PULP. It is very important to mention that the cellulose fibers have exhibited good overall performance and were ranked as 3rd overall, this justifies their widespread use in the pavement industry.

A comparison among the three MCDA methods is shown in Article 2. EDAS, WASPAS, and TOPSIS showed very good agreement with each other. Particularly, EDAS and WASPAS displayed a very good agreement with an R^2 value of 0.94. Meanwhile, TOPSIS vs WASPAS had a lower agreement with an R^2 value of 0.59.

Table 11. Results obtained by multi-criteria decision analysis.

	Technical				Environmental				Overall			
	EDAS		TOPSIS		EDAS		TOPSIS		EDAS		TOPSIS	
Mixtures/ criteria	ASI	Rank	CC	Rank	ASI	Rank	CC	Ra nk	ASI	Ran k	CC	Rank
PULP	**0.98**	**1**	**0.93**	**1**	0.28	6	0.67	6	**0.85**	**2**	**0.77**	**1**
PMB	0.83	2	0.85	2	0.78	3	0.83	4	**1.00**	**1**	**0.73**	**2**
CELLU	0.74	3	0.80	3	0.84	2	0.91	2	0.80	3	0.68	3
HYDLIM	0.57	4	0.74	4	0.00	7	0.19	7	0.38	5	0.58	5
ARA	0.47	5	0.70	5	0.32	5	0.68	5	0.25	6	0.56	6
BITU	0.33	6	0.56	6	**1.00**	**1**	**1.00**	**1**	0.70	4	0.61	4
ARA-POL	0.04	7	0.15	7	0.74	4	0.88	3	0.14	7	0.33	7

6.3. Bitumen fabrication

Different reaction times, polymer and sulfur concentrations were tested to meet the storage stability requirement for PMBs according to EN 14023 standard for the new modified bitumen. The results obtained in the three trials are given in Figure 18. In the first trial, the bitumen stayed 6 hours in the low shear mixer. However, the results were not favorable, as the bitumen was gelled and disintegrated by bitumen settling at the bottom and polymer at the top. After the first trial, it was concluded that a lower quantity of bitumen should be mixed which may be the reason for the non-uniform mixing of polymer in the bitumen. It was also found in the first trial that lower time in low shear devices might be sufficient.

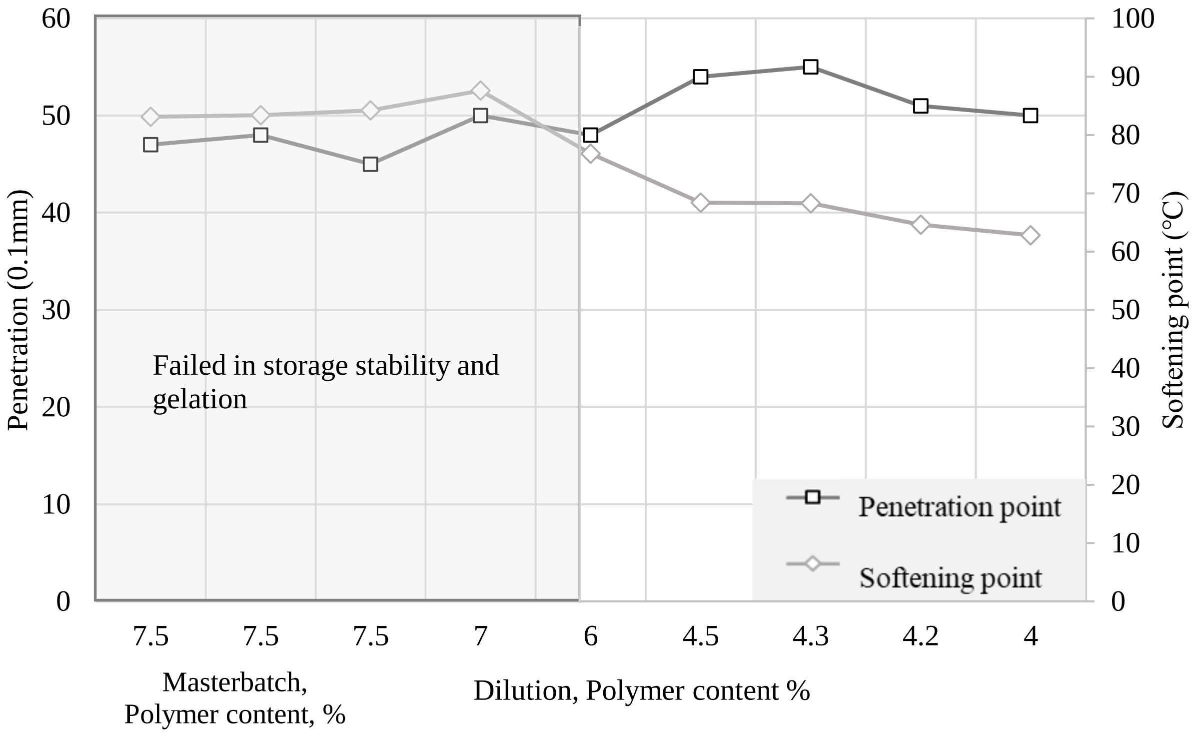


Figure 18. Results of the three trials for bitumen preparation.

In the second trial, these limitations were addressed. Hence, instead of 6 hours, the mixtures were kept in low shear for 2 hours. The results obtained were better than in trial 1 as there were no signs of gelation what signifies that the mixing was efficient. It can be observed that the softening point was rising on an increase in polymer content that suggests a possible reduction in permanent deformation with the addition of polymer. Polymer modification had a positive impact on the temperature susceptibility, as the penetration index was increasing with the polymer content. However, the masterbatch with higher polymer content failed in storage stability, as the difference between the penetration and softening point of the bitumen from the top and bottom layer was very high. Concerning the dilutions done, it was observed that the dilution of 4.5% showed good results.

Therefore, in trial 3, it was proposed to make dilutions between 4.5 and 7.5% of the polymer to find out the phase inversion point from being bitumen dominant to being polymer dominant. The dilutions were done so that the resulting polymer content was 6 and 7%. Unfortunately, both polymer content failed in storage stability as well as gelation, since gelation occurred within 3 days after the fabrication. Therefore, a polymer content between 4.5 to 6% will be the point of phase inversion.

Finally, a polymer content of 4.5% was selected as the most optimum and in trial 4. Bitumen modified with the polymer content of 4.5% was stable in storage stability, which is in agreement with Singh et al. 2018, (Singh, Kumar, and Ravindranath 2018), where 4.5% of high vinyl SBS polymer was added to modify the bitumen. The experimental bitumen (EXPBIT) was tested according to the standard EN:14023 (polymer modified bitumen) and it passed the requirements for PMB 45/80-65 bitumen with the properties shown in Table 12. It is to be noted that although EXPBIT has passed the requirements of PMB 45/80-65, some of the rheological characteristics are still unknown.

The comparison with the properties of the commercial PMB 45/80-65 (PMB) and virgin bitumen (VIRBIT) is included in Table 12. The three masterbatches with 7.5% polymer content (trials 1, 2, and 3) have a very similar penetration index, which indicates the accuracy of the fabrication process. It is interesting to note that the penetration indexes of PMB and the bitumen with 4.5% dilution (trials 2, 3, and 4) were very similar, which suggests low-temperature susceptibility. Meanwhile, the penetration index of virgin bitumen was high, indicating higher susceptibility towards temperature change.

Table 12. Properties of the binders VIRBIT, PMB, and EXPBIT.

Properties	Standards	Virgin bitumen 50/70 (VIRBIT)	PMB 45/80-65 (PMB)	Experimental bitumen (EXPBIT)
Polymer content (%)		-	-	4.5
Penetration, (0.1mm)	EN 1426	57	55	52
Softening Point (°C)	EN 1427	51.6	74.1	67.6
Penetration Index	EN 12591-Annex	-0.50	3.74	3.63
Cohesion (J/cm^2) 5ºC	EN 13588			6.27
Density (g/cm^3)		1.035	1,028	
Elastic Recovery at 25ºC (%)	EN 13398	-	92	73
Frass Point (°C)		-13	-	-
Viscosity at 100ºC (MPa)		-	23099	-
Viscosity at 135ºC (MPa)		-	1951	1471
Viscosity at 150ºC (MPa)	EN 13302	-	924	737
Viscosity at 175ºC (MPa)		-	-	247
Storage stability	EN 13399	-	-	Passed
Gelation	-	-	-	Passed

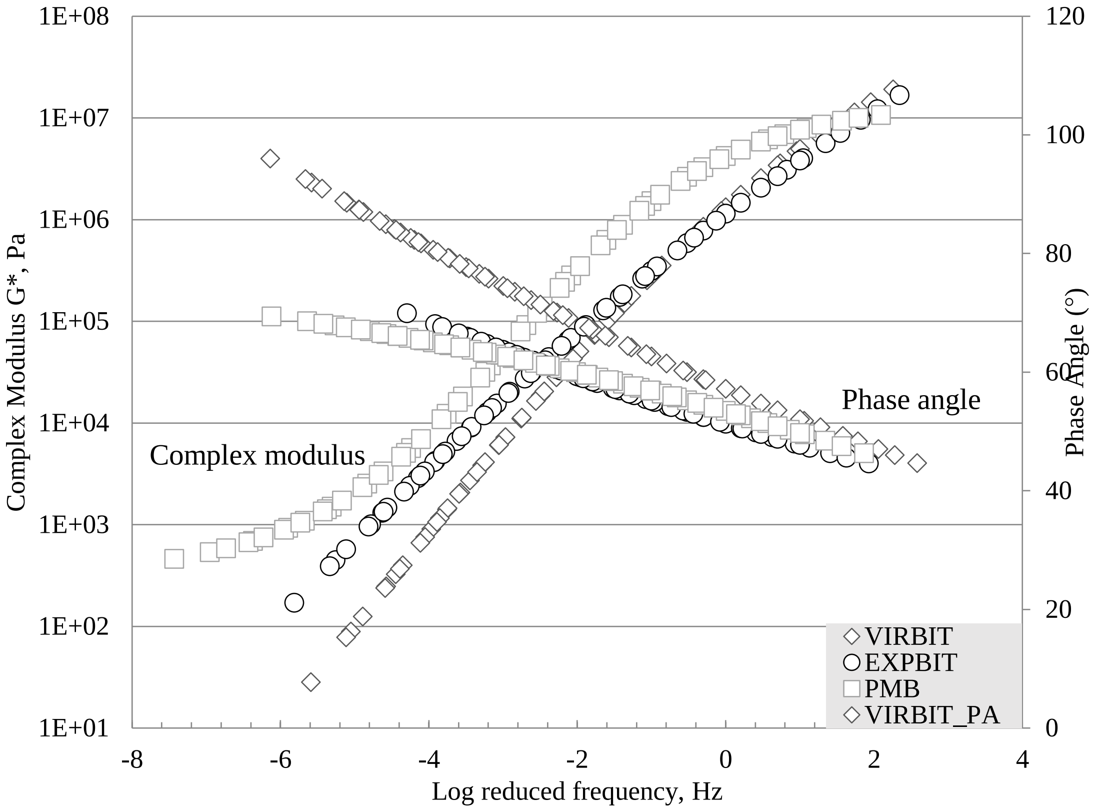
The results for viscosity for different contents of polymer in the three trials are depicted in Table 12. In trial 1, on increasing the polymer content the viscosity increases as well. Consequently, the result obtained for the masterbatch with the 7.5% polymer content is higher than commercially available PMB. On increasing the temperature, the rate of reduction of viscosity is similar at all-polymer content. In addition, it is interesting to note that on increasing the polymer content from 4 to 4.2%, the rise in viscosity is quite high. This phenomenon may be due to passing from the phase where bitumen is predominant, to the phase where bitumen and polymer are equally dominant. The viscosity for 4.3%, 4.5% dilutions (trial 3) and 4.5% (in trial 4), are in same range. While dilutions 6 and 7 are in the same range as the masterbatch. Hence, the phase inversion has taken place and the resulted binder is polymer dominated.

6.4. Rheological test results

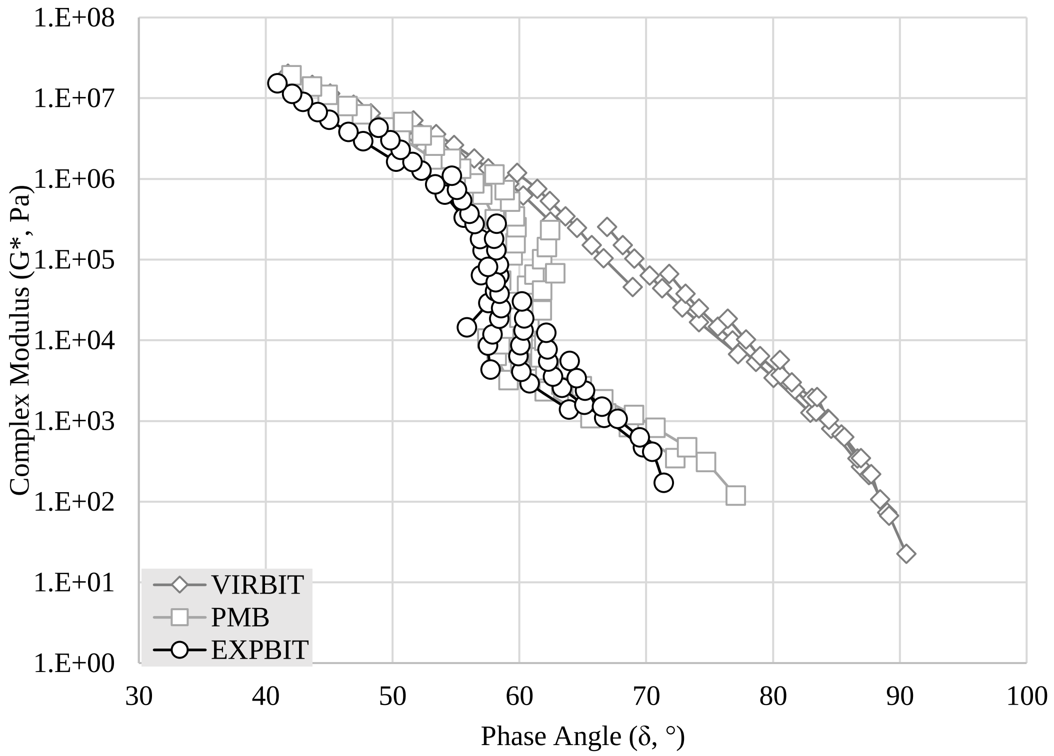
6.4.1 Complex modulus and phase angle mastercurves

The master curves of complex modulus and phase angle are given in Figure 19. A clear difference is observed at low frequencies: the PMB exhibited the highest stiffness as the complex modulus was highest for the PMB, whereas among the virgin binder and experimental bitumen, the latter is stiffer. At intermediate frequency, the curves of the two binders coincided. Regarding the phase angle, virgin bitumen had a higher phase angle that indicates its high deformation and low elastic response.

As an additional contribution to this study, the complex modulus, and phase angle were computed at the frequency of 1.59 Hz that is usually considered as a reference frequency for the traffic speed of 90kmph based on Superpave specifications. The results are given in Figure 20. It was found that though PMB had high stiffness based on the complex modulus curves, the experimental bitumen had shown the best adaptation to the temperatures. When the temperature is low, experimental bitumen was less stiff, resisting the crack formation and at higher temperatures where the deformation is most probable, the experimental bitumen had shown higher stiffness. This can be attributed to the high-vinyl SBS content which may influence the elasticity.



(a)



(b)

Figure 19. (a) Complex modulus and (b) phase angle mastercurves of the three binders.

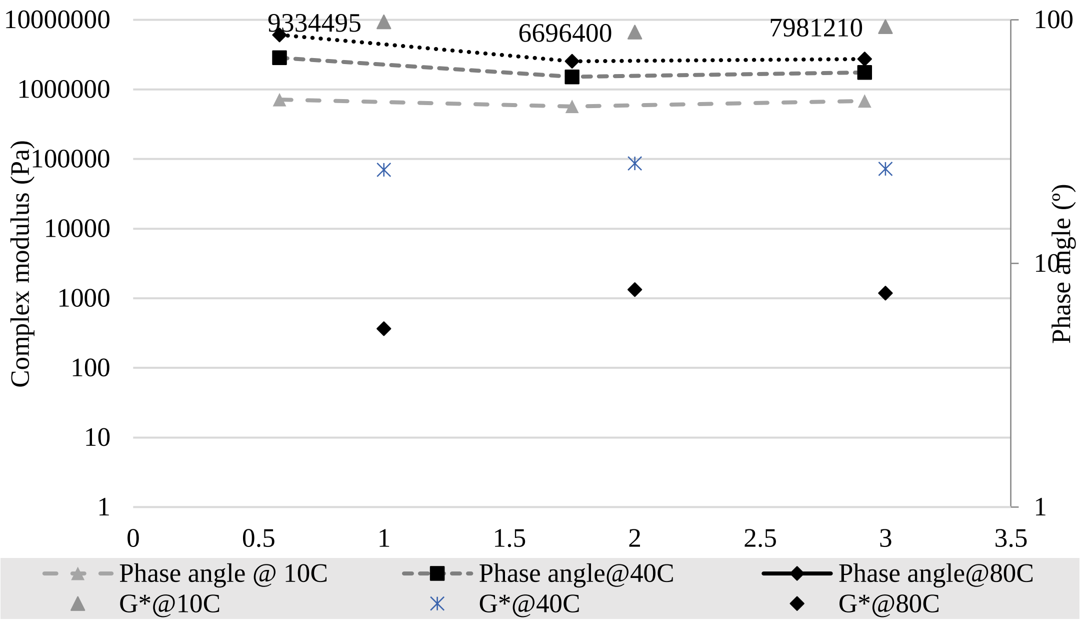


Figure 20. Complex modulus and phase angle parameters for each binder type at temperature 10℃, 40℃, and 80℃.

6.4.2. LAS and BYET results

The shear stress and strain curves obtained from the LAS tests are shown in Figure 21. Linear amplitude sweep tests were conducted at 25℃. The number of fatigue cycles to failure for EXPBIT is higher than its counterparts at strain levels 2.5%, 5%, 7.5%, and 10% (the results of the number of fatigue cycles to failure can be found in Article 3). At low strain levels, the experimental bitumen can be used for the higher number of fatigue cycles before failure. The fatigue life of EXPBIT was higher than PMB by up to 36.5% and 63.9% as compared to virgin bitumen. It was observed that at higher strain levels, the difference between the numbers of fatigue cycles is lower. This is confirmed by the shear and stress curves illustrated in Figure 21. Virgin bitumen has higher shear stress up to the strain of 22% afterward the failure occurred; therefore, at high-stress levels, PMB and EXPBIT may withstand higher strains as compared to virgin bitumen indicating unsuitability of virgin bitumen at higher stress levels.

Binder yield energy test results can predict the behaviour of bitumen at a monotonic load. The shear vs strain graphs is shown in Figure 22. The experimental bitumen had higher stress for the change in strain. A similar trend was observed for the maximum yield stress and yield energy. Virgin bitumen showed the lowest yield stress and yield energy. Multi-peaks were observed for the modified bitumens which may be the outcome of higher elasticity and good recovery due to the polymer. More explanation about the multi-peak can be found in section 3.1.3. of Article 3.

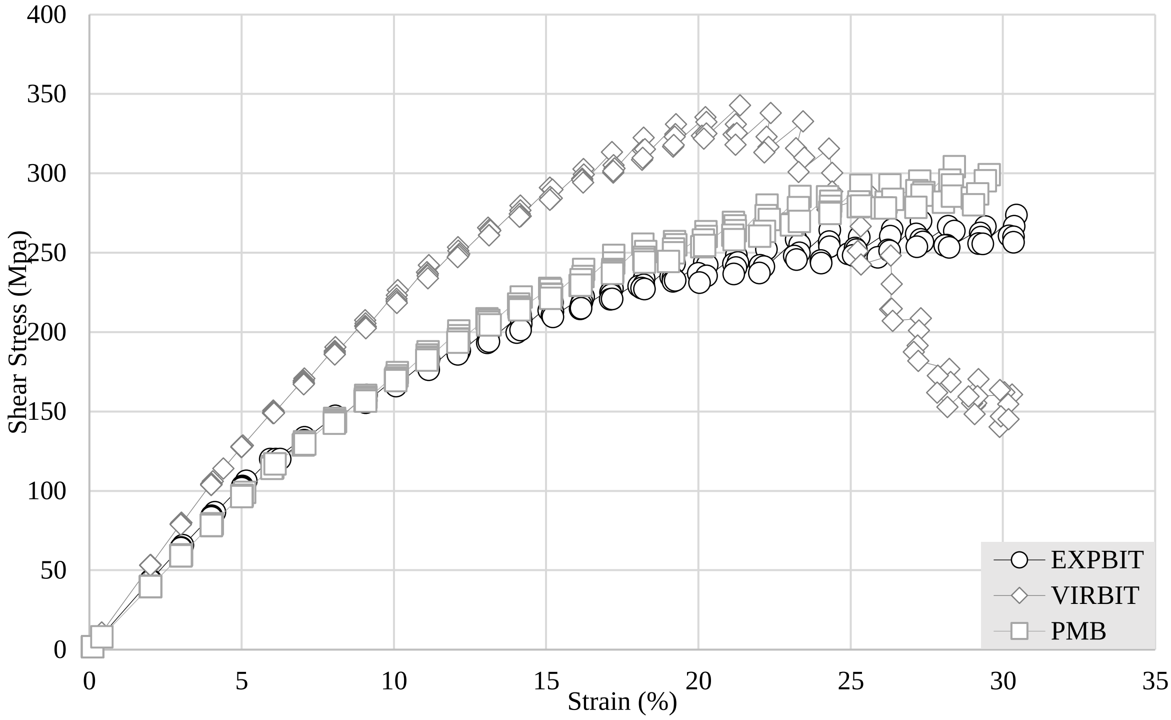


Figure 21. Shear-Stress curves obtained by LAS results.

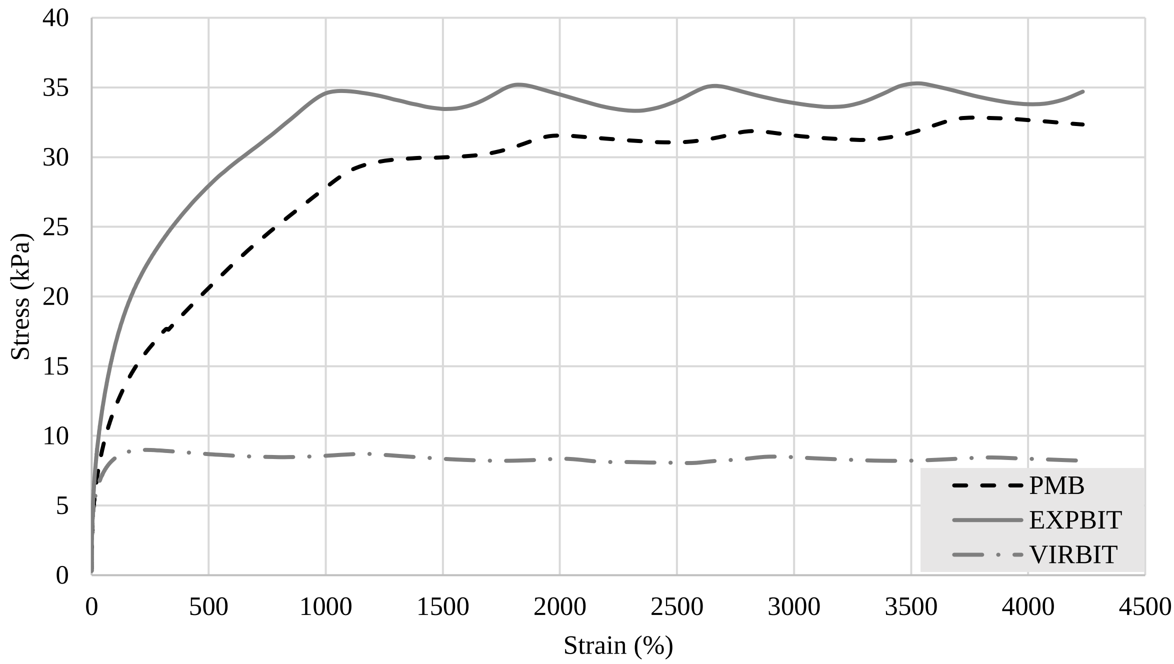
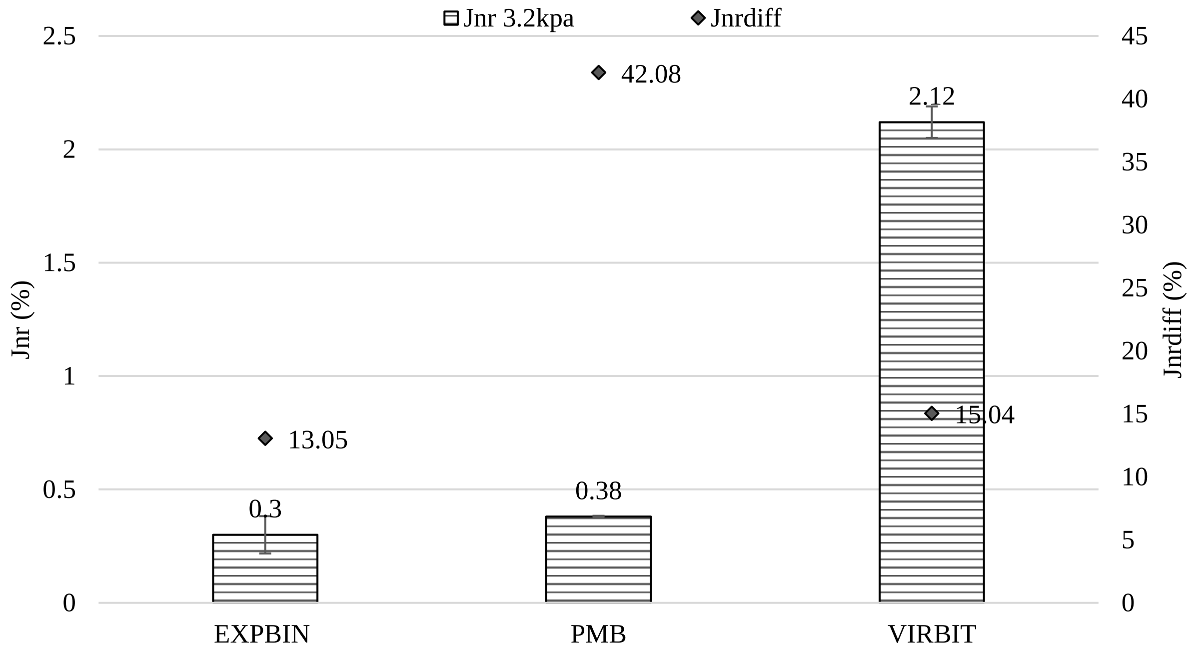


Figure 22. Shear Stress curves obtained by BYET.

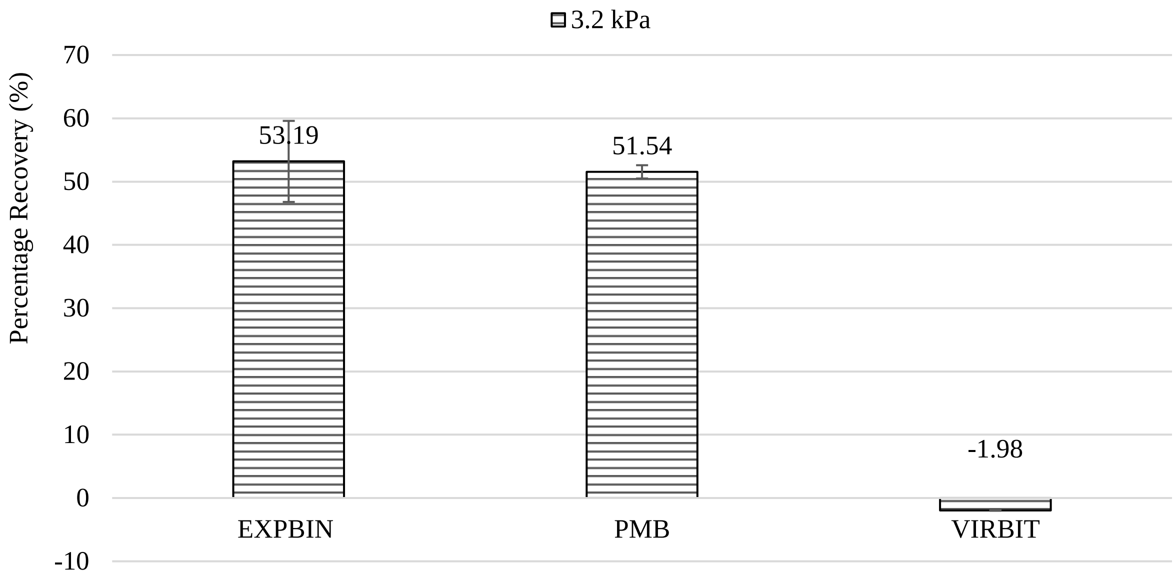
6.4.3. MSCRT

The multiple stress creep recovery test (MSCRT) is an indicator of the rutting behavior of the bitumen. The modified bitumens (EXPBIT and PMB) showed very similar behavior. Both experimental bitumen and commercial PMB have shown reshaping due to elastic components and recovery on unloading. Experimental bitumen had slightly lower strain values than the PMB, which may be due to the lower stiffness. On the contrary, virgin bitumen had much higher values of strain and due to the negligible elasticity of virgin bitumen, no reshaping was observed.

The creep compliance (Jnr) and Jnr-diff for the three bitumen are given in Figure 23. Lower Jnr indicates better resistance towards permanent deformation and vice versa. Meanwhile, percentage recovery indicates towards elastic response, the higher the recovery the higher is the elasticity, too. Experimental bitumen had the lowest value of creep compliance; highest recovery followed by polymer-modified bitumen. $J_{nr\text{-}diff}$ value should not be higher than 75% for 0.1 and 3.2kPa stress levels and the three bitumen samples were well within this limit. Therefore, it can be inferred that the experimental bitumen at high temperatures can have better rutting resistance. An important thing to note is that the virgin bitumen had a negative percent recovery that signifies that even on unloading, the strain in virgin bitumen is increasing.



(a)



(b)

Figure 23. MSCRT results (a) Creep compliance and (b) percentage recovery.

At a stress level of 3.2 kPa, J_{nr} indicates the rutting performance of the binder. For extreme, very heavy, heavy, and standard traffic, J_{nr} should be less than 0.5, 1, 2, and 4.5 kPa^{-1} respectively according to AASHTO M332. The two modified bitumens were within the limit for extreme traffic, whereas the value of J_{nr} for virgin bitumen was higher than 2 kPa^{-1}, which suggests that this bitumen is suitable only for standard traffic level according to Superpave. Moreover, it should be noted that the J_{nr} value for the experimental binder was less than PMB, which suggests that the rutting performance of EXPBIT is better than commercial PMB.

6.5. Porous asphalt mixtures with experimental bitumen

Mixtures with experimental bitumen were prepared to investigate its influence on the mechanical characteristics of PA mixtures as compared to commercial PMB and virgin bitumen. Figures 24, 25, and 26 present the air voids characteristics, particle loss, and indirect tensile strength results of the three bitumens used in the study. Figure 24 shows that there is a negligible effect of the experimental bitumen on the air voids characteristics.

The particle loss by the experimental binder and commercial PMB is similar but comparatively lower than the virgin bitumen. Particle loss in wet conditions for the experimental binder is lesser, however, the variation is small. Experimental binder suffered binder drainage problem with draindown of 0.32%. Therefore, the fibers were added in combination with experimental bitumen to address this problem and the resultant PA mixtures had lower binder drainage problems (<0.3%), more information can be found in Section 3.2.2. of Article 3.

The binders have shown very similar tensile strength, especially in dry conditions. The experimental bitumen had higher tensile strength in dry conditions while exhibiting similar tensile strength in wet conditions, and the difference in both conditions was insignificant (p-value< 0.05%) to both PMB and virgin bitumen mixtures.

To summarize, experimental bitumen improves the abrasion resistance as compared to PMB in wet conditions, in dry conditions the performance of two modified bitumen is similar. A similar trend was observed in the indirect tensile strength test, experimental bitumen has superior performance in wet conditions. However, the difference is not statistically significant. Binder drainage problem was observed in experimental bitumen and fibers were used to address the problem.

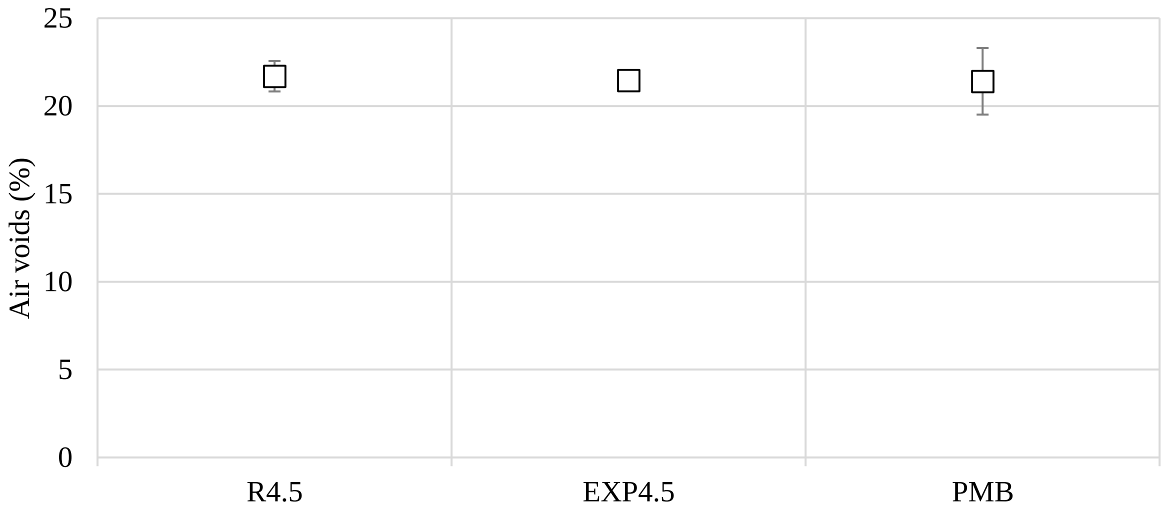


Figure 24. Air void characteristics of mixtures with additives.

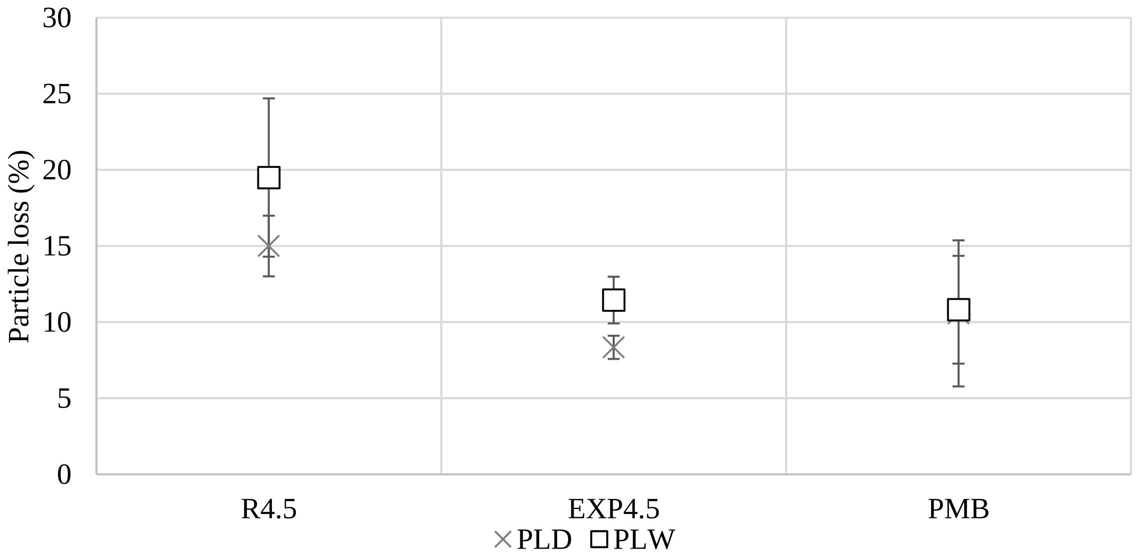


Figure 25. Abrasion loss of the mixtures with additives.

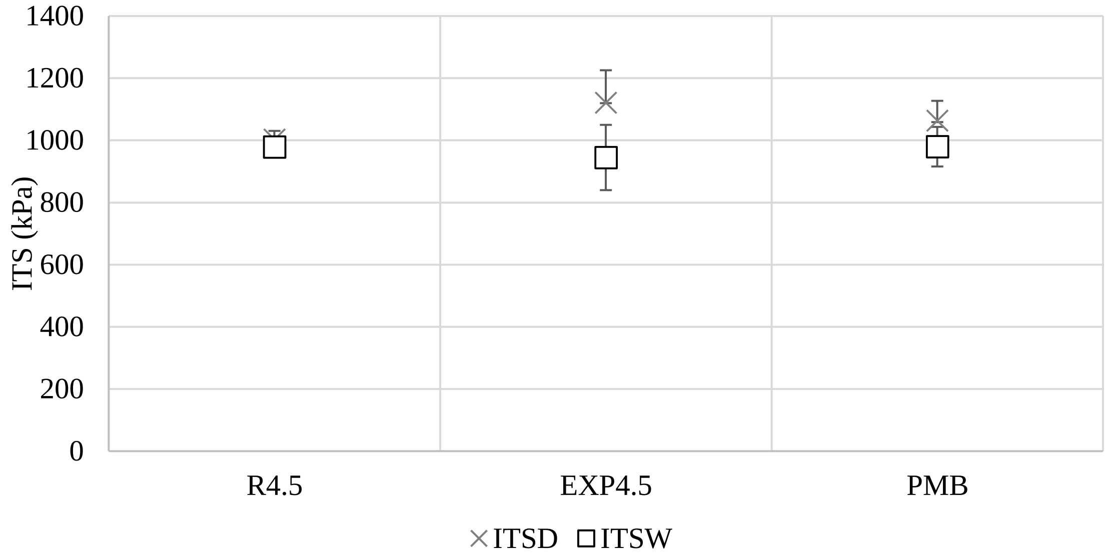


Figure 26. Indirect tensile strength test results of mixtures with different binders.

7. Conclusions

7.1. General conclusions

In this doctoral study, a new experimental bitumen and the influence of various additions such as seven aramid fibers, two glass-hybrid fibers, one cellulose fiber, and one hydrated lime filler as a replacement of limestone filler were investigated. The mechanical performance of PA mixtures was computed by performing dry and wet Cantabro test, indirect tensile strength, and moisture susceptibility tests, the functional performance was computed by volumetric analysis and permeability test. Finally, a multi-criteria decision analysis was performed to analyse the additions based on their mechanical, hydraulic, economic, and environmental impacts on PA mixtures. Besides, a new bitumen was prepared and assessed based on physical tests such as penetration, softening point, ductility, viscosity, storage stability, and gelation test and rheological tests such as temperature-frequency sweep test, MSCR, LAS, and BYET. Following are the main general conclusions of this doctoral thesis:

- The durability problems of porous asphalt mixtures can be addressed by the incorporation of additives especially fibers that act on improving the binder-aggregate matrix of the porous asphalt mixtures thereby enhancing the particle loss resistance. The maximum improvement in raveling resistance was observed by the incorporation of aramid pulp fibers.
- Overall, the use of aramid pulp, cellulose fibers, and PMB bitumen is recommended in the PA mixtures based on mechanical, hydraulic, economic, and environmental indicators. On the one hand, aramid pulp fibers have enhanced the mechanical characteristics considerably and have a lower economic impact, while on the other hand, cellulose fibers have the lowest impact on the environment.
- The preparation of polymer-modified bitumen with high polymer content (>4.5%) was not possible due to stability issues. Although, the new experimental bitumen prepared with 4.5% high-vinyl SBS copolymer exhibited better rheological performance in comparison to commercially used polymer modified bitumen 45/80-65 and virgin binder 50/70. On the use of this binder in porous asphalt mixture, the abrasion resistance was improved, however, due to lower binder stability, the fibers are needed to avoid the binder draindown.

7.2. Specific conclusions

7.2.1. Phase 1: Selection of additives based on multi-criteria decision-making analysis

A multi-criteria decision method was applied to rank the performance of various additives when incorporated in PA mixtures with two types of bitumen: virgin bitumen & polymer modified bitumen; three types of fibers: aramid fiber, aramid pulp, aramid-polyolefin fibers; two types of fillers: limestone (standard) & hydrated lime. Their performance was analysed based on four categories of indicators that are: mechanical indicators (abrasion resistance in dry conditions and wet conditions and indirect tensile strength in dry conditions and wet conditions); hydraulic indicator (air voids); economic indicator (initial investment) and environmental indicators (global warming potential, human toxicity potential, and marine aquatic eco-toxicity potential). The relative weights were calculated based on three methods (CRITIC, Delphi, and the 10 possible criteria method), and to rank the alternatives, three multi-criteria methods were used (EDAS, TOPSIS, and WASPAS). The following particular conclusions can be drawn from the study:

- Additives in porous asphalt mixtures slightly reduce the air voids content, as well as the permeability. However, all mixtures containing fibers had more than 19% air voids.
- For the Cantabro test, most of the additives improved the abrasion performance of the porous asphalt mixtures. Even a small amount of 0.05% of aramid pulp reduces the particle loss to less than half of the reference mixtures, both under dry and wet conditions. Ordinary aramid fibers and glass-hybrid fibers (GLST and GLCV) also have a positive influence on abrasion resistance both in dry and wet conditions. On the contrary, the use of aramid-polyolefin fibers presented the lowest abrasion resistance.
- Concerning the results of indirect tensile strength tests (ITS) of the mixtures, glass-hybrid fibers had a positive effect, while a significant reduction is observed in mixtures with aramid fibers. Likewise, moisture susceptibility is observed to be higher in the case of aramid fibers than glass-hybrid fibers, although, aramid pulp satisfies the minimum required ITSR. For stronger porous asphalt mixtures, the use of glass hybrid fibers is recommended.
- Incorporation of a combination of aramid pulp and glass-hybrid fibers was not found to be very promising as it reduced the air void content and abrasion resistance, while their addition individually to the mixtures led to superior performances.
- For multi-criteria decision-making analysis, the weights from the CRITIC method were not found to be very realistic. This method gave higher weighting to the air void content (19%) followed by dry ITS (18%), and then abrasion resistance (15%). Meanwhile, based on the Delphi method, experts gave the highest relative weights to abrasion loss in wet conditions, representing the main concern for porous asphalt mixtures. For the environmental indicator, the highest relative weight was allotted to global warming potential.
- The WASPAS multi-criteria approach is beneficial to make a decision based on the results from the laboratory analysis. Therefore, it can be concluded that multi-criteria analysis is a viable approach for the selection of materials for asphalt mixtures.

- Concerning the economic indicator, the lowest initial investment was required for hydrated lime among all the tested alternatives. This was closely followed by the aramid pulp, which was a waste product during the manufacturing of the aramid fibers, requiring the least initial investment among all the fibers included in the study.
- The environmental indicator suggested that the addition of cellulose fiber (the only natural fiber tested) had the least impact on the environment, whereas the hydrated lime had the highest global warming potential.
- The three multi-criteria decision-making methods used (EDAS, TOPSIS, and WASPAS) have shown very good agreement, especially for the mechanical indicators. “EDAS and WASPAS” have shown higher agreement as compared to “EDAS and TOPSIS” or “TOPSIS and WASPAS” methods.
- According to multi-criteria analysis, the ranking of additives is (best performance to worst performance): polymer modified bitumen > aramid pulp > cellulose fiber> reference mixture > hydrated lime> ordinary aramid fiber > aramid-polyolefin fiber fibers i.e., PMB > PULP > CELLU > BITU > HYDLIM > ARA > ARA-POL.

7.2.2. Phase 2: Preparation of experimental bitumen

A new experimental bitumen was prepared with high vinyl content SBS polymer. The physical and rheological characteristics of the new bitumen were compared with commercially available PMB (45/80-65) and virgin bitumen (50/70) with the following particular conclusions:

- Based on the trial-and-error approach followed in the development of the new bitumen, the 4.5% polymer content was found to be stable, and it conformed to the requirements of commercial PMB.
- While complex modulus and phase angle mastercurves showed that the commercial PMB had the highest stiffness and virgin bitumen had the highest susceptibility towards deformation due to its high phase angle; the experimental bitumen had lower complex modulus at low temperatures and high complex modulus at high temperatures that suggest higher resistance towards crack formation and deformation at low and high temperatures respectively. Consequently, the experimental bitumen has shown the best adaptation to the temperatures.
- Regarding the fatigue cycles obtained from linear amplitude sweep test results, it was found that the experimental bitumen had a higher number of fatigue cycles to failure up to 10% (maximum that is used in this study) as compared to virgin bitumen and commercial polymer-modified bitumen.

- The binder yield energy test results showed that the highest yield stress and yield energy was exhibited by the experimental binder, while the virgin bitumen showed the lowest values. Modified bitumens can withstand a higher load before yielding as compared to the virgin binder.
- According to multiple stress creep recovery test results, the deformation behavior of experimental bitumen is quite similar to commercial PMB. The creep compliance and recovery results of experimental bitumen indicated its superior elastomeric behavior with respect to commercial PMB and virgin bitumen.
- The porous asphalt mixtures prepared with experimental bitumen had higher particle loss resistance than the mixtures with PMB. However, mixtures with experimental bitumen had high binder draindown (>0.3%), which is unexpected in modified bitumen. This problem was addressed by the addition of fibers.

7.3. Future research lines

Based on the results drawn in the present study, the following research lines are proposed for further improvement in the performance of porous asphalt mixtures:

- To investigate the effect of aging on the physical, chemical, and rheological properties of the experimental bitumen and evaluate the performance of PA mixtures by simulating the field aging in the laboratory.
- To compare the fibers based on their influence on the energy parameters, low temperature cracking resistance, and high-temperature stability.
- To perform a cradle-to-gate life cycle assessment of porous asphalt with the incorporation of fibers, with a complete environmental assessment that includes the leaching possibility on the use of fibers.
- To clarify whether the fibers improve the strength of mastic or just improve the aggregate packing, perform tests on mastic of porous asphalt mixtures and check the influence of fibers on the void characteristics with computerized tomography (CT) scans.
- To study the effect of combining the fibers on the porous asphalt mixtures to see if there are any synergistic benefits as different fibers influence different properties of the mixtures.
- To assess the behavior of porous asphalt mixtures with fibers at low and high temperatures, assessing the impact of the increment in temperature on the environmental indicator by using polymer modified bitumen.

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