

UNIVERSIDAD POLITÉCNICA DE MADRID
ESCUELA TÉCNICA SUPERIOR DE INGENIEROS DE CAMINOS, CANALES Y
PUERTOS



**Influence of Crumb Rubber on the
Functional Characteristics of Asphalt
Pavements: Acoustic Performance, Skid
Resistance and Self-Sensing Behavior**

DOCTORAL THESIS

Submitted for the degree of Doctor by:

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Doctoral Degree in Civil Engineering Systems

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«Es preferible el resultado de un ensayo, que la opinión de cien expertos»

Arthur Casagrande

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Abstract

This thesis examines the growing challenges in the functionality of asphalt pavements due to increasing population density and the consequent increase in vehicle use. The motivation for this research stems from the urgent need to mitigate the negative externalities associated with noise pollution and skid resistance, as well as other problems such as traffic congestion, accidents, noise and air pollution. Every year, 1,350,000 people lose their lives on roads worldwide. In 2019, the WHO presented a 64% correlation of hearing loss due to noise pollution, a figure that is projected to reach 69% by 2050, underscoring the critical importance of understanding the complex dynamics of vehicle-road functionality and interaction.

The present study investigates the impact of crumb rubber on the functional properties such as acoustics and skid resistance of dense, discontinuous and open asphalt mixtures. The objective of this thesis is to evaluate the contribution of rubber to the functional properties and eco-sustainability of asphalt mixtures.

The research focuses on experimental methods of evaluating the influence of rubber on volumetric, mechanical, and functional characteristics. The effect of rubber on the surface texture of various asphalt mixtures and the influence on sound absorption are still understudied and requires further exploration to understand the impact of crumb rubber on pavement surface texture, as it plays a crucial role in the prevention of traffic accidents and the generation of rolling noise.

Acoustic functional properties were evaluated based on rolling noise absorption and impact attenuation properties by dynamic stiffness on cylindrical samples. In parallel, surface properties such as skid resistance at low and high-speed measurements on plate-type specimens were evaluated, in addition to the surface characteristics of resistance to tangential stress.

The results provided insight into the influence of crumb rubber on the volumetric, mechanical properties, and surface functionality of asphalt mixtures such as sound absorption and skid resistance. Finally, the use of crumb rubber in multifunctional asphalt mixtures with piezoresistive properties was studied to evaluate the sensing capabilities of crumb rubber showing promising results.

Resumen

Esta tesis examina los crecientes desafíos en la funcionalidad de los pavimentos asfálticos debido al aumento de la densidad poblacional y al consiguiente incremento del uso de vehículos. La motivación para esta investigación surge de la urgente necesidad de mitigar las externalidades negativas asociadas a la contaminación acústica y la resistencia al deslizamiento, así como otros problemas como la congestión del tráfico, los accidentes, el ruido y la contaminación atmosférica. Cada año, 1,350,000 personas pierden la vida en carreteras en todo el mundo. En 2019, la OMS presentó una correlación de 64% de pérdida auditiva debido a la contaminación acústica, una cifra que se prevé alcance el 69% en 2050, lo que subraya la importancia crítica de comprender la compleja dinámica de la funcionalidad e interacción entre vehículo y carretera.

El presente estudio investiga el impacto del polvo de caucho en propiedades funcionales como la acústica y la resistencia al deslizamiento de las mezclas asfálticas densas, discontinuas y abiertas. El objetivo de esta tesis es evaluar la contribución del polvo de caucho en las propiedades funcionales y la eco-sostenibilidad de las mezclas asfálticas. La investigación se centra en métodos experimentales de evaluación de la influencia del polvo de caucho en las características volumétricas, mecánicas y funcionales. El efecto del polvo de caucho en la textura superficial de diversas mezclas asfálticas y la influencia en la absorción acústica están poco estudiadas y requieren una mayor exploración para comprender el impacto del polvo de caucho en la textura superficial del pavimento, ya que aquella desempeña un papel crucial en el control de los accidentes de tráfico y en la generación de ruido de rodadura. Se evaluaron las propiedades funcionales de la acústica basadas en la absorción de ruido de rodadura y en las propiedades de atenuaciones de impactos por la rigidez dinámica sobre muestras cilíndricas. Paralelamente, se evaluaron las propiedades superficiales como la resistencia al deslizamiento a bajas y altas velocidades de medidas en muestras tipo placa además las características superficiales de resistencia al esfuerzo tangencial. Los resultados permitieron comprender la influencia del polvo de caucho en las propiedades volumétricas, mecánicas y en la funcionalidad superficial de las mezclas asfálticas como la absorción acústica y la resistencia al deslizamiento. Por último, se propuso el uso de polvo de caucho en mezclas bituminosas multifuncionales con propiedades piezorresistivas para evaluar sus capacidades como sensores mostrando resultados prometedores.

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Abbreviations and Acronyms

AR	Asphalt rubber
AB	Asphalt binder
AC	Asphalt concrete
AUC	Area Under Curve
APT	Accelerated Polished Testing
ANCOVA	Analysis Of Covariance
ANOVA	Analysis Of Variance
BBTM	Beton Bitumineux Tres Mince
BPT	British Pendulum Test
BPN	British Pendulum Number
BW	Bandwidth
CEDEX	Centro de Estudios y Experimentación de Obras Públicas
CR	Crumb Rubber
DS	Dynamic Stiffness
DP	Dry Process
FCR	Fractional Change of Electrical Resistance
HSD	Post-Hoc Tukey
ISO	International Organization for Standardization
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Strength Modulus
LTS	Laser Texture Scanner
MTD	Mean Texture Deep
MPD	Mean Profile Deep
P	The peak of the Gaussian fit
NFVU	End Of life of Tires
SMA	Stone Mastic Asphalt
SAI	Segmentation of Area of Interest
GF	Gaussian Fitting
PTTE	Polytetrafluroethylene
WP	Wet Process
W&S	Wehner Schultze
WTAT	Wheel Track Abrasion Test

1. Introduction

1.1. Research background.

In the final report of the Conference of the Parties (COP 21) held in France in 2015, the Paris Agreement was established with measures aimed at limiting the increase in global warming. These measures include the promotion of renewable energies and the reduction of industrial pollution. However, since the last COP in 2019, there has been the regrettable loss of more than five million lives due to diseases of unknown origin.

This impact has led to a reconfiguration of targets at COP26, held in Glasgow in 2021. At this event, the urgency of addressing climate change was recognized and hopeful proposals were put forward to reduce levels of air pollutants and achieve decarbonization.

Environmental noise, especially that generated by vehicular traffic, continues to be a significant environmental concern affecting the health and well-being of millions of people in Europe. More than 20 % of the European population, i.e. more than 100 million individuals, are exposed to prolonged levels of noise that are detrimental to health (Jarosinska et al., 2018). The data also show that the targets set in environmental noise policies have not been met. In fact, according to the forecasts, the number of people exposed to noise is unlikely to decrease substantially in the future due to the growth of urban areas and the increase in traffic.

In addition, waste management is a worldwide problem that has been increasing mainly in developing countries becoming a sustainable development problem within the factors of economy, and security and mainly resulting in serious health problems in the population.

In recent years, the experience in the use of recycled tires in asphalt mixtures has gained great importance due to the excellent results obtained and the improvements in mechanical behavior. The use of crumb rubber (CR) in asphalt mixtures has been widely accepted for its ability to improve fatigue resistance, resistance to permanent deformation and high resistance to cracking, surpassing traditional materials commonly used.

This material has been shown to significantly increase pavement life, resulting in lower maintenance costs and increased road durability. In addition, notable benefits have been obtained in the modification of asphalt binders, especially in the rheological structure, and their resistance to aging and degradation caused by environmental factors and ultraviolet radiation.

Figure 1.1 shows the number of the most relevant indexed publications obtained from the Web of Science (WOS) portal in relation to CR applied to asphalt mixtures and modifications to the asphalt binder in the last 20 years. It is evident that the number of publications on the use of CR has increased year after year, reflecting a growing interest in this field of knowledge. It is important to note that the use of CR has sparked increased research interest in binder modification. However, research focused on acoustic properties has received less attention. Similarly, CR applications have also shown a lower level of interest in skid resistance studies, as can be seen in Figure 1.1

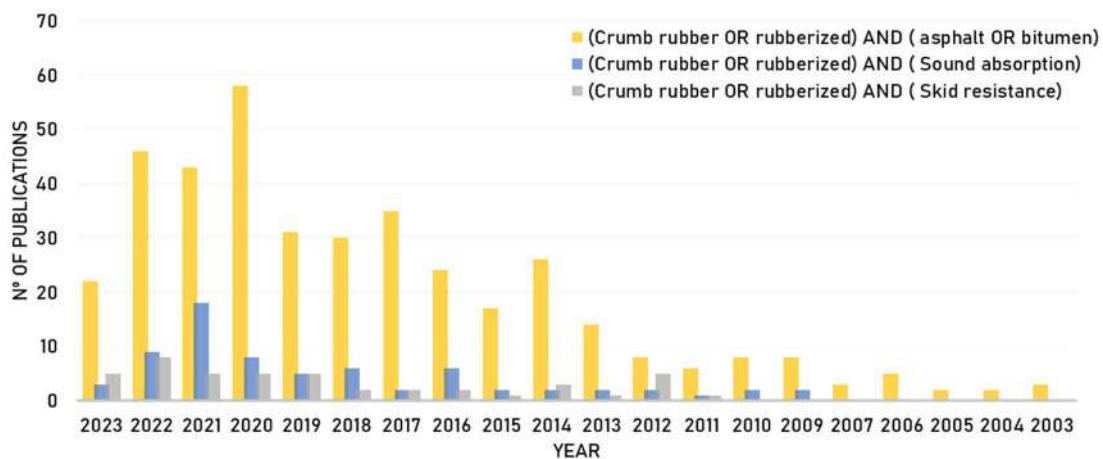


Figure 1.1: Crumb rubber publications in the last 20 years. Source: Author's elaboration.

Figure 1.2a show the global manifestation of research interest, showing the geographical distribution of countries according to their level of involvement. Figure 1.2b shows the number of publications on the use of CR in asphalt mixtures by country. It can be seen that these publications have been mainly concentrated in East Asian countries, especially China; in North America, especially in the United States; and in Southeast Asian nations such as Iran and India. However, in the European category, Spain leads in terms of research interest in the use of crumb rubber in asphalt mixtures, followed by Italy and England (Figure 1.2c).

It is clear that the level of interest and knowledge in this field is still limited, with relatively few studies carried out in the last two decades. Despite this, Figure 1.2b evidences a growing interest in the last three years in this topic, suggesting a possible increase in research in the coming years.

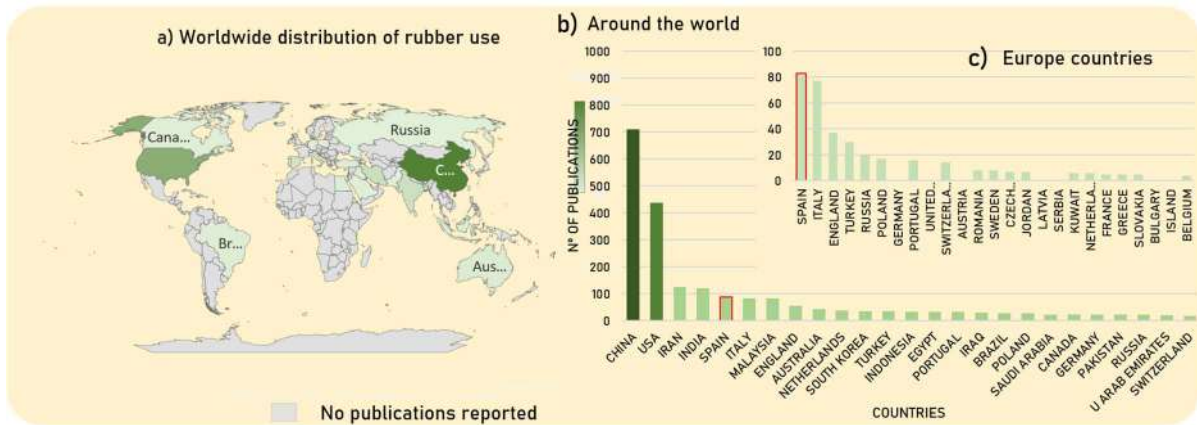


Figure 1.2: CR publications, a)Global publications, b) Around the world, and c) Europe countries during the last 20 years (WOS). Source: Author's elaboration.

Skid resistance and noise generation are significantly associated with the surface texture of the pavements. When a tire rolls over the pavement surface, traffic noise is generated and amplified (Bernhard & Wayson, 2005), and by the passage of traffic, the frictional roughness of the pavement wears away. In the field of road transportation, pavement texture can be designed to simultaneously attenuate noise and improve skid resistance (Callai & Sangiorgi, 2021).

Modern cities have long been built thanks to advances and the evolution of the transportation industry. However, this industry is responsible for managing and controlling noise generation and maintaining acceptable pavement skid resistance throughout the service, construction, and maintenance processes of roadways. This factor, which can have a significant impact on people's health and well-being, is often overlooked.

Exposure to noise generated by roads can have detrimental effects on human health, including hearing loss, increased stress, and sleep disruption. In Europe, long-term exposure to environmental noise causes 2,000 premature deaths and contributes to 48,000 new cases of ischemic heart disease. Yearly 22 million people in Europe suffer from chronic noise annoyance (Dzhambov et al., 2022). On the other hand, pavements with insufficient friction properties can increase the risk of skid-related accidents, which can lead to serious injuries while driving. In the EU,

road accidents claimed the lives of some 18,800 people in 2020. Of these, 44.2 % were drivers or passengers in passenger cars, and 19.2 % were pedestrians. Around 1.24 million people worldwide are killed in road traffic accidents each year, or almost 3,400 people per day. By 2030, it is anticipated that there will be 1.9 million traffic-related deaths annually, making it the seventh leading cause of death (World Health Organization, 2022).

In this context, there are numerous well-established detrimental effects on physical and mental well-being when one is exposed to environmental noise sources such as industry, air, road, and rail traffic. On the one hand, urban planners are under pressure to increasingly create and protect quiet spaces to create attractive urban soundscapes because noise reduction is a public health issue, and on the other hand, pavement engineers are working to maintain optimal frictional characteristics.

Sustainable pavements meet technical engineering requirements while conserving or regenerating surrounding ecosystems. Currently, analysis of road pavements focuses on the functionality of the asphalt pavement, with an urgent need for source-level mitigation, as the effectiveness of various noise mitigation techniques varies.

From this point of view, it is essential to reformulate the functional objectives of asphalt pavement within the framework of the sustainability and safety system of road transportation.

Historically, road pavement construction systems have been viewed as nothing more than a means to resist traffic loads, with their primary purposes being to support traffic and keep road users comfortable throughout their service life.

Traditional asphalt pavements cannot meet the increasing standards of resilience, and sustainability related to minimizing the environmental impact, and energy efficiency of advanced road infrastructures. Therefore, the circular economy has started to pay more attention to the sustainability and usability of pavements. Unlike conventional pavements, the new generation of asphalt pavements is being improved within the circular economy approach with the reuse of recycled materials such as waste. In addition, it has focused on improving sustainability through the use of road transport management systems and despite these advances, it is urgent to consider the functional surface characteristics to reduce noise pollution and preserve properly.

The use of this type of pavement is essential to reduce noise pollution in cities and increase safety in vehicular traffic, as it produces the least noise.

Low noise-generating mixtures and high skid resistance are two of the many cutting-edge features that are crucial for improving road safety and reducing noise pollution, which cannot always be balanced in traditional asphalt pavement construction but have an incredibly important role to play in construction operations and maintenance.

Creating acoustic pavements with excellent skid resistance functionality is therefore a current challenge in pavement engineering. Governments with jurisdiction over the area are urged to work with practitioners and researchers to develop new pavements that attenuate noise and improve skid resistance in the road infrastructure sector.

The growth of road connectivity and traffic in cities has brought both benefits and detriments. The increase in the number of motor vehicles has led to environmental impacts and noise pollution, negatively affecting the quality of life of people living in urban areas. Automobile pollution can be divided into two categories: noise pollution and environmental pollution. Private cars emit 18% of Carbon dioxide (CO₂) emissions, a major greenhouse gas, and other pollutants, while noise pollution is caused by passing vehicles (European Environmental Agency, 2020). Vehicular traffic has a significant impact on the environment worldwide, primarily due to air and noise pollution produced by cars and trucks. Carbon dioxide is the most prevalent pollutant gas in the atmosphere and a major contributor to air pollution, which can be detrimental to human health. Therefore, promoting sustainable transportation and reducing the number of cars on the road is crucial to address this issue.

Noise pollution is a major environmental problem that has been increasing worldwide in recent decades. According to the World Health Organization (WHO) (Jarosińska et al., 2018) about 1.1 billion people worldwide are at risk of hearing loss due to exposure to elevated noise levels. In addition, WHO has reported that traffic noise is the main contributor to noise pollution in many cities.

A report by the European Environment Agency (EEA) has also noted that the number of people affected by noise pollution has been increasing in Europe. The report (European Environment Agency, 2020a) indicates that around 20% of the population of the European Union is exposed to noise levels above the limits recommended by the WHO.

In Latin America, the situation is no different. According to the Inter-American Development Bank (IDB (Inter-American Development Bank, 2021) about 65 million people in the region are exposed to noise levels that can affect their health. In addition, the IDB has reported that noise pollution is responsible for the loss of labor productivity and a decrease in the quality of life of people in the region.

To reduce the impact of road traffic on noise and environmental pollution, it is suggested to improve road pavement, widen roads to make traffic flow more smoothly, and encourage alternative modes of transportation, such as bicycles and public transport (Pardo 2012, Czuka et al. 2016), and the measurement of the electricals self-sensing. These measures can help reduce the noise generated by vehicular traffic, which will improve the quality of life of city dwellers and reduce the negative effects on health.

The use of CR in asphalt mixtures has gained increasing attention in recent years as a sustainable solution for managing end-of-life tires. Despite the numerous benefits offered by rubberized asphalt mixes, such as improved skid resistance and reduced tire-pavement noise, it is still important to understand the long-term effects of rubber on these properties.

1.2. Principal objectives and structure of the research

In accordance with the background, **this study focuses on the assessment of the effect of CR on volumetric, mechanical behavior, surface texture, skid resistances, acoustic absorption, noise generation and self-sensing performance of the asphalt mixtures.** The results of this study will provide valuable insights into the sound acoustic properties and skid resistance performance of rubberized asphalt mixtures in this field. Likewise, the thesis addresses another characteristic function of the mixture that is gaining relevance: its capacity to activate as pavement sensors, a capacity that can be enhanced with the incorporation of the CR. The organization and structure of this thesis are ordered in the following chapters and summarized in Figure 1.3.

Chapter 1. Introduction: This chapter presents the background and context of the research, providing a comprehensive overview of the use of CR in asphalt mixtures and the related challenges and issues. The chapter also outlines the specific objectives of the study and the organization of the research. By presenting this information, the chapter lays the foundation for the subsequent investigation into the subject matter of contribution research and work delimitation.

Chapter 2. State of the art: The increasing interest in the use of crumb rubber (CR) in asphalt mixtures to prevent the disposal of tires can be seen in current research. While rubberized asphalt offers benefits such as improved skid resistance and reduced tire noise, understanding its long-term effects on these properties is critical. This chapter presents the research background, problem statement, and significance of the study. The objectives outlined guide the research and focus on evaluating the performance of CR by dry and wet applications, the effects of different CR dosages, and the overall feasibility of using CR to improve asphalt mixtures.

Chapter 3. Methodology and asphalt mixtures under study: This chapter outlines the approach for materials and asphalt mixtures under study and describes the evaluation of the experimental program. This chapter details the methodology to assess volumetric properties and permeability, the evaluation of mechanical behavior, and the application of CR in conventional asphalt mixtures. It covers the assessment of surface texture, skid resistance, acoustic characterization, self-sensing properties of the asphalt mixture, and its potential contribution to smart multifunctional pavements. The methodology provides a systematic and comprehensive understanding of the potential of CR in asphalt mixtures.

Chapter 4. Results and Discussions: The results, discussion, and analysis are presented in this chapter. It includes the outcome of the volumetric and mechanical characterization of the effects of incorporating CR. As well as the surface characterization, skid resistances, acoustic characterization and self-sensing response of the mixtures. These findings are presented and analyzed to provide insights into the impact of CR on asphalt mixtures.

Chapter 5. Conclusion: Presents the general findings obtained through the development of this research. Finally, the last part of the thesis includes the main block Scientific publications, and scientific communications sections. Compiles all the scientific articles, project reports, and documents consulted during the research.

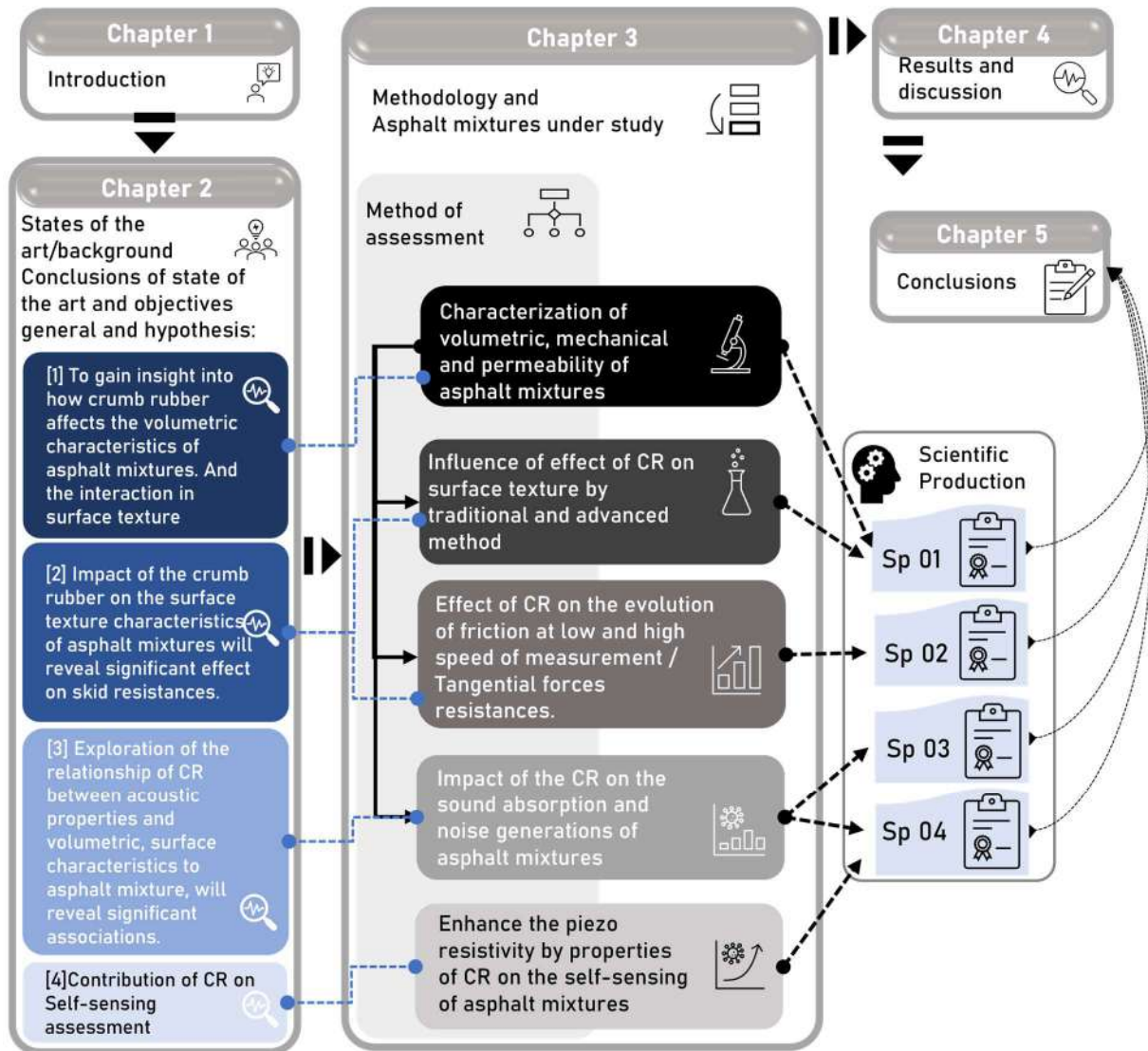


Figure 1.3: Structure of research. Source: Author's elaboration.

2. State of the art

2.1. Generation of tire waste and valorization in asphalt mixtures

This section describes the problems in the environment caused by tires during their service life, as well as the processes of the incorporation de CR into asphalt mixtures in America and Europe. Then, the effect of the interaction between the CR and the binders and asphalt mixtures is explained.

2.1.1. Introduction

The generation and accumulation of tire waste in substantial quantities pose a significant environmental concern, presenting a grave threat to ecological systems (Presti et al., 2021, Trevor.M, 2019). Discarded tires are classified as non-biodegradable materials that can exert a detrimental impact on the surrounding ecosystem (J. Xu et al., 2020). Transportation systems, including air travel, account for approximately 95% of tire usage.

In 2021, the global sale of new cars reached a staggering 75.8 million units, with imports to the European Union constituting 18.3% of the total trade. Projections indicate that car production will reach 98.9 million units by 2025. Furthermore, worldwide estimates suggest that by 2040, there will be two billion cars and 790 million trucks (U.S. Tire Manufacturers Association, 2022). With these increasing sales of cars, it is evident that the issue of tire waste will persist for the foreseeable future.

Tires are highly complex products made up of a combination of various valuable materials, such as fibers and steel, all bound together within the rubber compounds and other unique materials to fulfill their primary purpose: to provide safe and efficient mobility.

The diverse chemical composition and cross-linked structures of tires give them remarkable resistance to biodegradation, photochemistry, and corrosion, as well as to the action of chemical reagents and high temperatures. The composition and recycling of tires are shown in Figure 2.1.

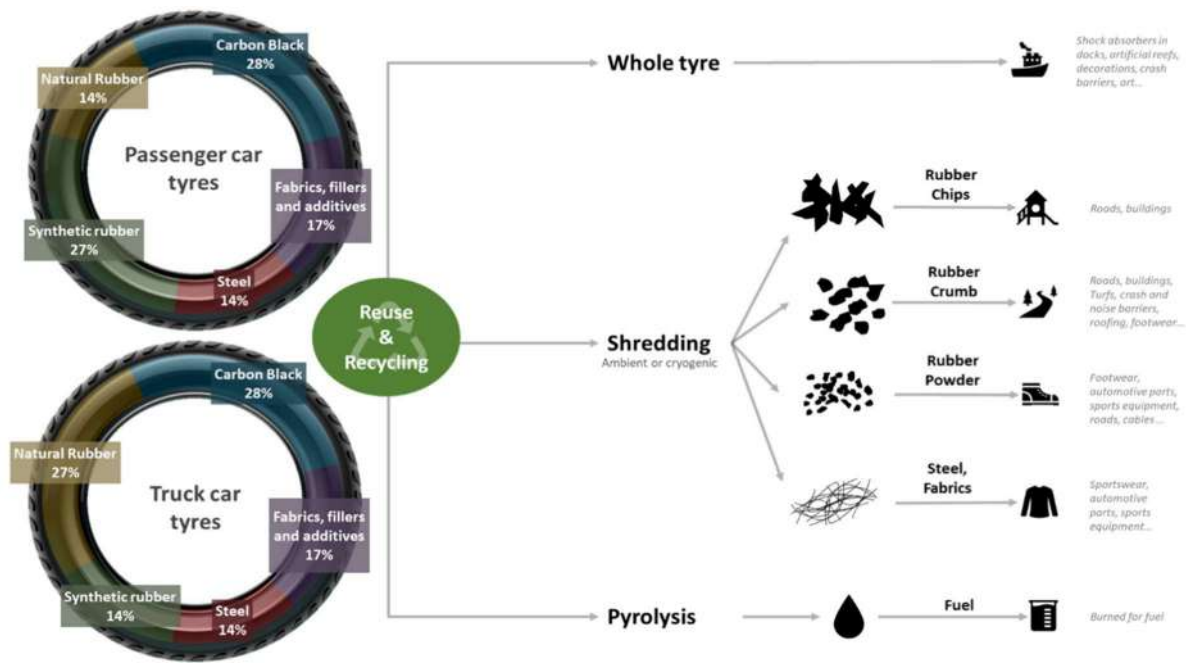


Figure 2.1: The rubber recycling process and applications.

The use of recycled rubber from scrap tires can play an essential role in other fields of application. The implementation of the European Landfill Directive 1999/31/EC was instrumental in promoting effective strategies for transforming ELTs into valuable material resources suitable for a wide range of engineering and non-engineering applications (Fazli & Rodriguez, 2020). Consequently, Europe has emerged as the global frontrunner in the field of waste tire recycling.

The Spanish Government has developed a Draft Ministerial Order (PG-3, 2019) that establishes the criteria to determine when granulated rubber and crumb rubber, obtained from the processing of used tires and intended for specific applications, cease to be considered waste according to Law 22/2011, of July 28, on waste and soils.

Currently, during the recycling process, materials from used tires are recovered, sorted, and reused by different methods: ambient temperature shredding, cryogenic shredding, and thermal pyrolysis (Figure 2.1). In addition to other processes for reuse in material design applications, the finer crumb rubber is being used as newly engineered products for road construction, buildings, sports equipment, clothing, and fuel (Adhikari et al., 2021). This has changed our perspective of use with the introduction of textiles, steel, and especially rubber contained in tires that can be recycled in various ways in order to replace the original constituent materials from natural sources, which reduces resource

extraction, green greenhouse gas (GHG) emissions, along with pollution and water consumption.

The proper management and environmentally friendly treatment of End-of-Life Tires (ELTs) have become a top priority in the tire industry, aiming to recycle and recover valuable materials from these discarded tires (Presti et al., 2021). Adopting a reuse approach for these tires is highly favorable, particularly considering the alarming statistics (Culley & Caroline, 2021). Currently, around 1.5 billion tires are discarded annually after reaching their end-of-life, and this number is projected to escalate to approximately 5 billion by the year 2030 (Moasas et al., 2022) (Permits Division, 2020). This massive volume of discarded tires contributes to their status as the most abundant waste globally, necessitating urgent attention and appropriate waste management strategies to mitigate the environmental impact.

The granulated rubber or crumb rubber (mass percentages) has to meet the graduation requirements: Ferromagnetic materials (less than or equal to 1), Textile and Fibers (less than or equal to 0.25), and other (less than or equal to 0.25) (Culley & Caroline, 2021) according to EN 13108-5:2016.

ELT (End-of-Life Tire) rubber is classified according to its granulometric distribution, following the categories defined in the standard EN 14243-2:2019. To be used directly for its specific purpose, ELT rubber must meet the requirements specified in the technical standards and other applicable regulations. In addition, ELT rubber must meet the additional specifications that it may contain a minimum of impurities described in EN 14243-2:2019. These materials must not exceed the maximum limits of impurities.

2.1.2. Environmental problems of end-of-life-tire (ELT)

End-of-life tires (ELTs) pose a significant environmental challenge due to their large volume and the difficulty of recycling them. ELTs contain a complex mixture of rubber, steel, and other materials, which makes them difficult to recycle and dispose of properly as shown previously in Figure 2.1.

World tire production is increasing year by year and is being dominated by strong market demand. All tires are collected and treated resulting in a current 95% treatment rate across Europe (The European Tyre & Rubber Manufacturers Association, 2021).

China is the world's largest tire producer, followed by Japan, India, the United States, and South Korea, accounting for 70% of the world's tire production.

The most common methods of disposing of ELTs (End-of-Life Tires) are landfilling, incineration, and stockpiling, all of which have negative environmental impacts. Landfilling contributes to soil and water pollution, as well as the release of greenhouse gases due to uncontrolled tire degradation. Incineration results in the release of toxic pollutants into the atmosphere and the generation of hazardous ash. Additionally, stockpiling ELTs can lead to mosquito breeding and an increased risk of fire. Every year, a significant number of waste rubber tires are stockpiled, making them a major global waste issue. It is estimated that between 1 billion to 5 billion more tires are expected to be discarded regularly each year (Sofi, 2018).

There is currently a regulatory and sustainability plan in place in the face of high demand and final disposal, but there is still much to be managed on an ongoing basis to avoid environmental impacts during the tire life cycle.

Over the last three decades, there has been a growing trend towards recycling ELTs, improving the two main methods of recycling ELTs, mechanical and pyrolysis (Gao et al., 2022). Mechanical recycling processes involve grinding the ELTs into smaller particles, which can then be used as fuel or as a material for new products such as asphalt. Rubberized asphalt is the largest market for crumb rubber. Crumb rubber can be blended into asphalt and used in various roadway projects. Pyrolysis involves heating the ELTs in the absence of oxygen, which results in the decomposition of the tire into oil, gas, and carbon black (Mikulski et al., 2021).

Despite the progress in ELTs recycling, there are still significant challenges that need to be addressed. These include the high cost of recycling, the lack of incentives for recycling, and the need for a more comprehensive recycling infrastructure. Additionally, there is a need for more research into the environmental impacts of ELT recycling and the development of new, more environmentally friendly methods of recycling.

In conclusion, the environmental problems of ELTs are significant and require a multi-disciplinary approach to be addressed. Efforts to promote recycling, improve the recycling infrastructure, and reduce the environmental impacts of ELT disposal should be a priority.

2.1.3. Description of the ELTs regulatory framework

Around the world, the regulation of end-of-life tires (ELTs) varies widely. These regulations are primarily aimed at reducing the negative environmental impacts of ELT disposal and encouraging recycling and reuse.

In the United States, ELT regulations are primarily set at the state level, with some states implementing ELT management programs to reduce their environmental impact and promote recycling. There are also federal regulations related to ELTs, such as the Resource Conservation and Recovery Act (RCRA) (United States Environmental Protection Agency, 2020). The implementation of the regulations for recycling tires undertaken by the US federal government has provided to use of a tire as a potential modified binder.

At present, the use of the crumb rubber-modified binder is used for multiple applications in pavement produced by dry and wet processes principally in four states (Arizona, California, Florida, and Texas) (Kayhanian & Harvey, 2020a)

In Europe, the main regulatory framework for ELTs is the EU Waste Framework Directive 2021 (WFD) and the End-of-Life Vehicles (ELV) Directive (The European Tyre & Rubber Manufacturers Association, 2021). These directives require EU member states to implement measures to reduce the environmental impact of ELVs, encourage their recycling and reuse, and promote the development of more environmentally friendly technologies.

All countries are seeking to promote the circular use of ELTs in various applications. In Spain, for example, national plans have been implemented to recycle more ELTs, especially for use in asphalt mixtures on pavements. This is supported by specific regulations and the creation of technical manuals to guide their proper use.

In Spain, the management of authorized tires is regulated by the Waste and Contaminated Soil Law and its subsequent regulatory development. The main managers and actors involved in the authorization and management of tires are the Integrated Management System for Used Tires in Spain. They are responsible for the collection, treatment, and recovery of used tires. It operates under the supervision of the Administration and works in collaboration with tire manufacturers, importers, and distributors. The larger integrated management system for waste tires is Signus Ecovalor.

In short, the regulation of ELTs seeks to reduce their negative environmental impact and encourage their recycling, particularly in applications such as asphalt mixtures, where they can improve the durability and performance of pavements, reduce tire waste, and contribute to a more sustainable economy. Harmonization of ELT regulations at the international level is a necessity to effectively address the environmental problems associated with these wastes.

2.1.4. Overview of application of crumb rubber in asphalt mixtures in America and Europe

a) A brief history of tire rubber use in the Americas.

The incorporation of crumb rubber into asphalt mixtures in the United States is closely linked to the development of the rubber industry in America, particularly its significance in manufacturing tires and other rubber products.

In the mid-19th century, the rubber industry in the United States was still in its early stages (Xiao et al., 2009). Natural rubber was primarily imported from South America, particularly Brazil, to produce items such as raincoats and shoes (Vayyaprontavida & Varghese, 2020). It wasn't until 1839 that Charles Goodyear, an American inventor, made a pivotal discovery by developing the process of vulcanizing rubber. Vulcanization involves heating rubber with sulfur, resulting in a stronger and more durable material (Loderer et al., 2018). This breakthrough revolutionized the rubber industry, enabling the production of high-quality rubber products, which started to gain demand both in the United States and globally.

In 1840, the first crumb rubber was used on asphalt mixtures to enhance the durability of conventional asphalt mixtures. Moreover, the recycled tire rubber in asphalt paving materials can be traced back to the 1940s and the industry of the paving has been using CR since 1950. This product was marketed as a dry particle additive for asphalt paving mixtures.

The idea of using rubberized bitumen emerged in the 1960s, primarily as an experimental concept aimed at finding sustainable ways to recycle old tires and reduce the environmental impact of tire disposal. The crumb rubber in 1975 was successfully incorporated into mixed asphalt in Arizona. By 1985 rubber modified binder usage was expanded by adding rubberized bitumen to hot mixtures including gap-graded and open grade mixtures. In 1988 the first recommendations for the incorporation of crumb rubber were presented by the American Society for Testing and Materials: “a blend of asphalt cement, reclaimed tire rubber, and

certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles” (ASTM D-8 and ASTM Standard D- 6114).

Researchers and engineers discovered that adding crumb rubber, obtained from shredded or ground-up tires to asphalt mixtures had the potential to enhance pavement performance (Lo Presti, 2013).

By the early 1980s, McDonald's determined the best methodology of the time and mixing to produce a good way pavement in terms of best characteristics (L. Cong et al., 2013). In the 1980s, California emerged as one of the pioneering states in actively experimenting with rubberized asphalt. The California Department of Transportation (Caltrans) initiated a program to explore the advantages of incorporating crumb rubber into asphalt mixtures, leading to the development of the "Rubberized Asphalt Concrete (RAC)" program (Rubberized Asphalt Concrete (RAC) - CalRecycle. 2020).

The application of rubberized hot asphalt mixtures in the United States primarily uses Rubberized Open-graded course (RHMA-O) mixtures, whereas Conventional Open Grade Friction (OGFC) mixtures are used for safety-related benefits. Furthermore, the noise reduction benefits (Kayhanian & Harvey, 2020a) are greater with the addition of crumb rubber.

Today, recycled tire rubber is a significant component in asphalt mixtures used in road construction across the United States, typically at a rate of 7.5 %, contributing to improved pavement durability and sustainability. This innovation not only reduces waste but also enhances the performance of road surfaces, showcasing the ongoing evolution of rubber used in asphalt materials.

b) Beginning of rubber usage in Europe

Rubberized asphalt mixtures were initially introduced in Europe 60 years ago. In the 1960s, there was a growing interest in finding ways to recycle scrap tires, which led to their use as secondary material in various industries, including the pavement industry. Two Swedish companies developed a new application for scrap tires, where ground rubber from discarded tires was added in small quantities to an asphalt mixture to substitute part of the mineral aggregate. This was done through a process known as the dry process. Similar to the United States, the idea of using crumb rubber in asphalt mixtures gained attention in Europe in the 1980s. Engineers and researchers began experimenting with the use of recycled rubber

from tires on asphalt pavements. Recycling scrap tires through the use of crumb rubber in asphalt mixtures offered a promising solution to this problem.

Several European countries, including the Netherlands, Germany, Australia (Wu and Turvey 2020), and the United Kingdom, conducted pilot projects to test the viability and performance of rubberized asphalt pavements. These projects aimed to assess the durability, noise reduction, and other benefits of using crumb rubber.

As the use of crumb rubber in asphalt mixtures gained traction, European countries developed standards and regulations to ensure the quality and consistency of rubberized asphalt pavements. These standards addressed factors such as the percentage of crumb rubber to be used, mix design, and performance testing.

However, their universal adoption has not been realized. In the past decade, notable advancements in technology and governance solutions, coupled with a growing impetus towards sustainable development and circular economy practices, have reignited interest in the use of rubberized asphalt mixtures.

As research progressed, it became evident that incorporating crumb rubber into asphalt mixtures could improve pavement performance. Rubberized asphalt was found to enhance pavement durability, reduce cracking, and contribute to better skid resistance (Putra et al., 2019).

c) Widespread Adoption and Innovation (2000s-Present)

Over the years, European countries have increasingly embraced the use of CR in asphalt mixtures. The adoption of this technology has grown steadily, with rubberized asphalt being applied to various types of roads. Now asphalt mixture rubber is widely used in the US, Canada, Europe, South Africa, and Asia.

A review of CR use worldwide was conducted using the Web of Science (WOS) scientific research platform. This review covered the period from 1970 to 2023 and was conducted by searching for the keywords "Crumb Rubber Asphalt," "Asphalt Mixture," and "Mixture."

2.1.5. Properties and improvements of the crumb rubber to asphalt materials

a) Binders' properties

The incorporation of crumb rubber derived from end-of-life tires (ELT) into binders has significantly enhanced their performance. As a polymer, it modifies the rheological properties of the asphalt binder in a manner similar to new polymer-modified asphalt, albeit to a slightly lesser extent (Rahman et al., 2019). These modifications lead to substantial improvements in the performance of the asphalt material, increasing properties such as the softening point, penetration, and viscosity in proportion to the amount of rubber (Wei et al., 2022).

The advantageous properties of rubber in bitumen and, consequently, in asphalt mixtures have been extensively researched and widely disseminated within the scientific field of pavement engineering (Xiao et al., 2009). One of the most remarkable benefits is its resistance to aging (Shatnawi, 2012). Rubber can enhance the asphalt's resistance to aging and cracking by absorbing stress and withstanding degradation caused by exposure to weathering and traffic volume (Ibrahim et al., 2013).

Furthermore, studies have shown that the incorporation of crumb rubber reduces susceptibility to temperature-related cracking, effectively mitigating issues related to thermal shrinkage and expansion during extreme temperature fluctuations (Shatnawi, 2012).

In terms of noise pollution control, research has indicated that rubber can significantly reduce vehicle rolling noise, thereby contributing to a healthier environment for residents. In terms of safety in vehicular traffic, rubber dust has also been proven to enhance pavement adhesion, which plays a pivotal role in reducing the risk of skidding incidents (Wu et al., 2023).

Modifications to the bituminous binder play a crucial role in enhancing the performance of asphalt mixtures, particularly in terms of their resistance to permanent deformation, fatigue, and thermal cracking (Gawel et al., 2006). In the case of wearing course applications, modifying the bitumen not only reduces surface maintenance costs but also could enhance skid resistance and reduce noise levels in some cases.

Crumb rubber (CR) modifications are among the methods used to alter the rheological properties of bitumen. It is also possible to simultaneously employ

crumb rubber from scrap tires and polymers, such as SBS copolymer, in a single binder modification process (Shirini & Imaninasab, 2016, Devulcanized et al., 2017). A new type of high-performance bitumen, modified with both SBS and CR, has been developed and is continuously produced in the Gdansk refinery.

2.1.6. Internal modification bitumen

Indeed, the incorporation of CR into bitumen brings several enhancements, primarily increasing its viscosity, increasing elasticity, increasing the softening point, and reducing the penetration and ductility (Lougheed & Papagiannakis, 1996, Zhu et al., 2022), observed these effects, there are various parameters influencing the ultimate performance of crumb rubber modified bitumen (CRMB) and the crumb rubber recycled bitumen (CRRB) binders as shown in Figure 2.2. This modification results in binders that exhibit heightened resistance to issues such as rutting, fatigue, and thermal cracking resistance of bitumen (Duan et al., 2021, Zhu et al., 2022).

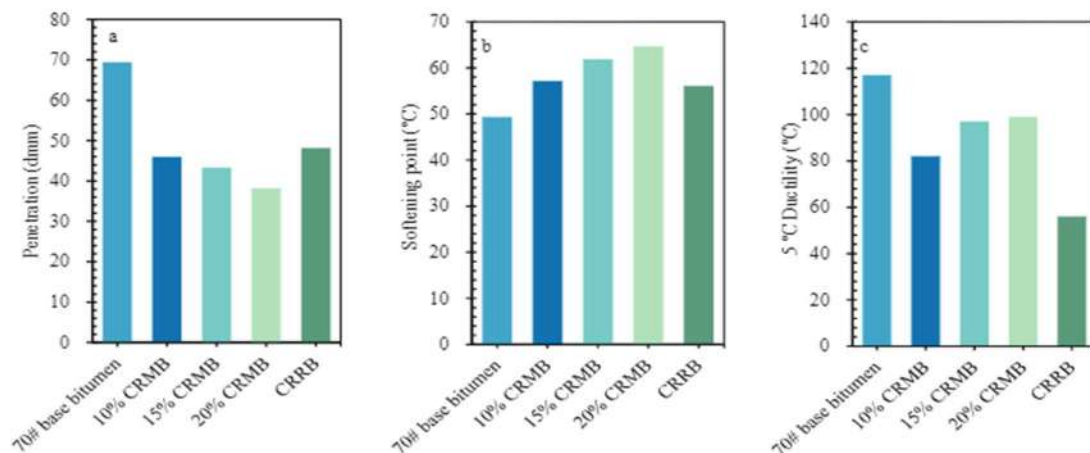


Figure 2.2: Effect of the crumb rubber modified binder on the physical properties of bitumen: (a) Penetration; (b) Softening point; (c) Ductility. Source: (Zhu et al., 2022).

Notably, the concentration of the modifier emerges as a pivotal parameter that demands close attention. The properties most characterized are:

1. Increased Viscosity: Crumb rubber can increase the viscosity of the binder, which improves its behavior at high temperatures and reduces susceptibility to plastic flow (Kim & Lee, 2015, Qasim & Al-Azawee, 2018b). Viscosity increases steadily and at faster rates with increasing percentages of crumb rubber (Dantas Neto et al., 2006).

2. Reduced Thermal Sensitivity: The presence of crumb rubber binders exhibited less thermal and aging sensitivity and can help reduce the variation of binder properties with temperature, thus improving thermal stability (Jimenez et al., 2016).
3. Anti-aging properties: There is no information available regarding the UV aging resistance of this type of asphalt. The first studies about the aging process do not present good results with 20% content crumb rubber-modified asphalt (Wang et al., 2022). However, in a study by (Lyu et al. 2022), the effect of UV aging on the physical characteristics and microstructure of heavily digested rubber shows no improvement and requires further investigation to understand the aging mechanism of rubber-modified asphalt.

In terms of the viscosity (Dantas et al., 2006) observed for high rubber contents, there seems to exist a critical time after which viscosity tends to decrease for continuing the digestion process. In the same line (Khalili et al., 2019) observed the two samples of CR incorporated by ambient (Am) and cryogenic (Cr) with 40 (425 μ m) and 20(850 μ m) mesh in the 10%,15% and 20% of CR. Binders made with 20 % crumb rubber content on average exhibited 52 % and 37 % increased viscosity compared to the ones with 15 % and 10 % CR, respectively as shown in Figure 2.3.

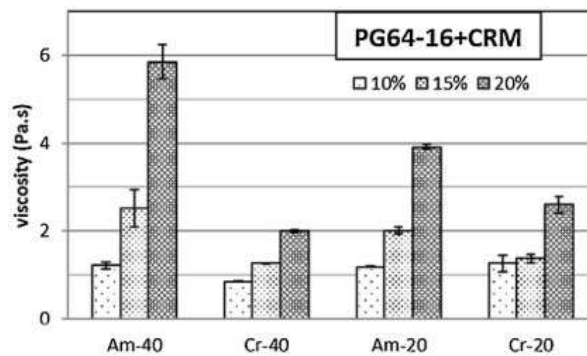


Figure 2.3: Effect of the crumb rubber in the viscosity: Source : (Khalili et al., 2019)

Other important observations of the benefits of the crumb rubber on the binder as shown in Figure 2.4 enhancing its elasticity and recovery into 80% by the addition of 10%,15%, and 20% of crumb rubber modified binder (CRMB) while the crumb rubber recycled bitumen (CRRB) present 35% elastic recovery, allowing it to deform and recover more effectively (H. Zhu et al., 2022). This modification enhances the bitumen's resistance to deformation and fatigue (Riekstins et al.,

2021). The modification by crumb rubber is influenced by the digestion time of crumb rubber in asphalt binder and can be influenced by the size and shape of rubber particles, mixture temperature, and asphalt binder type. Smaller rubber particles typically have a shorter digestion time because they disperse more easily throughout the mixture. Using temperatures and the use of a more elastic asphalt binder can also reduce the digestion time of crumb rubber. This is confirmed by studies conducted by (Moreno et al., 2012) that have shown that a moderate digestion time is more effective than a prolonged time. In addition, this process is influenced by the type and diameter of the rubber used.

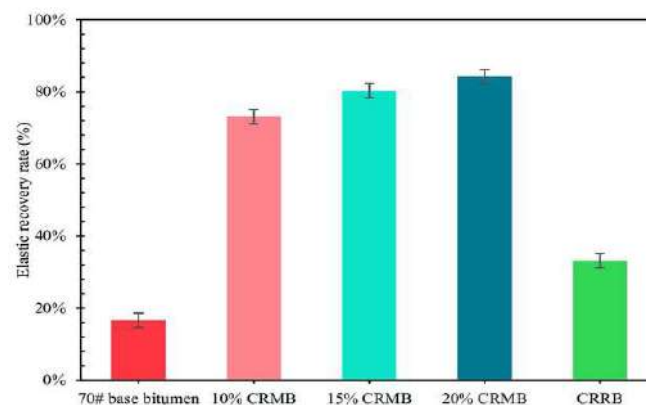


Figure 2.4: Elastic recovery of bitumen. Source: (H. Zhu et al., 2022).

It can be influenced by factors like rubber particle size, temperature, and asphalt binder type. Controlling the digestion time is essential to ensure optimal mixing and prevent the formation of non-uniform mixtures. The digestion process primarily occurs at elevated temperatures, where the physical characteristics of rubber-modified bitumen significantly differ from conventional binders (Sousa et al., 2013). Figure 2.5 shows the structural exchange process that has been proposed by (Sousa et al., 2013, Gawel et al., 2006).

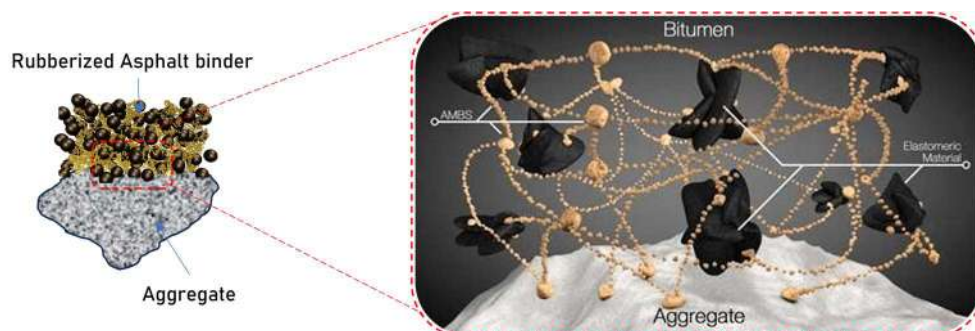


Figure 2.5: The structure and behavior of the crumb rubber in the modification's binders, and modifier. Source adapted: (Sousa et al., 2013)

b) Asphalt mixtures.

In recent years, there has been extensive global research aimed at validating and enhancing technologies related to rubberized asphalt pavements. These pavements incorporate recycled tire rubber as an additive through various processes into the asphalt mixture (Ragab et al., 2013). This practice offers numerous short-term and long-term benefits, including enhanced durability, skid resistance, and noise reduction (Lashari et al., 2022). As a result, it represents a sustainable and environmentally friendly option for the construction and maintenance of roadways. The ongoing research and development in this field play a crucial role in advancing the adoption and implementation of rubberized asphalt pavements as a viable solution for sustainable infrastructure.

The improvements resulting from the use of CR in asphalt mixtures have demonstrated significant advantages, primarily in terms of increased resistance to cracking, fatigue, and thermal fissuring (Ghafari et al., 2023a). Additionally, crumb rubber imparts greater flexibility and elasticity to the asphalt mixture, resulting in increased resistance to fatigue and the formation of fatigue cracks (Lougheed & Papagiannakis, 1996).

Additionally, this approach reduces maintenance costs and extends the pavements of the service life. The incorporation of crumb rubber through the dry process can increase the stiffness of the mixture but may reduce the indirect tensile strength (ITS) (Chavez et al., 2019) and cohesion of the mixture (Wang et al., 2019).

This innovative application of crumb rubber in the pavement industry represents a significant step forward in sustainable waste management practices and has been widely adopted in many countries worldwide.

c) Effect of CR on Asphalt mixtures.

The digestion time of crumb rubber in bituminous mixtures is a crucial factor affecting the asphalt mixtures' properties. According to (Çelik & Atiş, 2008) the CR affects the volumetric characteristic of the asphalt mixtures such as air void content on the different asphalt mixtures. The authors found that crumb rubber had the effect of increasing air void content, maybe because the CR suffers the process of swelling in high temperatures and tended to decrease the apparent density and theoretical maximum density in dense mixtures while open asphalt mixtures showed light changes (Mohammed et al., 2021). They observed the volumetric characteristic of the asphalt mixture with crumb rubber at 0, 2, 4 and

8 % CR, obtaining an increase of the air void content and reduce of the apparent density (Figure 2.6).

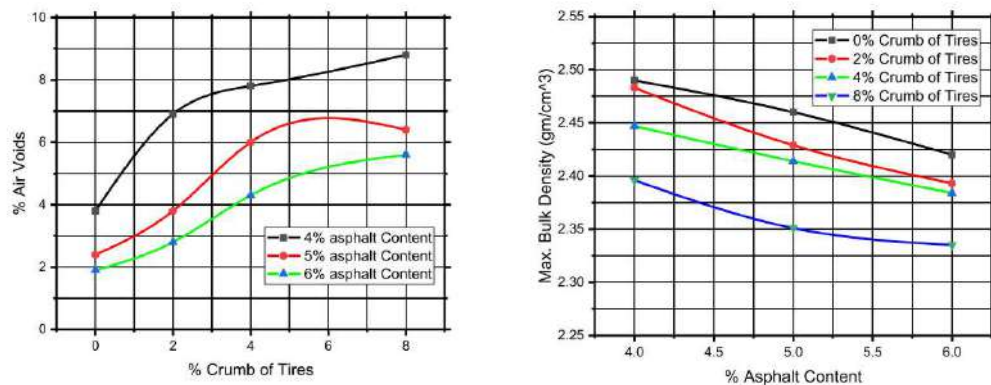


Figure 2.6: The effect of the crumb rubber on air void content and apparent density of different asphalt mixtures. Source : (Mohammed et al., 2021).

The mechanical improvement of the asphalt mixture is also affected by the incorporation of the CR. This was observed by (Moreno et al., 2012) who evaluated the effect of crumb rubber on the mechanical properties of asphalt mixtures. Moreover, studies by (A.-H. Mohammed et al., 2021), showed an increase of the CR content that causes a decrease in the indirect tensile strength from 10% to 30%. The result of the addition of CR to the asphalt mixtures can improve fatigue resistance and permanent deformation (Gallego et al., 2019, Chavez et al. 2019, Mohammed et al. 2021).

Several factors play a crucial role by the function of rubber within the asphalt mixture in creating elastic behavior. This behavior is influenced by the gradation of the crumb rubber, its content, and the method of incorporation of the recycled rubber or CR. Figure 2.7 illustrates how rubber particles respond to stress, showing the ability to recover their shape after load release (Ghafari et al., 2023a).

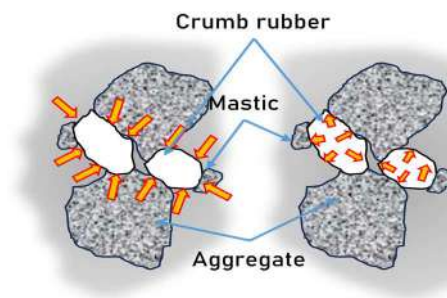


Figure 2.7: Elastic behavior of crumb rubber. Source: Author's elaboration.

The results of the Modulus of Elasticity E were gradually increased with an increased crumb rubber content in the asphalt binder due to the increasing elasticity factor (Qasim & Al-Azawee, 2018b). In addition, the CR effect of the percentage of incorporation in the elastic modulus response presents increased E values (Figure 2.8) with 5%, 10%, and 15 % of CR with increases in binder viscosity, which has a favorable contribution to rutting resistance of the mixtures (Ghafari et al., 2023a).

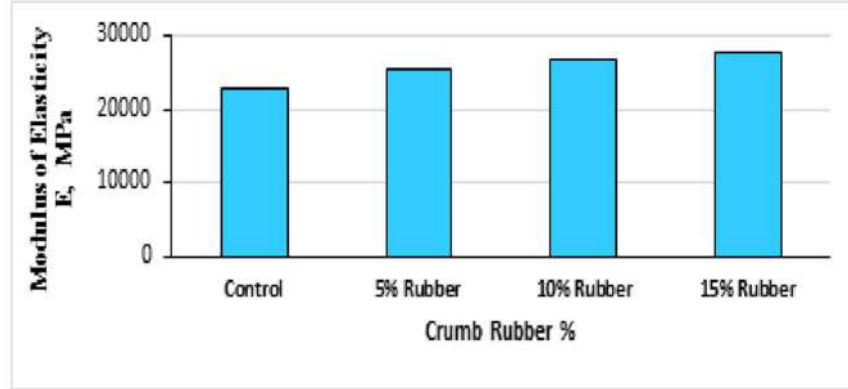


Figure 2.8: Modulus of elasticity of binders with crumb rubber. Source : (Qasim & Al-Azawee, 2018a).

Figure 2.9a. represents the behavior of asphalt mixtures with CR, exhibiting increased durability and resistance to cracking, especially under heavy traffic conditions (Ghafari et al., 2023b).

Figure 2.9b shows trends in mixtures with three different percentages of CR: 0%, 10%, and 20%. The mixtures modified with 10% and 20% CR exhibit higher resistance against unstable crack propagation at low temperatures.

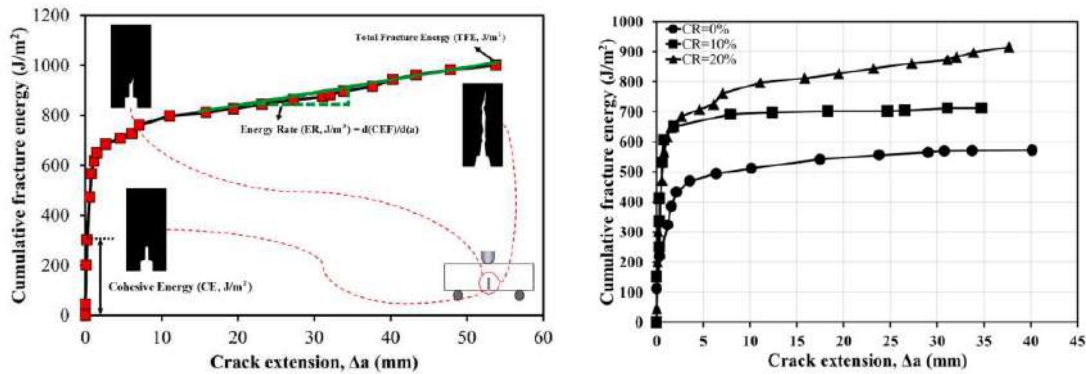


Figure 2.9: Crumb rubber modified mixtures tested at -20°C and the fracture resistance Source : (Ghafari et al., 2023b).

The effect of crumb rubber on mechanical performance has been displayed in Figure 2.10. Indirect tensile strength (ITS) results (unconditioned and conditioned) for mixtures under dry (unconditioned) conditions indicated a decrease in the strength of the mixtures with increasing recycled rubber content. A progressive reduction in conditioned strength is evident for all samples tested with increasing Crumb Rubber Powder (CRP) content in 20, 40, and 60% CRP by weight of filler (Tahami et al., 2019). The resistance of asphalt is enhanced, but high CRP content weakened it.

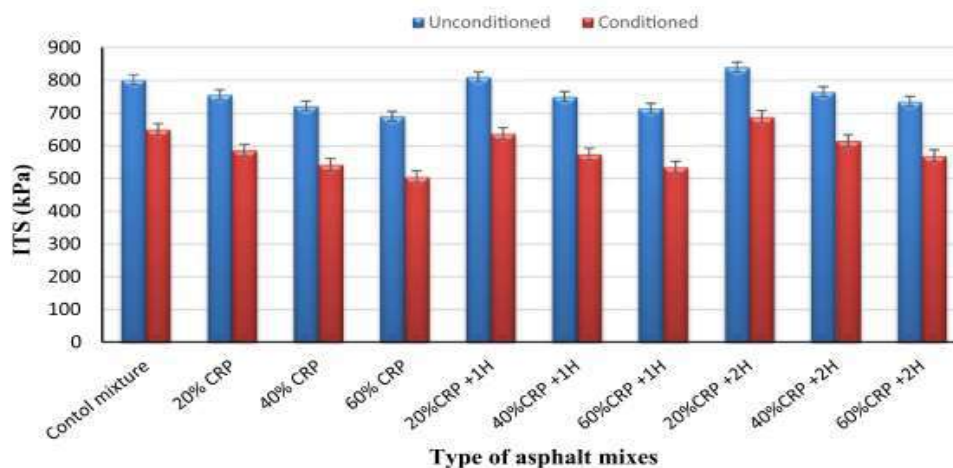


Figure 2.10: Effect of crumb rubber on Indirect Tensile Strength. Source: (Tahami et al., 2019).

A tensile strength rate (TSR) of 80 % is considered a threshold for the resistance of asphalt mixtures to moisture damage resistance. The reduction of the moisture damage resistance by incorporation of the CRP is observed in the study by (Tahami et al., 2019). Figure 2.11 show that CRP mixtures without a curing process did not meet the established criteria, and the incorporation of a CRP filler reduced the indirect tensile strength of the mixtures exposed to the wet conditioning period. The results evidence a positive effect of curing on moisture resistance, with an increase in curing time leading to an improvement in TSR values (Tahami et al., 2019).

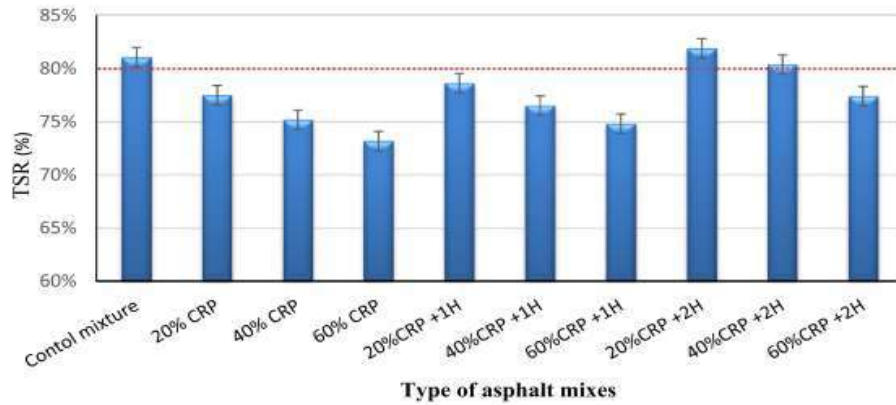


Figure 2.11: Effect of the CR on the moisture damage resistance. Source: (Tahami et al., 2019).

2.1.7. Procedures for incorporating rubber in asphalt mixtures.

There are different processes to incorporate crumb rubber modifiers (CRM) in asphalt mixtures, referred to as recycled tire rubber ground into fine particles for use as an asphalt binder modifier (Fazli & Rodriguez, 2020). The process of incorporation is referred to as the wet process (WP) the dry process (DP) and the new semi wet process (SWP) (Chavez et al., 2019, Picado-Santos et al., 2020).

In the wet process, CR is mixed with the asphalt binder as an asphalt modifier, while in the dry process, CR is used as a replacement for a small portion of aggregates. The semi-wet process involves pre-digesting crumb rubber with the binder. This process includes some additives and is blended at industrial plants (Picado-Santos et al., 2020).

According to the database provided by the Web of Science (WOS), documents published on various processes of incorporating crumb rubber in asphalt mixtures have been available since 1993. The search was conducted between 1990 and 2023, using keywords such as "Dry process," "Wet process," and "Semiwet process" of crumb rubber in asphalt mixtures. Figure 2.12 illustrates the results of these queries by year and by country, ranked in terms of the number of publications.

In the dry process category, the top year for publications was 2021, with 19 documents. For the wet process, the highest number of publications was in 2022, with 14 documents. In the case of the semi-wet process, the most documents were published in 2021, totaling 11.

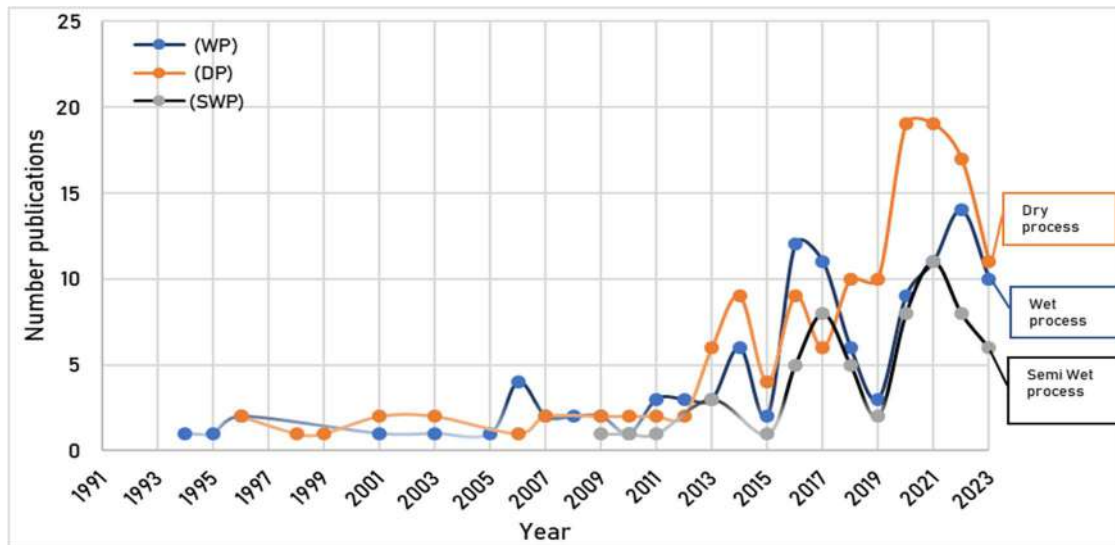


Figure 2.12: Evolution of publications of use of the crumb rubber in asphalt mixtures.

Source: Author's elaboration.

a) Dry process (DP)

The DP involves the addition of CR at a high temperature to the asphalt mixture as shown in Figure 2.13. The CR is added directly to the aggregate as another type of material. The bitumen is then modified when in contact with the crumb rubber (Moreno et al., 2012). This process is typically performed in asphalt plants, where the crumb rubber is blended with asphalt binder and aggregates. During this reaction time, the rubber particles absorb the light fractions of asphalt binder and swell, which affects its performance properties (Ibrahim et al., 2013). This process provides a way to blend the crumb rubber with the asphalt and aggregate without the use of special equipment. The dry process is a simple, direct, and cost-effective method of incorporating the crumb rubber into asphalt mixtures, but it can result in inhomogeneous mixing and poor bonding between the CR and asphalt.

b) Wet process (WP)

The wet process for incorporating crumb rubber into asphalt binders involves blending the crumb rubber with asphalt cement before adding it to the aggregate. The wet process involves the modification of asphalt binder with 5-25% fine crumb rubber at elevated temperatures (Riekstins et al., 2021). The WP includes different methods of blending the crumb rubber with a binder like as: batch blending, continuous blending, and terminal blending. Batch blending defines those wet process technologies that mix batches of CR and asphalt in production. Continuous blending describes those wet process technologies that have a continuous

production system. Terminal blending is associated with wet process technologies that obtain products with extended storage (shelf life) characteristics (Mashaan, 2010). The rubberized asphalt binder has a liquid form as shown in Figure 2.13. In this process, the rubber is first dissolved or dispersed in a liquid bitumen and then added to the hot aggregates. The wet process results in a more homogeneous mixture, and better bonding between the crumb rubber and asphalt, leading to improved properties of the mixture. However, the wet process is typically more complex and expensive than the dry process and requires specialized equipment and expertise.

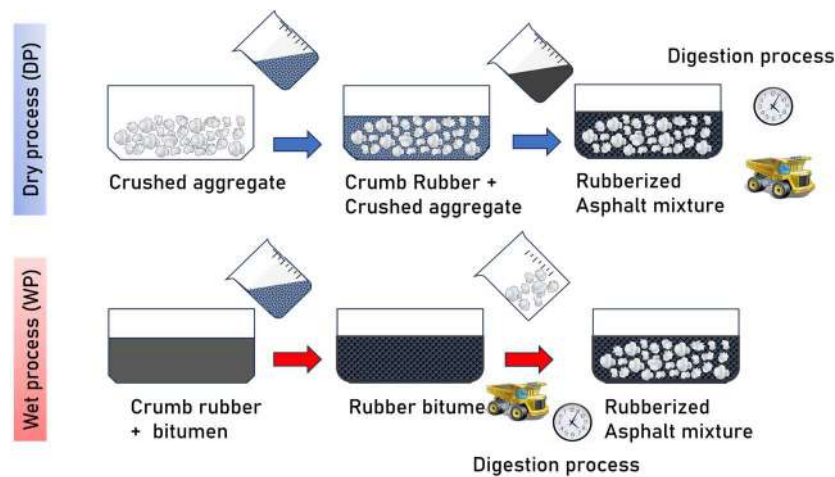


Figure 2.13: Process of the digestion of the crumb rubber, a) Dry process and b) Wet process. Source: Author's elaboration.

In summary, the DP and the WP have advantages and disadvantages for the incorporation of CR into asphalt mixtures. The wet process results in a more homogeneous mixture and better bonding between the CR and asphalt but is more complex and expensive. The choice between the two processes will depend on factors such as the availability of resources, the desired properties of the mixture, and the specific requirements of the application.

c) Semi wet process (SWP)

Despite the benefits previously obtained by the incorporation of rubber in asphalt mixtures, new material has recently been developed and innovatively applied using Reacted and Activated Rubber (RAR) technology (Kedarisetty et al., 2016; Sousa et al., 2013; Sousa et al., 2012). Several studies have investigated this material, which is referred to as a pretreatment of modified rubber with a reduced binder content through a controlled digestion process (J. S. Sousa, 2015). Initially,

a virgin binder is used and modified by interaction with the rubber particles, resulting in significant improvements in the performance of asphalt mixtures in terms of rutting resistance, fatigue, and cracking caused by moisture damage, compared to conventional mixtures (Sousa et al., 2013; Sousa, 2009). This approach allows crumb rubber to be effectively optimized for use as an essential component in the asphalt mixture production process Figure 2.14.

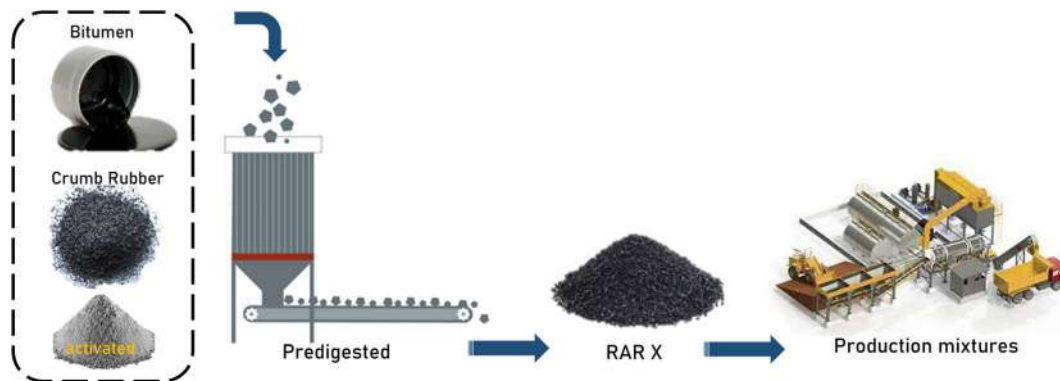


Figure 2.14: The predigested process of the crumb rubber. Source: Author's elaboration.

On the other hand, in Spain, the RARX approach has generated a great deal of interest. In this process, the semi-wet process is used for the manufacture or modification process before digestion (stages necessary to achieve the fusion between the rubber and the binder). This allows its use in the production of asphalt mixtures as another component in the dry process. This approach simplifies its incorporation in the production of asphalt mixtures without affecting the traditional process or the controls during production in the corresponding plants. Moreover, it has been shown to obtain results similar to those obtained in asphalt mixtures produced by the wet process (Chavez et al., 2019).

2.1.8. The factors of the interaction of crumb rubber with bitumen

The interaction factors of CR and bitumen are especially evident during digestion time. The initial interaction focuses on physicochemical modification. Research indicates that the incorporation of CR results in improvements in bitumen properties, including softening point, penetration, and viscosity. These improvements are observed in direct proportion to the amount of CR added (Kim & Lee, 2015). In the case of asphalt mixtures, this interaction is considered a critical factor that affects the final properties of the mixture. It leads to increased

fatigue resistance, improved durability, and reduced thermal susceptibility (Moreno et al., 2012).

Figure 2.15 shows the physical-chemical digestion of crumb rubber and bitumen. This process was meticulously carried out in the laboratory, with rigorous control over the high temperature and digestion time, based on parameters established by numerous previous experimental tests by (Del Val Melus, 1999; Munoz et al., 2014). During digestion process, the components of bitumen (asphaltenes and maltenes) fuse with the crumb rubber at high temperature.

The digestion process of the CR in DP is applied during the production of the asphalt mixtures, while by the WP the digestion is produced during the modification of the bitumen with the CR. In both cases, the objective is to achieve good incorporation of the CR into the asphalt binder since it is the component that controls the resilient behavior of the asphalt mixtures.

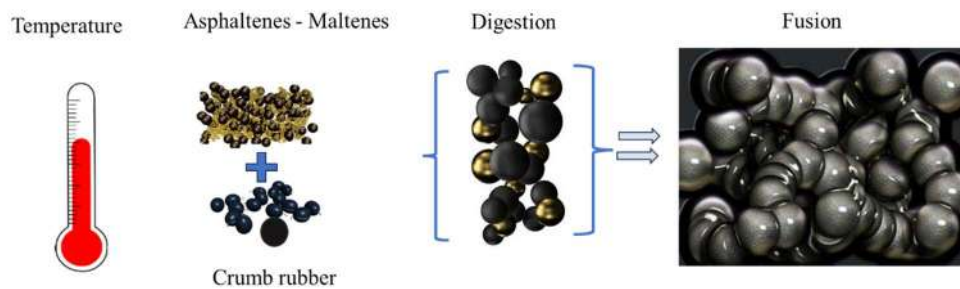


Figure 2.15: Process of physical-chemical digestion of rubber and bitumen. Source: Author's elaboration.

2.1.9. External factors

a) Aging

The aging of the rheological properties of asphalt mixtures has been of great interest because it is a factor that is not directly controlled, since it depends mainly on the chemical components and their ability to resist aging changes. CR has extensively demonstrated that digestion time is beneficial to achieve better melting between binder components and recycled rubber (S. J. Lee et al., 2008). Studies by (Sutanto et al., 2018) with the Rolling thin film oven test (RTFOT) showed that the CR improved the after aging verified by penetration test (0.1 mm) in approx. the 8.10-1 mm with 8 % of CR, and the softening point increase in more than 10 % with 8 % of CR (Figure 2.16). The significant reduction in penetration values may be beneficial in improving the modified binder resistance against

temperature defects which can be expected to increase its durability and performance during service life. In addition, binders with CR, after the RTFOT process, show that they do not age easily throughout their service life (Sutanto et al., 2018).

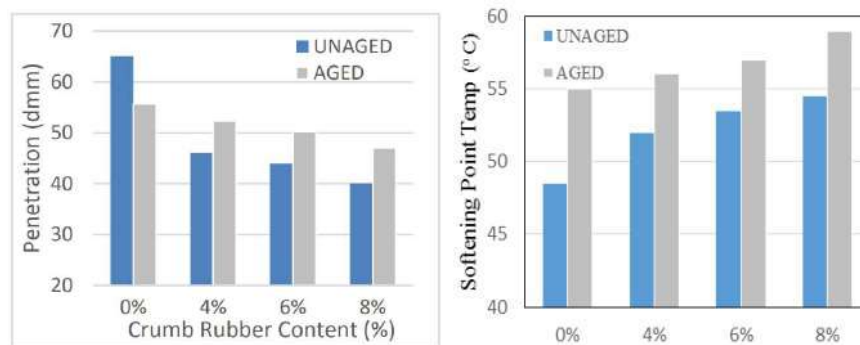


Figure 2.16: Effect of the CR on the aging process. Source: (Sutanto et al., 2018).

b) Net bitumen modified with crumb rubber.

Crumb rubber is commonly introduced into asphalt binders to primarily improve their physical and rheological properties, leading to enhanced pavement performance. Sousa's studies have highlighted alterations in the binder's structure attributed to the presence of CR (Sousa et al., 2013).

Soft binders are more used for modification with crumb rubber, especially when greater flexibility over a wide temperature range is sought (Bermejo Muñoz et al., 2014). The incorporation of rubber in bitumen tends to provide greater consistency in the intermediate to high-temperature range (Gallego et al., 2021). Several authors have noted that the addition of rubber reduces penetration and increases the softening temperature of bitumen (Gallego et al., 2019, Carpani et al., 2022).

It is recommended that binders used for rubber modification should have a higher proportion of naphthenic and aromatic components. These components are known to provide greater elasticity and flexibility to the bitumen, which is beneficial when seeking to improve asphalt properties with the addition of recycled rubber (Gallego et al., 2019).

2.2. Skid resistance

2.2.1. Friction

In this section, the fundamental principles of friction, specifically rolling friction exerted by the tire on the pavement, will be summarized. Then, adhesion and its characterization in relation to pavement friction will be addressed concisely. Finally, skid resistance will be explored in detail.

Friction on the pavement is the force that opposes the relative movement between a vehicle's tire and the road surface. This resistive force, illustrated in Figure 2.17, occurs as the tire rolls or slides over the pavement.

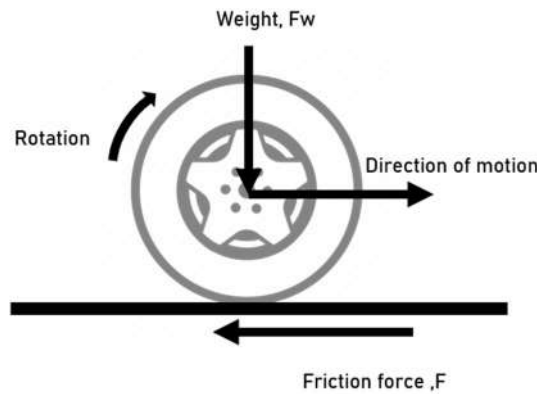


Figure 2.17: Scheme of forces acting on a rotating wheel.

Rolling friction, also known as rolling resistance, is the resistance that opposes the motion of an object rolling on a surface. In the context of tire-pavement interaction, rolling friction is crucial to the safety and performance of vehicles on the road.

The resistive force characterized using the non-dimensional friction coefficient μ is the ratio of the tangential friction force (F) between the tire rubber and the horizontal traveled surface to the perpendicular force or vertical load (F_w) and is computed using Equation 1.

$$\mu = \frac{F}{F_w} \quad \text{Equation 1}$$

Pavement friction plays a crucial role in keeping vehicles on the road, enabling drivers to control and maneuver their vehicles safely in both longitudinal and lateral directions.

Longitudinal frictional forces occur between a rolling tread tire (in the longitudinal direction) and the road surface when operating in either the free-rolling or

constant-braked mode. In the free-rolling mode (no braking), the relative speed between the tire circumference and the pavement, referred to as the skid speed, is zero. In the constant-braked mode, the slip speed increases from zero to a potential maximum, matching the speed of the vehicle. The Equation 2 related of slip speed.

$$s = V - V_p = V - (0.68 \cdot \omega \cdot r) \quad \text{Equation 2}$$

Where S: slip speed,(mi/hr.), V: Vehicle speed (mi/hr.), Vp: Average peripheral speed of the tire (mi/hr.), ω : angular velocity of the tire, (radians/sec), and r: Average radius of the tire (ft).

Again, during the free rolling state of the tire, Vp is equal to the vehicle speed ; thus S, is zero. For a locked or fully braked wheel, Vp is zero , so the sliding speed or slip speed is equal to the vehicle speed (V). A locked-wheel state is often referred to as a 100 percent slip ratio, and the free-rolling state is a zero percent slip ratio. The equations 3 to determine the slip ratio :

$$SR = \frac{V-V_p}{V} \cdot 100 = \frac{s}{V} \cdot 100 \quad \text{Equation 3}$$

Where SR: slip ratio (%), Vehicle speed(mi/hr.), Vp : Average peripheral speed of the tire (mi/hr.), S: Slip speed (mi/Hr.).

The coefficient of friction between a tire and the pavement changes with varying slip , as shown in figure 2.18. The coefficient of friction increases rapidly with increasing slip to a peak value that usually occurs between 10 and 20 percent slip (critical slip). The friction then decreases to a value known as the coefficient of sliding friction, which occurs at 100 percent slip. The difference between the peak and sliding coefficients of friction may equal up to 50 percent of the sliding value, and is much greater on wet pavement than on dry pavements.

The relationship shown in Figure 2.18 is the basis for the anti-locking brake system (ABS), which takes advantages of the front side of peak friction and minimizes the loss of side/steering friction due to sliding action . Vehicles with ABS are designed to apply the brakes on and off (i.e pump the brakes) repeatedly, such that the slip is held near the peak.

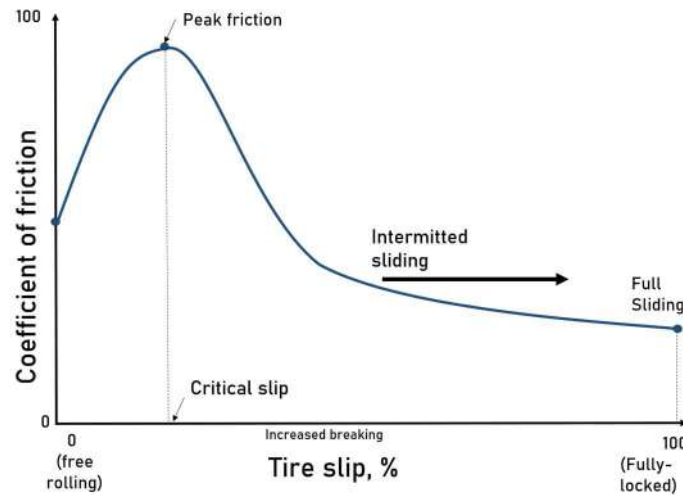


Figure 2.18: Pavement friction versus tire slip.

2.2.2. Mechanisms of skid resistances

The interaction principles between the tire/pavement are rooted in two pivotal concepts: adhesion and hysteresis (Lastra-González et al., 2017). Adhesion and hysteresis are mechanisms that profoundly impact the friction between the tire and the road surface. These mechanisms are primarily contingent upon the contact area of the tire tread and the roughness of the pavement (Smith, 2011).

Adhesion is engendered by intermolecular bonds between the rubber of the tire and the flat surface of the pavement, giving rise to Van der Waals forces. Given that rubber is a viscoelastic material, the frictional behavior varies with changes in surface temperature and velocity, making it a domain predominantly governed by microtexture. It's worth noting that adhesion is significantly influenced by the surface roughness of the aggregates, which, in turn, is subject to variations stemming from their shape, size, and mineralogical characteristics. The rubber friction reduces at 30°C (Bazlamit & Reza, 2005), depending on the chemical composition of the rubber (Al-Assi & Kassem, 2017a).

Once deformed, it does not immediately return to that position, but exhibits an asymmetric motion (energy loss), which occurs on a microscale of contact (Al-Assi & Kassem, 2017a). Hysteresis effects are inherent to the loss of cohesion due to tread wear. The contribution of hysteresis is minor, as most of it governs adhesion when water negates adhesion (Al-Assi & Kassem, 2017b). The hysteresis mechanism decreases with increasing temperature, irrespective of the surface roughness state (Bazlamit & Reza, 2005) or in dry conditions at high speeds.

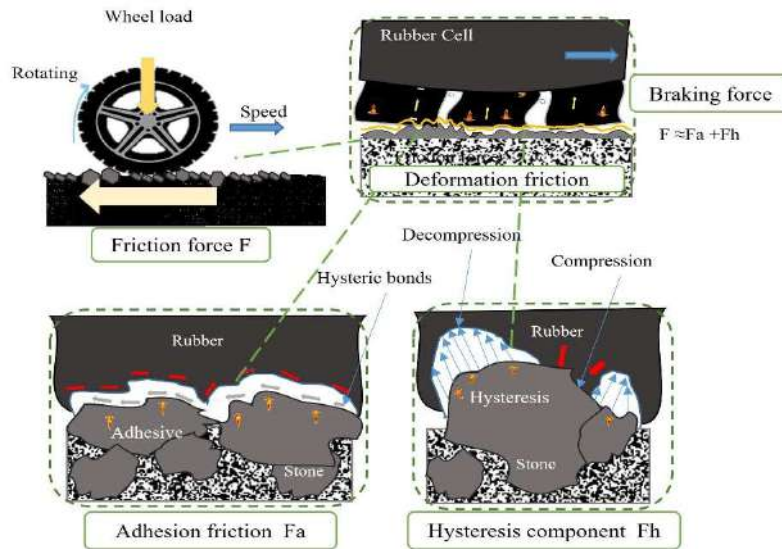


Figure 2.19: Mechanism of interaction of adhesion and hysteresis. Source: Author's elaboration.

2.2.3. Factors influencing on skid resistances

The interaction between pavement and friction forces is intricate and influenced by various factors. The National Cooperative Highway Research Program (NCHRP) Report 108 has distilled these factors into four broad categories, pavement surface characteristics, vehicle operating parameters, tire properties, and environmental factors (Table 2.1). It's crucial to conceptualize friction as the comprehensive outcome of the interplay among these categories, rather than isolating it to the inherent properties of the pavement. A comprehensive understanding of all these factors is essential for accurately characterizing friction.

Table 2.1: Factors affecting pavement friction.

Pavement surface characteristics	Vehicle operating	Tire properties	Environment factors
Microtexture	Slip speed	Tread design and condition	Climate (wind, temperature, rainfall/condensation, snow, and ice)
Macrotexture	(Vehicle speed, braking)	Rubber composition and hardness	Contaminants
Megatexture/ unevenness	Driving manoeuvre	Inflation pressure	(anti-skid, material; dirt mud, debris)
Temperature		Load temperature	

Skid resistance, in general terms, is a concept that summarizes the whole process of describing the degree of adherence between the tire and the pavement surface. From a physical point of view, skid resistance is the force generated when a tire,

prevented from rotating, slides along the pavement surface (Rosta & Gáspár, 2023) Figure 2.20 shows the interface of the tire pavement in dry (normal condition) and wet (hydrodynamic). European standards define skid resistance as the "characterization of the friction of a road surface when measured according to a standardized method." This force acts tangentially on the contact area developed in the contact patch between the tire and the pavement and is referred to as skid resistance. This phenomenon is also referred to as the coefficient of friction or skid resistance.

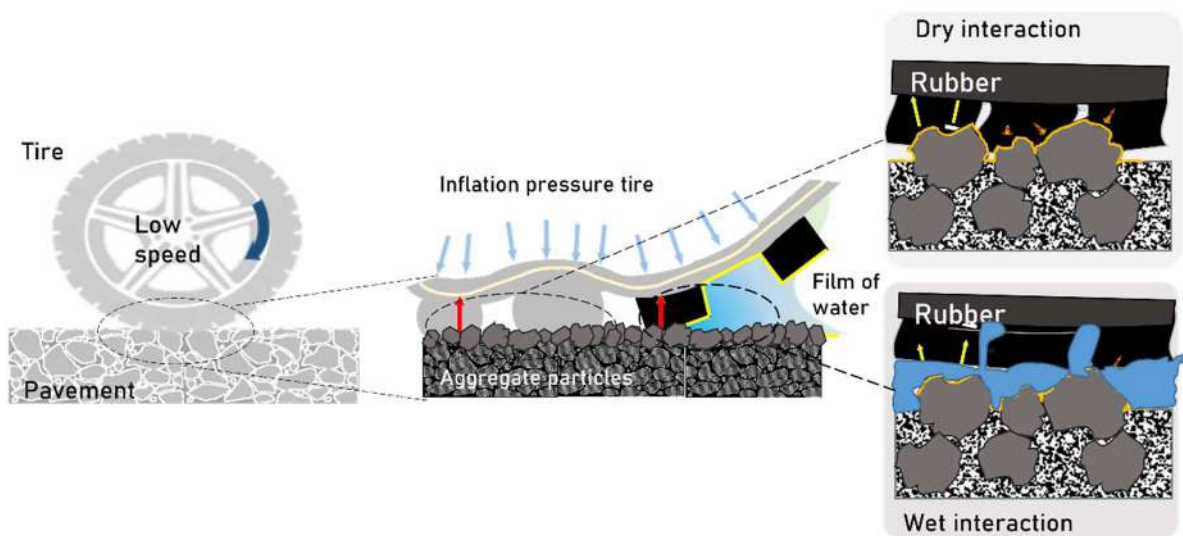


Figure 2.20: Skid resistance process of interaction in the dry and wet interface of the tire/pavement. Source: Author's elaboration.

Skid resistance is a critical factor in the safety of road surfaces, as it affects the ability of tires to grip the road and maintain traction. Figure 2.21 shows the interaction between tires and pavement. It is a complex phenomenon that is influenced by several factors, including the properties of the tire and pavement (texture), weather conditions, and the type of vehicle (load).

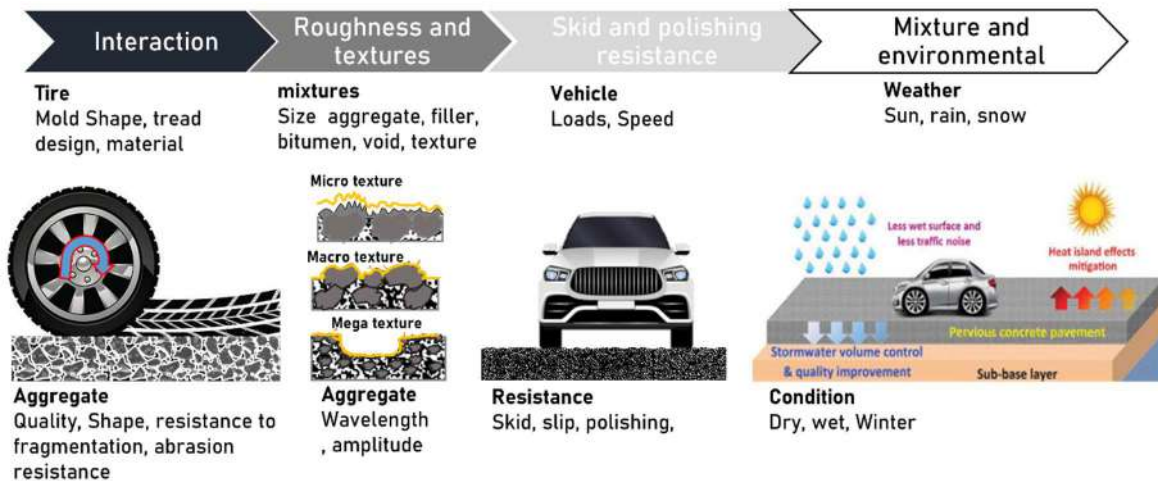


Figure 2.21: Factor influencing the skid resistance. Source: Author's elaboration.

Based on the work of (Sabey et al., 1970a) and (Kumar & Gupta, 2021) the interaction factors affecting skid resistance present high variability in a short and long time: pavement surface characteristics, tire characteristics, and environment-related parameters.

Skid resistance consists of two mechanisms: hysteresis and adhesion. Adhesion refers to the interaction between the tire and pavement surfaces at the molecular level, resulting in the cyclic deformation of the tire rolling pattern over pavement surface roughness. This interaction is significantly affected by the presence of water. On the other hand, hysteresis involves the dissipation of energy in the contact by the deformation of the tread on the pavement texture. Both mechanisms are closely related and depend on the pavement texture. On dry and smooth surfaces, adhesion is affected, while hysteresis is more affected on rough and saturated surfaces (Villani et al., 2011). Speed also influences skid resistance, as its frictional response is related to the pavement surface. At low speeds, the macrotexture allows for better drainage capacity and greater tire-pavement contact.

Environmental factors represent significant risks to skid resistance. Tire-pavement adhesion decreases in prolonged rainy conditions, and the presence of contaminants also plays a crucial role. Pavement aging decreases skid resistance and negatively affects several aspects, such as tire geometry and structure, wheel load, tire pressure, vehicle speed, and tire slip ratio. In addition, extreme weather conditions, such as heat and cold, affect the sensitivity of the measurements, especially in the polishing phase (Oh et al., 2010).

Given the complexity and importance of skid resistance, it is essential to consider pavement surface, tire characteristics, vehicle properties, and environmental factors in its evaluation. These aspects have been addressed by various researchers and will be summarized in the following sections.

Figure 2.22a show how the tread pattern of a tire affects the tire-pavement interaction on different pavement surfaces. Figure 2.22b shows that the type of tire and its tread pattern can significantly influence skid resistance, as different tire designs offer different levels of traction. For example, tires with more aggressive tread patterns or tires designed for winter conditions tend to provide better traction than tires with smoother tread patterns and prevent hydroplaning. Figure 2.22c illustrates the effect of the presence of contaminants, such as water, fine particles, and oil, on skid resistance.

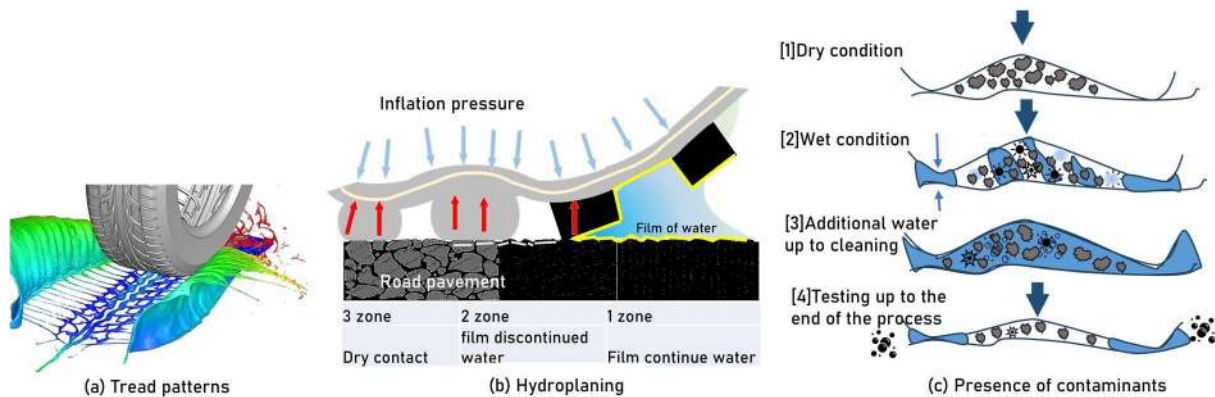


Figure 2.22: Influence of the tire tread pattern on the surface in wet conditions. Source: Author's elaboration.

Studies (Lubis et al., 2018a) have shown that skid resistance can be influenced by a variety of factors, including weather conditions, road surface roughness, and the presence of contaminants such as water, fine particles, and oil. Over time, skid resistance can deteriorate, leading to an increased risk of accidents (Mahmoud et al., 2023). The concept of hydroplaning is illustrated using the idea of three zones as shown in Figure 2.23a. Zone (a) is called the dry zone or adhesion region, where the wheel adheres completely to the ground. Initially, at low speeds, the vehicle is in full contact with the road. As vehicle speed increases, dynamic water pressure builds up on the leading edge of the tire and lifts the wheel completely. Figure 2.23b is the thin film zone, where partial hydroplaning occurs. At this point, Full road contact (a) decreases, and Transition reduced contact (b) becomes dominant. Dynamic Hydroplane (c) is known as the main zone, where full hydroplaning

occurs. The three sceneries are a widely used method of describing hydroplaning. As the vehicle increases its speed, a certain amount of time is required to remove water from the tread/road interface, allowing contact with the road surface. With increasing vehicle speed, this time is reduced, and a significant portion of the contact patch becomes supported by the squeezed film, which reduces the friction capacity of the tires.

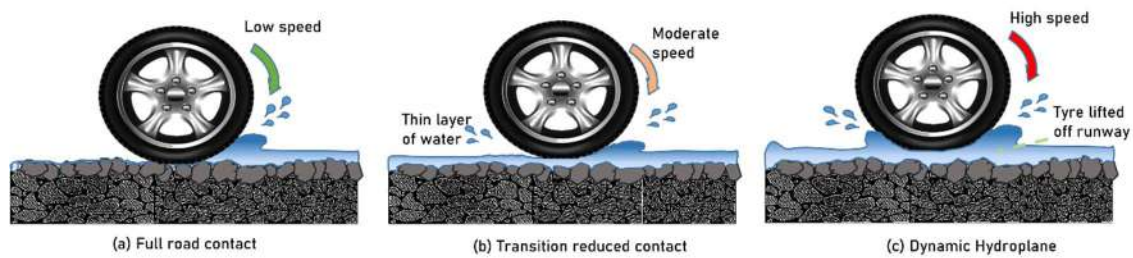


Figure 2.23: Hydroplaning phases and their effects on the tire/pavement interface.

Source adapted:(Lubis *et al.* 2018b).

Two factors that influence hydroplaning are microtexture and macrotexture. (Mahadevan & Taheri, 2020) describes microtexture as the degree of polish of the pavement surface, which varies from rough to polishing, and is necessary to develop frictional forces between the tire and it is pavement on wet surfaces. The magnitude of frictional forces increases with higher microtexture. Microtexture plays an important role in preventing hydroplaning at low vehicle speeds. The microtexture of the pavement provides the roughness necessary to break up the thin layer of water present between the tire and the road surface, allowing the tire to contact the road surface. The macrotexture plays an important role in reducing hydroplaning and maximizing the interaction between the tire and the pavement surface (Lubis et al., 2018b).

Several methods have been developed to assess the evolution of skid resistance loss, including laboratory tests and field evaluations (section 2.31). Laboratory tests typically involve preparing test samples of road surfaces and measuring the skid resistance properties under controlled conditions, such as temperature and humidity. Field evaluations involve measuring skid resistance on real road surfaces over time, considering factors such as weather conditions and road traffic.

Studies in field evaluation have found that skid resistance loss can be influenced by a number of factors, including the type of road surface, the climate, and the traffic conditions (Mahmoud et al., 2023). Some road surfaces, such as concrete and asphalt, are more susceptible to skid resistance loss than others, while certain

climates, such as areas with high rainfall, can accelerate the deterioration of skid resistance. Unfortunately, with time and traffic, road surface roughness tends to decrease, leading to a decrease in skid resistance.

The evolution of skid resistance involves different factors and has to be considered together with drainage, rolling resistance, ride comfort, and vehicle wear (Sabey et al., 1970b). The researchers identified several factors that influence pavement surface friction. These factors can be classified according to Figure 2.24 :

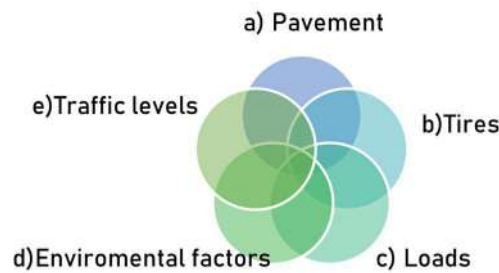


Figure 2.24: Factors influencing the friction. Source: Author's elaboration.

- a) Pavement factors: including surface texture, aggregates, surface type, and age.
- b) Tire factors: such as speed, concerning angle, tread wear, and inflation pressure.
- c) Load factors: related to traffic and road geometry.
- d) Environmental factors: such as temperature and the presence of water.
- e) Traffic factors: Growth of traffic levels.

2.2.4. Texture and measurement

To ensure road safety, it is important to monitor and measure skid resistance. Various devices and methods are available worldwide for developing skid resistance. Despite the differences in the devices, they all work on the same principle: measuring the resistance to the friction of the road surface with a rubber slider, which represents a tire that has to slide over a wet road under load.

The techniques for measuring skid resistance in wet conditions can be roughly divided into two types:

a) Outdoor in-situ measurement road surface devices:

- In these techniques, measurements are taken on-site directly on roads under real-life conditions (on-site).
- The devices dynamic / continuous are designed for outdoor use to measure skid resistance on existing road surfaces.

- Examples include the Grip Tester (GT), the Sideway-force Coefficient Routine Investigation Machine (SCRIM), and the British Pendulum Tester (BPT).

b) Indoor laboratory with predictive devices:

- These techniques static/portable are conducted in a controlled laboratory environment, allowing for precise conditions and reproducibility (static devices).
- Devices in this category often aim to predict skid resistance performance rather than measure it directly.
- Examples include the British Pendulum Tester (BPT), Dynamic Friction Tester (DFT), and various laboratory-based friction testing devices.

The application of these techniques contributes to the development and maintenance of safe road surfaces by assessing and ensuring adequate skid resistance under different conditions.

2.2.4.1. Measurement of the Macrotexture

Measurement of macrotexture in pavement refers to the assessment of the surface texture characterized by wavelengths ranging from 0.5 mm to 10 mm. Various methods exist for measuring macrotexture, and they typically involve determining an average surface texture depth. The specific details of these methods are summarized in Table 2.2:

Table 2.2: Different methodologies for assessment of macrotexture

Type of system	Method of Test	Type of test	Type of texture	Standard	Reference
Direct conventional	Sand Patch Test	Mean Texture Depth MTD	Macro	ASTM E 965 ISO13473-1	(Ergin et al., 2020)(Hao et al., 2016)
Direct stational	Outflow meter	Drainage Capability	Macro	ASTM E2380	(Al, 2001)(Ergin et al., 2020)
Direct stational	Mechanical stylus	Profile Texture	Macro	ISO/TS 13473-4	(Texture, 2020)(Santos & Júlio, 2013)
Direct stational	Laser Scanning	Mean Profile Depth MPD	Macro, Micro	ASTM E 1845	(Luong et al., 2012)(Sengoz et al., 2012a)
Direct stational	Image processing System	Surface Profile	Macro, Micro	AASHTO TP 81 EN 13473-2	(Masa et al. 2006)(Gree & Heitzman, 2017)

a) Volumetric texture method

The Sand Patch Test (SPT), also known as the Sand Circle Method, is a widely recognized technique for measuring macrotexture on pavement surfaces. The method involves pouring a known volume of sand into the pavement surface, spreading it in a circular fashion, and then measuring the covered area. The key parameters obtained from this method are the mean diameter (ranging from 90 mm to 250 mm) and the Mean Texture Depth (MTD). The calculation of MTD is determined based on the known volume of sand and the estimated area it covers as shown in Figure 2.25.

Test methods for the Sand Patch Method are specified in standards such as BS 5971-5:2000 ASTM E965 and EN 13036-1. The Sand Patch Method provides an estimate of the macrotexture of the pavement surface by Equation 4.

$$MTD = \frac{4V}{\pi \cdot D^2_{avg}} \quad \text{Equation 4}$$

Where: V is the volume of the glass spheres in ml, and D_{avg} is: the mean diameter of the sand stain in mm.

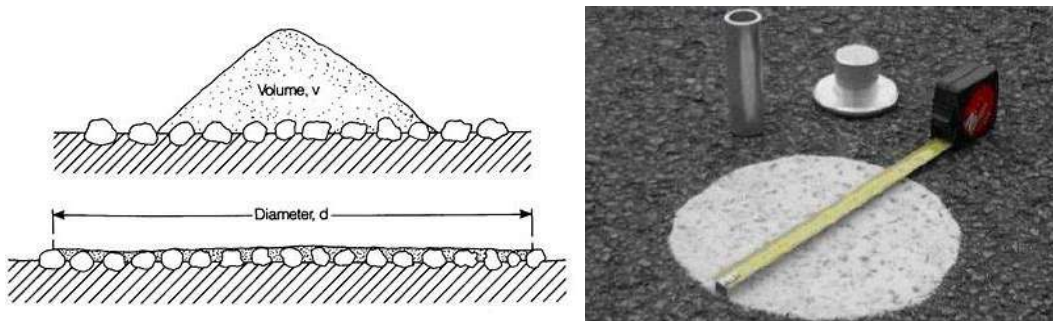


Figure 2.25: Sand patch test (SPT).

b) Laser Profile Method

The Laser Profile Method, using profilometers, represents a more recent development in the measurement of macrotexture, specifically in terms of Mean Profile Depth (MPD). This technology has seen significant advancements since the 1980s and 1990s. Vehicle-mounted profilometers are commonly employed, making a sequence of displacement measurements along the pavement surface.

The basic principle of the MPD involves the use of laser pulses at high frequency. As the sensor moves along the pavement surface, it captures a two-dimensional

profile of the surface, specifically the MPD. This method is specified by standards such as ASTM E1845-01:2001. Figure 2.26 shows the laser scanner AMES and the scheme of laser capture of the surface.

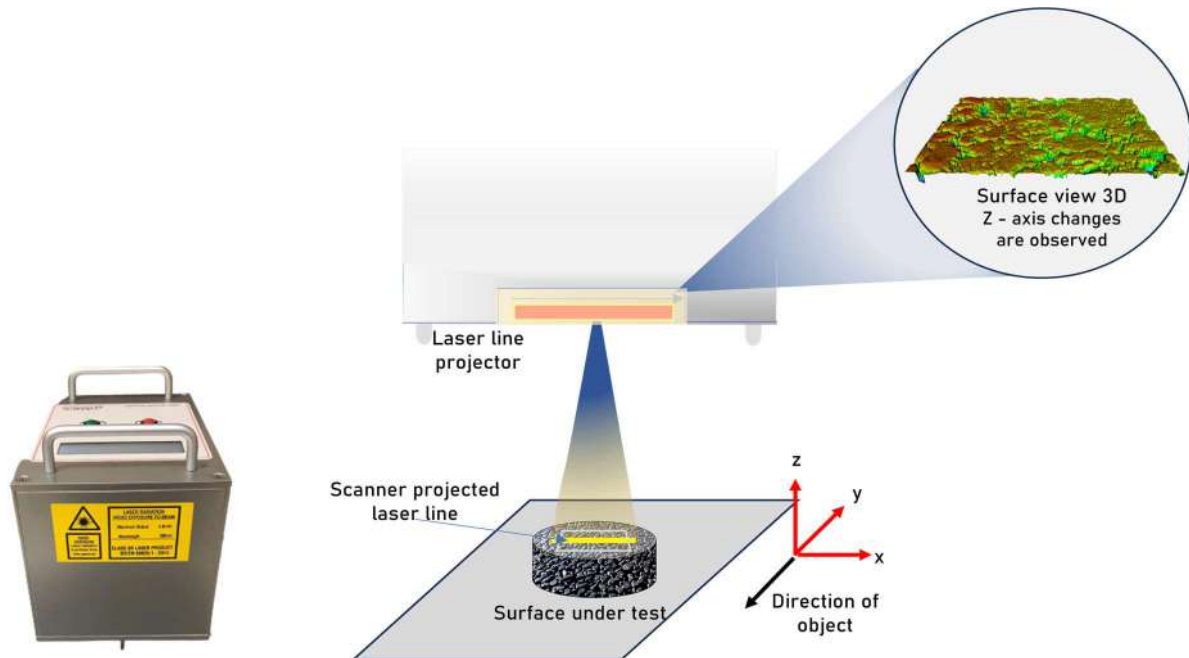


Figure 2.26: Laser scanner. Source: Author's elaboration.

2.2.5. Assessment of skid resistance

2.2.5.1. Methods based on the measurement of pavement texture

There are several methods proposed to obtain skid resistance through pavement texture information. Pavement texture is categorized into three types: microtexture, macrotexture, and megatexture. These categories are defined by their wavelengths and amplitudes.

The overall texture of an asphalt pavement can be represented by the deviation of the pavement surface from an ideal plane. This texture has been classified into categories based on the specific ranges of wavelengths considered (Kanafi et al., 2015a; PIARC, 1995). Following this criterion, the World Road Association (PIARC) has established the following texture levels: Microtexture, Macrotexture, and Megatexture in terms of Wavelength (Short, Mean, and Long) are shown in Table 2.3 and Figure 2.27. The two surface texture components that affect skid resistance are microtexture at low speed and macrotexture at high speed, which influences friction and rolling resistance. Megatexture and irregularity, on the

other hand, influence driving comfort and vehicle wear. So far, these factors have been considered essential for understanding and improving pavement safety and performance (Kanafi et al., 2015a; PIARC, 1995).

Table 2.3: Wavelength pavement texture classifications

Domain	Dimensions	
	Horizontal Wavelength (mm)	Vertical Amplitude (mm)
Microtexture	0 - 0.5	0- 0.2
Macrotexture	0.5-50	0.2 -10
Megatexture	50 - 500	1-50

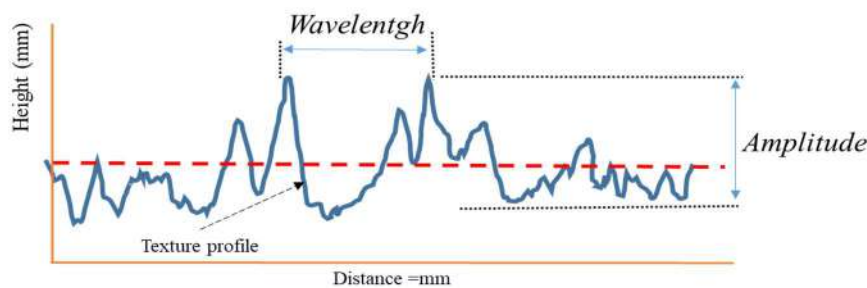


Figure 2.27: Basic representation of texture by wavelength and amplitude. Source: Author's elaboration.

The geometric characteristics of the aggregate determine one of the most relevant properties affecting skid resistance, being the surface texture responsible for controlling skid resistance. In turn, texture is divided into the following elements according to the horizontal size of the irregularities :

- a) Microtexture: smaller than 0.5 mm. It defines asperities and mineralogy. Microtexture refers to the roughness of the surface of individual mineral aggregate grains. It involves the fine-scale irregularities present on the surface.
- b) Macrotexture: Between 0.5 mm and 50mm. Defines roughness of geometric aggregates. Macrotexture, on the other hand, refers to the texture of the pavement surface at the scale of the mineral aggregate grains protruding from the pavement surface. It encompasses the larger features and irregularities that are noticeable on a broader scale.
- c) Mega texture: Between 50mm and 500mm. Associated to the bumps or peeling present in the pavement. Megatexture extends to the unevenness at the scale of the contact surface between the vehicle tire and the pavement

surface. It considers the overall surface characteristics that impact the interaction between the tire and the road.

- d) Irregularity: From 500mm and above. From this size onwards, pavement faults are considered surface irregularities.

Figure 2.28 shows all these texture characteristics that play a significant role in influencing the contact surface area between the road and the tire. Understanding and measuring microtexture, macrotexture, and megatexture is crucial for assessing road safety, vehicle handling, and overall pavement performance.

The importance of texture characteristics in skid resistance is greatly increased in curves, as opposed to straight roads, since in curves there is the longitudinal and transverse displacement of the vehicle at the same time, a process in which sliding along the pavement surface can occur, causing various accidents due to loss of driving control.

The effectiveness of the micro and macrotexture is lost if they are covered by water (in the case of adverse weather conditions), as well as by excess of binder or fine in the mixture since separation is created between the aggregate and the tire, which reduces their interaction, and therefore the skid resistance of the road.

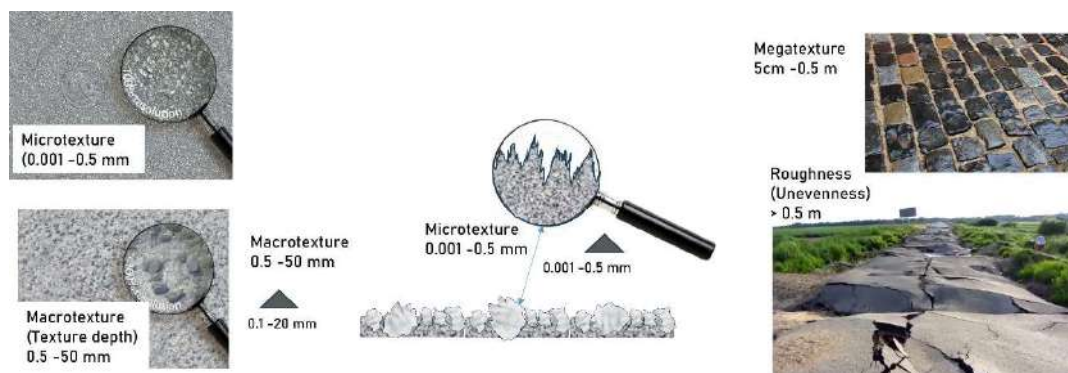


Figure 2.28: Categorizations of the texture. Source: Author's elaboration.

The surface texture of asphalt pavements is a subject of significant interest and has garnered special attention from various researchers, given its crucial role in safer and more comfortable driving for the user.

The safety-related benefits associated with open graded mixtures in pavements have been corroborated by various international studies. For instance, a study conducted in Japan by Shimento and Tanaka (2010) revealed that the fatality rate on open graded mixture pavements was approximately 1.9 per 100 million miles

traveled, whereas the fatality rate for dense-graded asphalt pavement was 6.2 per 100 million miles traveled.

The study's findings by (Kayhanian & Harvey, 2020b), depicted in Figure 2.29, are based on the change in the number of accidents during the year before open graded mixtures were layer down constructed and the number during the year after. It compared these results with accident numbers from the same period on a standard dense-graded pavement. The results clearly indicated that open grade significantly reduced the number of fatalities during rainy weather in Japan when compared with the standard dense-graded asphalt pavement (Miljković et al., 2014).

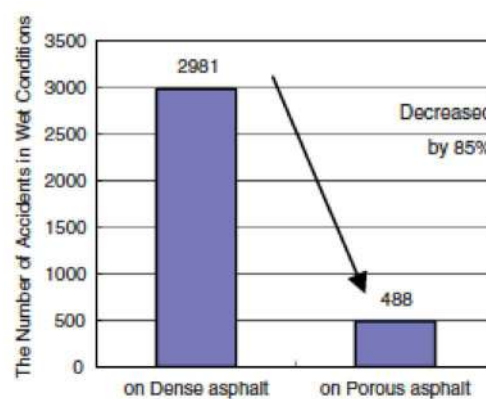


Figure 2.29: Effect of the surface texture on the accidentally. Source: (Kayhanian & Harvey, 2020b).

The relationship between surface texture and tire/road is complex, texture principally presents a difference between macrotexture and microtexture on friction as shown in Figure 2.30.

The change of the micro and macrotexture is considered to exert the most significant influence on skid resistance. Additionally, macrotexture influences water drainage, splash and spray, and optical properties of the pavement surface. Microtexture plays a vital role in the friction between the tire and the pavement, while megatexture impacts aspects such as rolling resistance, driving comfort, and vehicle wear. According to (Miljković et al., 2014) the effects of texture are primarily dominated by macro and microtexture in terms of favorable outcomes as presented in Figure 2.30. This underscores the importance of understanding and optimizing surface texture for various factors, including influence on noise generation, water drainage, and overall road performance (Flintsch et al., 2021, Do et al., 2013).

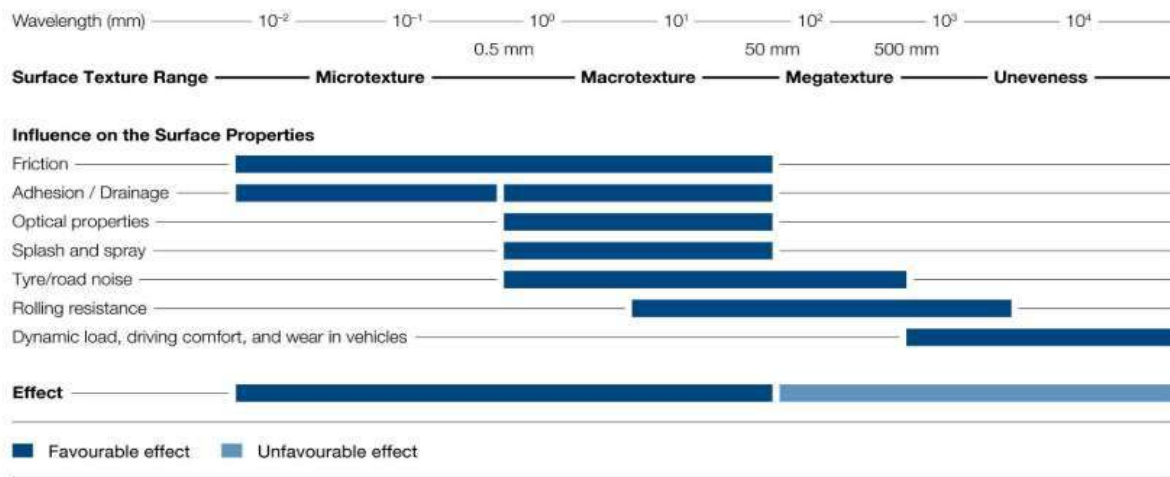


Figure 2.30: Effect of the surface texture on the different mechanisms. Source: (Miljković et al., 2014).

Conventional methods that relate texture measurements to skid resistance, such as the SPT sand patch test (EN 13036-1) as a fundamental measure, have been used to characterize pavement texture. This method provides the mean texture depth (MTD), which characterizes the macrottexture of the pavement in millimeters, as presented in Equation 5.

Another method, the outflow meter (OFT) EN 12697-19, has been used to characterize the correlation between pavement texture and the drainability capabilities of the pavement surface. It measures the average flow time of a known volume of water under gravity. Additionally, this method allows the determination of the MTD by averaging the outflow time.

$$MTD = \frac{\left(\frac{3.114}{OFT}\right)}{0.636} \quad \text{Equation 5}$$

Where OFT is the average outflow time.

In general, several studies have observed that large MTD values are related to good skid resistance performance.

2.2.5.2. Methods based on coefficient of friction measurement (coefficient of friction)

a) Sideways forces SCRIM

These devices measure sideways forces perpendicular to the plane of rotation in the direction of motion, typically at a high velocity of 50 km/h. The measurements complement macrottexture measurements. The Sideways Force Coefficient Routine

Investigation Machine (SCRIM) BS 7941-1:2006 determines the sideways force coefficient as the force at a right angle to the plane of the angled wheel, expressed as a fraction of the vertical force acting on the wheel as shown in Figure 2.31.

The formula for the Sideways Force Coefficient (Sfc) is given by equation 6:

$$Sfc = \frac{F_p}{Q} \quad \text{Equation 6}$$

Where Sfc : Sideways force coefficient, F_p : horizontal force at right angle, Q : weight force (vertical force).

This coefficient provides valuable information about the skid resistance of road surfaces and is an essential parameter for assessing road safety.

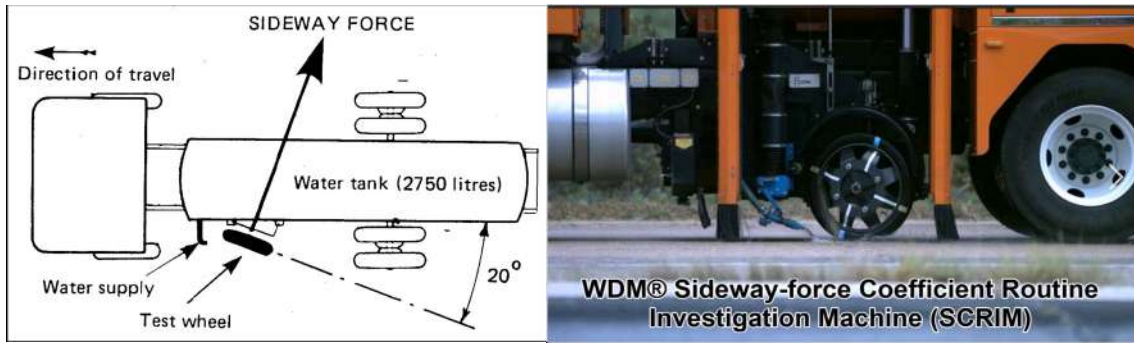


Figure 2.31: Sideways forces SCRIM. Source: WDM®.

b) Grip Tester GT

The Grip Tester GP is a three-wheeled Continuous Friction Measurement Equipment (CFME) built by Findlay in 1987 for airport runway operations. Figure 2.32 depicts the Grip Tester, which has a single test wheel bracket and a two-bogey drive mechanism. Equation 9 gives the surface friction coefficient, also known as the Grip Number (GN), which is a percentage of the tractive drag force (F_d) over the weight force (Q). GN is determined by equation 7.

$$GN = \frac{F_d}{Q} \quad \text{Equation 7}$$

Where: GN : Braked friction force coefficient by Grip tester., F_d : Drag force (horizontal), Q : Weight (vertical).

The Grip Tester survey uses an automated water delivery system that creates a 0.25mm water layer beneath the testing tire. The Grip Number (GN) is measured every 1 meter and averages over a length of 10 meters. This measurement gives

useful information on surface friction characteristics, which aids in the assessment of roadway safety. As shown in Figure 2.32.



Figure 2.32: The Grip Tester devices.

c) The dynamic Friction tester DFT

The Dynamic Friction Tester (DFT) uses the dynamic friction method specified in ASTM E1911-98. This approach involves taking measurements with three rubber skids powered by a rotational torque motor that achieves a tangential speed between the slider and the pavement surface. The spinning disks are equipped with three rubber sliders centered on a diameter of 284 mm. A disc is rotated horizontally at a set velocity before being put onto a wetted test surface, reaching a maximum speed of 90 km/h. Torque is continuously measured and converted to friction via a skid resistance slider on the surface of the rotating disc. Equation 8 determines the coefficient of friction (μ).

$$\mu = \frac{F}{Q} \quad \text{Equation 8}$$

Where: μ coefficient of friction as measured by the DFT, F Torque force (Horizontal), Q weight force on the three rubber sliders (vertical).

The DFT is adaptable and may be used for both laboratory investigations and field observations, providing useful information about surface friction properties for road safety assessment. The equipment is shown in Figure 2.33.

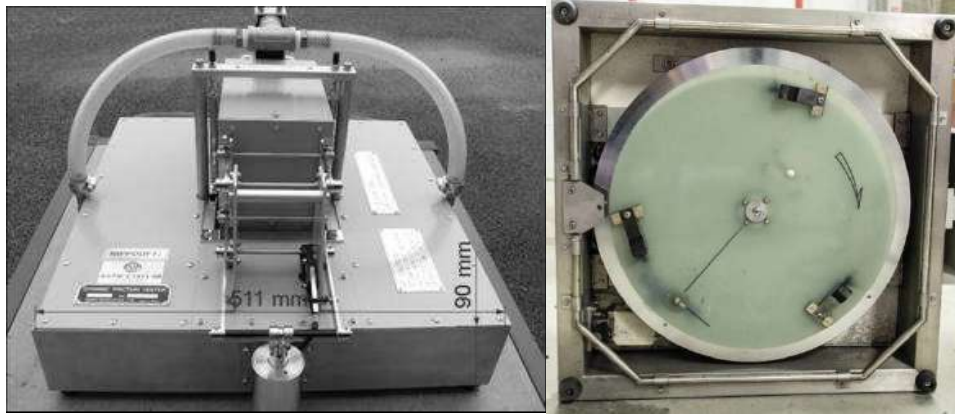


Figure 2.33: The dynamic friction tester.

d) British Pendulum Test (BPT)

The British Pendulum Tester (BPT) is widely utilized for measuring the frictional resistance resulting from energy loss during skidding on pavement surfaces. It conforms to standards such as ASTM E303 and EN 13036-4 (2011). The energy loss is measured by pushing a rubber shoe over the surface to be tested, relying on the kinetic energy loss converted into frictional force from the pavement response. Figure 2.34 shows the forces applied by BPT. The obtained values are expressed in BPN (British Pendulum Number), and the test is conducted at a shearing speed of 10 km/h. BPN is used for both laboratory assessments and on-road service.

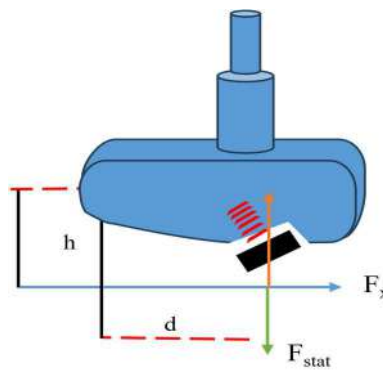


Figure 2.34: Forces applied by the BPN skid. Source: Adapted (Hamlat, 2006).

The normal force (F_n) is the reaction exerted by the surface and depends on the tension of the spring in place, which is in response to the force (F_{Stat}). The tangential force (F_x) is the force acting parallel to the surface. Together, these forces are critical components in determining the coefficient of friction (μ). The

formula for calculating the coefficient of friction (μ) in the British Pendulum Tester is given by Equation 9:

$$\mu = \frac{F_x}{F_n} \quad \text{Equation 9}$$

Where: F_x : tangential force, F_n : Normal force.

It's important to note that the British Pendulum Tester provides friction values in terms of energy loss (BPN), not as a coefficient of skid resistance. The test has historically been used to approximate microtexture levels influencing friction at low speeds. Nevertheless, the present research is addressing the impact of macrotexture on skid resistance as measured by the pendulum test. Figure 2.35 shows the BPN and process of measurement.

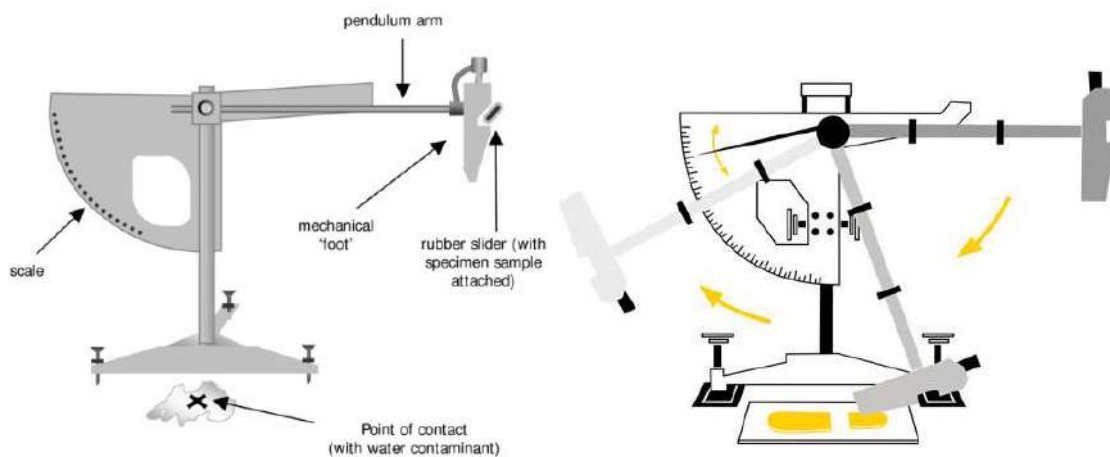


Figure 2.35: The British Pendulum Tester DFT. Source: Author's elaboration.

2.2.6. Temporal variation of skid resistance

Devices for testing and measuring the temperature variation of sliding resistance have been developed for both laboratory and field use. Laboratory devices, such as the Polished Stone Value (PSV) EN 1097-8:2009 and the Wehner Schulze (W&S) test (EN 12697-49), are specifically designed to evaluate sliding resistance under various wear cycles. These devices are essential for assessing how different pavement materials respond to wear, providing critical data for improving pavement design and maintenance.

In terms of spatial variability, skid resistance performance will vary under different vehicle loads and tire types, as well as across different road surfaces and environmental conditions (water, snow, temperature). Temporal variability also

plays a role, with skid resistance showing seasonal variations induced by surface polishing, contaminants, etc., over the long term.

Skid resistance of pavement refers to the contact and sliding between the tire and pavement under various conditions, leading to spatial variability in skid resistance. Current measurement techniques primarily focus on evaluations based on different pavement materials. Compared to dry friction, the contact distance between the tire and pavement surface changes under different conditions, resulting in spatial variability in skid resistance when the tire slides on the surface.

a) The Polished stone value (PSV)

The Polished Stone Value (PSV) is determined through the assessment of the resistance of aggregate sources, following the procedure outlined in EN 1097-8:2009 by the UK Transport Research Laboratory. The PSV, developed as a British Standard in 1960 after World War II, involves a two-stage process.

In the first stage, accelerated polishing of the aggregate is conducted, followed by the determination of the resulting coefficient using the British Pendulum Tester (BPT). The BPT assesses the frictional resistance of the polished surface.

In the second stage of the test, the state of polishing reached by the specimens is measured using the BPT as shown in Figure 2.36. The result is a laboratory-assessed Polished Stone Value (PSV), ranging from 30 to 80 where a higher value indicates better resistance to polishing. Therefore, a higher PSV is indicative of superior aggregate performance in terms of resistance to polishing, contributing to better skid resistance properties.



Figure 2.36: Equipment of Polishing Stone Value and specimens. Source: Author's elaboration.

b) Wehner Schulze (W/S)

After 1960, a new equipment called the Wehner/Schulze (W/S) machine was developed in Germany. It was introduced under the European standard BS EN 12697-49 in 2014, specifically designed for determining the friction of FAP (Frictional Asphalt Paving) asphalt mixtures after polishing (Figure 2.37). The standard, EN 12697-49, outlines the operational procedures, sample preparation methods (both in the laboratory and field), measurement techniques the evolution of friction, and the reporting of final friction results.

The W/S test has notable advantages over other tests, particularly in the ability to extract field samples (Kinner et al., 2018). This feature allows for the analysis of the bituminous surface, in addition to the coarse aggregate. The W/S test, provides valuable insights into the skid resistance properties of asphalt mixtures after polishing, contributing to the overall assessment of road safety (Arampamoorthy et al., 2011a).



Figure 2.37: Wehner Schulze equipment and specimens.

The formula used to measure friction with the Wehner&Schulze (W/S) equipment in the context of the FAP (Frictional Asphalt Paving) is expressed as the ratio of the frictional force to the vertical load applied to the pavement. Is determined by Equation 10:

$$\mu = \frac{F_{friction}}{F_{vertical}} \quad \text{Equation 10}$$

Where: μ : Friction coefficient, $F_{friction}$: measurement force vertical, $F_{vertical}$: vertical force applied to surface pavement.

The standard polishing operation involves the roller head rotating at 500 rpm for an hour, resulting in 180,000 rollers passing over the sample surface. Each roller is independently loaded to a contact pressure of approximately 400 kPa, and polishing is performed using a mixture of 5% quartz powder in 95% water (Kane et al., 2013a). Figure 2.38 shows the polishing of cones and the skid resistance measurement of the surface of the asphalt mixture.

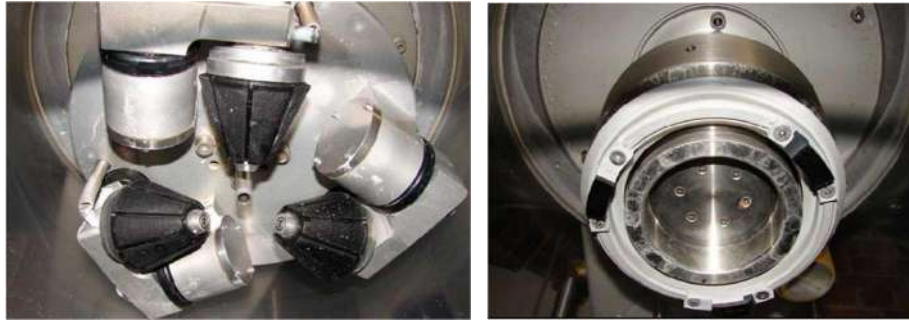


Figure 2.38: Friction cones for wearing and skidding slides for friction measurement.

After the polishing process is complete, the specimen is washed and placed on the skid resistance tester. The skid resistance tester evaluated features rubber pads (the third pad is not clearly visible in Figure 2.38). The disk can rotate on the specimen at various speeds. In the standard test, the rubber pads are accelerated to rotate at 3000 rpm, which is approximately equivalent to 100 km/h. Water is applied to the surface to create a 0.5mm film thickness, and the tester is lowered to the surface. The coefficient of friction at 60 km/h is taken as the test result, although other speeds could be used for assessment purposes.

The long-term spatial variation of pavement skid resistance can be attributed to the variation in texture, which plays an important and dominant role in skid resistance. Different textures can be induced by the various contact states between the tire and the pavement. Currently, several studies have linked texture to skid resistance using parameters such as MPD (Mean Profile Depth), MTD (Mean Texture Depth), and the coefficient of friction. However, the efficient relationship and variability with texture information are not always clear. Moreover, the macrotexture and microtexture of the pavement contribute to the spatial variability of skid resistance.

2.2.7. Evolution of the friction with the wear surface texture

It is well known that the type of pavement and size of aggregate present important influences on the surface characteristics, particularly in terms of texture and surface roughness (Lorenz et al., 2015). The surface texture of a pavement is largely defined by the grain size and shape of the aggregates that make up the pavement (Nejad et al., 2016). The roughness level has an effect on the coefficient of friction, which occurs at the contact surface between the rotating wheel and the pavement. The coefficient friction is regulated by the relative vertical (load on the wheel) and horizontal (friction) forces between the wheel and the road surface (Lorenz et al., 2011). It is important to note that different types of pavements show varying responses when tires are driven over them.

Figure 2.39 shows the evolution of the texture observed by (Zhu & Ji, 2022). The Mean profile depth (MPD) evolution texture characteristics were divided into three processes on 10.000 polishing times. The evolution of the texture reveals a loss measured by MPD, which allows highlighting changes in texture. However, previous research has not determined whether these effects are temporary and, if so, the duration of these effects has not been established.

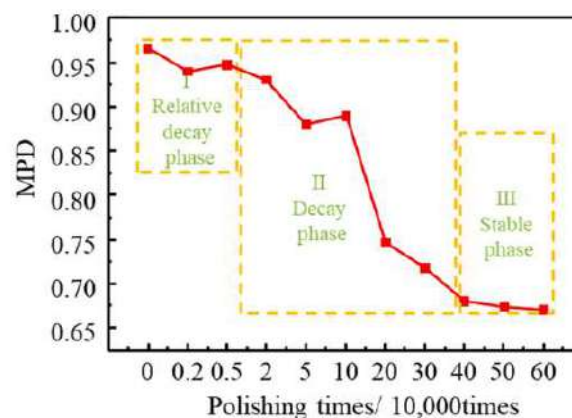


Figure 2.39: Evolution of the texture by traffic. Source: (Zhu, Ji, et al. 2022).

The evolution of texture is directly linked to the variation in friction since the latter behaves as a measured response of texture (microtexture and macrotexture). Figure 2.40, the effect of sliding velocity on the sliding coefficient of friction. Macrotexture reduces the friction-velocity gradient by facilitating water drainage. It affects skid resistance at high speeds but has little effect at low speeds. Therefore, at lower speeds of sliding, the predominant factor defining the level of friction is the high microtexture and high macrotexture (Lorenz et al., 2015). While

the low macrotexture and microtexture present a reduction rate of sliding. On the other hand, increased friction presents a high microtexture and high macrotexture.

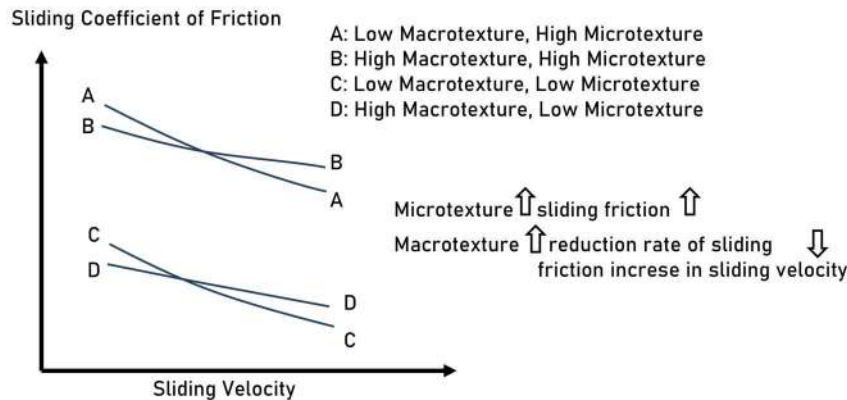


Figure 2.40: Effect of the texture on the friction.

Resistance is critical on wet surfaces, while maximum resistance occurs on dry pavements. Figure 2.41a, b, and c explain the frictional interaction by tire tread and microtexture, macrotexture, and mega texture which force allows the driver to maintain control of the vehicle, especially on wet surfaces (Vieira, 2018). Surface texture influences this friction, and microtexture and macrotexture are especially important (Ye et al., 2021). The interaction phases between the tire and the pavement are largely due to the deformation of the tire tread on the pavement texture. In addition, the characteristics of the longitudinal profile of the road, including macrotexture, microtexture, and mega texture, play an essential role in the skid resistance processes (Sullivan, 2018).

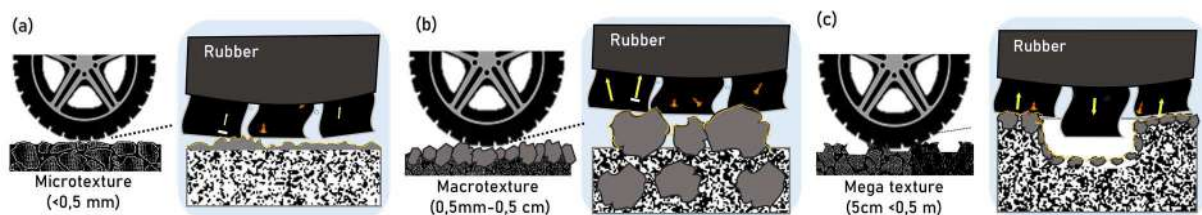


Figure 2.41: Interaction tire treats between textures of pavement a) microtexture b) macrotexture, c) megatexture. Source: Author's elaboration.

Regarding the in deep description of the evolution of the skid resistance over time. Figure 2.42 shows the progressive stages of the tire-road skid resistance. Initial resistance is provided by the bitumen wrapped around the aggregate (adhesion), generating minimal friction (Kane et al., 2010). The development towards maximum skid resistance at the loss of the binder film wrapped around the micro

texture avoids direct contact with the tire in free rolling. Then, phase 2, presents a process of wear of the enveloping binder [A], which undergoes the progressive detachment of the exposure of the micro texture considered as the peak of the maximum skid resistance. In parallel in phase [C] the macro texture is reduced by the direct contact of the tire. In phase 3, the exposure of the macro roughness of the aggregate presents the progressive polishing passing a stage of regeneration and wear of the micro texture [B]. Finally, in stage [D] the stabilized wear is attributed to seasonal variations affecting the aging of the binder, oxidation of the pavement favoring the general polishing of the aggregate itself, and its final skid resistance is attributed to its mineralogical composition and hardness of the aggregate. All evolution of polishing directly affects the aggregate's roughness and begins at the point of loss of skid resistance. According to studies by (Cerezo et al. 2019), the typical polishing pattern is between 15,000 and 20,000 cycles. The residual skid resistance in the polishing phase depends on both the type of aggregate and the remaining asphalt.

The microtexture controls the magnitude of skid resistance at this stage, while the macrotexture contributes structurally, defining the relationship between skid resistance and speed over the pavement's service life (Hoyer et al., 2020). Consequently, in the equilibrium stage, skid resistance depends mainly on the mineralogical properties of the aggregate.

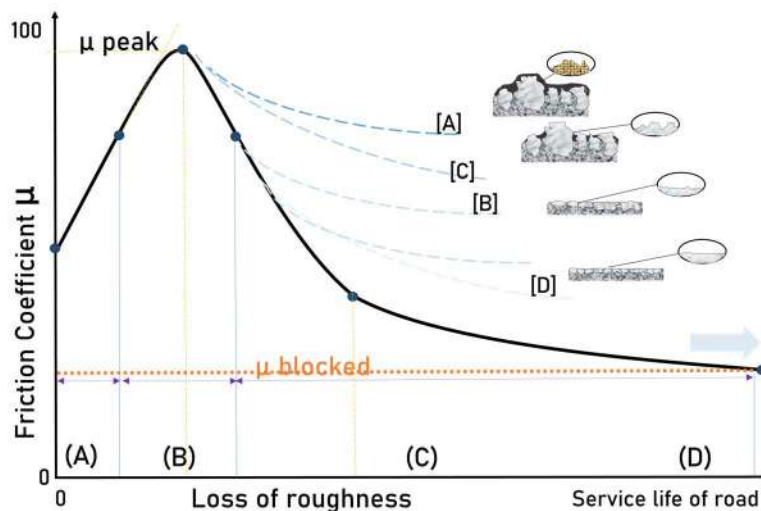


Figure 2.42: Evolution of texture by the coefficient of friction. Source: Author's elaboration.

The texture is due to aggregates, by random ordering after the construction process (Flintsch et al., 2021). Figure 2.43 shows the variation of the components that make

up the texture type (microtexture and macrotexture). These components change constantly during the service life of the pavement. However, polished and smooth textures represent unfavorable conditions.

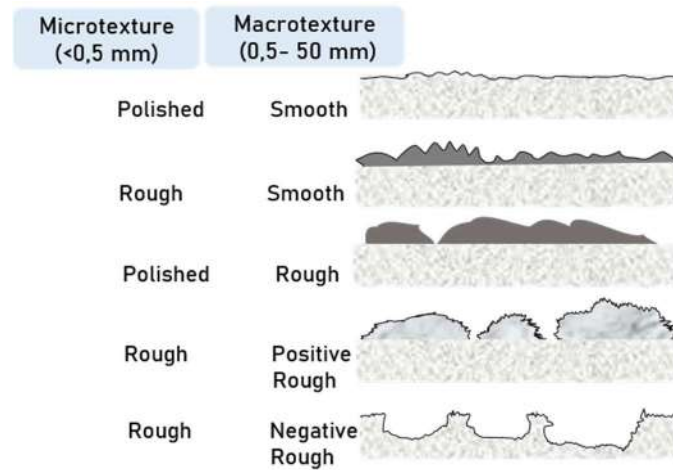


Figure 2.43: Texture variations in microtexture and macrotexture. Source: Author's elaboration.

Road roughness has a substantial effect on maximum friction in dry conditions, particularly when foreign bodies are present on the road-rubber interface. Friction varies between wet and dry roads based on micro or macro texture, with $\mu_{\max}$ ranging from 0.9 to 0.2. Microtexture rough surfaces have maximum friction values of 0.5-0.9. In contrast, microtexture smooth wet surfaces have minimum friction values in the range of 0.20-0.1, as revealed in the review by (Acosta et al., 2017), and summarized the Table 2.4.

The seasonal variation has an impact on the coefficient of friction and approaches one million equivalent axle loads, which is referred to as the seasonal variation equilibrium phase (Edmondson et al., 2021). Moreover, (Cerezo et al., 2019) confirmed this equilibrium phase by superimposing the friction curve measured on samples containing only aggregates and pavement cores. Both curves intersect at the residual tangent of the polishing phase, showing variations only due to the influence of seasonality as shown in Figure 2.44. Other studies have also pointed out fluctuations and variations in the friction coefficient due to seasonal changes (Do et al., 2014a), although the skid resistance decreases steadily (Pomoni et al., 2020).

The ultimate skid resistance equilibrium phase characterizes the degree of adhesion at the smooth aggregate tire-surface interface. However, this resistance

varies in the short term due to seasonality and traffic accumulation over time. For example, in winter, rain removes fine particles and other contaminants, renewing micro and macro roughness. However, in summer, the coefficient of friction decreases by up to 30%. Therefore, the evolution varies in contrast to winter seasons, with higher values (Edmondson et al., 2021). This leads to evaluations being carried out in summer, which provides more realistic values under critical skid resistance conditions (Acosta et al., 2017).

Table 2.4: Friction coefficients for four different categories (Acosta et al., 2017).

Pavement Category	Friction Coefficient Range $\mu_{\max}$
Macrotexture rough/microtexture rough surface (draining mixtures, bituminous concretes)	0.5-0.9
Macrotexture smooth/microtexture rough surface (fine mixture)	0.4-0.8
Macrotexture rough/microtexture smooth surface (rolled aggregates)	0.2-0.3
Macrotexture smooth /microtexture smooth surface (flushing asphalt)	0.1-0.2

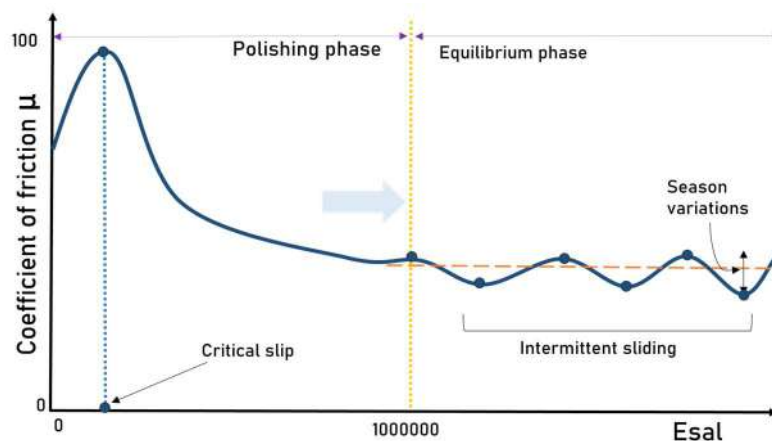


Figure 2.44: Evolution of polishing in seasonal changes. Source: adapted by (Kane et al., 2010)

2.2.8. Empirical models to represent the variability of skid resistance

It is common practice to report the skid resistance condition of a pavement based on skid resistance measurements made at a given speed under specific test conditions. The inadequate representation of skid resistance has led to the reliance on empirical approaches for making skid resistance predictions and conducting driving safety analyses. To address these inadequacies, Fwa and Chu (2021)

proposed the concept of the "skid resistance state" to provide a mechanistic representation of pavement skid resistance conditions.

Currently all road pavement skid resistance surveys and skid resistances evaluation studies are conducted using a standard measuring device under a pre-specific set of test conditions. Each measuring device its own specific conditions speed, dimensions test wheel, magnitude of wheel load, friction test.

Penn State two parameter skid resistances model: (pennsylvania 1980), represent pavement skid resistances as a negative function of vehicle speed V , as shown in equations 11, by defining two parameters SN_0 and β which are related to pavement surface characteristics.

$$SN_V = SN_0 e^{-\beta V} \quad \text{Equation 11}$$

Where SN_V is the skid number at speed V , which is the skid resistances measured by the ASTM standard test method E274, SN_0 is zero-speed skid number, representing the skid resistances intercept at $V = 0$, and β is a regression constant. The term SN_0 is governed by the microtexture of the tested pavement, while the term $e^{-\beta V}$ indicates the rate of skid resistance deterioration with speed. The coefficient β is strongly influenced by the macrotexture of the pavement surface both SN_0 and β are to be determined experimentally.

Research has found correlation between SN_0 and the British Pendulum Number (BPN), which is generally regarded as a proxy measurement of pavement microtexture. The following regression Equation 12 was proposed to estimated SN_0 based on test data from 30 locations at 6 sites.

$$SN_0 = -35 + 1.32 BPN \quad r = 0.95 \quad \text{Equation 12}$$

The second parameter β is obtained from curve fitting of at least three skid resistance test data measurement at three different speeds.

The suitable test speeds for modeling the skid resistances performance of a road pavement are 48, 64 and 80km/h.

The problem of the Pen state model is that it cannot be applied to predict pavement skid resistance at different water films thicknesses.

PIARC two parameters base skid resistances model IFI: The Permanent International Association of Road Congress (PIARC) elaborated a two parameters concept of the skid resistances-speed relationship measure termed as international friction index (IFI).

Parameters F60 and Sp is reports as IFI(F60,Sp) for skid resistances measured using a smooth tread test tire . F60 and Sp are given by the following regression relationship on equation 13 and 14.

$$S_p = a + b TX \quad \text{Equation 13}$$

$$F60 = a + b FRSe^{(60-s)/Sp} \quad \text{Equation 14}$$

Where Sp is a speed constant known as speed number , and TX (mm) is the mean texture depth of the pavement surface tested. TX is the measurement by the sand patch method, or the mean profile depth measured by a laser device, a and b are regression constants.

FRS is the skid resistance measured by the measuring device at a slip speed of S.

The F60 is calibrated for a given skid resistances measuring device the friction FS on standard IFI scale at any speed S can be predicted using Equation15.

$$FS = F60e^{(60-S)/Sp} \quad \text{Equation 15}$$

Therefore, besides harmonizing skid resistances measurements from different devices, the PIARC IFI model can predict skid resistance at any specified slip speed. In summary the Penn State models also suffers from the inability to consider the effect of water film thickness, which is an acritical factor in road safety analysis due to the variation of skid resistances with water films thickness in wet weather. This limitation significantly weakens the practical applicability of two parameters skid resistances models in road safety studies and networks-level pavement management operations.

It is indeed challenging to develop a comprehensive model that accurately accounts for all conditions. To determine real-time skid resistance values on a road, it is essential to use well-calibrated simulation models. These models can account for various factors such as road surface texture, water film thickness, temperature, and traffic conditions, providing more accurate and reliable predictions for road safety analysis and pavement management.

2.3. Evaluation of tangential friction resistances

In this section, we delve into the examination of tangential force resistance. In asphalt pavement there are curved sections of the asphalt roadway where the stress and resistance conditions are different from those of a straight directional section. Normal road conditions in a straight line are uniform but in curved areas,

they are mainly affected by the centrifugal force due to the speed exerted by the vehicle. Figure 2.45 shows the friction conditions on a curved section.

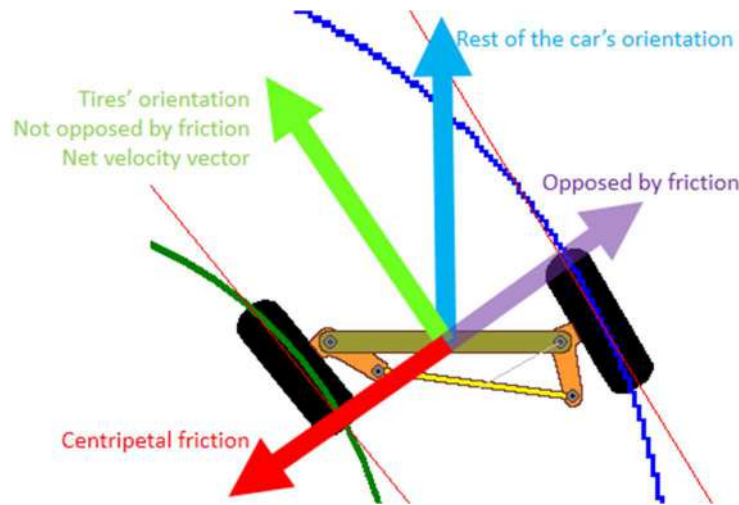


Figure 2.45: Behavior of tires on the curve section.

These points produce irreversible effects on the asphalt mixtures by the development of the tire-pavement interaction, producing alterations due to braking but also to the tearing produced by the tire. Figure 2.46 shows pavement deterioration by the repeated and intense tangential forces subjected during driver maneuvers (braking, acceleration, change of direction) (Hamlat et al., 2007).



Figure 2.46: Deformation and loosening of aggregates due to the effects of the tangential forces of the tires. Source: (Hamlat et al., 2007).

When tangential resistance is may loosen the aggregates and cause accidents. The contact and tangential resistance response is given in braking as well as in traction of the pneumatic on in the interface creating a contact patch change of the stress (Figure 2.47). The tread pattern of the tire pressed against a surface of the

pavement, the external force and load of the car acting (lateral force) on the tread will deform it with the pavement surface.

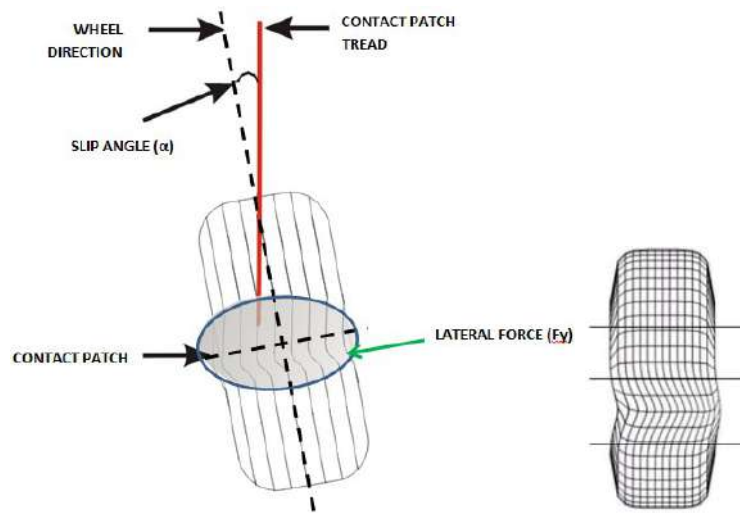


Figure 2.47: Traction tire by tangential section of road. Source: (Hamlat et al., 2007).

Figure 2.48. illustrates a scheme of the lateral force and the slip angle. The chart delineates distinct regions: the elastic linear zone, the transitional zone, and the frictional zone, each corresponding to lateral forces generated upon contact with the entire contact patch of the pavement. In this interaction, a lateral force is generated, guiding the vehicle across the road surface and through the curve. This force induces deformation relative to the contact patch on the surface pavement.

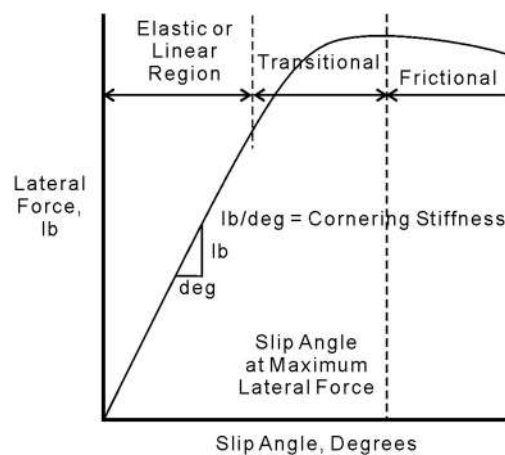


Figure 2.48: Lateral force/slip angle response between pneumatic tires and pavement in curves.

When the direction and speed of a vehicle change, different frictional forces arise between the wheels and the pavement surface, manifesting themselves as lateral and longitudinal forces. However, when the tangential forces exceed the horizontal

forces, serious problems are generated in both the structure and functionality of the pavements.

The surface texture is rearranged among themselves in some cases with loss of material. However, there is also another type of aggregate rearrangement that occurs more rapidly in curves and is caused by transmitted tangential stresses of the tires (Hamlat et al., 2007). At high stress cycles due to traffic, tangential forces cause surface deformation and horizontal displacement of the aggregate's leakage (Figure 2.49).

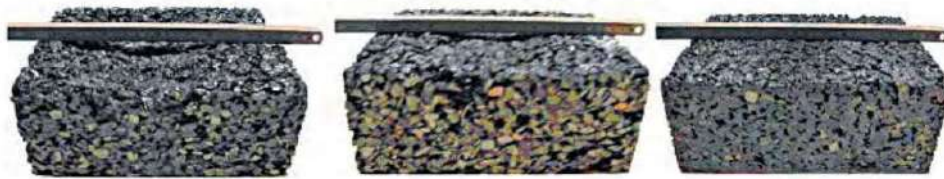


Figure 2.49: Mass loss of different types of mixtures. Source (Hamlat et al., 2007).

This phenomenon is also linked to the cracking-cohesive behavior of the binder at the interface between the aggregates and the binder. The cracking performance of the binder is measured by Vialit cohesion (Rowe, 2017). According to studies carried out by (Hamlat et al., 2007), the research evaluations of mass loss in SMA-type asphalt mixtures with various types of binders characterized the displacement and degradation of surface pavement, evidencing the migration of their shape and position from the beginning of the test. Figure 2.50 clearly illustrates the phenomenon of performance adhesion and cohesion in the interface aggregate/binder due to repetitive rubbing cycles.

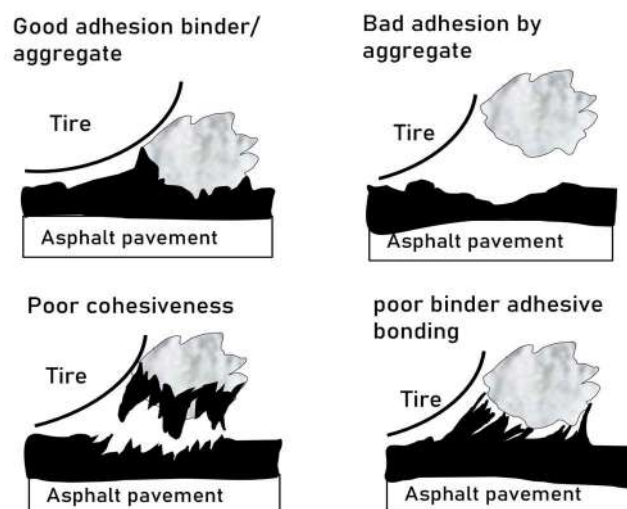


Figure 2.50: Mass loss of the asphalt pavement during the rubbing test. Source: Author's elaboration.

Studies by (Hamlat et al., 2007) observed that tangential resistance involves the measurement of mass loss after 1800 cycles of charge and discharge. Figure 2.51 shows the evolution of mass loss of SMA mixtures by the effect of different binder A.B.C.D.E. Friction can not only cause wear on the surfaces but also material loss.

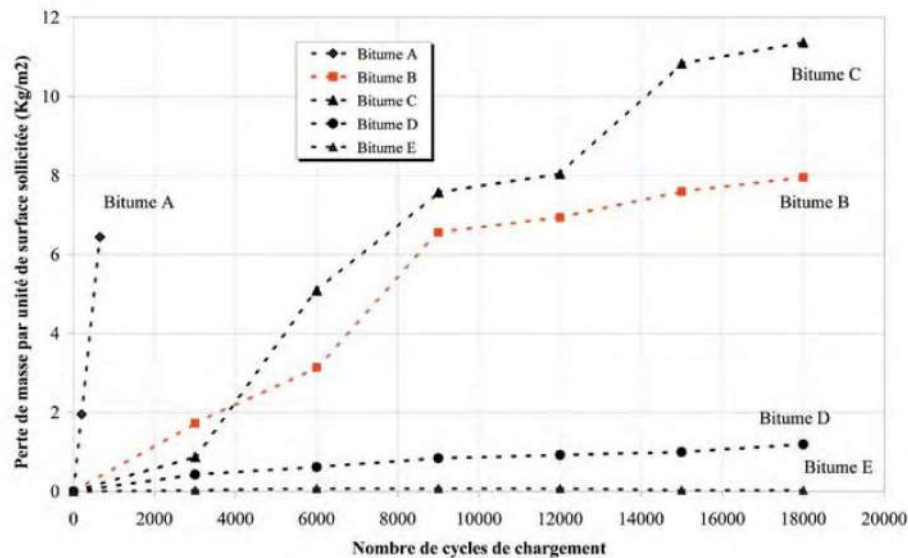


Figure 2.51: Mass loss evaluated for different types of binders. Source : (Hamlat et al., 2007).

According to the current state of research, no further studies have been found that focus on shear strength and its effects on mass loss. Given this research gap, it is necessary to conduct an evaluation with different asphalt mixtures to categorize the mass loss in these different combinations.

2.4. Noise pollution

In this section, the origins and fundamental principles of noise pollution will be summarized in relation to its effects on human health. The generation of vehicular traffic noise caused by tires on pavement will also be addressed. In addition, a brief description of road noise characterization will be provided, and the characteristics of asphalt mixtures in relation to sound absorption will be examined in detail.

2.4.1. Noise Generations

Today, noise has acquired significant relevance as an invisible threat that exerts a strong presence in human habitats. It is defined as an unwanted acoustic phenomenon to which we are exposed from birth and throughout our lives. Noise

is measured using sound level meters, which quantify sound pressure in decibels (dB). Common parameters include sound pressure level (Lp), A-weighted sound pressure level (LpA), and noise exposure level (LEX). The main sources of noise affecting humans come from traffic, airports, industry, construction, and recreational activities. Transport contributes about 80 % of noise pollution (Haider & Conter, 2008) and tire/pavement interaction is considered the main source of this pollution. Although noise from automobiles comes from diverse sources such as engine/transmission, vibrations, and air friction (aerodynamic), tire/pavement is the largest component at speeds above 40 - 55 km/h (Bueno et al., 2011; Greer, 2006). The impact of noise pollution on human health has been the subject of numerous scientific studies, and it has been shown that it can have negative effects on people's physical and mental well-being. Prolonged exposure leads to negative cardiovascular and metabolic effects (Jarosinska et al., 2018). According to the World Health Organization (European Environment Agency, 2020; World Health Organization, 2011), traffic noise ranks second among environmental stressors with significant public health impacts in European countries. Noise exposure is increasing in growing cities (Bekke et al., 2013; Klompmaker et al., 2019).

This problem has been aggravated by the constant development of cities and the incessant population growth. As a result, noise pollution has emerged as one of today's greatest environmental and public health challenges (European Environment Agency, 2020b). The main source of this pollution in decibels is of anthropogenic origin, i.e., it is caused by human activities (Figure 2.52). The effects of noise on human health range from hearing loss, physical and mental health problems, interference with communication, and psychological well-being. Regulations and standards limit noise exposure, and technologies and practices are developed to reduce noise generation from various sources.



Figure 2.52: Levels of the intensity of the noise pollution and source of noise.

According to available data, 28% of the EU population suffers from noise-related problems. In addition, more than half of the residents in the largest cities of the European Union are regularly exposed to excessive traffic noise (Mikhailenko et al., 2020). This highlights a significant prevalence of noise especially in urban areas, where traffic noise tends to be a prominent factor. Addressing and mitigating these noise problems is essential to improve the overall quality of life in these regions.

Throughout history, various solutions have been developed to address the problem of noise pollution. The following summarizes an evolution from the beginning to the present day:

- Studies on road noise assessment started in the 1960s, driven by the increase in traffic and the expansion of road networks due to population growth. In the 1970s, the first regulations and standards for measuring and controlling road noise were introduced in different countries.
- In the 1980s, advanced research was carried out in the field of acoustics, leading to the introduction of more accurate and sophisticated measurement techniques. In the 1990s, predictive models were developed that considered factors such as pavement type, traffic volume, and the surrounding environment.
- In the early 21st century, advanced sensor technologies were adopted that enabled the acquisition of real-time noise data with high accuracy. Prior to the 2010s, research was conducted on technologies and materials aimed at reducing road noise, including the development of quieter pavements and the implementation of noise barriers.
- In the 2020s, there was an integration of traffic, geospatial, and meteorological data, enabling advanced analyses of the impact of noise on people's quality of life. In the future, innovative and sustainable solutions are expected to be found that focus on reducing noise generation and effectively mitigating this problem.

These advances represent a continuous evolution in the understanding and addressing of noise pollution, incorporating aspects of population growth, road networks, advanced technological measures, urban interaction, and regulations to improve sound quality in urban and rural environments.

The commonly used approaches, such as median strips and acoustic barriers, are typically designed to address traffic noise by focusing on the propagation path. However, these methods may have limitations in mitigating the problem at its source (Rey-Gozaló & Barrigón-Morillas, 2015). While these measures can help reduce the impact of noise along the transmission path, they might not effectively tackle the generation of noise by the traffic itself.

2.4.2. Principles of the noise generation on interface tire-pavement

Sound is a physical phenomenon resulting from a mechanical alteration caused by the vibration of an object capable of inducing an auditory perception. Its propagation of noise occurs through rarefaction and compression waves generated by string close to the vibrating object in long and short wavelengths Figure 2.53a. These variations, induced by acoustic pressure, are transmitted through the medium in the form of longitudinal waves, which are perceived by the human ear as sound as shown in Figure 2.53b. Sound is demonstrated as the vibration that helps in propagating as an acoustic wave through a conveyance medium such as solid, liquid, or gas. Sound waves are referred to as longitudinal waves (Andre, 2006).

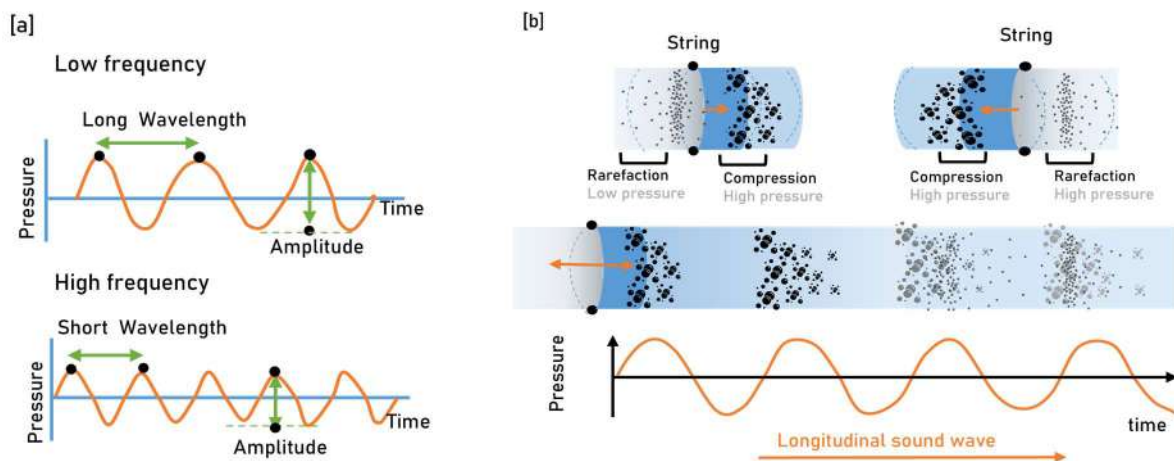


Figure 2.53: Characterization of the sound a) type of frequency of waves and b) behavior of the wavelength.

2.4.3. Characteristics of the physical and metrological of the sound waves

Noise waves possess mainly five characteristics which include "amplitude", "frequency", "velocity", "wavelength" and "time".

Amplitude: The amplitude is mentioned as the size of the provided wave.

Frequency: The frequency is mentioned to the sound waves' numbers, created per second, and is calculated in hertz (Hz). The sound of low frequency possesses fewer waves whereas the sound of high frequency has more (Raghuvanshi & Snyder, 2018).

Velocity: The velocity of the wave is mentioned as the speed. It is determined as the distance in meters per second that a wave progresses in one second depends on the medium.

Wavelength: The most essential feature of sound waves is wavelength. Sound comprises a longitudinal wave that consists of refractions and compressions as they advance through a particular medium (Xu et al., 2022).

In pavement engineering, the generation of sound entails several considerations and management aspects. Noise at the tire-pavement interface arises from various mechanisms, which are typically classified into four key categories (Figure 2.54).

(a) Mechanical: These mechanisms originate from impacts and shocks generated by the contact between the tire tread and the road surface, which causes vibrations.

(b) Frictional: These effects are related to adhesion and micro-movements of the tread when in contact with the road, such as the "Stick-slip" and "Stick-snap" phenomenon.

(c) Aerodynamic: This includes processes both between and within the tread patterns and the road surface. This encompasses phenomena such as air turbulence, tire tube cavity resonance, air pumping, Helmholtz resonance, and tube resonance.

(d) Propagation: Refers to surface properties that relate to an acoustic impedance that influences noise transmission and amplification such as horn effect, absorption, and directivity.

These mechanisms are essential to understanding noise generation at the tire-pavement interface and are key to research and development of strategies to reduce road noise pollution.

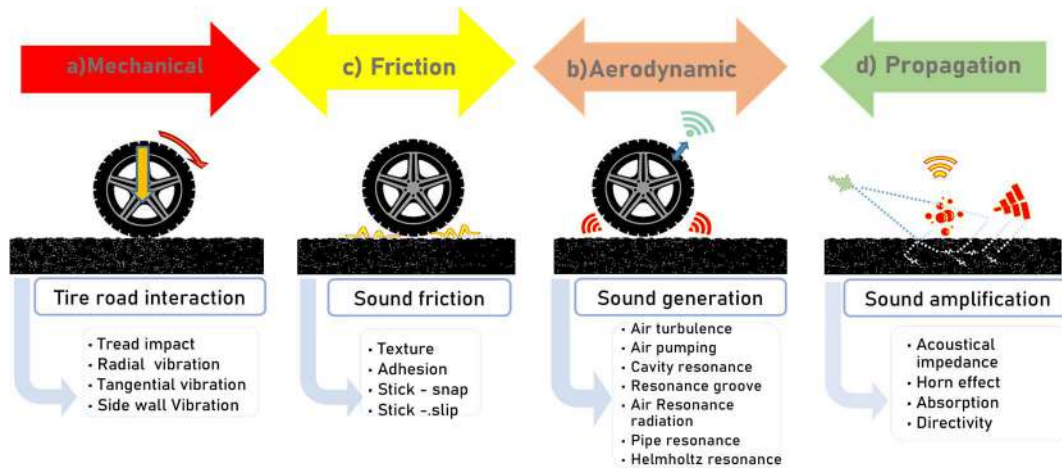


Figure 2.54: Mechanisms of the noise generation on the interface tire-pavement. Source: Author's elaboration.

Tire/pavement interaction is a complex phenomenon that generates noise. There are several mechanisms of noise generation, including tread/texture impact, stick/slip, and air cavity resonance (more details Li, 2018). The stick/slip mechanism is caused by sudden impulse contact between the tire tread and the texture of the pavement texture depth, information (Li, 2018, Li, 2019). Air cavity resonance occurs when air trapped in the tire-pavement interface is compressed and released, creating a resonance frequency. These characteristics have been observed in the pneumatic-pavement interaction, which will not be addressed in this research.

2.4.4. The principle of sound interacting with the pavement.

The principles of energy transfer of an acoustic wave on a material have a similar behavior in most cases. When a sound wave strikes a rigid (ideal) pavement surface, it is reflected in its entirety, since the pavement does not undergo deformation and does not absorb the energy of the wave as shown in Figure 2.55. Sound absorption is the property that all materials have to absorb acoustic energy, allowing only part of it to be reflected (Sandberg and Ejsmont, 2003; Zhang et al., 2019). However, in deeds, pavements are not completely rigid, which allows them to absorb part of the energy of the incident sound waves. In this process, a fraction of the wave energy is transformed into heat energy, while another fraction is transmitted through the material and the remaining energy is reflected. When traffic noise is generated, one part of the acoustic wave is reflected by the surface of the pavement, and another part is transmitted through the pavement surface pores (Vieira et al., 2019).

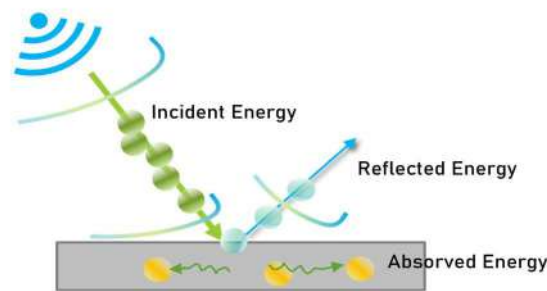


Figure 2.55: Scheme of the absorbed process of the acoustic energy. Source: Author's elaboration.

2.4.4.1. Tire/pavement noise measurement methods

The measurement of the noise produced by the interaction tires /pavement is of utmost importance for the research and development of strategies to reduce noise pollution on rural and urban roads. There are several scientifically sound methods to carry out these measurements. The following are some of the common methods and their rationale from the point of view of pavement-pneumatic interaction:

1) Sound Level Meters and Microphones: Noise measurements are made using properly calibrated sound level meters and microphones. These devices record sound pressure in decibels (dB). Based on the theory of sound and the ability of these instruments to convert sound waves into quantifiable signals. Sound level meters comply with international norms and standards to ensure accurate and comparable measurements (Figure 2.56a).

2) Pavement texture: Based on the influence of pavement texture on noise generation, texture surface (texture exposure) measurement methods are used in Figure 2.56a. Pavement texture is associated with sound absorption and reflection. The rationale for physical acoustic engineering lies in the relationship between pavement roughness and sound reflection, which affects the propagation and perception of noise Figure 2.56b.

3) Computational Modeling: From the data obtained (sound level meters, pavements), computational models are used to simulate noise generation under different traffic conditions and pavement types (Figure 2.56c). These models are based on acoustic and porous media mechanics equations, which consider the interaction between tire vibrations and pavement properties. These models allow for predicting the noise level and assessing the impact of pavement type.

4) Field and Laboratory Tests: are the most traditional and primary source, field tests involve direct measurements on real roads, while laboratory tests are carried

out in controlled facilities. Both methods allow the collection of noise data under real or reproducible conditions and therefore support the scientific substantiation of the measurements (Figure 2.56a).

5) Frequency and Sound Spectrum Analysis: Scientifically based and substantiated, these methods are based on the decomposition of noise into its frequency spectrum. This allows for identifying the dominant frequencies and determining how pavement texture and other tire factors affect the energy distribution in different frequency bands (Figure 2.56c).

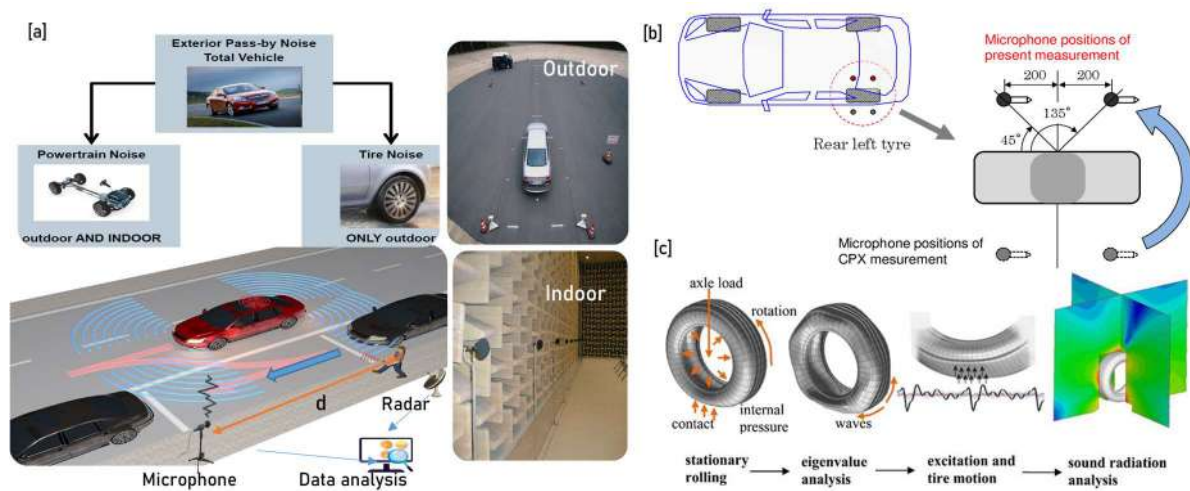


Figure 2.56: Tire/pavement noise methods and modeling. Source adapted by (Biermann et al., 2007).

2.4.4.2. The sound absorption

Studies by (Beranek, 1986; Beranek, 1985) on sound reverberation led to the proposal of absorbent materials to reduce reverberation. Since then, various techniques have been developed to measure and control sound absorption in the automotive industry (Cheer, 2018). To determine the absorption of a material, we use the sound absorption coefficient, represented as Alpha (α). This value, which ranges from 0 to 1, indicates the ratio of absorbed energy to incident energy per unit area (Equation 16). Values close to 0 indicate that materials are poorly absorbent, while those close to 1 have a high absorptive capacity. Since the absorption coefficient of a material varies as a function of the frequency of sound incident on it, it is common to specify an absorption coefficient for different frequency ranges in relation to each type of material. This provides detailed information on how a material interacts with different sound frequencies in terms of sound absorption.

$$\alpha = 1 - \frac{E_r + E_t}{E_i} = \frac{E_a}{E_i}$$

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Where: E_i = is the total incident sound energy, E_r = is the sound energy reflected, E_t = of the sound energy transmitted, and E_a = is the sound energy absorption.

2.4.4.3. Sound absorption mechanism.

The sound absorption mechanism can be described in Table 2.5 as the consumption of sound energy, based on the transformation in heat of part of the energy of the sound wave through the impact of the acoustic waves on the internal walls of the structure's channels and tunnels, together with the vibration of the material through the resonance process.

Table 2.5: Factors influencing sound absorption.

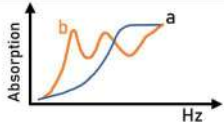
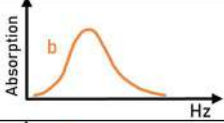
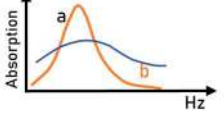
Material	Scheme Absorption/frequency	
Materials: a) Rigid b) flexible		
Helmholtz Resonator		
Absorbing panel: a) without absorption b) with absorption		

Figure 2.57 shows the behavior of the sound absorption process in asphalt mixtures. Most materials absorb acoustic energy through three fundamental principles, each associated with a type of wave transmission (Ling et al., 2021a). However, in the case of solid materials, only the first two are fulfilled:

- **Viscosity effect:** In this principle, air molecules penetrate the material and interact with the pore walls, generating heat and compression effects in the channels through vibrating longitudinal waves.
- **Thermal effect:** When acoustic waves enter the material, they compress the air molecules inside, generating shear stresses and heat in the internal channels through vibratory bending waves.
- **Submergence in the material:** The absorption of sound energy occurs through the resonance that occurs when sound waves impact the walls of

the channels, generating compression in the interior of the material by means of longitudinal acoustic waves.

It is important to emphasize that the third principle does not apply to pavements since solid materials do not allow the sinking of sound waves, limiting their energy absorption to the first two principles mentioned.

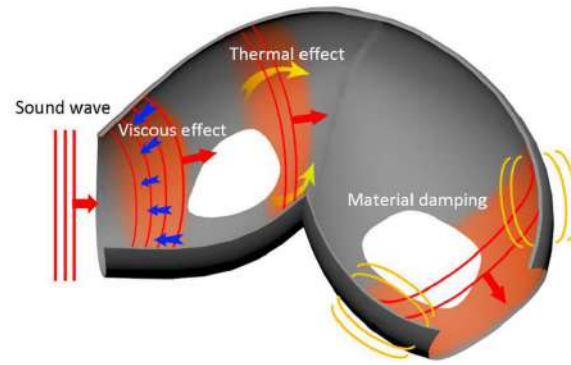


Figure 2.57: Graphical illustration of the sound energy attenuation on the internal void.
Source : (Ling et al., 2021b).

Under acoustic principles, sound absorption is the property that all materials have to absorb acoustic energy, allowing only part of it to be reflected (Sandberg and Ejsmont, 2003; Zhang et al., 2019). When traffic noise is generated, one part of the acoustic wave is reflected by the surface of the pavement, and another part is transmitted through the pavement surface pores (Vieira et al., 2019). Figure 2.58 shows sound reflection on a dense pavement and the partial sound is absorbed on the pavement with high void content through the interconnected internal air voids. The acoustic energy is transformed into heat due to friction with the internal void surface and the tortuosity of interconnected channels.

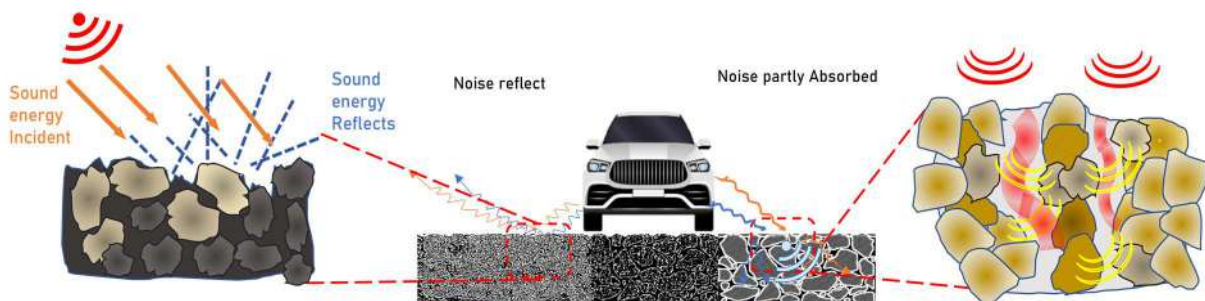


Figure 2.58: Graphical illustration of the sound energy attenuation on the internal void.
Source: Author's elaboration.

The sound absorption in a laboratory is measured by the impedance tube ISO 10534-2, 1998, and its reliability is based on an average of several specimens. The absorption coefficient is expressed as a coefficient, with a value of 1.00 being a material that absorbs 100% of the incident energy and a value of 0.00 meaning that all sound is reflected. The absorption for the normal incidence is evaluated in between the frequency range of 100 Hz - 1600 Hz (Paje et al., 2009), partially within the noise generation of tire tread pitch frequencies which are in the range 500Hz - 1000Hz (Li, 2019).

2.4.4.4. Factors affecting sound absorption.

a) **Internal porosity :** Sound absorption in asphalt mixtures has been described as an energy consumption in the internal walls of the pavement. According to the literature perspective (Islam et al., 2022) the most relevant factors in sound absorption include pore connections, internal resonance, control of the sound propagation path, and sound absorption by pavement porosity.

Another property of the asphalt mixture that plays a crucial role in the sound absorption phenomena is permeability. The interconnectivity of the air void is important in the process of sound absorption. The authors indicated that an increase in asphalt binder content resulted in a lowering of air void content, and thus caused a reduction in permeability (Liu et al., 2009).

However, (Liu et al., 2009) found that although the bitumen content slightly improves the sound absorption response of the asphalt mixture, its effect is negligible. (Alber et al., 2018) studied the effect of air void content on acoustic performances. Results found that the air voids had the effect of increased consumption of the sound energy, maybe because more aggregates tended to create voids in open-graded mixtures. On the other hand, (Alauddin Ahammed & Tighe, 2011), found that the sound absorption of the conventional (dense and durable) AC surfaces was shown to decrease at 1.4% for each 0.1 increase in the density. This is also confirmed by the observation of (Ongel & Harvey, 2010) that dense-graded asphalt mixtures have lower peak and average values of sound absorption coefficients and poorer sound absorption performance. The main reason for this is the larger air voids and connected air voids. (Gardziejczyk et al., 2021a) found that a minimum amount of 11% in the air void content is required for sound absorption of the cylindrical (C) compared to slab (S) and Standard Deviation (SD) of the specimen's asphalt mixture, each specimen 1=16.1Va, 2=18.6Va, 3=22.5Va, 4=20.4Va, 5=24.2Va, 6=22.3Va and 7=25.2Va respectively (Figure 2.59).

By contrast, the optimal solution in the content of voids is in the range of 17–24%. They also indicate the influence of aggregates with grain sizes of 1.18 mm and 2.36 mm on sound absorption.

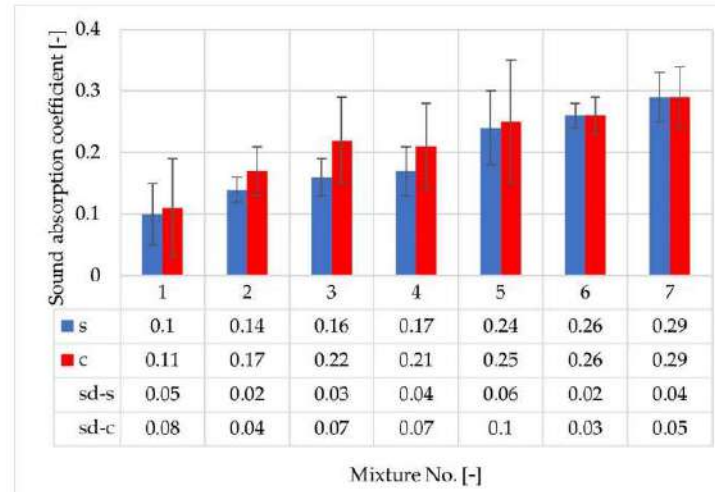


Figure 2.59: Effect of the void content on the sound absorption on the asphalt mixtures.
Source: (Gardziejczyk et al., 2021b).

Porous asphalt mixtures present pore structures that can be classified into effective pores, semi-effective pores, and invalid pores. The pore structures as shown in Figure 2.60a present a principal effect: connected pore excretion, and resonance sound absorption (Figure 2.60b), both controlled the sound propagation path and porous sound absorption. This dynamic factor is similar to the oscillation of a spring. During this vibration process, the amplitude of the vibrations inside the pavement cavity increases and dissipates the larger the network of connected pores.

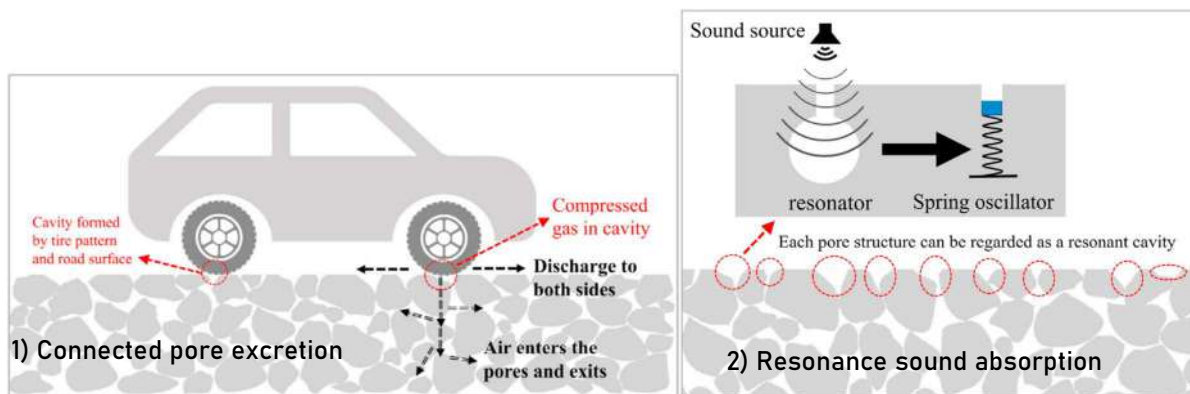


Figure 2.60: Porous structure of the pavement. Source: (Ling et al., 2021a).

The sound absorption process means that pavements with a high percentage of air void content are able to absorb a part of the sound generated by any source of a vehicle in motion, i.e., engine, aerodynamic, and rolling noise. The control of sound propagation in porous pavement is due to connected voids (Figure 2.61a). Moreover, it is necessary the presence of tunnels connecting between pores of asphalt mixtures to achieve a real attenuation of the acoustic energy inside the mixture Figure 2.61b. However, ‘unconnected’ air voids of asphalt mixtures limit the effectiveness of the sound absorption phenomenon (Saurenman et al., 2005). Sound waves propagate repeatedly in the internal pores, they cause air vibrations in the pores and on the tunnel walls. The air molecules generate friction and thermal conduction with the effect of the surface material, gradually transforming the sound energy into heat and dissipating it. Simultaneously, the viscous resistance of the air in the pores also consumes part of the sound energy. Therefore, the sound energy reflected in the human ear has less energy than that of the original sound due to the continuous conversion and dissipation of energy during the process of interaction with the complex porous structure of the pavement connection.

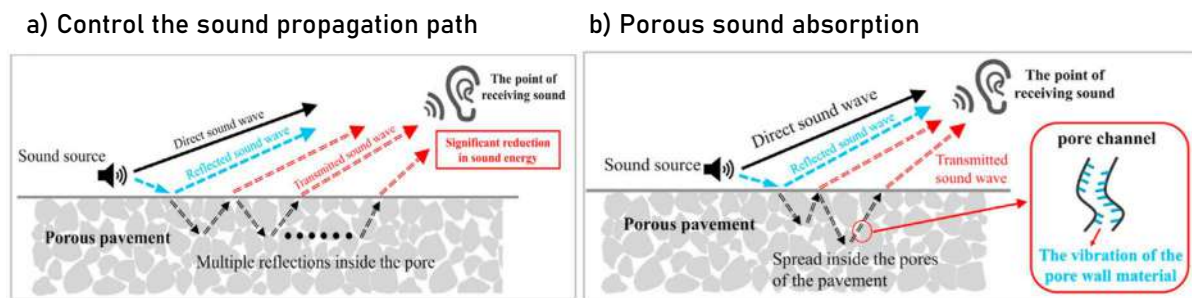


Figure 2.61: Effectivity of the porosity on the sound absorption process. Source : (Mohd Hasan et al., 2017).

b) Surface texture : Figure 2.62 shows the effectiveness of the texture and how the channels connect with the pores. Some pores are not connected, which prevents them from fulfilling the sound attenuation mechanism. On the other hand, when the pores opened by the pavement texture are effectively connected to the texture holes, a better sound attenuation phase is achieved. In addition, there are pores with a reduced connection that fail to complete the sound attenuation phase.

In asphalt pavements, when the sound waves are incident on the specimen surface as plane waves, one part of the sound waves are absorbed by the specimen, and the other part of sound waves are reflected by the surface (Ling et al., 2021b). This parameter is influenced by the diameter of the aggregate, its grain size configuration, the ratio of fines to coarse, and the binder content. These factors

govern the ability of the texture to allow sound waves to enter and connect with the pores, thus affecting the overall effectiveness of sound absorption in porous asphalt pavement.

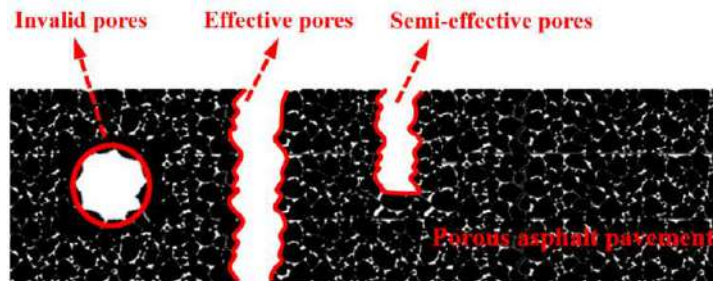


Figure 2.62: Configuration of the connectivity of the porosity. Source: (Ling et al., 2021b)

The surface texture has a major influence on noise generation/reduction in the contact area between the tire/pavement (Nelson, 1986). Figure 2.63 illustrates the conversion of noise into heat energy through the vibration-friction process, contributing to the pore friction mechanism that aids in sound absorption. The effectiveness of sound absorption primarily relies on the ease with which the sound wave enters the open pores of the surface. As the sound wave penetrates these open pores, its absorption is further enhanced through multiple reflections occurring within the void. According to (Allard, 2018), the absorption rate will depend on the friction with the surface structure and the intrinsically interconnected cavities, which interact in the dissipation of the propagated sound energy.

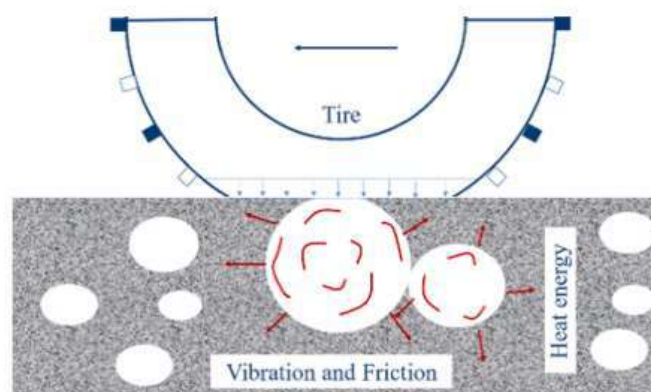


Figure 2.63: Scheme of noise attenuated in asphalt pavement. Source: (Lou et al., 2022).

Studies have shown that pavements with a positive texture (more peaks) usually have higher noise levels than those with a similar macrotexture but arranged in different patterns (Ejsmont et al., 2014). The friction coefficient is often used to

evaluate roadway surface characteristics such as texture, friction, and tire/pavement noise (Fang et al., 2020). Digital image technology can be used to characterize the distribution characteristics of surface textures and predict skid resistance and tire/pavement noise reduction (Weng et al., 2022).

c) Temperature: Temperature significantly affects asphalt mixtures, particularly the binder component. There are methods to determine whether the binder is thermoplastic and susceptible to temperature changes, which subsequently impact both the mechanical and functional behavior of the asphalt mixture. In terms of the acoustic studies the results of (Anfosso-Lédée & Brosseaud, 2009) show that for every 1°C increase in ambient temperature, the tire-pavement noise of dense asphalt pavement is reduced by 0.1 dB(A), and for porous asphalt pavement, the reduction is 0.06 dB(A). Contrary to this statement, other authors suggest that the effects of temperature on tire/road noise are linear phenomena (Bühlmann et al., 2021). On the other hand, other researchers have observed that noise generation changes with temperature variations, as illustrated in Figure 2.64. Furthermore, it has been shown that applying a single generic correction factor is insufficient, highlighting the need for a semi-generic approach that considers the main types of road surfaces and the types of asphalt mixture.

It is important to note that at any temperature of the pavement there is noise generation by traffic. However, when temperatures are excessively high, the generation of noise can be smaller, with variations that depend on the type of mixture (Tang et al., 2016; Liu et al., 2012). This concept can be seen in Figure 2.64 (Bühlmann et al., 2021), which illustrates this concept, indicating that an excessive increase in temperature up to 85% caused a reduction in the asphalt mixture's acoustic capacity. (Haider et al., 2014) recommend that noise measurements should not be made if the ambient air temperature is below 15 ° C or above 35 ° C and propose a temperature correction of $\pm 0.09 \text{ dB (A) / } ^\circ \text{C}$ considering a reference air temperature of 20 ° C (Ejsmont et al., 2014, Bühlmann et al., 2021, Del Pizzo et al., 2020a, Mioduszeewski et al., 2018) with noise being higher at 15 ° C and lower at 35 ° C. This underscores that it is not entirely clear and the importance to understanding and managing the effects of temperature on asphalt properties, that is important to achieve optimal acoustic performance.

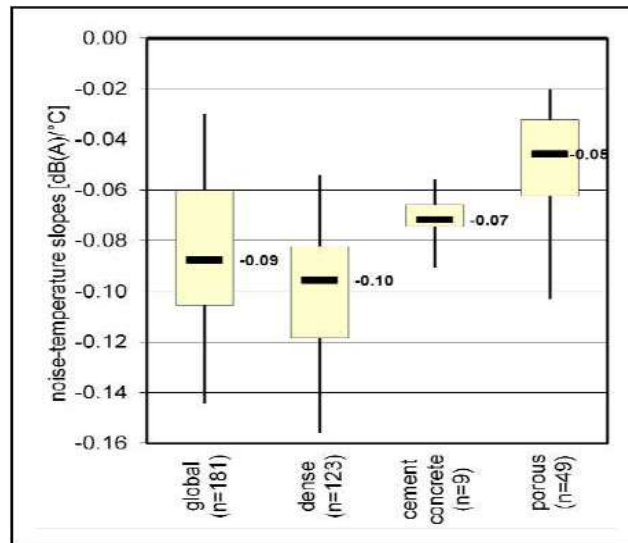


Figure 2.64: Effect of the temperature on the noise generation. Source : (Bühlmann & Ziegler, 2011).

Studies by (Zhang et al., 2020) show the effect of the temperature of porous mixtures. The mean sound absorption coefficient increases with the increased temperature in specimens of asphalt mixtures. However, given this variability, the level of noise absorption at different temperatures is still unclear and further research is needed.

d) Attenuation of noise by dynamics stiffness : The vibration of pavement for more researchers is linked to the acoustic properties (Mohammad Hassan et al., 2023; Schiavi et al., 2018; Vázquez, 2015). Other researchers are found related to noise generation (Kim et al., 2009; Schiavi et al., 2005; Vázquez & Paje, 2016). The inherent stiffness of asphalt mixtures is related to the mechanical behavior of the asphalt mixtures (Tayebali et al., 1994). In the area of acoustics, the stiffness measurement is related to mechanical impedance (Li et al., 2016a; Wahengbam & Rajbongshi, 2015). All of the studies achieved the assessment of the vibrations and control the damping mechanics of the surfaces. So, it is important determining elastic vibration behavior of the asphalt mixture, which influences vibration attenuation. Previous studies have reported that tire/pavement noise may be affected by the dynamic stiffness or mechanical impedance (Czech & Gardziejczyk, 2020) which are considered as a related amplification/reduction noise generation mechanism (Sandberg & Ejsmont, 2003).

Currently the evaluation of dynamic stiffness using the standard EN 29052-1. Figure 2.65a resonance method involves the hammer method Figure 2.65b shows the

accelerometer method fixed on the load plate and shaker the force response was measured by the impedance head.



Figure 2.65: a) Hammer method and b) Shaker excitation was used to evaluate the dynamic stiffness.(Urbán & Roozen, 2020).

The dynamic stiffness presents a great correlation $R^2 = 0.74$ (Figure 2.66) (Crispin & Mertens, 2013) with the compressibility.

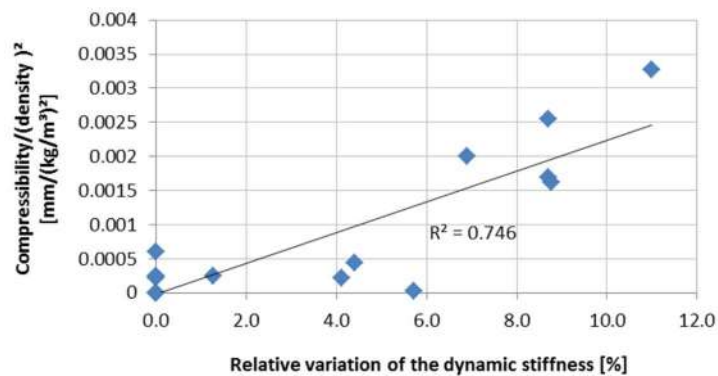


Figure 2.66: Correlation between the variation of dynamic stiffness and the compressibility/density. (Crispin & Mertens, 2013).

The observation of results across various materials, following the measurement of dynamic stiffness, indicates a reduction in impact noise and the propagation of vibrations. This effect is particularly noticeable in materials exhibiting low dynamic stiffness, often associated with low density (Dikavičius & Miškinis, 2009). In the context of asphalt mixtures, the impact of poroelastic properties on rolling noise has been affirmed through dynamic stiffness measurements conducted under real conditions. Dynamic stiffness plays a crucial role in influencing the varying levels of tire/road noise on poroelastic surfaces. From an acoustic perspective, there

is a necessity to delve deeper into research across different asphalt mixtures to comprehend the nuanced dynamics involved (Bietz & Wittstock, 2018).

Another noteworthy aspect is that the dynamic stiffness properties of resilient materials exhibit a decrease as the thickness of the resilient material increases. This decrease is associated with a notable reduction in sound levels. Specifically, materials with low dynamic stiffness show a correlation between dynamic stiffness and impact sound levels as show Figure 2.67 (Kim et al., 2009).

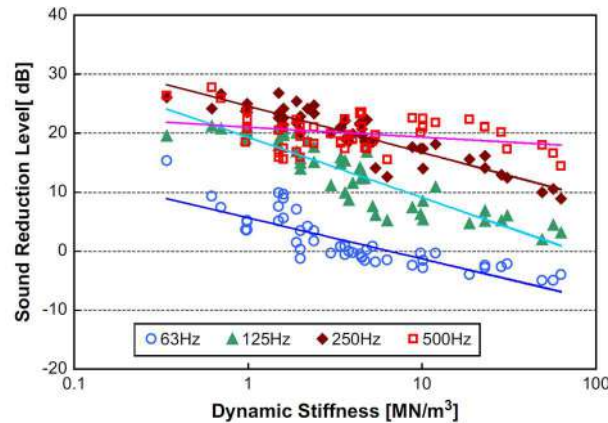


Figure 2.67: Correlation between the dynamic stiffness and heavyweight impact sound reduction level. Source : (Kim et al., 2009).

The result of hot asphalt mixture (HMA) compared to other materials resin and crumb rubber (CR) and steel is evaluated in the laboratory and shown in Figure 2.68. The result on asphalt mixtures does not present a clear view and terms of the mechanic properties present weak results (Praticò et al., 2021).

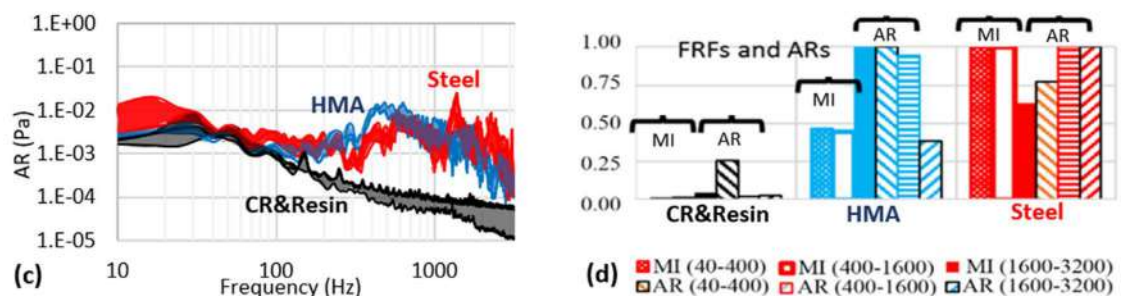


Figure 2.68: Dynamic spectra and result of the dynamic stiffness. Source : (Praticò et al., 2021).

The initial evaluation of roads, conducted by (Vázquez, 2015), involved field assessments on pavements to discern their contribution to tire/pavement noise generation. The analysis revealed a positive correlation between pavement density

and dynamic stiffness. Notably, dense asphalt mixtures exhibited higher values of dynamic stiffness, while BBTM 11 displayed lower values. The influence of crumb rubber (CR) was assessed (Figure 2.69) only in one grade, necessitating a comprehensive evaluation across all asphalt mixtures, including dense, semi-dense, and open-grade formulations. Further assessments are crucial to comprehensively understand the impact of CR on different asphalt types.

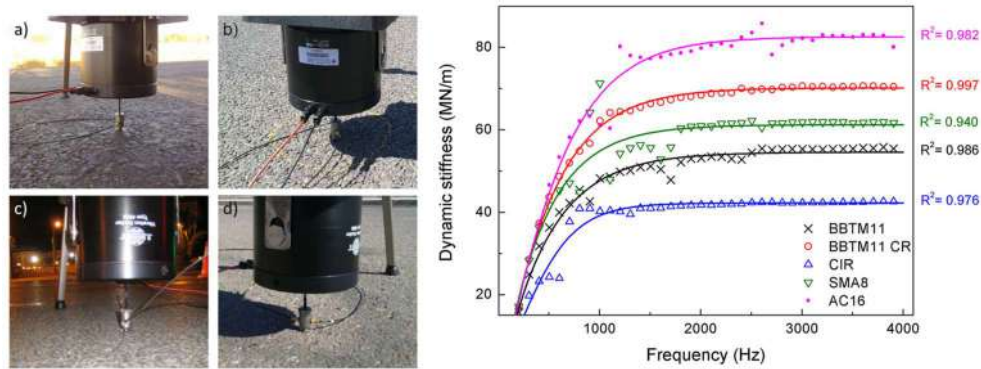


Figure 2.69: Dynamic spectra of real surface pavement. Source : (Vázquez, 2015)

2.5. Self-sensing

2.5.1. Self-sensing pavements as a multifunctional alternative

The performance of transportation infrastructures is impacted by the deterioration and degradation of road conditions due to both operational and environmental factors. Monitoring the asphalt mixture layer of pavements is crucial for addressing these challenges (Wang et al., 2018). With the technological advancements in transportation systems' digitalization, an essential role is played in traffic management by technologies as the Internet of Things (IoT) that may significantly improve communication by expanding connection, supplying real-time data of the infrastructure, improving real condition of the pavements, and developing smart applications (Ali, 2023). However, the sensing capabilities of pavements are still under development, generating considerable interest in this area.

The concept of Self-sensing pavement has attracted attention for its potential sensorial capabilities in monitoring pavements or smart road pavement monitoring systems. Self-sensing pavement These innovative systems can autonomously monitor their condition and provide real-time feedback. Traditional imbedded sensors, while advantageous, have several downsides (Gulisano et al.,

2024). These include high prices, considerable labor and time requirements, environmental sensitivity, limited accuracy, and sophisticated data analysis. To address these issues, intrinsic self-sensing cement-based materials have been used for Structural Health Monitoring (SHM) in civil engineering projects. Pavement instrumentation with different kinds of embedded sensors is generally employed to acquire long-term monitoring data, as shown in Figure 2.70. However, several limitations of intrusive sensors are related to the risk of premature damage and deterioration. This strategy provides a more cost-effective and efficient alternative, eliminating some of the limitations of previous nondestructive methods.

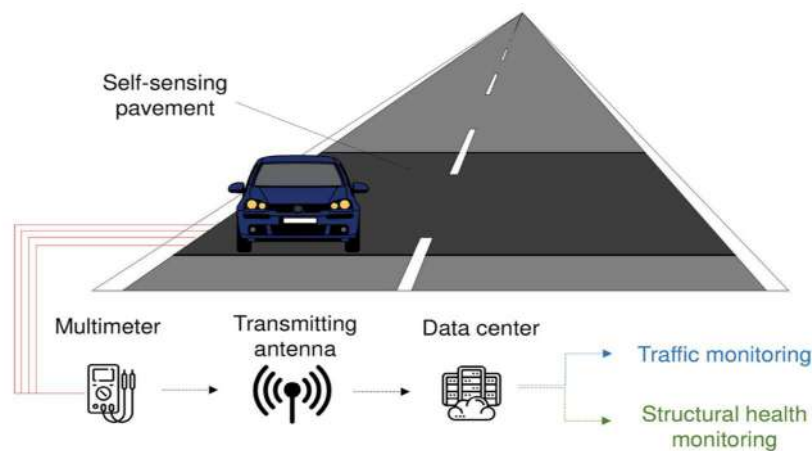


Figure 2.70: Self sensing monitoring pavement: Source: (Gulisano et al., 2024).

This technology holds promise for significantly enhancing pavement maintenance and management, leading to increased efficiency and cost-effectiveness.

The nanomaterials used for self-sensing are categorized as carbon black fibers, nanofibers, and carbon nanotubes. An example of these materials are (graphene nanoplatelet and graphite plate). They were used in the past for damage detection in concrete (Roshan et al., 2024). These findings indicate that the self-sensing Carbon Nanotubes (CNT)/cement composite has great potential for traffic monitoring use, such as in traffic flow detection, weigh-in-motion measurement, and vehicle speed detection (Han et al., 2009).

However, further research is needed to fully understand the effect of crumb rubber (CR) on the self-sensing properties of asphalt mixtures and to develop more efficient and effective methods for its incorporation. CR can contribute to asphalt mixtures by providing flexibility during the loading and unloading cycles caused

by traffic. Additionally, CR could enhance the effectiveness of piezo resistivity assessment.

In conclusion, the use of CR in self-sensing pavements represents a promising area of research with the potential to significantly improve the maintenance and management of pavements. Further research is needed to fully understand the effect of CR on the self-sensing properties of asphalt mixtures and to develop efficient and effective methods for its incorporation.

2.5.2. Self-sensing in asphalt mixtures

The state of the art regarding use of CR in self-sensing pavements is a relatively new and emerging field of research. With the increasing demand for smart infrastructure and the need for real-time monitoring of pavement conditions, there has been a growing interest in developing self-sensing pavements that can provide information on various properties, such as structural integrity, load-bearing capacity, and skid resistance. The addition of CR to asphalt mixtures has been shown to have a significant impact on the mechanical properties of the material, and it is believed that it may also influence its sensing properties. However, research in this area is still limited, and much more needs to be done to fully understand the potential benefits and limitations of using crumb rubber in self-sensing pavements. This chapter aims to provide an overview of the current state of the art and identify research opportunities and challenges in this field.

2.5.3. Advantages self-sensing of asphalt mixtures

The state of the art in self-sensing of asphalt mixtures has shown several advantages over traditional pavement monitoring methods. These advantages include:

- Real-time monitoring: The self-sensing capability of asphalt mixtures provides real-time information about the condition of the pavement, which can help in the early detection of any issues and reduce the risk of sudden failure (Gulisano et al., 2023).
- Increased efficiency: With self-sensing, monitoring can be automated, reducing the need for manual inspection and increasing efficiency.
- Improved accuracy: The self-sensing technology provides more accurate and detailed information about the pavement, as compared to traditional methods,

which can help in making informed decisions regarding maintenance and repair (Vittorio et al., 2014).

- Cost-effective: Self-sensing technology can help reduce maintenance and repair costs, as issues can be detected early and addressed on time (Aygün et al., 2023).
- Environmental benefits: Self-sensing pavements can also have environmental benefits, as they reduce the need for manual inspection and reduce the carbon footprint associated with traditional monitoring methods (Gulisano et al., 2024).

Overall, the use of self-sensing technology in asphalt mixtures has the potential to revolutionize the way we monitor and maintain our roadways and pavements, providing numerous benefits and helping ensure the safety and longevity of our infrastructure.

2.5.4. Additives that improve of self-sensing of asphalt mixtures

The limited sensing properties of conventional asphalt mixtures necessitate the use of additives to enhance sensing efficiency, thus improving the self-sensing capabilities of pavements. Existing literature highlights that asphalt inherently lacks sensing properties, prompting the incorporation of Electric Arc Furnace Slag (EAFS) materials to imbue sensing capabilities into asphalt mixtures (Gulisano et al., 2022). Consequently, Carbon Fiber (CF) compositions have emerged as crucial elements in enhancing the sensing properties of conventional asphalt mixtures.

Previous research has shown that the sensing properties of asphalt mixtures can be significantly enhanced to enable multifunctional capabilities. These capabilities primarily involve sensorial detection of traffic and the ability to quantify the weight of vehicles in traffic volume assessments. An effective solution for enhancing the conductivity of asphalt mixtures involves the addition of Carbon Fiber (CF) and Graphite Powder (GP) (Figure 2.71)(Ullah & Yang, 2021). This combination has demonstrated superior performance compared to individual additives. Similar findings have been reported by other authors, who have successfully improved conductivity through the addition of CF and GP (Leow et al., 2023).

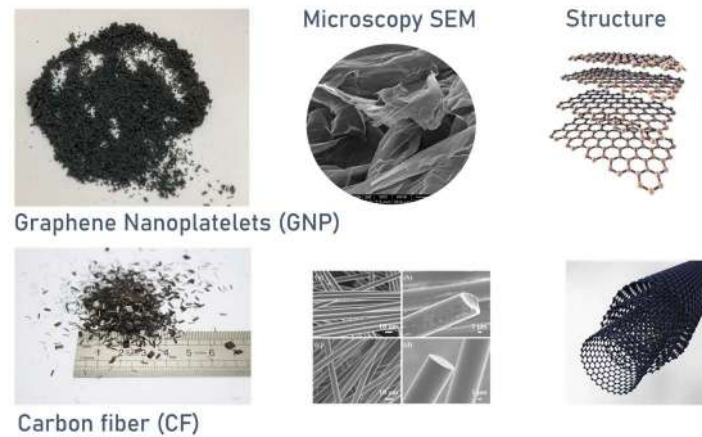


Figure 2.71: Carbon fibers and graphene additives: Source: Autor elaborations.

2.6. Conclusion of the state-of-the-art

The literature review conducted in Chapter 2 provided insights into the most significant published works on the use of crumb rubber in asphalt mixtures and its effects on volumetric properties, permeability, mechanical, texture, skid resistance, acoustic capabilities and self-sensing properties. Given the novelty and interdisciplinary nature of these topics, the decision was made to analyze the state of the art and the fundamental principles of the impact of crumb rubber on different asphalt mixtures, focusing primarily on modifications to texture, skid resistance, acoustic properties and self-sensing assessment.

It has been reported that crumb rubber can be incorporated into asphalt mixtures through both dry, semi-wet, and wet processes. The incorporation of crumb rubber at varying contents may present advantages and disadvantages during the service life of the pavement. The primary challenges in using crumb rubber in asphalt mixtures stem from the dimension sizes of the crumb rubber particles and the digestion time. And second, temperature control during compaction is crucial.

Furthermore, the effect of crumb rubber on asphalt mixtures typically involves modifications to the bitumen, which can result in changes to characteristics such as volumetric properties, mechanical strength, texture, skid resistance, acoustic capabilities, and influences on the assessment of piezo resistivity.

For this reason, some enhancements to incorporate crumb rubber into asphalt mixtures have been developed to characterize its influence on volumetric-

mechanical properties, texture, skid resistance, acoustic behavior, and self-sensing assessment.

a) **Texture, skid resistance, and sound absorption:** The surface properties of conventional asphalt mixtures tend to decrease. Some authors found that the addition of additives to the asphalt mixtures can improve the texture and consequently skid resistances and acoustic efficiency. The addition of the crumb rubber seems to be the best solution. And valorization could be contributing to the reduction of noise pollution and the circular economy.

b) **Lack of assessing the benefits and deficit of crumb rubber:** There is a gap in understanding the actual advantages of incorporating crumb rubber in terms of eco-suitable and safe pavement, particularly in enhancing skid resistance pavements. However, it is essential to highlight the real acoustic capabilities to improve the functional performance of dense, semi-dense, and open-graded asphalt mixtures. This type of physical acoustic analysis enables the evaluation and optimization of sound absorption capacities, and the noise generation helping define the optimal content for incorporation in asphalt pavements.

c) **Asphalt Binder Improvement Analysis:** It has been found that crumb rubber can modify the chemical properties of asphalt binders. However, there are characteristics such as cohesion, friction, and resistance to mass loss at the interface that need further explanation.

d) **Contribution to Self-Sensing Assessment:** Self-sensing pavement is a new line of research with increasing interest in multifunctional roads. However, CR is not a sensory material; its composition primarily consists of elastic components. The main contribution of CR in asphalt pavements is to enhance mechanical behavior. The potential self-sensing contributions of CR need further explanation and exploration.

On the other hand, the concept of eco-suitable and multifunctional pavements using crumb rubber has not yet been fully investigated. Despite numerous advancements in asphalt mixtures, exploration of their skid resistance, acoustic capabilities and self-sensing properties has been neglected. However, research on the incorporation of crumb rubber into asphalt mixtures still raises the question of whether it is an innovative eco-sustainable material for asphalt mixtures and requires urgent investigation.

2.7. Research objectives

Based on that, the specific objectives of the doctoral thesis were as follows. The aim of this work is to investigate and explain in detail how **the crumb rubber (CR) affects the volumetric, mechanical and functional properties of asphalt mixtures, including skid resistance, and acoustic capabilities. Additionally, the influence of crumb rubber on the piezoresistive response of asphalt mixtures is examined.** The study contributes to this field by focusing on three research objectives (O):

O1 To gain insight into how crumb rubber affects the volumetric and mechanical characteristics of asphalt mixtures.

While previous research has extensively explored the factors influencing the rheological properties of CR in asphalt binders and specific mixtures, this thesis investigates the impact of CR on volumetric characteristics such as densities and permeability. This study aims to fill gaps in the current knowledge regarding the influence of CR on these volumetric characteristics. Through this research, the thesis seeks to provide comprehensive insights into the role of CR and its influence on the behavior of continuous, discontinuous, and open-graded asphalt mixtures.

Concerning this objective, the following specific objectives are defined:

- **Determine how CR interacts with the volumetric characteristics of the different asphalt mixtures, considering other parameters such as permeability.**
- **Evaluate the effectiveness of CR by the dry process incorporated in the behavior and mechanical performance, including mass loss by Cantabro test in the different asphalt mixtures.**
- **Categorize the parameters positively affected by the presence of CR, identifying the volumetric and mechanical benefits from its inclusion in the mixtures.**

O2 Evaluation of the effect of CR on the surface texture and skid resistances of asphalt mixtures.

The study aims to comparatively explore the impacts of CR on the surface texture of dense, semi-dense, and open-grade asphalt samples. Pavement surface texture is crucial for road safety. While previous research has often relied on fractal methods and traditional measurements, this thesis collects data at the macrotexture and microtexture levels in the laboratory by laser scanning. By

methodologically examining the impact of CR on texture parameters, it promotes the use of more resilient and environmentally friendly asphalt mixtures. The thesis aims to fill a crucial research gap in understanding the effectiveness of microtexture and macrotexture on skid resistance. Related to this objective, the following specific objectives are defined:

- Evaluate factors that influence the texture characteristics of asphalt mixtures with the incorporation of CR by dry process.
- Determine how CR influences texture evaluation by traditional and advanced methods on asphalt surfaces.
- Evaluate the evolution of the texture and the skid resistance at low and high speeds with different degrees polishing and assess the influence of the CR in the process.
- Evaluate the resistance to tangential stress, which leads to surface mass loss in asphalt mixtures, and analyze the effect of CR in this process.

O3 Impact of CR on sound absorption and its influence at different temperatures.

The thesis aims to examine the effects of incorporating (CR) in asphalt mixtures on acoustic capabilities and to determine options for sustainable asphalt mixtures. Recognizes the need for further testing of CRs impact on sound-reducing capabilities. By investigating how the use of CR can encourage these sound-reducing mixtures. Despite the widespread adoption of these asphalt mixtures, their comprehensive effects on CR utilization and promotion of sound-reducing behavior remain under-researched, which this thesis aims to address. With respect to this objective, the following specific objectives are defined:

- Analyze the effectiveness of incorporating CR in the dry process to promote acoustic performance, measuring its direct influence on the use of CR as a sustainable asphalt mix alternative.
- Understand the impact of CR on thermal evaluation of sound absorption.
- Examine noise attenuation characteristics and their integration into vibration modes in noise generation.
- Propose evidence-based improvements for incorporating CR, aiming to optimize its effectiveness in encouraging more sound-reducing and sustainable mix choices while addressing potential current challenges.

O4 Impact of CR on Self-sensing influence in asphalt mixtures

The thesis aims to examine the contributions of crumb rubber (CR) in enhancing the self-sensing capabilities of asphalt mixtures. Despite the widespread adoption of these mixtures, their comprehensive effects of CR on self-sensing behaviors remain under-researched. This research seeks to address this gap by understanding the role of CR in the self-sensing performance of asphalt mixtures:

- Evaluate the sensing properties induced by the CR effect on asphalt mixtures under stress (piezoresistive effect).
- Demonstrate improvements based on tests of CR incorporation, aiming to contribute effectiveness self-sensing properties in pavements and address current challenges.

3. Methodology and mixtures under study

Road pavement, from an engineering perspective, consists of multiple layers designed for the purpose of ensuring safe and comfortable vehicular traffic along their length. Initially, pavements exhibit a solid mechanical stability that allows them to withstand loads and climatic variations.

In general, pavements are composed of sections established according to design criteria, as illustrated in Figure 3.1:

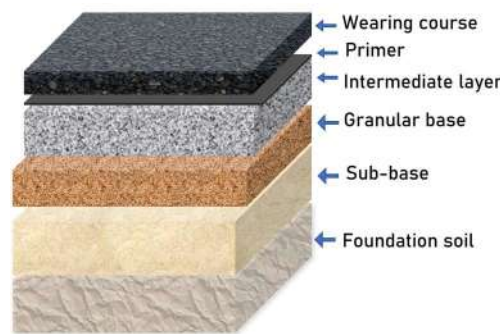


Figure 3.1: Structure scheme of the pavements. Source: Author's elaboration.

The different layers of pavement play specific roles in the structure: the wearing course resists vehicular wear, the primer improves adhesion, the binder course provides structural strength, the granular base distributes loads, the sub-base contributes to stability and drainage, and the foundation soil provides support for the entire structure. Each of these layers plays a crucial role in the pavement structure, contributing to the safety and durability of the road.

Asphalt Pavements consist mainly of layers of a bituminous matrix, with a proportion of approximately 95% of aggregate and 5% by binder by the mass of the mixture. These proportions are determined according to the required structural response, following engineering criteria to achieve good compaction to ensure durability and the ability to satisfactorily resist stresses and deformations.

3.1.1. Asphalt-wearing courses under study.

As per European regulations, asphalt wearing course design adheres to calculated proportioning methods, to achieve characteristics like voids, surface texture, and drainage (PG-3, 2019). These factors depend heavily on traffic effects and weather conditions, crucial for meeting pavement surface functionality criteria such as

adhesion, rolling resistance, and skid resistance. An asphalt mixture comprises a granular matrix with aggregate size reflecting the maximum diameter distribution, often characterized by discontinuities in particle size expressed as percentages passing through various aggregate-size sieves in mm. The granulometric distribution of compositions of the asphalt mixtures under study is shown in Figure 3.2.

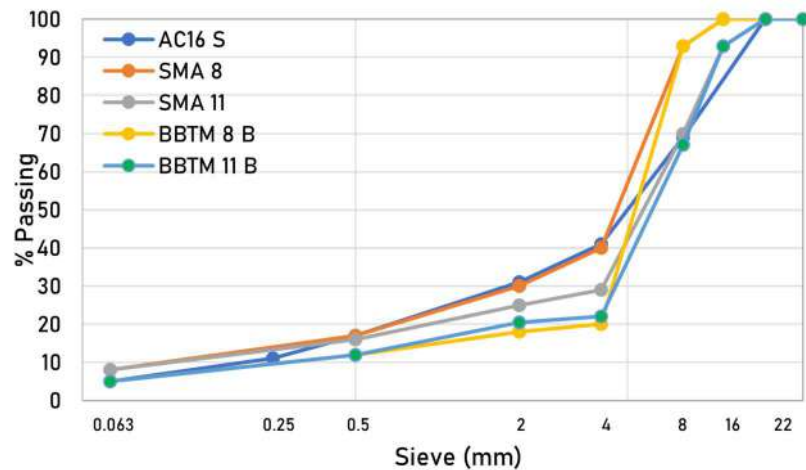


Figure 3.2: Granulometric curves of the mixtures under study. Source: Author's elaboration.

The balanced granular structure in the asphalt wearing course is crucial for strength and stiffness in the pavement structure. Graphically represented in the granulometric distribution, optimization of the gradation curve plays a key role to successfully address the stress to be faced by the asphalt layer. Different curves, ranging from dense to semi-dense to open, are employed based on the layer position, the stress levels and the functionality to be accomplished.

This balance significantly influences the mechanical and dynamic properties of the pavement. The composition of the mixture classified as dense, semi-dense, or open grade depends on the specific percentage of particles within different aggregate dimensions. This gradation generates internal voids, density, and surface texture.

Coarse fractions contribute to increased internal voids and reduced binder content, resulting in pavements less prone to rutting. Fine fractions aid in producing semi-dense mixtures and ensure good workability. However, an excess of fine fractions can compromise mechanical stability by densifying the internal structure.

Increasing coarse fractions enhances contact points, providing greater mechanical strength. Continuous graded asphalt mixtures exhibit a closed structure with low

internal void percentages (typically 4-6%). Discontinues graded mixtures have intermediate aggregate dimensions, allowing voids in the range of 4-7%. Mixtures with an open structure, featuring a void ratio between 12 - 18% (Art 543 -PG-3), offer advantages, particularly in drainage and friction compared to dense mixtures. The mixtures under study in this research were Asphalt Concret AC; SMA: Stone Mastic Asphalt, and BBTM: Beton Bitumineux Tres Minces. They are detailed in Table 3.1.

Table 3.1: Specifications for the compositions of the asphalt mixtures under study (PG-3)

Type of asphalt mixture	Minimum bitumen content (%)*	Air void content (%)
ACS16	4.5	4-6
SMA 8	6	4-6
SMA11	5.8	5-7
BBTM8B -11B	4.75	>12 - <18

*Over the mass of the mixture

The mineral skeleton that composes asphalt mixtures exerts great dominance in the aggregate granulometry interaction, directly impacting mechanical stability and sensitivity to permanent deformations. The percentages of these particles influence the mechanical and dynamic properties. The use of different gradations curves depends on the layer and the level of stress it will have to withstand, as well as on the functionalities that relay on it: permeability, acoustic performance, etc. Gradations from dense semi-dense to open grade can be observed in Table 3.2.

Table 3.2: Type of the asphalt mixtures from aggregate gradation of several types of asphalt mixtures.

Type of mixture		Sieve, mm UNE EN 933-2										
		32	22	16	11.2	8	5.6	4	2	0.5	0.25	0.063
Dense	AC16 D		100	90-100		64-79		44-59	31-46	16-27	11-20	4-8
	AC22 D	100	90-100	73-88		55-70			31-46	16-27	11-20	4-8
Semi dense	AC16S		100	90-100		60-75		35-50	24-38	11-21	7-15	3-7
	AC22S	100	90-100	70-88		50-66			24-38	11-21	7-15	3-7
BBTMA	BBTM8A				100	90-100	50-70	28-38	25-35	12-22		7-9
	BBTM11A			100	90-100	62-82		28-38	25-35	12-22		7-9
BBTMB	BBTM8B				100	90-100	42-62	17-27	15-25	8-16		4-6
	BBTM11B			100	90-100	60-80		17-27	15-25	8-16		4-6
SMA 8					100	90-100		30-45	25-35	12-22		7-9
SMA11				100	90-100	55-85		22-33	20-30	12-20		6-10

3.1.2. Surface macrotexture and skid resistance of the mixtures.

Table 3.3 details the minimum values required for the surface macrotexture and the skid resistance of different asphalt mixtures (PG-3).

Table 3.3: Minimum values of surface texture (MTD) and skid resistance (CRT)

Type of asphalt mixture	Macrotexture EN 13036-1	Skid résistance EN 41201IN
ACS16	≥ 0.7	≥ 65
SMA 8	≥ 0.9	≥ 60
SMA11	≥ 0.10	≥ 60
BBTM8B -11B	≥ 1.5	≥ 65

3.1.3. Types of Asphalt wearing course mixtures.

Within the diverse granulometric compositions of asphalt wearing mixtures, the selection is based on achieving optimal mechanical performance and skid resistance. Continuous Asphalt Concrete (AC) mixtures are commonly used on medium-traffic roads, while discontinuous Stone Matrix Asphalt (SMA) mixtures are preferred in areas with heavier vehicular loads. Open-graded Permeable Asphalt (PA) or Beton Bitumineux Tres Minces (BBTM B) mixtures stand out for excellent skid resistance, good surface drainage, and exceptional texture. BBTM mixtures, in particular, offer a favorable combination of friction, effective surface drainage, and outstanding texture. SMA mixtures, known for their excellent texture with a grain size of 0/4 diameters and a higher binder proportion, have gained widespread adoption in Germany and Great Britain due to their performance. Figure 3.3 illustrates the samples produced in this study; AC, SMA, and BBTM surfaces.



Figure 3.3: Different surface texture of the asphalt mixtures under study. Source: Author's elaboration.

While AC mixtures are traditional and proven for their mechanical strength, they exhibit lower properties in terms of texture and permeability. Despite these characteristics, this research includes their evaluation in various aspects. The techniques and surface characterization of asphalt mixtures will be detailed in the methodology chapter.

3.1.4. Crumb Rubber

The crumb rubber (CR) from end-of-life tires (ELT) used in this study were produced by mechanically grinding tire buffing and scrap tire rubber. Is produced in Spain from 50% cars and 50% trucks tires (Figure 3.4). The scrap tires were reduced to particle sizes ranging from 9.52mm to 40mm mesh, and over 90% of the steel was removed during the process. The features of CR are reported in Table 3.4.

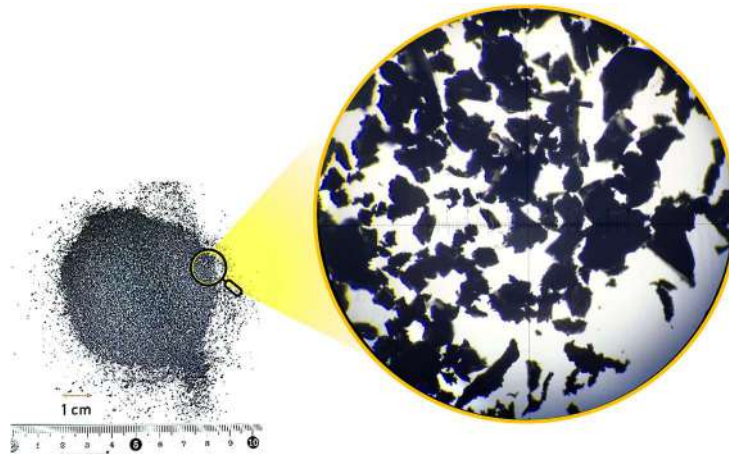


Figure 3.4: The maximum crumb rubber size is 0.6 mm. Source: Author's elaboration.

Table 3.4: Properties and composition of the crumb rubber used.

Properties	Description
Density	1.1 g/cm ³
Color	Black
Particle morphology	Irregular
Water content	<0.75%
Textile Fiber content	<0.5% in weight
Metal content	<0.1% of the rubber weight

The CR used in this study is processed and produced in Spain. The size gradation of CR is summarized in Table 3.5 and Figure 3.5.

Table 3.5: Gradation of crumb rubber

Sieve (mm)	Passing (%)
2	100
1.5	100
1	100
0.5	94.1
0.25	23.7
0.125	3.7
0.063	0.4

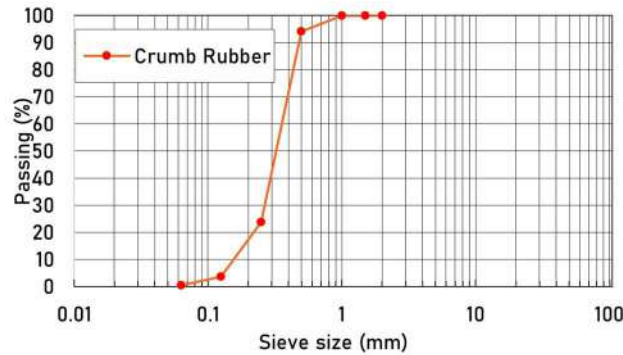


Figure 3.5: Granulometric distribution of the crumb rubber. Source: Author's elaboration.

3.1.5. Carbon fiber (CF)

To easily assess the electrical response of piezoresistive rubberized asphalt mixture, Carbon fiber is used to reduce the electrical resistance of the bituminous mixtures, SIGRAFIL® C C3-4.0/240-E100 carbon fibers (CF or CFL) with a length of 3 mm and a diameter of 7 μm were used. And the other hand, the carbon fiber fine (CFf) is used to Cohesion test, is which have the appearance shown in Figure 3.6.



Figure 3.6: Carbon fibers large and Carbon fiber fine.

3.1.6. Electric Arc Furnace Slag (EAFS)

EAFS has been used for the self-sensing studies due to its electrical characteristics, with a diameter of 0.063 /2 mm and a specific density of 3.65 g/cm^3 . It will be used exclusively for self-sensing study. Figure 3.7. Fine aggregates (0/4 mm) and filler consisted of Electrical Arc Furnace Slag (EAFS) with a specific gravity of 3.78 g/cm^3 as shown in Figure 3.8. Previous research has shown that incorporating fine EAFS can reduce the electrical resistance of the mastic.



Figure 3.7: Electric arc furnace slag (EAFS).

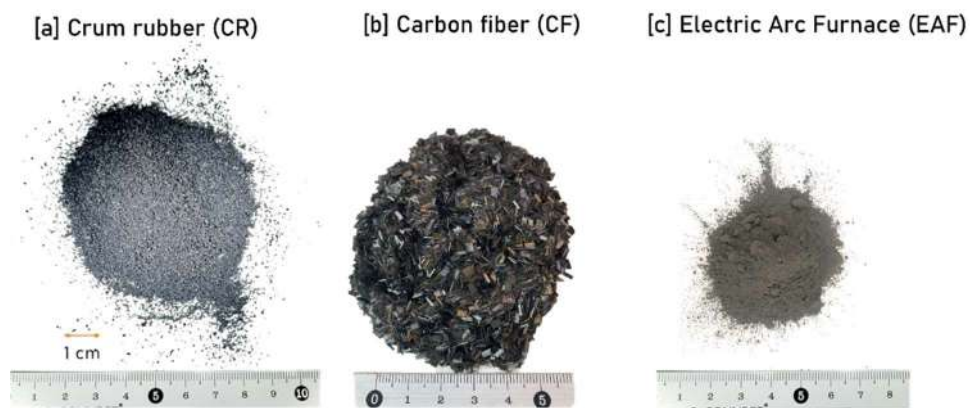


Figure 3.8: Crumb rubber, Carbon fiber and Electrical Arc Furnace Slag.

The use of CR in asphalt mixtures is limited to a maximum quantity of 1.50 % of the total weight of aggregates, added through a dry process.

3.1.7. Asphalt binder

The binder used in this study by the dry process (DP) is detailed in Table 3.6. It is a 50/70 mm penetration, widely used to incorporate crumb rubber and to produce asphalt mixtures.

The penetration test was evaluated according to EN 1426 and the Softening point was assessed according to EN 1427.

Table 3.6: Basic specifications of the 50/70 bitumen

Properties	Test method	Unit	Results 50/70
Penetration (25°C)	EN 1426	0.1 mm	55.3
Softening point	EN 1427	° C	51.1



Figure 3.9: Asphalt binder 50/70. Source: Author's elaboration.

3.1.8. Aggregates

The manufacture of the asphalt mixture samples is porphyry (of magmatic origin) with a specific gravity of 2.80 g/cm³ (EN 1097-6), Los Angeles Abrasion (LA) resistance of 15% (EN-1097-2), and an Accelerated Polishing Value (PSV) of 56% (EN 1097-8). The filler was calcium carbonate. Applying the criteria of standard EN 933-1, the granulometric gradation for the mixtures under study is shown in Figure 3.10 and Figure 3.11.

To assess the performance of the asphalt mixture and to ensure consistency in the production process, the same aggregates were used for the dry process.

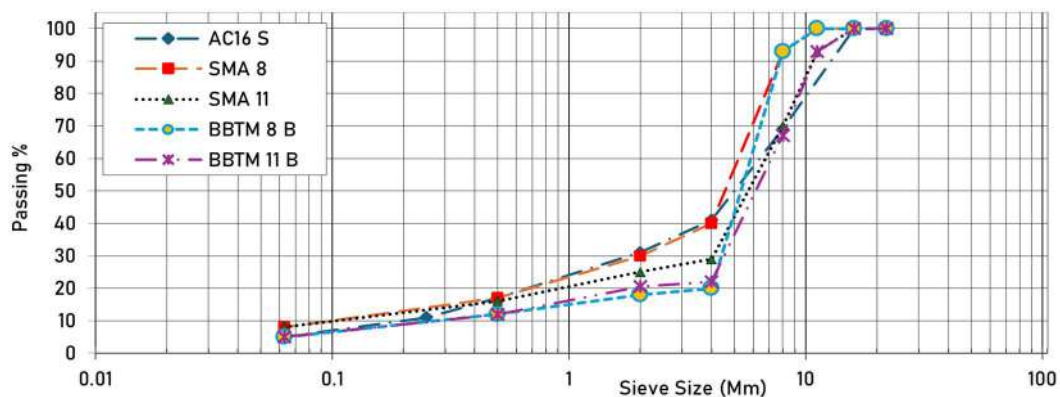


Figure 3.10: Gradation curves for the studied asphalt mixtures with rubber by dry process. Source: Author's elaboration.



Figure 3.11: Gradation for different asphalt mixtures. Source: Author's elaboration.

3.2. Manufacturing and testing of asphalt mixtures.

CR incorporation into asphalt mixtures has been performed across different types asphalt mixtures, namely AC 16 S, SMA 8, SMA 11, BBTM 8 B, and BBTM 11 B. The addition of CR was primarily done through the dry process (DP). The mixing process was accomplished by procedure EN 12697-35, the samples were compacted following the Marshall hammer procedure (EN 12697-30) and the roller compactor (EN 12697-33), depending on the type of sample to be produced.

The design of the mixtures followed the PG-3 specifications guidelines for the dosage of bituminous mixtures. The dosing guidelines for AC, BBTM, and SMA, asphalt mixtures are detailed in PG-3 specifications : article 542, 543, and 544, respectively.

The asphalt mixtures in this study were manufactured using crushed aggregate (porphyry), CR (50% from car tires and 50% from truck tires), bitumen, and filler (calcium carbonate). The aggregate gradation and distribution were according to Spanish PG-3 specifications (2019). The optimal dosage of CR has demonstrated significant improvements in the mechanical behavior of asphalt mixtures (Xie & Shen, 2016). However, an excessively high percentage of CR could compromise mechanical performance. Therefore, the use of CR in this study was limited to a maximum of 1.50% of the total weight of asphalt mixtures incorporated through the dry process.

Cylindrical specimens of asphalt mixtures of 99.5 mm diameter and 60 mm height were manufactured for the assessment of acoustic and dynamic assessment. For mechanical characterization, the samples were 101.6 mm in diameter. The aggregate and CR was mixed for approximately 30 seconds at 170 °C. Then the bitumen was added at 160 ° C and mixed for 30 seconds. Next, the filler was added, and all the components were mixed in for 2 minutes. Subsequently, the samples were placed in an oven at 160 ° C for 90 minutes to ensure proper digestion of CR. The mixtures without CR were subjected to 90 minutes in the oven to have the same thermal process for all the mixtures under study. Finally, the samples were compacted at 160 ° C using the Marshall hammer method according to (EN 12697-10:2003/AC, 2007), applying 75 blows (AC mixtures) or 50 blows (SMA and BBTM mixtures) on each side of the specimen.

Five asphalt mixtures were manufactured (AC 16 S, SMA 8, SMA 11, BBTM 8 B, and BBTM 11 B), with (0.0%, 0.75% and 1.50 % CR). Figure 3.12a shows the aspect

of cylindrical and slab-shaped samples produced and tested during the investigation.

Figure 3.12b shows slab samples produced to assess the surface texture and the evolution of the skid resistance. For assessment purposes of the skid resistance, the dimensions of the samples were 220 mm x 40 mm x 220 mm, manufactured by roller compactor.

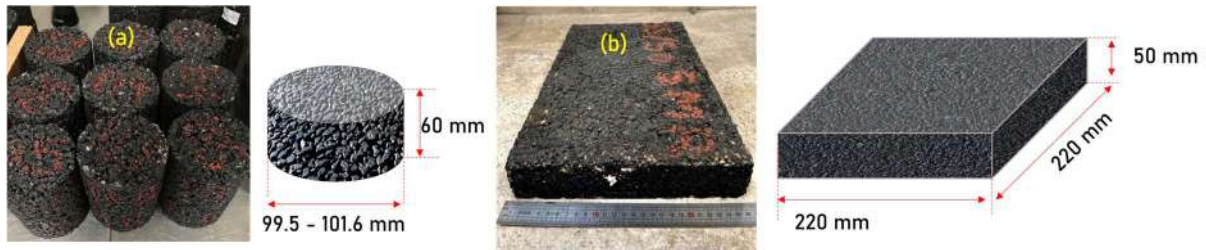


Figure 3.12: a) Cylindrical and b) Slab asphalt mixtures samples. Source: Author's elaboration.

The dry process (DP) consisted of adding the CR directly to the mixer of the asphalt plant like as aggregate (Figure 3.13. Interaction of CR with asphalt binder requires controlling the temperature to achieve a homogeneity interaction with the asphalt binder.



Figure 3.13: Digestion by Dry process. Source: Author's elaboration.

Table 3.7 presents the parameters of the manufacturing of the asphalt mixtures resulting from the dry process.

Table 3.7: Production parameters of the mixtures by the DP.

Sample Mixtures	Max. Size (mm)	N° samples	B 50/70 /mixture (%)	CR (%)	PT (°C)	DT (°C)	DTi (min)
AC 16 S	16	6	5.1	0.00	170	160	90*
	16	6	5.2	0.75	170	160	90*
	16	6	5.3	1.50	170	160	90*
SMA 8	8	6	6.0	0.00	170	160	90*
	8	6	6.1	0.75	170	160	90*
	8	6	6.2	1.50	170	160	90*
SMA 11	11.2	6	6.0	0.00	170	160	90*
	11.2	6	6.1	0.75	170	160	90*
	11.2	6	6.2	1.50	170	160	90*
BBTM 8 B	8	6	5.0	0.00	170	160	90*
	8	6	5.1	0.75	170	160	90*
	8	6	5.2	1.50	170	160	90*
BBTM 11 B	11.2	6	5.0	0.00	170	160	90*
	11.2	6	5.1	0.75	170	160	90*
	11.2	6	5.2	1.50	170	160	90*

AC: Asphalt Concrete, SMA: Stone Mastic Asphalt, BBTM: Discontinuous Asphalt Mixtures design. CR: Crumb Rubber, PT: Production Temperature, DT: Digestion Temperature, and DTi: Digestion time.

*Although mixtures with do not require digestion time, they were subjected to 90 minutes in an oven at 160°C to undergo the same thermal process as the rubber-containing mixtures.

For the case of self-sensing a bituminous mix type SMA 8 was utilized in this study. The granulometry of the mixtures, falling within the range established in Article 544 of the General Technical Specifications (PG-3), is displayed in Table 3.8.

Table 3.8: Gradation of the aggregates for SMA mixture.

Sieve (mm)	22	16	11.2	8	4	2	0.5	0.063
MIN			100	90	30	25	12	7
MAX			100	100	45	35	22	9
Adopted curve			100	95	37.5	30	17	8

• Digestion process

Digestion is a fundamental process when elaborating rubberized mixtures by the DP (Juan. Gallego et al., 2021). This process is basically the interaction between the binder and the CR. This process involves the dissolution of CR and subsequent absorption of the volatile components of the binder by CR (Chavez et al., 2019). The digestion process in oven was used for the incorporation of CR, and the manufacturing process was rigorously controlled in the laboratory, with precise monitoring of factors such as temperature, digestion time, and the compaction system for each asphalt mixture. Figure 3.14 shows the processes for cylindrical and slab samples compaction and Figure 3.15 present the aspect of the manufactured samples.



Figure 3.14: Process to digestion and compaction of asphalt mixtures cylindrical, and slab samples. Source: Author's elaboration.



Figure 3.15: a) Cylindrical and b) slab specimens manufactured. Source: Author's elaboration.

The following outline presents a methodical strategy to thoroughly investigate the effect of crumb rubber (CR) on volumetric properties, mechanical strength, and functional features, as frictional safety, noise pollution absorption, and self-sensing capabilities of asphalt mixtures. This strategy is produced in four stages, each with its own set of analytical procedures (see Figure 3.16). Step 1: Investigate the interaction of CR with the volumetric parameters of asphalt mixtures through the collection of experimental data, followed by a systematic statistical analysis. Step 2: Examine the impacts of CR on the texture surface of asphalt mixtures and the evolution of skid resistance. Data are collected from laboratories in Spain and France. Step 3: Investigate the effect of CR on the characterization of noise pollution caused by tire/pavement interactions. Step 4: Examine the contribution of CR to the self-sensing assessment through piezo resistivity measurement. All data consist of genuine data gathered from controlled laboratory measurements for analysis.

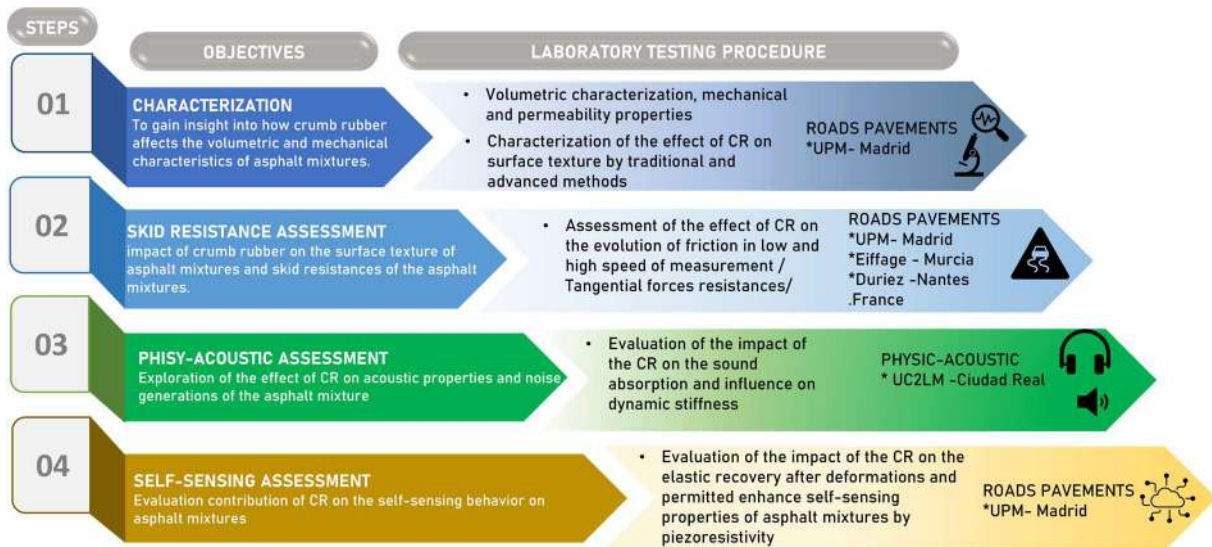


Figure 3.16: Overview of the methods. Source: Author's elaboration.

Figure 3.17 illustrates the laboratory flowchart of the procedure for characterization of properties assessment of asphalt mixtures under study.

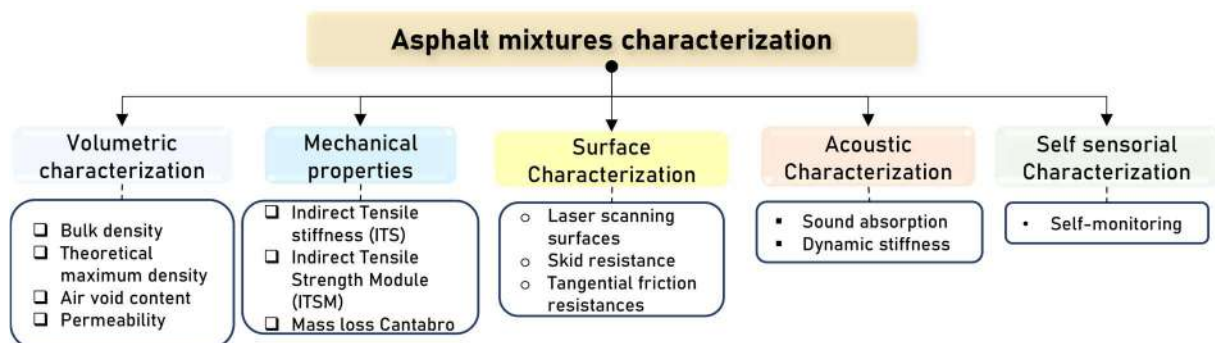


Figure 3.17: Laboratory test on the asphalt mixture samples Source: Author's elaboration.

3.3. Volumetric properties: Maximum and apparent density

The assessment of the asphalt mixtures consisted of a test to evaluate the volumetric and physical properties of AC 16 S, SMA 8, SMA 11, BBTM 8 B, and BBTM 11 B (cylindrical and slab specimens).

To assess the influence of CR on the volumetric properties of asphalt mixtures, cylindrical specimens were tested. Figure 3.18a illustrates the apparent density test (Gmb), while Figure 3.18b depicts the maximum density test (Gmm) as detailed in Table 3.9.



Figure 3.18: Volumetric characterization of the test to evaluate a) Apparent density (Gmb), and b) maximum density (Gmm). Source: Author's elaboration.

Table 3.9: Different methods of measurement of the density

		Asphalt Mixture	Number blows	Maximum density	Apparent density	Nº samples
CR content 0,0.75, 1.50 %	AC16	150 (75/side)	EN 12697-5	EN 12697-6 Determined through saturated surface dry at the end compaction	18	
	SMA8	100 (50/side)	Determined		18	
	SMA11	100 (50/side)	without compacting		18	
	BBTM8B	100 (50/side)	through the pycnometer	EN 12697-10 Geometric density through thickness	18	
	BBTM11B	100 (50/side)	method	and diameter	18	

The experimental process has been carried out according to the test for specific bulk density (Gmb) EN 12697-6, (20022), and maximum theoretical density (Gmm) EN 12697-5, (2020). The air void content (Va) was determined using the Gmm and the Gmb of the mixtures through EN 12697-8, (2020).

The air voids content is related to Gmm and Gmb by:

$$v_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \quad \text{Equation 1}$$

3.3.1. Permeability

The permeability assessment by the hydraulic conductivity test is of interest to know the effect of CR on asphalt mixtures. The principal reason is that asphalt mixture is permeable if it allows the passage of an appreciable quantity of water in a given time, and impermeable if the quantity of liquid is negligible. This property influences the generation of aquaplaning on the asphalt mixture during rainfall episodes.

Figure 3.19 shows the experimental process of the permeability test. The open or accessible porosity is measured using the flow of water. The vertical permeability was measured according to EN 12697-19 (2013). These tests were carried out at room temperature between 15 ° C and 25 ° C and consisted of applying a vertical flow of water from the height of 300 mm of the water column to a final height of 100 mm of the water column. The time taken to drain the water is measured to determine the flow rate through the test tube (m^3/s) “ Q_v ” by Equation 2:

$$Q_v = \frac{(m_2 - m_1)}{t} \times 10^{-6} \quad \text{Equation 2}$$

Where: m_1 is the initial water mass over the sample (g), m_2 is the final water mass (g), and t is the water drainage time (s).

Moreover, the vertical permeability (m/s) K_v is calculated by Equation 3:

$$K_v = \frac{4 \cdot Q_v \cdot L}{(h \cdot \pi \cdot D^2)} \quad \text{Equation 3}$$

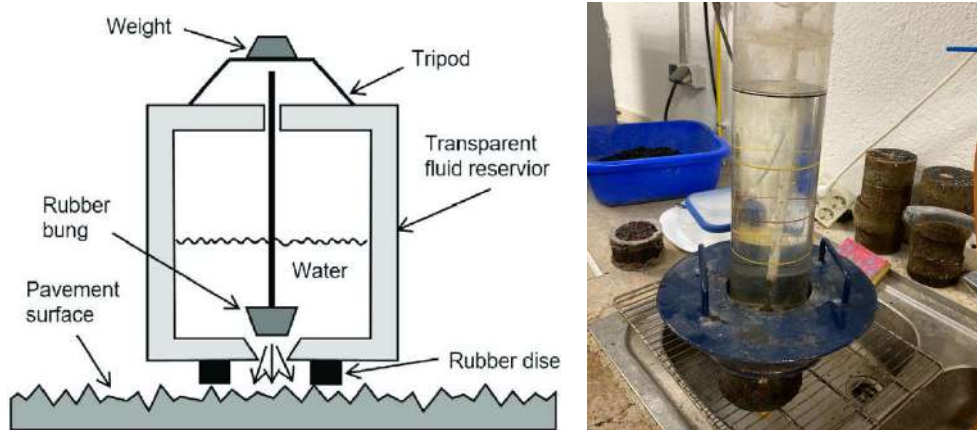


Figure 3.19: Drainage test and experimental assessment on the cylindrical samples at the laboratory. Source: Author's elaboration.

3.4. Mechanical properties

The mechanical performance of the asphalt mixtures was assessed by the Indirect Tensile Strength (ITS) and the Indirect Tensile Strength Modulus (ITSM). The principal objective is to evaluate the effect of the CR on the mechanical performance of the asphalt mixtures.

3.4.1. Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) of the asphalt mixture was evaluated using the EN 12697-23:2018 standard. The ITS is a measure of the tensile strength of

the asphalt mixture and is an important parameter to assess its ability to resist cracking. The ITS test was conducted at a temperature of 15 °C and involved applying a constant deformation of 50 ± 2 mm/min to the cylindrical sample until it broke through its vertical diametral plane.

The ITS, measured in MPa, was calculated using the following equation.

$$ITS = \frac{2 \cdot p_{max}}{\pi \cdot d \cdot h} \quad \text{Equation 4}$$

where p_{max} is the maximum peak load applied to the specimen at failure in newton (N), “ d ” is the diameter of the specimen in mm, and “ h ” is the thickness of the specimen in mm. Figure 3.20 shows the test with the specimen subjected to the indirect tension strength test.

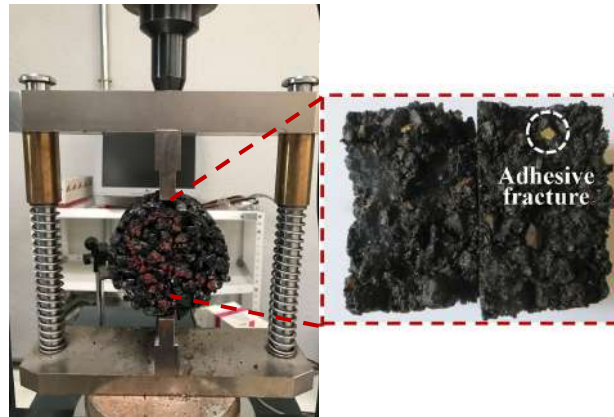


Figure 3.20: Equipment of Indirect Tensile Strength. Source: Author's elaboration.

3.4.2. Indirect Tensile Stiffness Modulus (ITSM)

The Indirect Tensile Stiffness Modulus (ITSM) test was conducted by EN-12697-26:2012 standard. The ITSM represents the relationship between the applied stress and the maximum measured strain response of the asphalt mixture. The device with the mounted sample is shown in Figure 3.21.



Figure 3.21: Indirect tensile stiffness modulus equipment. Source: Author's elaboration.

The standard specifies that five haversine-shaped load waveform pulses with a rise time of 124 ± 4 ms should be applied to the sample in the indirect tensile mode to produce a horizontal target deformation of 5 ± 2 μ m. The test was carried out at a temperature of 20 ° C. Measured in MPa, is calculated using the following Equation 5:

$$ITSM = \frac{p \cdot (v + 0.27)}{zh} \quad \text{Equation 5}$$

where “ p ” is the load (N), “ v ” is the Poisson ratio, “ z ” is the maximum horizontal deformation (mm), and “ h ” is the height of the specimen.

3.4.3. Mass loss by Cantabro

In order to assess the particle of mass loss, the Cantabro test was carried out in accordance with Spanish standard EN 12697-17 as shown Figure 3.22. The samples were tested at 25 °C. Another set of samples were immersed at 60 °C for 24 hours, and then dehydrated at 24 °C before being tested. The particle loss is calculated as a percentage ratio of the weight after and before the test (Equation 6). The maximum allowable particle loss under dry and wet conditions is set at 20% and 35% respectively. In this test, the Los Angeles Abrasion (LAA) method machine is used to measure the degradation of compact samples, which gives an insight into the durability of asphalt mixtures as assessed by Cantabro (Equation 6) .

$$\text{Cantabro loss} = \frac{m_0 - m_1}{m_0} \cdot 100\% \quad \text{Equation 6}$$

Where: m_0 and m_1 refer to the mass of the asphalt sample before and after the Cantabro abrasion test.

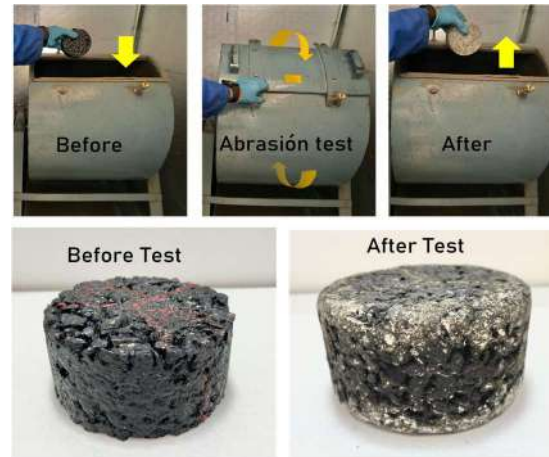


Figure 3.22: Cantabro loss. Source: Author's elaboration.

3.5. Surface texture characterization

Texture characterization of asphalt mixtures was performed to evaluate the effect of CR on texture parameters using traditional and advanced scanning methods. The traditional measurements were performed using the Sand Patch Method (SPT) and the advanced measurements were performed using Laser Texture Scanning (LTS).

3.5.1. Sand Patch Test (SPT).

Traditional methods are used to carry out texture characterization by the SPT. The volumetric texture, related to the macrotexture, was quantified by the Mean Textural Depth (MTD). This procedure is in line with the method established by EN 13036-1 and is calculated by a mathematical equation (Equation 7) that is based on the inverse relationship between the texture attributes and the diameter of the circle covered by the standard volume of sand.

$$MTD = \frac{4V}{\pi \cdot D^2_{avg}} \quad \text{Equation 7}$$

Where: v is volume, and D is diameter.

3.5.2. Advanced Texturometer Laser Scanner (LTS)

The Texturometer Laser Scanner (LTS) is used for characterizing micro asperities and texture properties in the horizontal range of the microtexture (0.00 to 0.05 mm) and also roughness properties such as macrotexture (0.50 to 50 mm) as shown Figure 3.23 . This process follows the guidelines of EN 1347-2:2002.

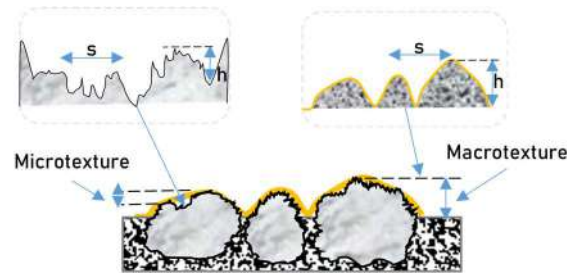


Figure 3.23: Diagram of microtexture, macrotexture. Source: Author's elaboration.

Unlike macrotexture, microtexture has received less attention in pavement investigations, largely due to the difficulties encountered in the past in measuring it accurately. This is because the evaluation segments are much smaller than in the case of macrotexture, and the maximum wavelength to be considered is 0.5 mm (Serigos et al., 2016b).

Macrotexture and microtexture characterization have been achieved by creating profiles that allow the identification of texture changes. In Figure 3.24, a texture profile of asphalt pavement is presented, highlighting the valley areas where water drainage occurs and the peaks representing the effective tire contact areas.

Firstly, it allows the extraction of parameters in multiple different segments within a single profile. In this way, it is possible to specifically select the area of the profile that is in direct contact with the vehicle wheel, i.e. the exposed peaks, and omit the valleys. This contact area is the one that will experience the most significant wear during the polishing process of the pavement surface. The hypothesis considered in this study, where it is assumed that the contact area (direct tire-pavement interaction) is obtained from the profile corresponding to the macrotexture and includes those points that have a special relevance due to their elevation higher than the average elevation of the part of the profile with an elevation higher than 0.

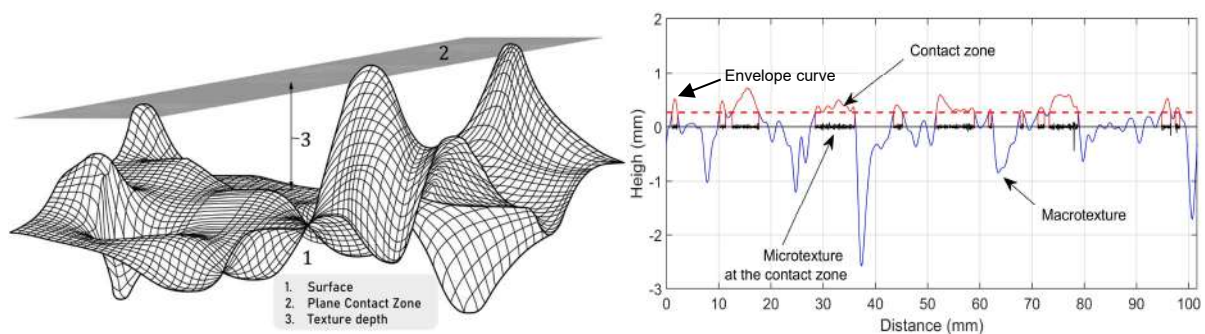


Figure 3.24: Contact Zone a) surface and b) profile surface texture. Source: Author's elaboration.

a) Laser scanning on cylindrical samples

A laser Texture Scanner (LTS) by AMES, following the procedure outlined in EN 1347-2 (2002), was utilized to measure Mean Profile Depth (MPD). The scan underwent a 2.5 mm 3-order Butterworth lowpass filter, ensuring accurate sampling at approximately 0.00635 mm intervals. This method not only assesses macrotexture but also delves into the microtexture domain of the surface profile.

These detailed macrotexture measurements contribute to a comprehensive understanding of the asphalt mixture surface characteristics, crucial for noise evaluation and other pavement performance considerations. LTS known for its very low scanning speed (approximately 15 mm/sec), high resolution, and small spacing, was employed to establish macrotexture and microtexture measurement references and gain a deeper understanding of microroughness texture characteristics. Figure 3.25a shows the cylindrical sample and Figure 3.25b shows the LTS, first one presents the area of the scanner (50 mm x 50mm) as well due to the small dimension of the cylindrical samples.

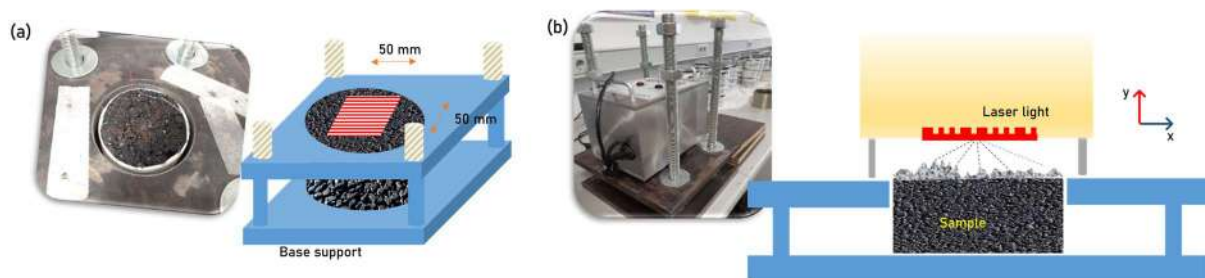


Figure 3.25: a) Cylindrical samples and b) Laser Texture Scanner AMES (LTS) and scanning process. Source: Author's elaboration.

b) Profile decomposition for texture analysis

The process of decomposition and analysis of the pavement surface texture profiles is performed by means of Gaussian filters according to the EN ISO 25178-3 standard, as illustrated in Figure 3.26a. The separation between microtexture and macrotexture is carried out by filtering. The primary profile (P) is obtained by low-pass filtering, adjusting to a cutoff wavelength $\lambda_s = 0.002$ mm, which corresponds to the lower limit of the microtexture. This filter separates components of wavelengths shorter than 0.002 mm.

The roughness profile (R) is obtained by high-pass filtering ($SO - P$) with a cutoff wavelength $\lambda_c = 0.5$ mm, marking the boundary between the components of longer

wavelengths, which is the range of maximum microtexture dominance and the initial range of macrotexture dominance.

Finally, the waviness profile (W) is obtained by low-pass filtering (SO - F) of the primary profile, starting with a cutoff wavelength $\lambda_c = 0.5$ mm, followed by high-pass filtering with a final cutoff length of $\lambda_f = 50$ mm, corresponding to the macrotexture domain range.

Some signals were identified as anomalous points (outliers) within the obtained profiles. These anomalous data can be due to several factors, from anomalies in the scanning process, the capture of contaminants such as fine particles or water by the laser equipment, or errors in the laser reflection. The anomalous data correction process was performed by removing the maximum surface irregularity slope according to ISO 13473-4 (ISO/TS 137473-4, 2005). This process consists of extrapolating the isolated data of the consecutive profile by linear interpolation. Figure 3.26a show the three-dimensional morphologies reconstructed allowing visualization of the textures at the microtexture (Figure 3.26b) and macrotexture levels (Figure 3.26c). From these asperities and roughness on the specimens, it has been possible to characterize various parameters, including height, shape, and texture depth, among others.

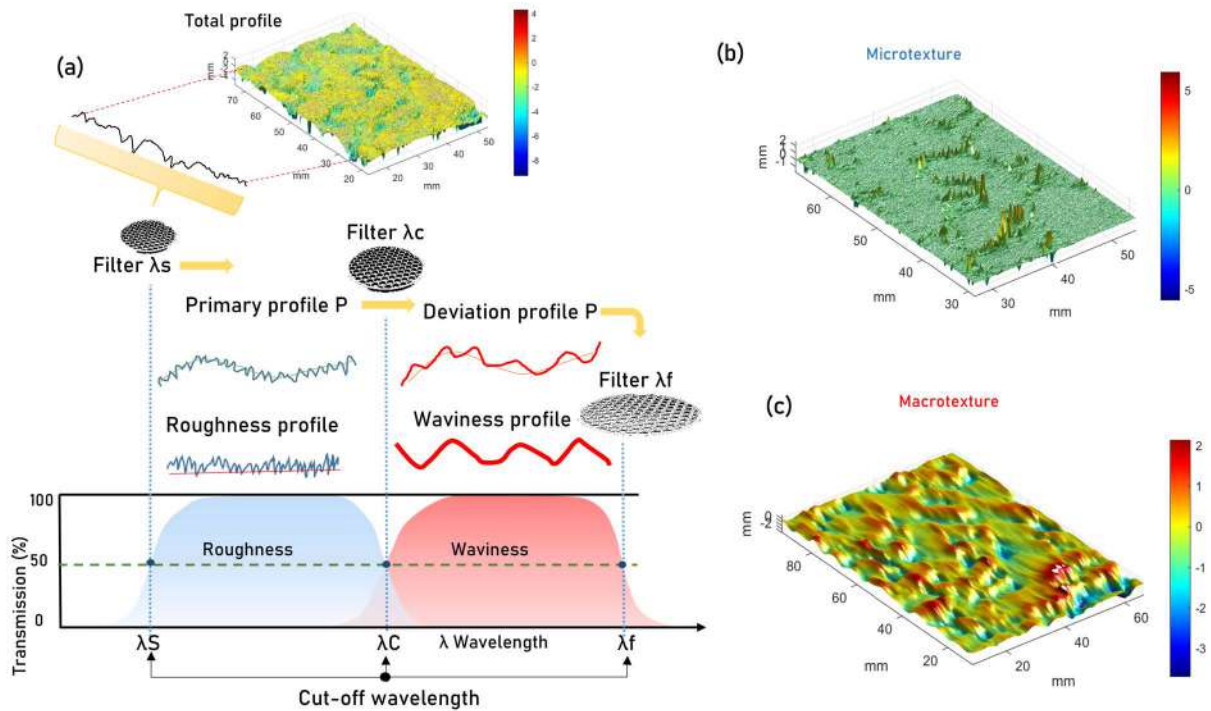


Figure 3.26: a) Filtering signal and discretization (roughness and waviness of the total profile). b) 3D microtexture, c) 3D macrotexture. Source: Author's elaboration.

Figure 3.27 shows macrotexture and microtexture profiles obtained after the scanning and filtering process of AC, BBTM, and SMA asphalt mixture surfaces respectively. The macrotexture and microtexture parameters will be studied from the profiles. An interesting observation is that the variations in microtexture depths are in a similar range regardless of surface type. This differs from the observation in the macrotexture profile, which indicates that macrotexture depths varied by different mixtures. The microtexture profiles are obtained from the 100 mm long segment extracted from the original texture profiles using the LTS laser. Through close inspection of these texture profiles, two observations can be made. First, the microtexture profile is composed of many wavelength (or frequency) components. It should be noted that since the LTS laser has a profile wavelength range of 0.03 mm to 0.5 mm, the highest frequency corresponds to a wavelength of 0.03 mm. Second, the microtexture profile is similar for AC, BBTM, and SMA mixtures. This could be due to the fact that all the mixtures had the same aggregates.

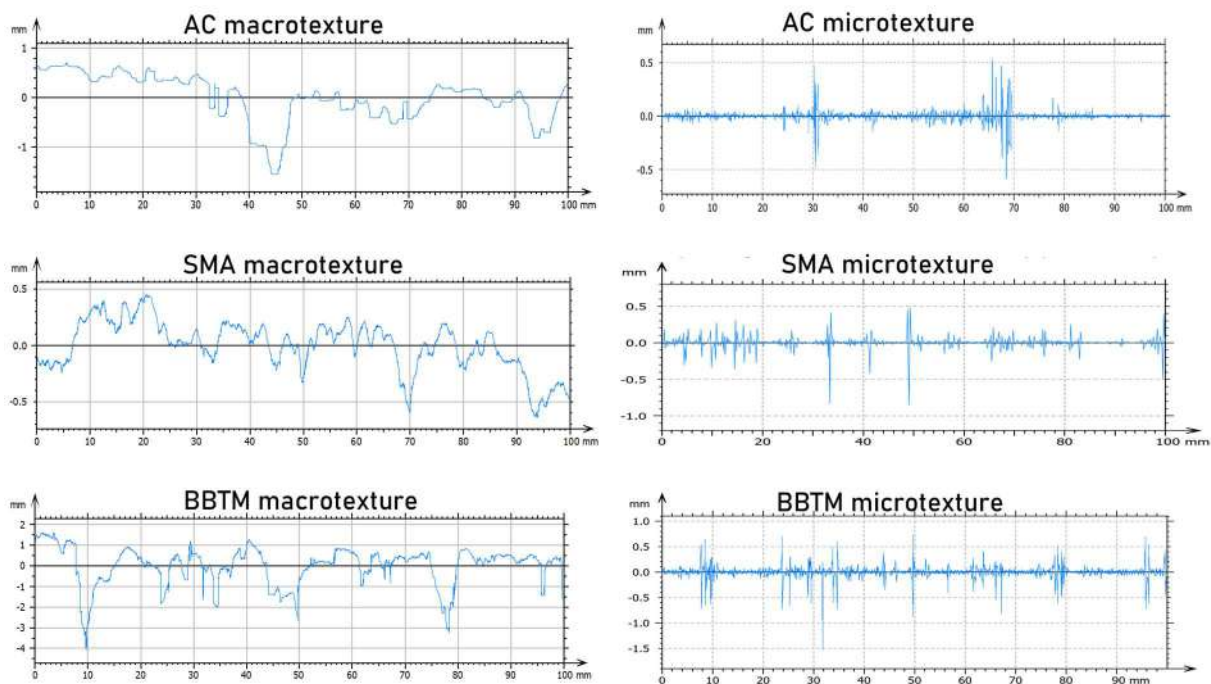


Figure 3.27: Macrotexture and microtexture profiles for asphalt mixtures. Source: Author's elaboration.

c) Analysis of texture parameters

Asymmetry or skewness (R_{sk}) is an indicator of positive and negative texture profiles. The positive texture is related to influence mechanisms in the generation

of rolling noise (Chen et al., 2020), whereas the negative texture reduces vibrations in the tire/pavement interaction, generally represented by valleys (Vieira et al., 2019). A surface with a positive profile represents mainly peaks and asperities (Figure 3.28d). The skewness is determined by means of the Root Mean Square of the texture profile (RMS) normally expressed in millimeters (mm) EN 1347-2, 2002, as shown in Equation 8. and Figure 3.28c. The texture orientation has defined the asymmetry of the amplitude distribution of the Rsk. A negative value of Rsk indicates that the surface is made up of valleys, while a surface with a positive asymmetry Rsk is said to contain peaks (Equation 9). The Rsk is dimensionless. In addition, negative texture has been reported to decrease rolling noise, while the positive texture is more acoustically aggressive (Pizzo et al., 2020b).

$$RMS = \sqrt{\frac{1}{L} \int_0^L Z^2(x) dx} \quad \text{Equation 8}$$

$$R_{sk} = \frac{1}{RMS^3} \left[\frac{1}{L} \int_0^L Z^3(x) dx \right] \quad \text{Equation 9}$$

Where: “ $Z(x)$ ” is the real value of the texture profile at the position of the profile, and “ L ” is the evaluated length.

Once the macrotexture and microtexture profiles of a scanned profile are obtained, it is possible to select one of them and compute the value of some parameters to characterize its roughness. In this research, for both the macrotexture and microtexture profiles, the roughness average (Ra) quantifies the mean absolute deviation of the profile considered, macrotexture or microtexture, and has been used as an indicator for the magnitude of macrotexture or microtexture respectively. The mathematical formulation is shown in Equation 10. And Figure 3.28b.

$$R_a = \frac{1}{N} \sum_{i=1}^N |h_i| \quad \text{Equation 10}$$

Where : h_i represents the height of the profile considered (microtexture or macrotexture) measured at point i in mm. N is the total number of measurement points along the sample length.

The roughness average (Ra) is a parameter that provides quantitative information on the roughness of the surface when calculated with the macrotexture profile (Rama), and on the asperities of the aggregates when calculated with the microtexture profile (Rami). High roughness in macrotexture and high asperities on microtexture (Rami) offer a higher skid resistance compared to smooth and polished surfaces (Marinello & Pezzuolo, 2019).

Other parameters derived from the amplitude distribution have been defined for specific use in pavement engineering. One that is of great interest is the Mean Profile Depth (MPD) (EN-13473-1) which allows the determination of the mean depth of the macrotexture of the surface (Equation 11). MPD is considered to be insensitive to the microtexture of the pavement and its surface regularity characteristics (Figure 3.28a). This parameter has found application in various studies serving as a crucial metric for estimating pavement skid resistance, evaluating acoustic characteristics, and assessing the appropriateness of paving materials or pavement finishing techniques (Grzesik, 2016). To estimate the MPD value, the segment length is required to be at least 100 mm, which is twice the maximum wavelength to be considered (50 mm in the case of macrotexture).

$$MPD_{micro} = \frac{1}{2} \left[\max(h_1, \dots, h_{N/2}), \max(h_{N/2+1}, \dots, h_N) \right] \quad \text{Equation 11}$$

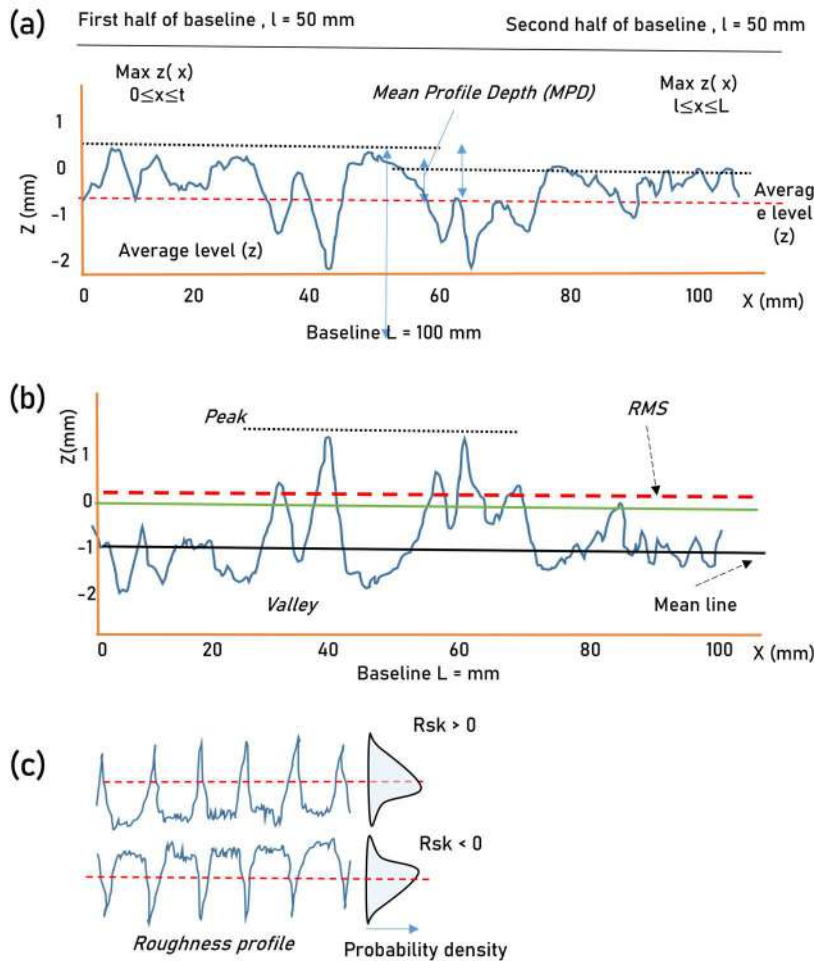


Figure 3.28: Parameters of the texture a)MPD, b) RMS, c) Skewness. Source: Adaptation by: (Tokyo Seimitsu, 2015).

d) Laser scanning slab surfaces

The texture is obtained using the Laser Texture Scanner (LTS) (Figure 3.29a) which is a light and portable equipment that allows scanning the pavement surface employing a laser sensor that moves along parallel straight lines. Each line can have a maximum length of 101.60 mm and a minimum distance between points of 0.00635 mm. The maximum number of parallel lines is 2000 evenly distributed over a maximum width of 70 mm (Figure 3.29b). The accuracy of the dimensions measured by the device is 0.001mm. In this research, each sample is scanned using 150 lines of 101.6 mm length and 0.00635 mm spacing between points, the area of the scanner is 100mm x 70mm as shown in Figure 3.29c.

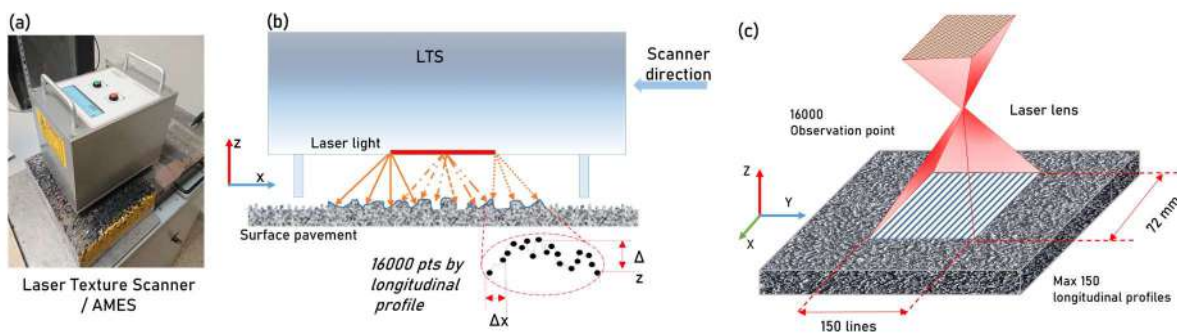


Figure 3.29: a) Laser Texture Scanner AMES (LTS), b) Scheme of scan line profile, and c) Area scanner. Source: Author's elaboration.

This allows each line of profile to be divided into components with wavelengths within the range 0.0127 mm to 101mm, which encompasses the macrotexture spectra (wavelengths 50 mm to 0.5 mm), the first decade of the microtexture (wavelengths 0.5 mm to 0.05 mm) and much of the second decade of the microtexture.

From time to time, the measurements of the scanned points along each line may show errors, often appearing as pronounced peaks in the profile. These anomalies usually originate from particles or contaminants that interfere with the profile, and their corresponding frequencies are usually embedded in the microtexture spectrum (Sengoz et al., 2012b). It is crucial to remove these errors in the analysis process, either by eliminating the peaks or by using statistical parameters that take anomalous data into account. For example, replacing the mean with the median in statistical characterizations will mitigate the influence of these peaks on the analysis results.

e) Signal processing by wavelet analysis.

Signal analysis is based on decomposing a signal into sinusoids of different frequencies (Figure 3.30a), with Fourier analysis being the best-known method for performing this decomposition. However, Fourier analysis has an important limitation: it is not able to determine specific events occur in a signal. This becomes a disadvantage when working with signals that contain non-stationary or transient features, such as drifts, trends, abrupt changes, and the beginning or end of events.

These non-stationary features are often critical in signal analysis and cannot be effectively detected by Fourier analysis. This is where wavelet analysis, a technique that uses variable-size windows, comes into play (Figure 3.30b). This technique allows the use of longer time intervals when higher accuracy is required to analyze signals with non-stationary characteristics. Wavelet analysis becomes a valuable tool to accurately address these features in many signals of interest. Figure 3.30c shows the transformation in low and high scales.

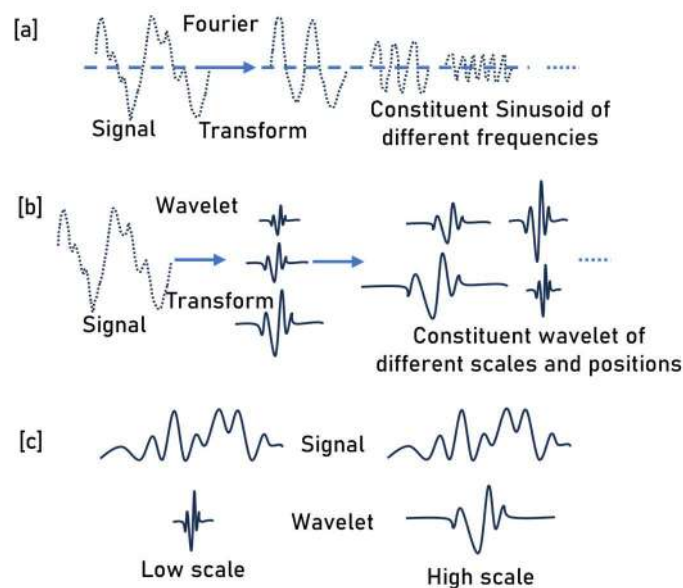


Figure 3.30: Decomposition signal a) Fourier, b) Wavelet, c) low-high scale wavelet.

Source: Author's elaboration.

In this study, the main focus is on the extraction of two frequency bands from the original profile: the macrotexture and the microtexture. By decomposing the profile into these two frequency bands, specific information on the macrotexture and microtexture of the pavement is obtained, allowing a detailed analysis of these textural characteristics and their influence on skid resistance. A common method

for decomposing a signal into frequency components is the Fourier transform, but it has the disadvantage that the spatial reference is lost (Lin et al., 2023). To overcome this drawback the discrete wavelet transform is used (Li et al., 2021). This technique decomposes signals into progressively finer octave bands (called detail levels) and a remaining residual component (called approximation level). Subsequently, it is possible to reconstruct a new signal containing only some of the previously generated levels.

The signal has been decomposed into five octave bands and the approximation level. Joining the levels 1 to 5 the microscopic component is obtained (wavelengths from 0.127 ($0.00635 \cdot 20$) mm to 0.406 mm ($0.00635 \cdot 26$)), and the approximation level (wavelengths above 0.406 mm) represents the macroscopic component. The latter is true as long as the evaluation lengths are 100 mm.

Figure 3.31a show an example of a profile that has been decomposed according to the described procedure. In addition to the original profile (to which the slope and offset suppression have been applied), the macroscopic component and the microscopic component are shown in Figure 3.31b, and Figure 3.31c shows the wavelength range of each decomposition level.

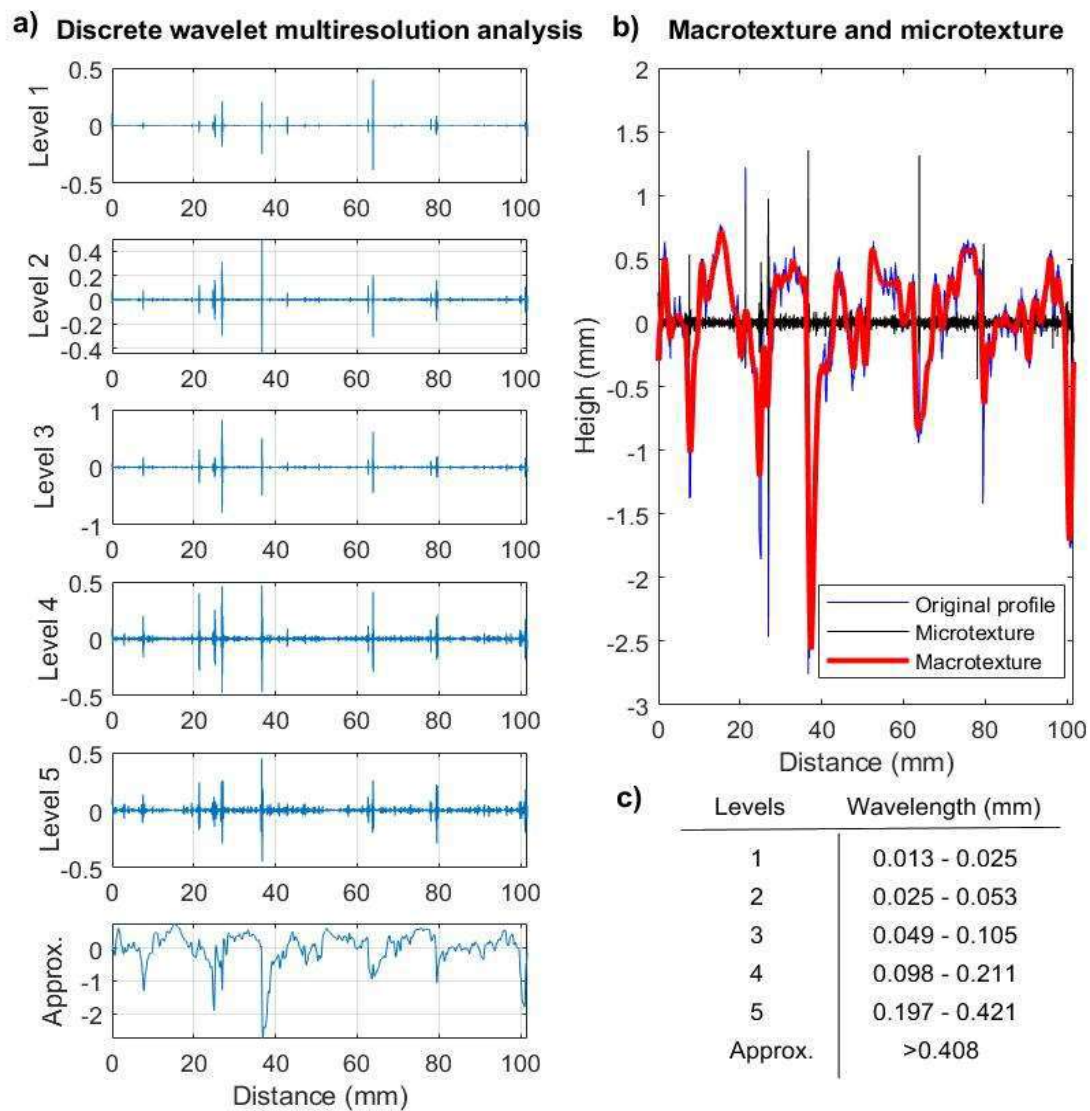


Figure 3.31: a) Example of a profile decomposed into octave bands, b) macrotexture and microtexture profiles, and c) Corresponding wavelengths for octave frequency band selection. Source: Author's elaboration.

3.6. Skid resistance.

The assessment of the skid resistance of various asphalt mixtures, including dense, semi-dense, and open asphalt mixtures has been performed during the investigation. The evaluations will be carried out in a comparative manner with the purpose of highlighting the effects of CR and its influence on the performance of these asphalt mixtures. Figure 3.32 illustrates the scheme of the evaluation

program to measure the skid resistance of the asphalt mixtures tested in this research.

The experimental evaluation in the laboratory involved evaluation friction measurements at different speeds at 10km/h and 60km/h. Table 3.10 outlines two methodologies: British Pendule Test (BPT) and Wehner-Schulze (W&S), additionally, tribology tests T2R were carried out. Slab shaped samples were used to assess AC, SMA, and BBTM asphalt mixtures with incorporation of CR contents (0.0%, 0.75%, and 1.50%). Thus, a total of nine mixtures compositions were tested.

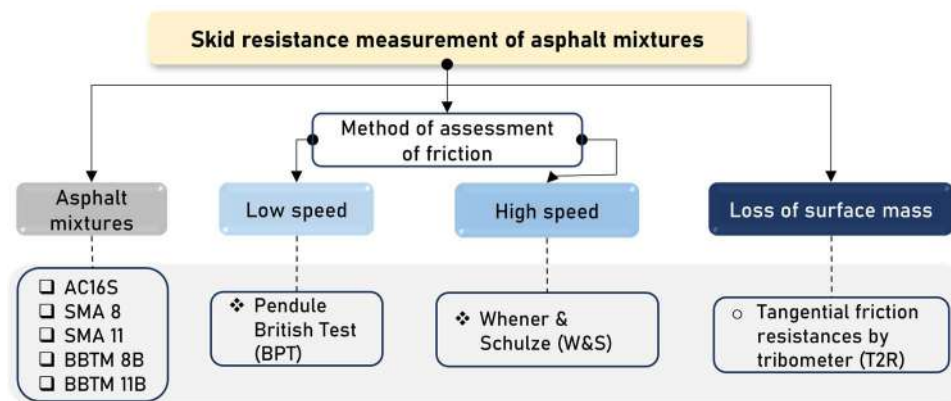


Figure 3.32: Scheme of experimental evaluation. Source: Author's elaboration.

Table 3.10: Friction test and composition of the asphalt mixtures

Test	Asphalt mixture	% B50/70 /mixture	CR (%) /mixture	CF (%) /mixture
British Pendulum Test (BPT)	AC 16 S	5.1, 5.2, 5.3	0.0, 0.75, 1.50	-
	SMA 8	6.0, 6.1, 6.2	0.0, 0.75, 1.50	-
	SMA 11	6.0, 6.1, 6.2	0.0, 0.75, 1.50	-
	BBTM 8 B	5.0, 5.1, 5.2	0.0, 0.75, 1.50	-
	BBTM 11 B	5.0, 5.1, 5.2	0.0, 0.75, 1.50	-
Whener & Schulze (W&S)	AC 16 S	5.1, - 5.3	0.0, - 1.50	-
	SMA 11	6.0, - 6.2	0.0, - 1.50	-
	BBTM 11 B	5.0, - 5.2	0.0, - 1.50	-
Tribologic (T2R)	AC 16 S	5.1, - 5.3	0.0, - 1.50	0.3
	SMA 11	6.0, - 6.2	0.0, - 1.50	0.3
	BBTM 11 B	5.0, - 5.2	0.0, - 1.50	0.3

3.6.1. Low speed measurement by British Pendulum Test (BPT)

Figure 3.33 shows the process of assessment of the friction coefficient at low speed by the British Pendulum Test (BPT) EN 13036-4. In this investigation, the British Pendulum Number (BPN) is employed to measure the frictional resistance using rubber with dimensions of 76 mm x 25 mm x 6 mm. Overall, it is anticipated that

the test results will be influenced primarily by the microtexture of the pavement and less significantly by the macrotexture.

The measurement of the skid resistance on a sample is performed in the present investigation by determining the BPT value in four areas of the surface affected by the wear process. The measurements are performed in directions perpendicular to each other and towards the interior of the sample. Finally, the average of the four measurements is adopted as the representative BPN value of the specimens.

Five asphalt mixtures, with porphyry aggregates, concluded on AC, BBTM, and SMA types, with increasing contents of rubber 0.0, 0.75, and 1.50 %. were manufactured and tested by the procedure described in this section.

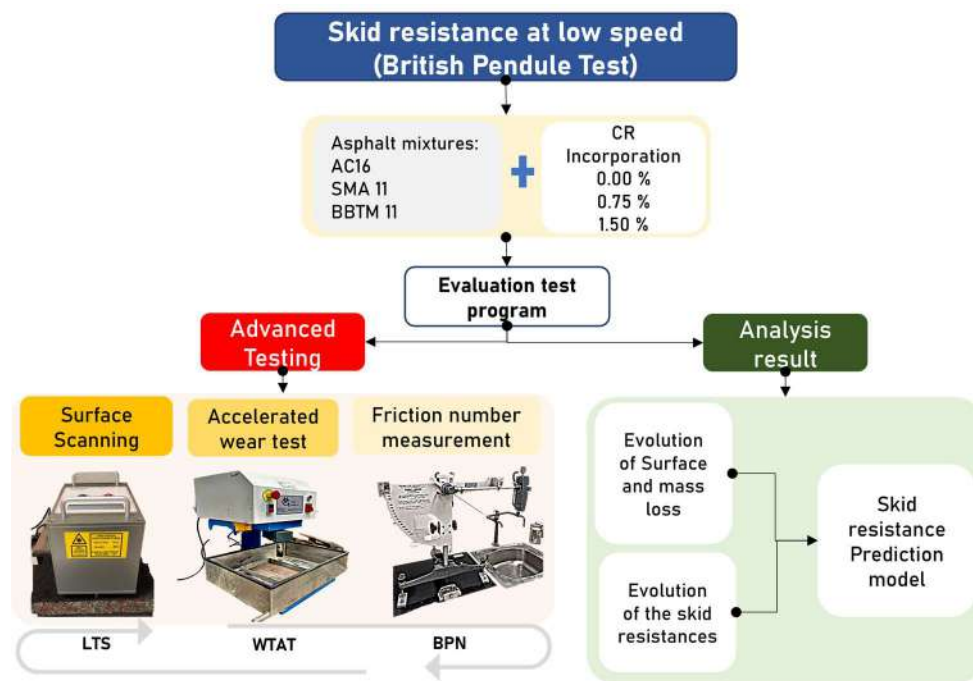


Figure 3.33: Experimental phases. Source: Author's elaboration.

The manufacture and incorporation of CR in asphalt mixtures are detailed in section 3.2. The area of polishing on slab samples is shown in Figure 3.34a, and Figure 3.34b shows the set-up of the BPN measurement.

The coefficients of friction at low speeds were measured using the British pendulum test (BPT) at speeds of 3 m/s (10 km/h). In this study, 6 samples were used to obtain an average British Pendulum Number (BPN), in accordance with EN 13036-4. Figure 3.34c shows the BPT device used in this study.

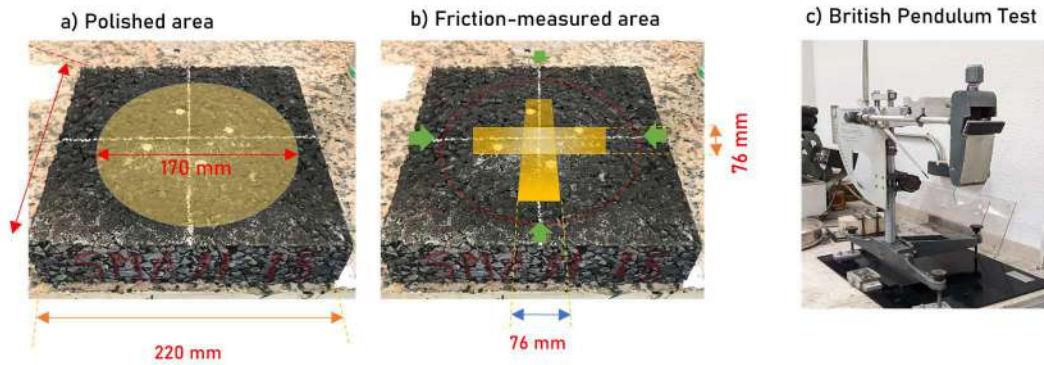


Figure 3.34: a) Area polishing, b) friction measurement and c) BPN. Source: Author's elaboration.

3.6.1.1. Forecasting models

The laser scanner allows us to obtain values related to both R_a of macrotexture, as R_{ama} , and R_a of microtexture, as R_{ami} . The content of CR has to be considered as well in the models for predicting the skid resistance (BNP). The skid resistance is measured by the BNP to have experimental results of the dependent variable BNP. With this working scheme a model was obtained for the AC 16 S mixture, a second one for the SMA 11 mixture and a third one for the BBTM 11 B mixture.

The BPN of each type of mixture is measured after each of the 17 set of wear cycles (Table 3). Since 3 contents of CR were incorporated and tested for each type of mixture, a total of $3 \times 17 = 51$ BPN values were obtained for that type of mixture. For the same reasons, 51 values of macrotexture (R_{ama}) and 51 values of microtexture (R_{ami}) were obtained, which could then be used together with the BPN values to build the prediction model for that type of mixture.

The coefficients of the models were obtained using the least squares technique. The goodness of fit for each potential model is evaluated using the coefficient of determination R^2 and the adjusted R^2_{adj} , which modifies R^2 to account for the number of independent variables in the model. A significance level of $\alpha = 0.05$ for the estimated coefficient was chosen to select the best model.

Finally, after developing the Multiple Linear Regression (MLR) model, its performance was assessed by the Root Mean Square Error (RMSE). Moreover, the analysis of the standardized Beta coefficient (β) was conducted to explain the impact of variables.

a) Accelerated Polishing Machine (APM)

To study the evolution of the texture and skid resistance of the asphalt mixture in the laboratory an accelerated wear process (Figure 3.35) was applied to the samples in this study to simulate changes in asperities and evaluate their impact on skid

resistance. This accelerated wear procedure developed during the doctoral thesis is based on the standardized Weet Traction Abrasion Tests (WTAT), standardized EN-12274-5. Although WTAT was originally designed for asphalt in slurry cold modifications were made in this study for application to asphalt mixtures.

The importance of the self-developed wear prototype is emphasized in this research phase, as it enables the simulation of real road wear in operation. The adaptation of the WTAT test for asphalt mixtures required modifications due to the presence of large-sized coarse aggregates in asphalt mixtures, requiring necessitates a more aggressive wear process. These modifications included the development of a special fixture for testing asphalt mixtures samples and the use of two types of standardized abrasive powder during the wear process, coarse emery (0.300 - 0.600 mm) and fine emery (0.020 - 0.050 mm), standardized for use in the Polished Stone Value (PSV) test (EN-1097-8). The axis, equipment with a rubber cylinder for abrasion rotates at 150 r.p.m. The modified test incorporates stages outlined in the wear and polishing protocol:

Stage I: New, unpolished test specimen.

Stage II: Wear cycles are applied exclusively by means of the rubber cylinder, without an abrasion grinder.

Stage III: The wear is performed using rubber gum and adding coarse emery (Coarse grinder) on the surface of the sample in order to accelerate the wear process.

Stage IV: The wear is carried out by means of the rubber with the addition of fine emery (Fine grinder) to achieve the start of polishing.

Stage V: Wearing is carried out exclusively by means of the rubber, aiming to simulate the polishing of the macrotexture. This is the most critical stage, where the texture is reduced, and the friction does not present skid resistances. Table 3.11 defines the duration of cycles and the number of cumulative turns achieved at the end of each set.

Table 3.11: Abrasive material dosage and wear time

ABRASIVE*	--	RUBBER								COARSE GRINDER	FINE GRINDER			RUBBER			
STAGE	I	II								III	IV			V			
WEAR SET	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
TIME (min)**	0	0.5	0.5	1	1	1	1	1	10	10	10	10	10	10	10	10	10
Σcycles ***	0	75	150	300	450	600	750	900	2400	3900	5400	6900	8400	9900	11400	12900	14400

*Abrasive material according to EN-1097-8,

** Time of polished set

*** Accumulated number of cycles.

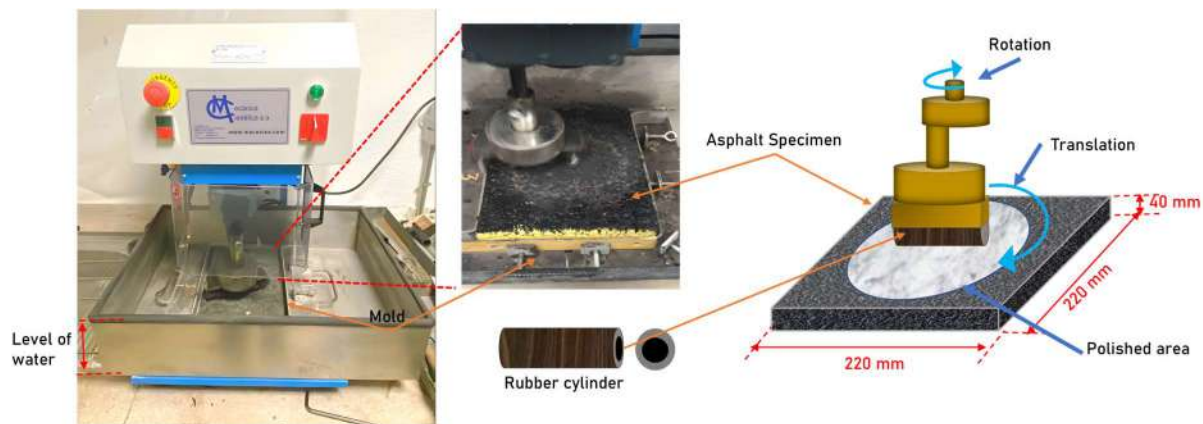


Figure 3.35: Accelerated Polished Machine (APM). Source: Author's elaboration.

During polishing, a rubber cylinder is used at a speed of 150 revolutions per minute (r.p.m.), exerting a constant pressure of 2.533 MPa. Two types of standardized emery are used: coarse (0.300 - 0.600 mm) and fine (0.020 - 0.050 mm). The process comprises 17 wear sets until a total of 14,400 revolutions have been completed.

Figure 3.36 displays an example of the evolution of the BPN for three specimens of mixtures (AC)

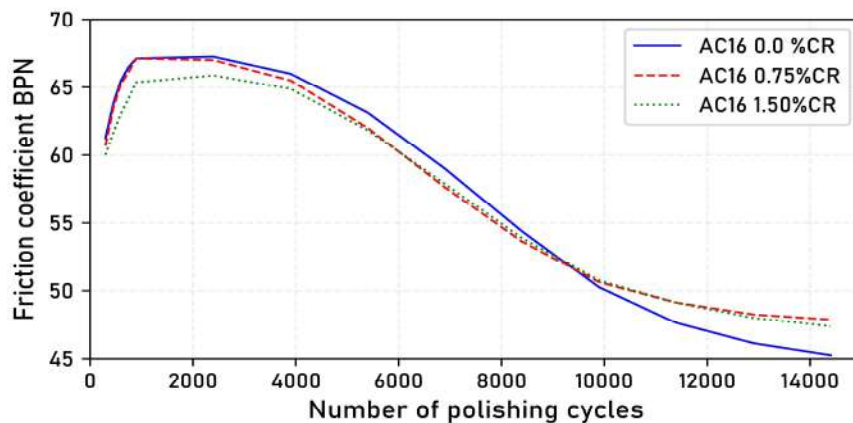


Figure 3.36: Evolution of polishing test. Source: Author's elaboration.

b) Evolution of the mass loss by APM

After of accelerated polishing process, the mass loss at 14,400 cycles of the rubber pass by APM is examined. The trend of the mixtures is shown in Figure 3.37. and Figure 3.38 describes the stages of the mass loss (kg/m^2) of surface texture during the accelerated polishing stages by APM.

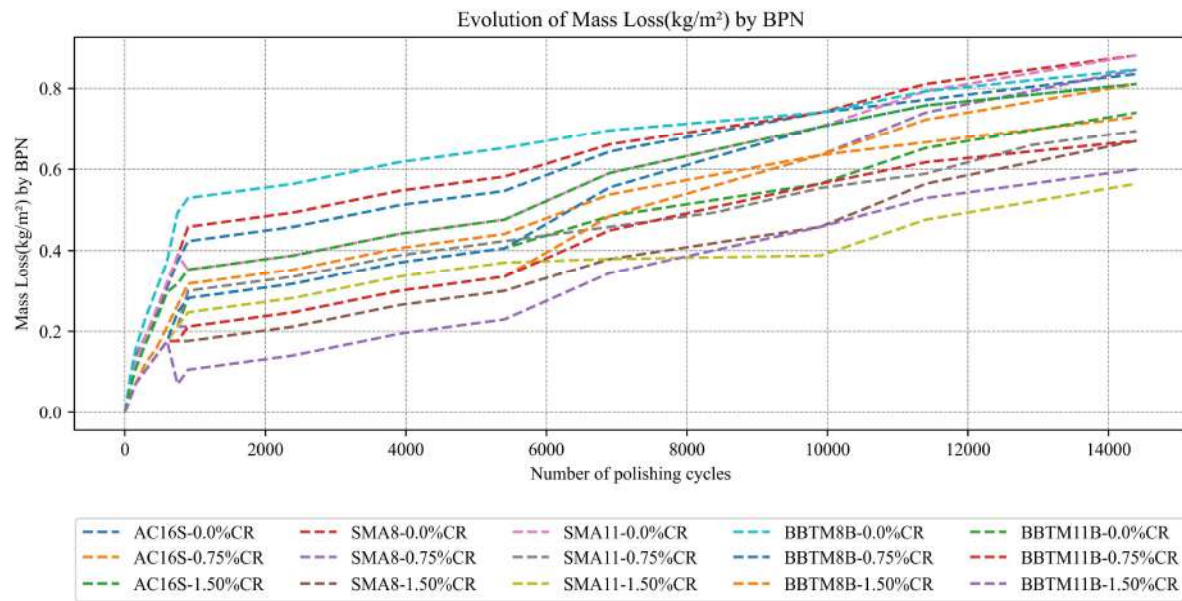


Figure 3.37: Evolution of mass loss by APM. Source: Author's elaboration

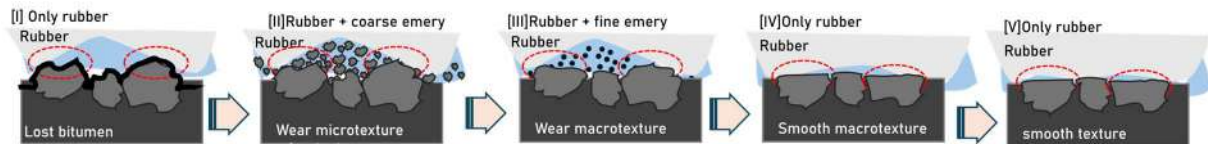


Figure 3.38: Stages of mass loss by APM. Source: Author's elaboration.

c) Evolution of the BPN by APM

Figure 3.39 provides an overview of the experimental design for assessing all slab specimens. The assessment includes four key steps:

1. Surface scanning before and after polishing using APM,
2. Polishing by APM (Accelerated Polishing Machine),
3. Evaluation of mass loss, and
4. Assessment of friction using BPN (British Pendulum Number) with four measurement points for each specimen.

Following these steps, changes in texture and skid resistance (μ) were measured at various stages as outlined in Table 3.12.

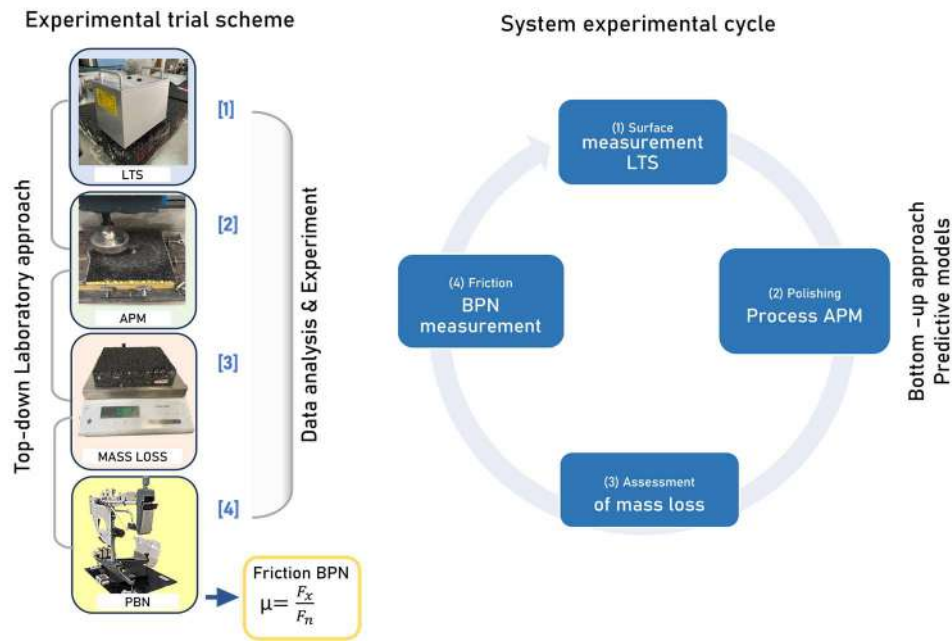


Figure 3.39: Experimental phases of the friction BPN. Source: Author's elaboration.

d) Correlation BPT with construction parameters

Many highway agencies and manufacturers have developed equations to correlate skid resistance measures obtained with the British Pendulum Test (BPT) and other devices and methods (Bustos & Echaveguren, 2006). Table 3.12 shows the correlations between different devices for measuring the friction coefficient and the Scrim coefficient.

Table 3.12: correlations equations between several tests.

Table 1— Correlation equations between several tribometers ^{5-7,9-11}				
Id	Author	Year	Country	Equation
1	Transportation & Road Research Laboratory	1990	United Kingdom	SC = 0.823 GN – 0.046
2	Highways Agency	1994	United Kingdom	SC = BPN/ 105
3	Highways Directorate	2000	Chile	SC = 0.0139 BPN – 0.228
4	Transit NZ	2001	New Zealand	ESC = 0.0071 BPN + 0.033
5	Transit NZ	2001	New Zealand	ESC = 0.42 GN + 0.2
6	Central University of Chile	2003	Chile	SC = 0.7521GN + 0.154
7	Findlay Irvine Ltd	2004	United Kingdom	SC = 0.85 GN

GN: Grip Number; BPN: British Pendulum Number; SC: SCRIM Coefficient; ESC Equivalent SCRIM Coefficient

The friction threshold is used as a control point for the Spanish road maintenance phase roads. In our case, the evolution of BPN friction is determined using the correlation obtained by the Scrim (SC) control threshold, according to equations 12 and 13 (Bustos & Echaveguren, 2006). For a SC threshold equal to 50, the BPN threshold would be:

$$SC = 0.0139BPN - 0.228 \quad \text{Equation 12}$$

$$BPN = \frac{0.50+0.228}{0.0139} = 52.37$$

$$SC = \frac{BPN}{105}$$

Equation 13

$$BPN = 0.50 \cdot 105 = 52.5$$

Where SC: Scrim coefficient, BPN: British Pendulum Number. The threshold established for this laboratory study will be **BPN = 52**.

e) Evolution of the texture parameter

Data collection was carried out creating a database containing information characterizing the surface of each sample at different stages of polishing. Each record in the database contains information about the surface texture, its polishing stages, mass loss of surface texture, and skid resistance BPN at 10km/h.

Figure 3.40 shows the analysis of the evolution of friction and texture process at 10 km/h in asphalt mixtures of three types of mixtures, AC, SMA, and BBTM, each with different contents of CR (%). The process was carried out according to the procedures described in section 3.5.2. A) Texture measurement for different asphalt mixtures, B) Texture description in terms of macrotexture and microtexture, C) BPN friction measurement, D) Synthesis of friction and texture results, E) Evolution of friction measurement at 10 km/h (BPN), F). Texture evolution in different asphalt mixtures and G). Models for BPN prediction are based on macrotexture and microtexture.

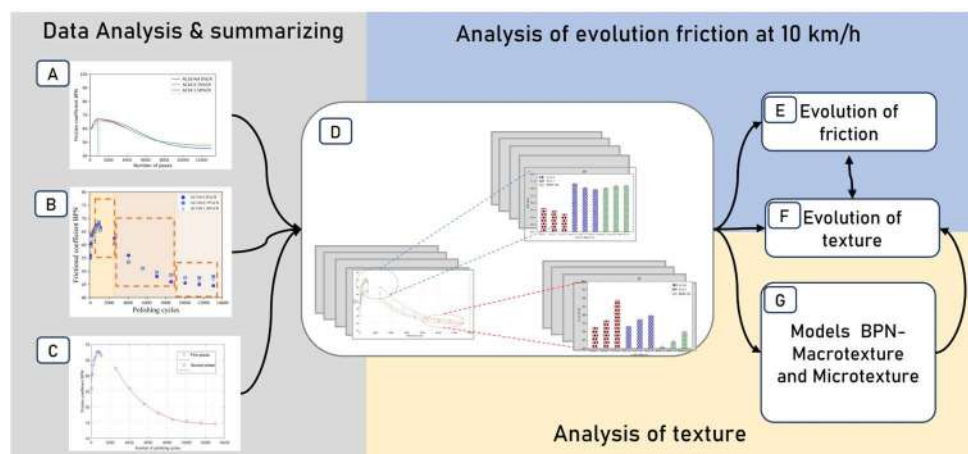


Figure 3.40: Analysis of friction and texture. Source: Author's elaboration.

3.6.2. High-speed measurement by Wehner & Schulze (W&S)

The evaluation of skid resistance at a high speed of 60km/h is carried out with the Wehner & Schulze (W/S) device EN-12697-49. It was carried out in the laboratory of Los Serrano (Eiffage) – Abanilla- Spain. The W/S is used to determine the evolution of friction with polishing cycles of asphalt specimens (Kane et al., 2013b).

The principle and procedure of this test are detailed in Figure 3.41. This machine consists of two stations, one for polishing purposes and the other one for measuring friction, operating independently. The first has three rubber-coated metal rollers and a speed of 500 rotations per minute on a 60 mm wide circular belt. To accelerate wear, a mixture of water and abrasive is sprayed onto the belt. The second head, equipped with rubber pads, slides over the tested surface in wet conditions from 100 km/h to a complete stop. Torque values are recorded during braking, and tangential forces are calculated. The analysis results in uses the coefficient of friction at 60 km/h. Although the method is standardized in Europe, an alternative protocol has been used in this study that measures friction before and after several passes, simulating the evolution of friction on service roads. The polishing is stopped periodically to wash the test surface and make a friction measurement.

The system monitors each previously planned programmable wear cycle and performs automated friction measurements.

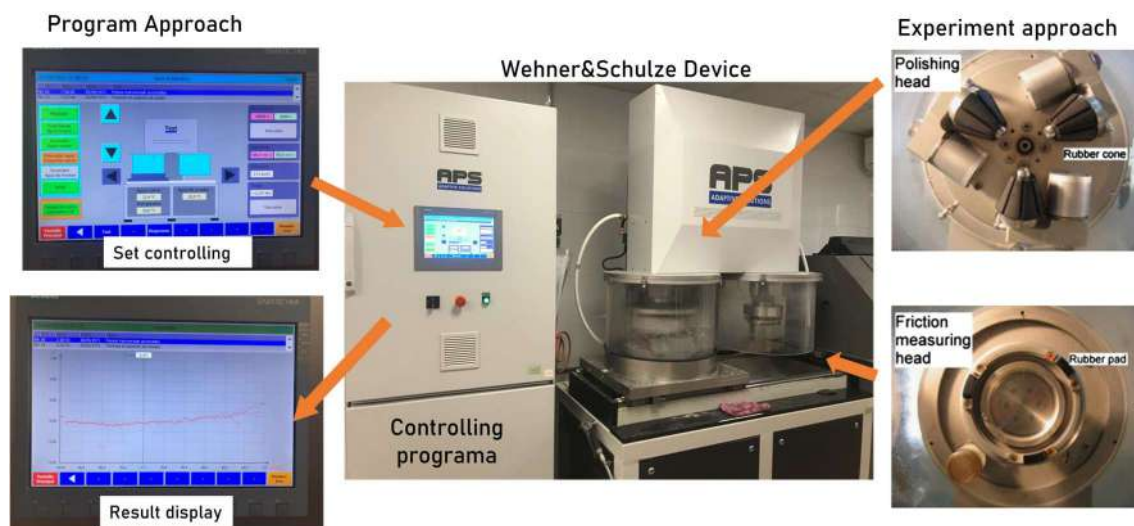


Figure 3.41: Wehner & Schulze system with modules for wear and friction measurement. Source: Author's elaboration.

Asphalt samples with dimensions of 250 mm x 220 mm and a thickness of 50 mm were prepared using a laboratory roller segment compactor (EN-12697-33), as detailed in Section 3.2. The asphalt samples were then cut into dimensions of 220 mm x 180 mm x 50 mm³ to the assessment of the skid resistance at high speed.

Texture information was subsequently acquired using the LTS (explained in detail in section 3.5.2) for both reference mixtures and those with crumb rubber at 1.50% CR. This study encompassed three types of asphalt pavements, including AC, SMA, and BBTM with porphyry aggregate. The experimental process allowed us to assess the skid resistance at high speed by the Wehner Schulze device. Figure 3.42 shows the factors used in the research as independent variables, while in Table 3.13, a more detailed illustration of the experimental parameters is shown.

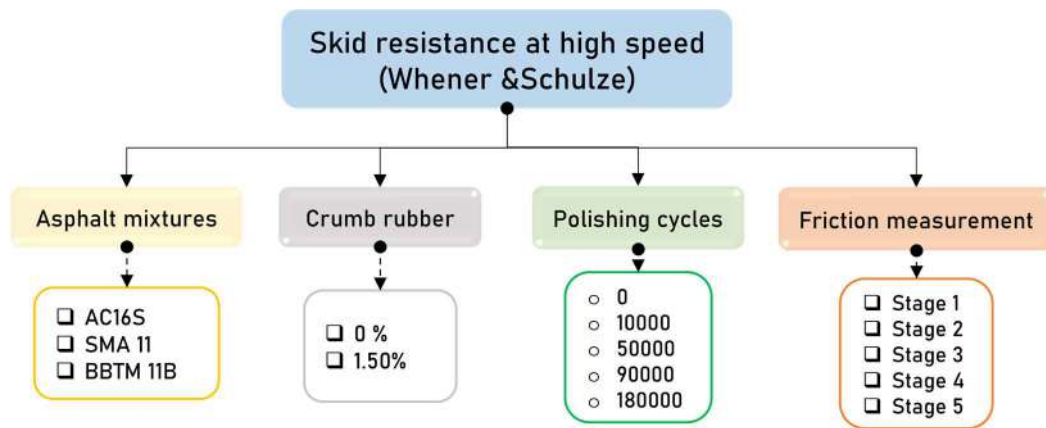


Figure 3.42: Experimental design. Source: Author's elaboration.

Table 3.13: Experimental points

Stages (N°)	Accumulated Number of cycles W&S	Accumulated Time (min)
1	0	0*
2	1000	5*
3	50000	100*
4	90000	180*
5	180000	350*

*The duration of the standard tests is 360 minutes, however, to make the friction measurements in each polishing state, the total working time was approximately 15 hours.

In order to collect the data in an orderly and systematized way, an ad hoc laboratory procedure was used for each stage of polishing and W/S friction measurement. Figure 3.43 shows the experimental flow scheme for the collection of surface data from the asphalt samples in this study.

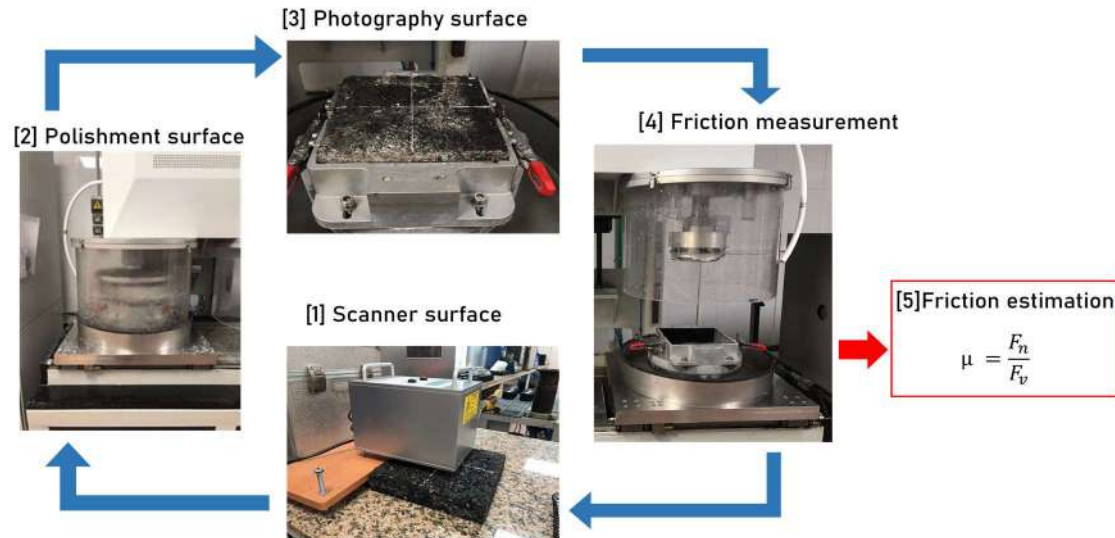


Figure 3.43: Experimental design of W&S on the evolution assessment. Source: Author's elaboration.

The whole testing process for a sample can be summarized as follows: In the polishing station the three rubber cones are mounted (Figure 3.44) on a rotating disk that rolls over the sample surface with a predetermined load. To speed up the polishing process, a mixture of 5% quartz powder with a diameter of 0.06 mm injected in 95% water is applied during the rotation of the wear cones. The surface is polished along a ring band that runs along the sample, and the machine can be programmed to stop after a specified number of rotations. After each polishing cycle, water is sprayed on the sample to remove the residue resulting from the polishing phase of the cones.

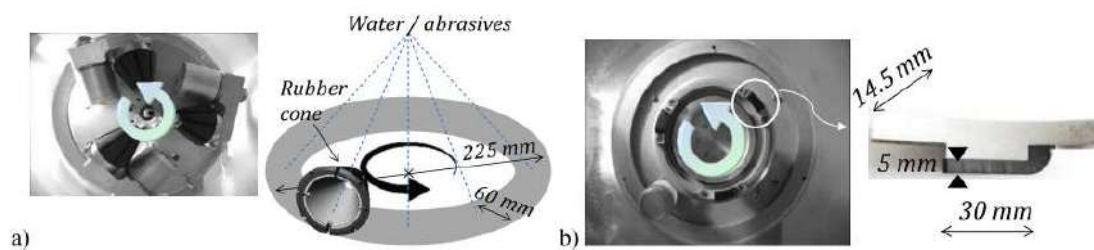


Figure 3.44: Dispositive Wehner &Schulze: a) cone for polishing and b) friction measurement by rubber pads (Do et al., 2014). Source: Author's elaboration.

After the washing period, the sample is manually transferred to the friction measuring station for each set wear cycle. This station consists of three small rubber pads (with an area of 4 cm² each) arranged at 120° on a rotating disk. The contact load between the rubber pads and the sample surface is approximately 0.2

N/mm². The friction system is accelerated to a speed of 100 km/h. When the speed reaches 90 km/h, water is projected onto the sample surface. At 100 km/h, the motor stops, and the disk is dropped until the rubber pads and touches the surface of the abraded sample. The rotation stops due to friction between the rubber pads and the sample surface, and the friction-time curve is recorded. For the analysis, the friction value at 60 km/h is considered. After each polishing process and friction measurement, the samples are removed from the testing machine to collect the surface texture by means of the LTS device.

Figure 3.45 presents the areas of polishing and friction measurement that are the same Segmentation of Area of Interest (SAI) for surface scanning. The profiles are scanned with the LTS in an area of 50 mm x 50 mm. Four zones (1, 2, 3, and 4) have been designated within the area of W&S wear and friction measurement. This facilitates the monitoring of texture evolution in different cycles, as set out in Table 3.13 of the experimental points.

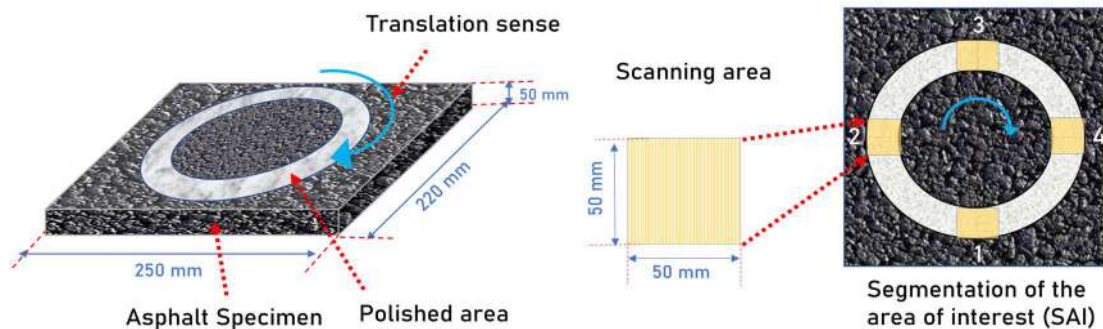


Figure 3.45: Segmentation of the area of interest to be monitored by scanning. Source: Author's.

The profiles collected in the database are processed with the Matlab program in the following order: outliers are replaced by interpolation, using a high-degree polynomial (5 or 7, as recommended by the software developer), and the surface is leveled using a least squares plane.

3.6.2.1. Evolution of the skid resistance

The evolution of the W&S friction resistance at 60 km/h for asphalt mixtures with varying CR contents (%) was investigated using the methodology according to EN 12697-49. Figure 3.46 shows a summary of data filtering. A) Sum and summary of the W&S friction behavior of AC, SMA, and BBTM mixtures; B) Analysis of

maximum friction; and C) Influence of CR on W/S results. The details will be provided in the outcomes chapter.

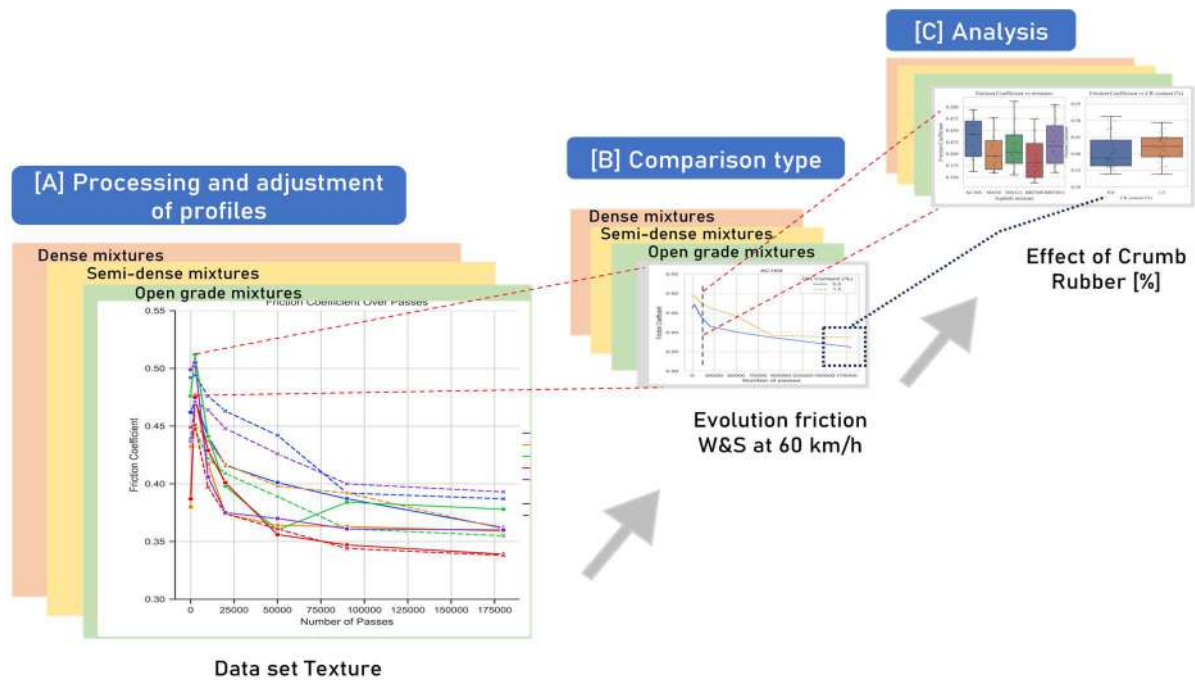


Figure 3.46: Segmentation of the area of interest to be monitored by scanning. Source: Author's elaboration.

3.6.2.2. Forecasting models

The laser scanner allows us to obtain values related to both R_a of macrotexture, as R_{ama} , and R_a of microtexture, denoted as R_{ami} . The content of CR must also be considered as well in the models for predicting the skid resistance (W/S). The skid resistance is measured by the W/S to have experimental results of the dependent variable W/S. Using this working scheme, a model was obtained for the AC 16 S, SMA 11 and BBTM 11 B mixtures.

The W/S of each type of mixture is measured after each of the five stages points of assessing (Table 3.13). Since three contents of CR were incorporated and tested for each type of mixture, a total of $3 \times 6 = 18$ W&S values were obtained for that type of mixture. Consequently 18 W/S values of macrotexture (R_{ama}) and 18 values of microtexture (R_{ami}) were also obtained, which could then be used alongside the W/S values to build the prediction model for each type of mixture.

The coefficients of the models were obtained using the least squares technique. The goodness of fit for each potential model is evaluated using the coefficient of determination R^2 and the adjusted R^2_{adj} , which modifies R^2 to account for the number of independent

variables in the model. A significance level of $\alpha = 0.05$ for the estimated coefficient was chosen to select the best model.

Finally, after developing the Multiple Linear Regression (MLR) model, its performance was assessed by the Root Mean Square Error (RMSE). Moreover, the analysis of the standardized Beta coefficient (β) was conducted to explain the impact of variables.

3.6.2.3. Correlation W&S with construction parameters

In order to relate the results to road measurements, it is necessary to convert the results of the evolutionary wear cycles. The evolution of skid resistance measured with SCRIM equipment proposes the following relationship in accordance with the UK HD28/04 standard, which is determined by Equation 14

$$CRT(50km/h) = (0.96 \cdot \mu WS + 0.06) \cdot 100 \quad \text{Equation 14}$$

The transformation results in a minimum skid resistance threshold in terms of $CRT = 50$. NLT-336, establishes the minimum skid resistance threshold with transverse friction measuring equipment ($CRT \geq 0.50$) for skid resistance in wet conditions, in order to control the preservation and maintenance of minimum friction of paved roads.

The comparison of the W&S friction evolution is determined by a control threshold according to Equation 14 (Barral et al., 2014). The minimum reference value is obtained from Equation 15:

$$CRT[50km/h] = \frac{0.50+6}{96} = 0.46 \mu W\&S \quad \text{Equation 15}$$

The threshold established for the control of the laboratory result will be **W&S= 0.46**.

3.6.3. Tangential friction resistance by tribometer (T2R)

This evaluation by a tangential force on the surface of the asphalt mixtures was performed at the laboratory Duriez in Nantes - University Gustave Eiffel -France. The equipment consisted of a Tribometer for surface Road T2R and accessories (scale, molds, and pad rubber) as shown in Figure 3.47.



Figure 3.47: a) weight of the specimen, b) positioning of the specimen, c) Tribometer T2R device, d) Rubber Pad positioning, and e) Applied force by Pad. Source: Author's elaboration.

The test procedure consists of three steps, one of which is used to evacuate any residues that may have been generated during the stress.

a) In the preload phase: The rubber pad is put into contact with the pavement's surface using an imposed displacement, and it is then passed to a force control to continue loading the sample until it reaches the average imposed vertical average compressive force of 2500 N, and the amplitude of 833 N. The pad's footprint size of 43 cm² results in a maximum apparent pressure of 0.78 MPa in an average of 40 seconds.

b) Cyclic loading phase: Once the set point is reached, a sinusoidal tension is applied with an amplitude of 1/3 of the average force to provide good pad grip, i.e. a consistent sliding speed, the greatest possible friction of 3300N, and the lowest friction of 1700N. The average vertical load is set to 2500N to simulate an apparent contact pressure similar to that produced by a tire. The load frequency is equivalent to one Hz.

c) The lift phase of the pad: The rubber pad resumes its high position. This position frees up around 15 mm of space under the pad, allowing the torn aggregates to be evacuated (10 seconds) before continuing the 2000 cycles for 10 phases up to 180000 accumulated cycles with the same cyclic contact force.

This procedure for preload (pre-charge) and cycling charge and discharge to the final position is described as three phases repeated as many times as necessary to obtain a certain degree of degradation (Figure 3.48).

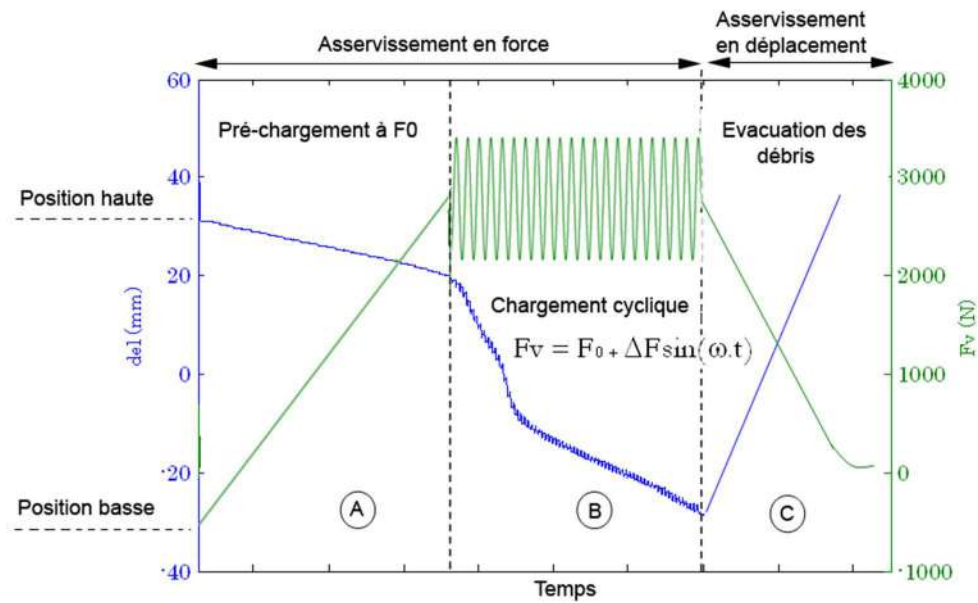


Figure 3.48: Tangential stress strength test protocol. Source: (Hicher & Terrier, 2007).

The three-phase technique described above is performed as many times as necessary to achieve the desired level of deterioration (Figure 3.49).

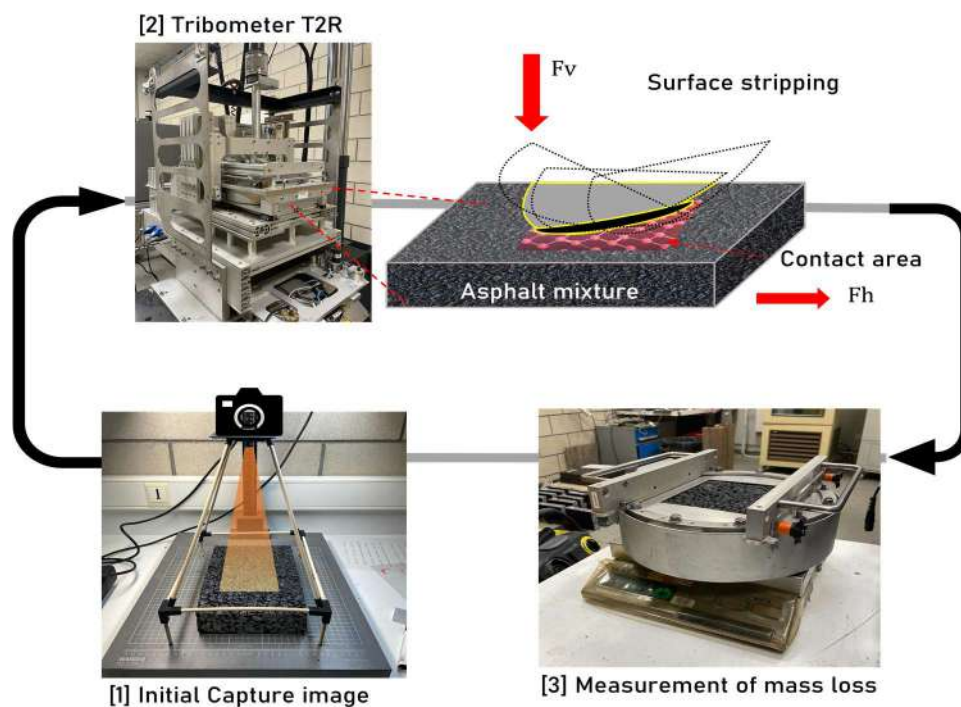


Figure 3.49: Evaluation of tangential stress strength T2R.

Table 3.14 shows the features of the mixtures under study.

Table 3.14: Composition of the asphalt mixtures

Test	Asphalt mixture	(%) B50/70 /mixture	CR (%) /mixture	CFL (%) /mixture
Tribology (T2R)	AC 16	5.1, 5.3	0.0, 1.50	0.3
	SMA 11	6.0, 6.2	0.0, 1.50	0.3
	BBTM 11	5.0, 5.2	0.0, 1.50	0.3

CFL: Carbon fiber large, CR: Crumb Rubber.

The binder used in all specimens is B 50/70 which incorporates 1.50% CR total of the mixture weight and 0.3% CFL and 0.3% CFf total mix weight.

These mixtures were specifically designed, considering the unique characteristics of the materials such as porphyry, CR, and carbon fibers, to assess their performance in terms of mass loss using the T2R device.

The determination of the mass loss is obtained by the weight of the specimen tested after each stage of the T2R equipment testing. The evaluation of mass loss performance for the asphalt mixture specimens was conducted at an ambient temperature of 20°C. Three specimens were tested for each combination to ensure reproducibility, resulting in a total 27 recorded data points.

a) ImageJ processing analysis

Additionally, to the standard protocol for the tribometer T2R, a novel image-based treatment was used for the analysis of the surface degraded by the T2R test. The image processing program ImageJ, which specializes in digital image processing and transformation, was used. Figure 3.50 illustrates the photogrammetry and treatment process: a) Capture picture (before and after testing by T2R), b) Process picture by ImageJ software, and c) Analysis data in profile and areas of the change in intensity after the wear phases performed by the tangential stress resistance test. The idea behind the ImageJ program was a comparison between the before-after images based on intensity levels and the number of pixels for different intensity levels.

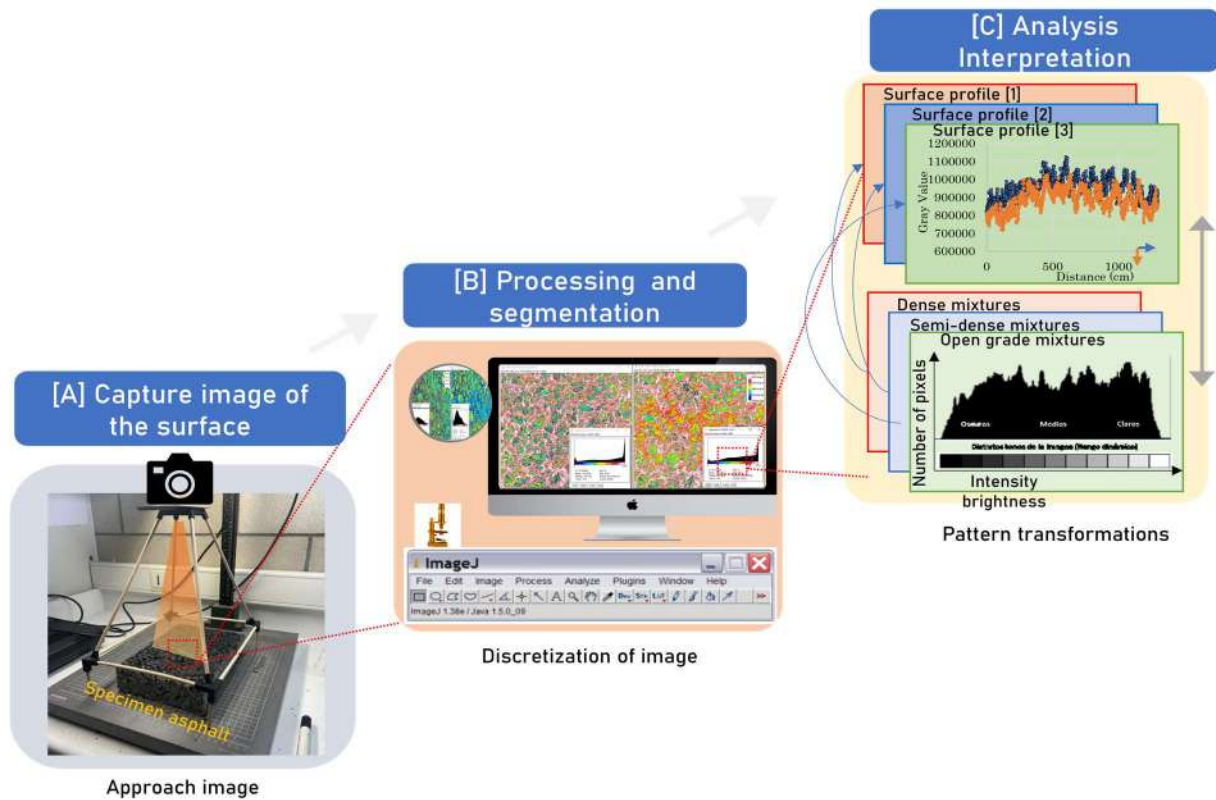


Figure 3.50: Photogrammetry of asphalt samples. Source: Author's elaboration.

Figure 3.51 illustrates control of the light at the objective (surface texture). Reference images were used before the test and those corresponding to the mass loss after the test. Images were captured in 8-bit format with a resolution of 12 megapixels, using an aperture of $f/2.4$.

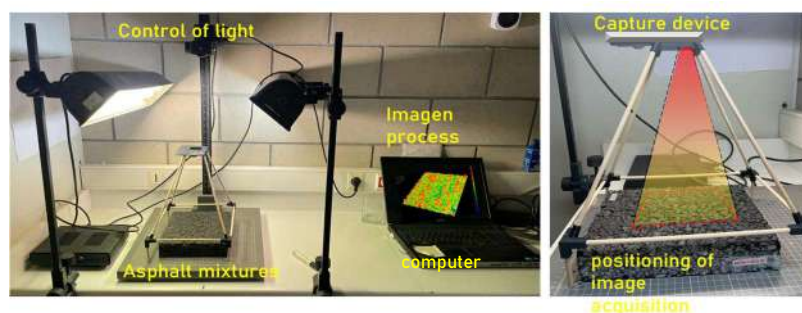


Figure 3.51: Light control and positioning of the set. Source: Author's elaboration.

The principle of image processing is based on the comparison of the area of the Region Of Interest (ROI) with another image of the same element but in a different state of wear. Both images recognize the ROI, and the comparison is performed to reflect the material characterization matrix. This ranges from the evaluation of

surface pores on textures to homogeneous zones at the granular level. The image serves as a detailed comparison pattern of the characteristics of the materials in initial and final states.

Figure 3.52 shows the location of the Zones Of Interest (ZOI). These specific areas have been identified to perform a detailed and comparative analysis between the images corresponding to the initial-final states of the specimens. This approach allows a thorough study of variations in the surface and structure of the materials, providing valuable information on the impact of repetitive stresses in the selected region of interest.

The analysis of ZOI using this **ImageJ** method facilitates the identification and quantification of changes in texture, homogeneity at the granular level, and other key material properties, thus contributing to a deeper understanding of the evolution surface mass loss of asphalt mixtures under specific loading conditions and repetitive cycling.

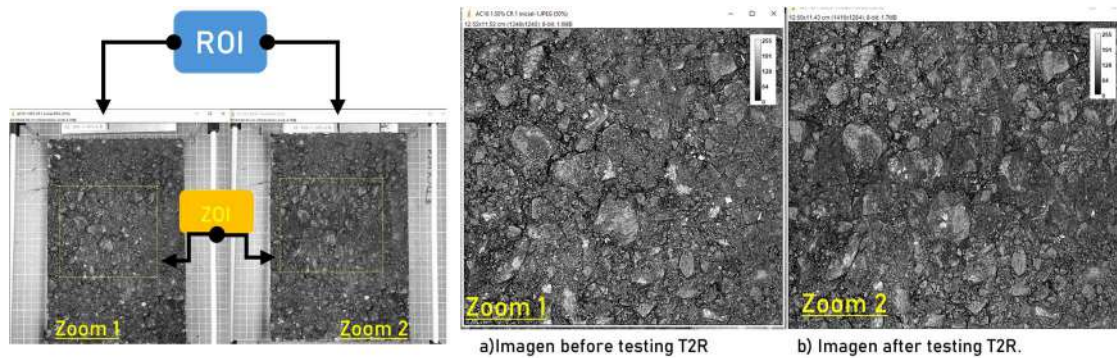


Figure 3.52: Region of interest ROI and the Zone of interest ZOI. Source: Author's elaboration.

The image processing has made it possible to obtain a comparison pattern between both images within the zone of interest (ZOI), corresponding to the average values of intensity change and number of pixels in the ZOI. In this study, the ZOI has been established in the contact area of the rubber on the pavement surface, with dimensions of 11.50 cm x 12.50 cm. The intensity levels have been standardized in 8 bits (from 0 to 256 pixels of intensity), which implies that each intensity level corresponds to a gray level. In terms of levels and degree of comparison, it has been processed in different colors in order to explain the variations observed in both photographs.

In Figure 3.53 b, it can be seen that the skid is in the central contact position. To compare both states, the same light conditions and capture configurations have been maintained. Figure 3.53c) shows the area with higher surface deterioration compared to the reference sample and profile concentration. This approach to image processing and ZOI analysis provides a visual and quantitative representation of the effects of shear force on the surface of the asphalt sample. The same figure represents a calibrated base on a set of pictures, resulting in actual concentration profiles. The calibration and validation for the described experiment are illustrated, showing satisfactory performance.

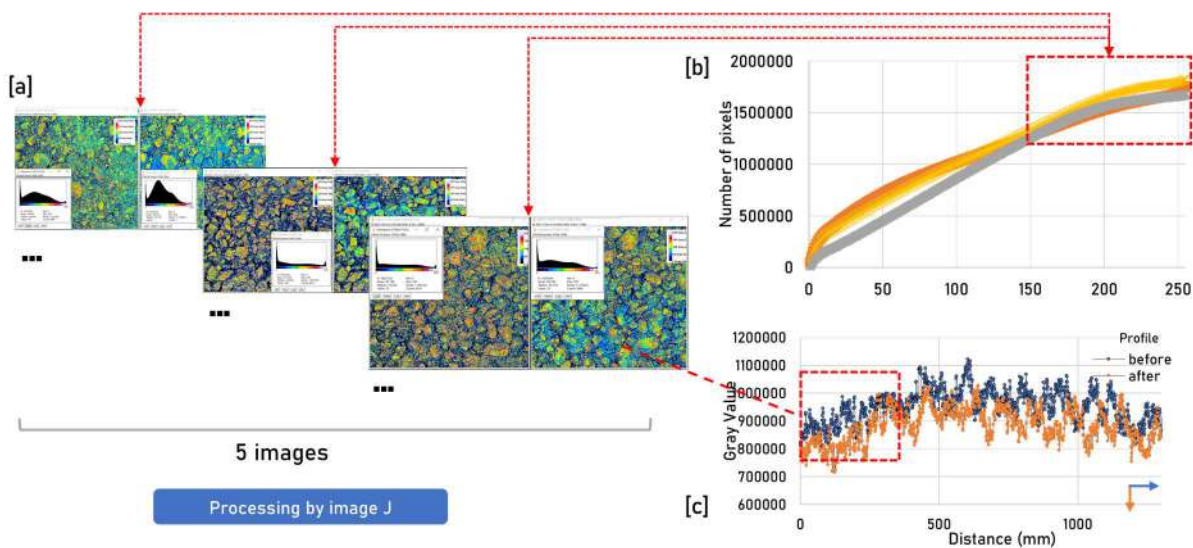


Figure 3.53: Calibration routine. a) Pre-processing of the image before, b) Post-processing after, and c) Profile difference in the zone of interest (ZOI). Source: Author's elaboration.

Although the deterioration process is minimal, the procedure has been able to highlight the changes in texture. This profile represents the gray intensity levels in relation to a distance established as a comparison threshold, being only visual within the zone of interest (ZOI).

The visual representation of the intensity profiles provides an intuitive understanding of the variations in the surface texture of the asphalt sample under T2R test conditions. The application of a visual comparison threshold within the ZOI allows differences in intensity levels to be effectively identified, highlighting specific areas that have undergone noticeable changes during the test. This visual approach contributes significantly to the qualitative and quantitative assessment of surface deterioration and variations in sample texture.

3.6.4. Cohesion test

The effect of the additives crumb rubber (CR) large carbon fiber (CFL) and fine carbon fiber (CFf) on binder cohesion has been studied by EN 13588: 2017. The aim is to analyze how the inclusion of CR influences the internal cohesion of binders within asphalt mixtures as shown in Figure 3.54.

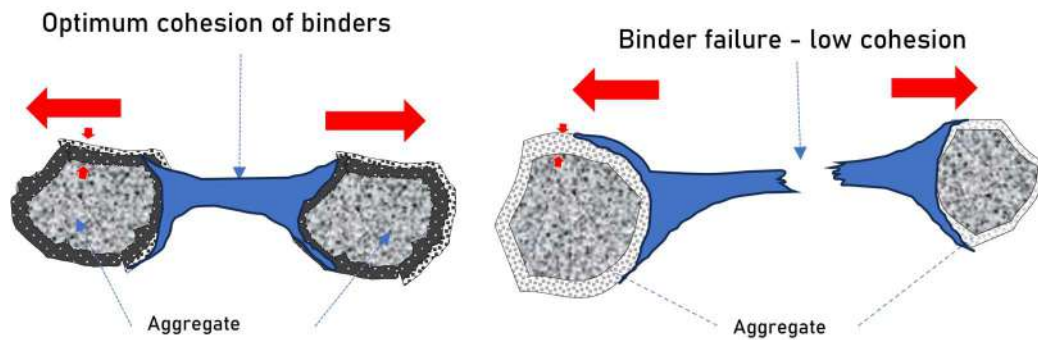


Figure 3.54: Cohesion performance of binder. Source: Author's elaboration.

The cohesion test focuses on evaluating the cohesive forces between binders and aggregates, with an emphasis on assessing how additives such as CR and CF can potentially alter these cohesive interactions. The Cohesion test is shown in Figure 3.55.

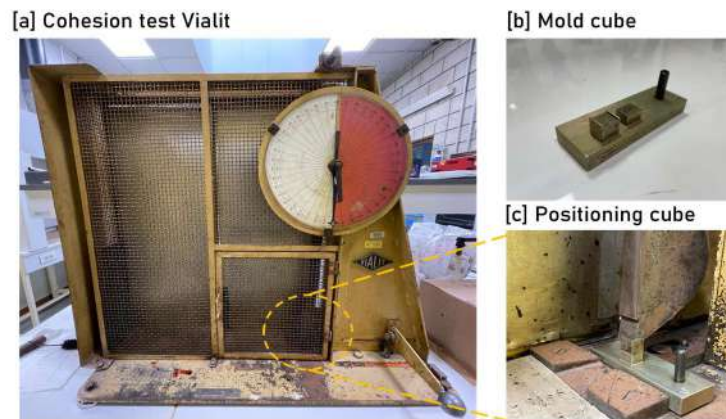


Figure 3.55: a) Cohesion test device, b) Steel cube, and c) Operations.

This method is based on the measurement of the energy absorbed (J/cm^2) by a binder by the impact of a pendulum on the test assembly: a support on which there is a metal cube glued to it by a thin layer of binder. The cohesion pendulum has an approximate speed of 4.4 m/s when it hits the binder samples. At the point of

impact, a load is rapidly applied within the sample and the velocity changes from zero to that of the pendulum.

The cohesion test is carried out over a range of temperatures, from six specimens per temperature, up to a total of eight different temperatures. In the test, the angle obtained after the pendulum collision is recorded at a selected temperature. Each angle is converted to a value according to Equation 16, and Equation 17.

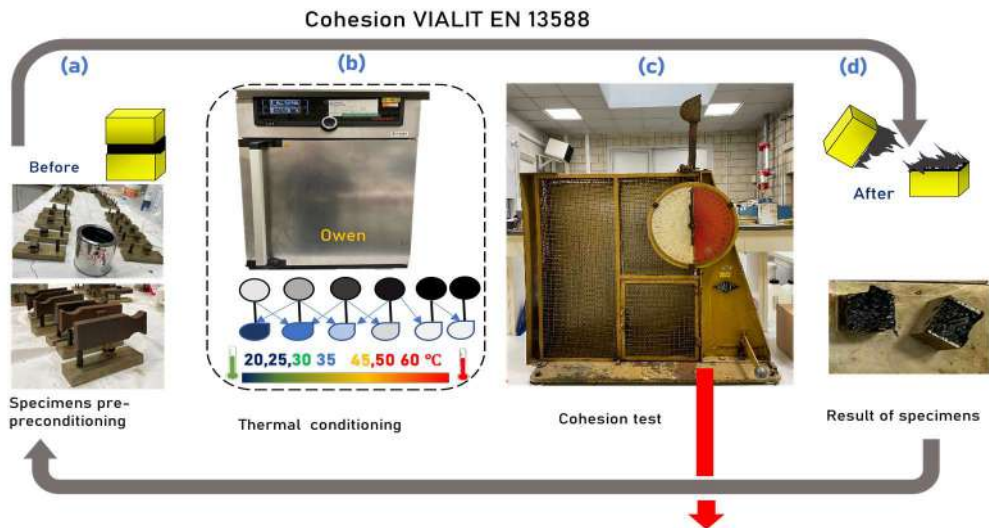
$$E = mgr(1 + \cos\alpha) \quad \text{Equation 16}$$

Where: E: energy absorbed by impact, expressed in joules.

$$C = \frac{(E-E')}{s} \quad \text{Equation 17}$$

Where : s: is the breaking area (contact of the cube with the binder cm²). The cohesion test values are expressed to the nearest 0,01 J/cm².

The comprehensive laboratory testing includes the following steps: (a) Preconditioning of the sample binder, (b) Thermal conditioning of the binder sample in an oven, c) Cohesion test, and d) Analysis of the samples and elaboration of the results. Figure 3.56 shows the process of evaluating the cracking resistance of the binder. The cohesive strength measurements include binders with different cohesion ratios (CR) and the incorporation of large carbon fibers (CFL) and fine carbon fibers (CFf).



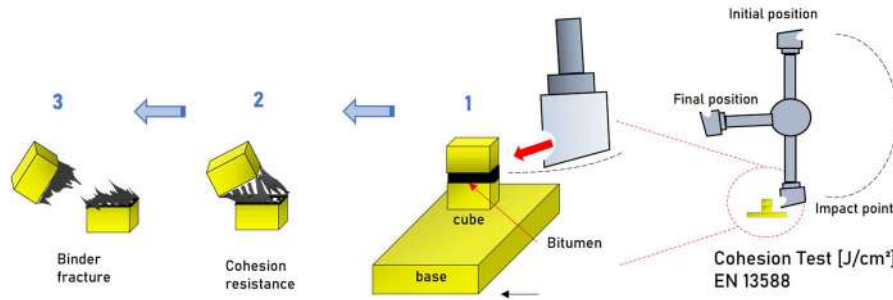


Figure 3.56: Cohesion measurement of binders. Source: Author's elaboration.

The cohesion test is performed binders with additives. In this case, the base binder is B 50/70 which is additive with 28.8% CR (1.50CR by weight of the mixture), 6.7% CFL (0.3 %CFL by weight of the mixture), and with 6.7%CFf (0.3 CFf by weight of the mixture).

In all cases, the CR, CFL, and CFf were incorporated by the WP. The additive-binder mixture has been very basic, with manual mixing. The aspect of the binders under study can be seen on Figure 3.57. The results obtained from these studies provide information on how CR affects the overall performance and properties of asphalt mixtures in terms of cohesion.



Figure 3.57: Binder's base, and binders with crumb rubber, large carbon fiber, and fine carbon fiber. Source: Author's elaboration.

3.7. Acoustic characterization

The method of acoustic assessment determined the coefficient of acoustic absorption as established in the ISO-10534-2 standard. Figure 3.58 shows the experimental design for the evaluation of sound absorption. First, a series of specimens were conditioned at different temperatures to carry out the acoustic evaluation to obtain the acoustic parameters at various temperatures.

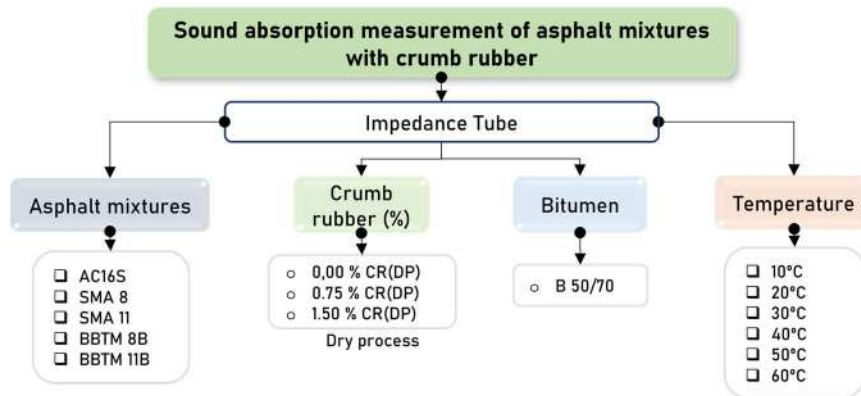


Figure 3.58: Scheme of experimental sequence. Source: Author's elaboration.

3.7.1. Sound absorption.

The sound absorption coefficient was evaluated by the impedance tube method outlined in ISO 10534-2 (1998). This coefficient is presented as a numerical value, where 1.00 signifies a material that absorbs the complete 100% of incident sound energy, and 0.00 indicates complete sound reflection. All calculations are according by ISO-13472-3 and ISO-10534-1,2. The assessment of absorption at normal incidence occurs within the frequency span of 100 Hz to 1600 Hz (Paje et al., 2009) encompassing the range of tire tread pitch frequencies which extends from 500 Hz to 1000 Hz (Li, 2019).

The experimental assessment was carried out in the Laboratory of Acoustics Applied to Civil Engineering LA2IC of the University of Castilla –La Mancha Spain. In order to assess the acoustic properties and the influence of CR as a sound-attenuating material proper equipment was used, as shown in Figure 3.59.

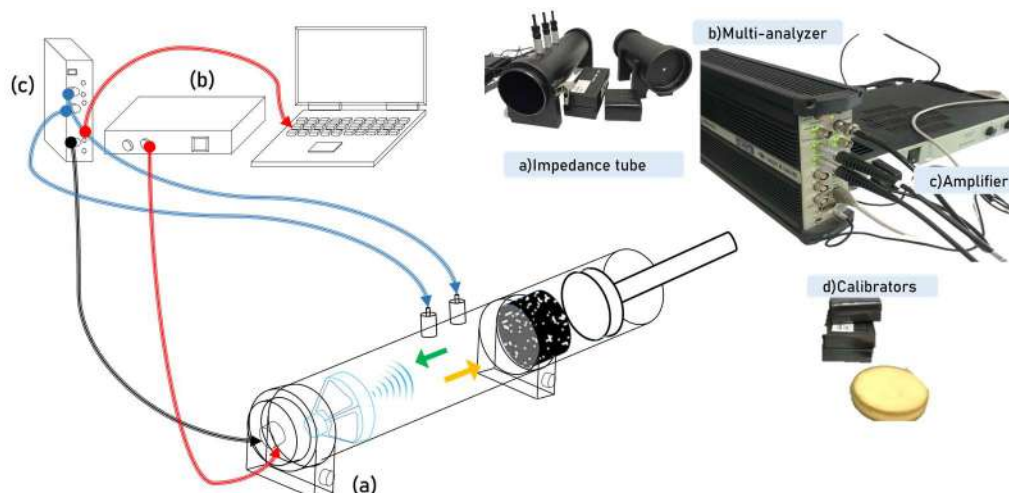


Figure 3.59: Set of acoustic equipment a) Impedance tube, b) Multi analyzer, c) Amplifier, d) Calibration accessories. Source: Author's elaboration.

The impedance tube is calibrated by 100% absorption sponges prior to all acoustic measurements to ensure the accuracy of the result, of absorption coefficients across a frequency range of 100 Hz to 1600 Hz.

This investigation encompassed the determination of standard normal incidence sound absorption spectra for a total of 90 bituminous mixture specimens (comprising 5 distinct bituminous mixtures, each with 3 levels of CR content, and 6 specimens per configuration).

The methodologies ISO-10534-1 (2002) and EN-10534-2 (2002) outline the impedance tube technique and the two-microphone transfer function approach, respectively. The experimental apparatus included the multi-analyzer PULSE system type 3560 B-T06, an amplifier B&K 2716C and multi-analyzer 4206 Bruel&Kjaer (B&K) (Vázquez et al., 2018), and two condenser microphones type 4187. These microphones, positioned along the tube, were utilized to compute the sound absorption coefficient (α) across an extended frequency spectrum, with a resolution of 1 Hz. The investigation entailed a total of 100 averaged spectra at distinct microphone positions (Paje et al., 2008).

To ensure the proper procedure of sound signal emission and reception, safety measures have been implemented, in particular at the joints where the metal junction occurs, in accordance with the design of the metal tube impedance. Prior to the acoustic evaluation, the samples were laterally coated with a thin Teflon film (polytetrafluoroethylene - PTFE) as shown in Figure 3.60, to eliminate the clearance between the sample contour and the tube walls (Luong et al., 2014).



Figure 3.60: Pre-conditioning specimens with PTFE on their lateral surface. Source: Author's elaboration.

a) Influence of the temperature by sound absorption

The effect of temperature on asphalt pavements is widely known to alter their mechanical response and could have an impact on sound absorption characteristics.

One of the main objectives of this phase is to evaluate the thermoacoustic effectiveness of hot asphalt mixtures and the determination of the optimum temperature of maximum absorption of acoustic energy, as well as the influence of granulated rubber to maximize the absorption capabilities of asphalt mixtures. In addition, the influence of other factors not considered in Section 2.4 on acoustic absorption on thermal conditioning performance is evaluated.

Figure 3.61 shows the manufacturing process, the absorption energy testing process, and the analysis of the acoustic evaluation spectra at different temperatures.

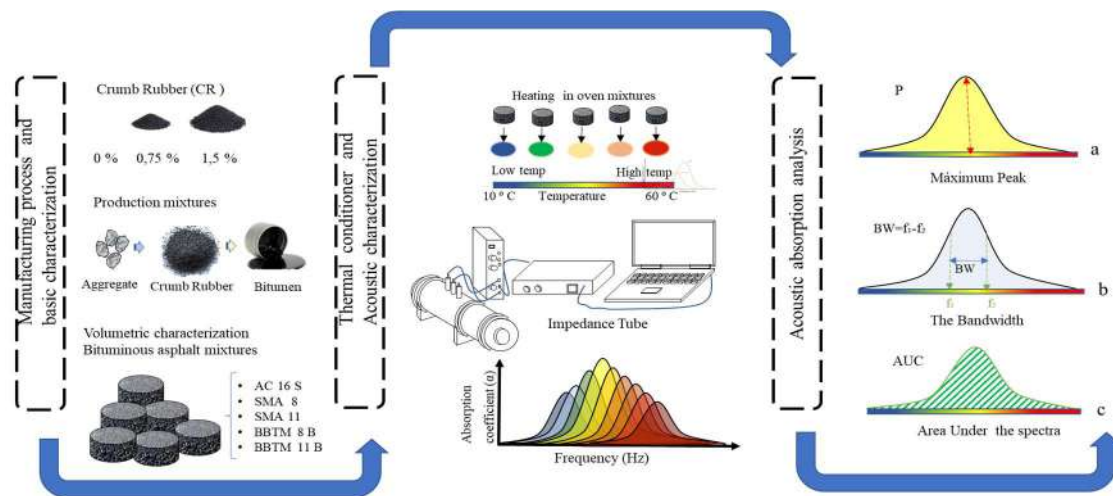


Figure 3.61: Experimental design, acoustic characterization, and analysis. Source: Author's elaboration.

As mentioned above to minimize the presence of an air gap between the specimen and the tube walls, a thin layer of Teflon (polytetrafluoroethylene, PTFE) was applied to the lateral surfaces of the samples as recommended by (Luong et al., 2014)(Figure 3.62).



Figure 3.62: Rubberized bituminous specimens with a lateral band of PTFE, a) AC 16 S, b) SMA 8, c) SMA 11, d) BBTM 8 B, and e) BBTM 11 B. Source: Author's elaboration.

Temperature effects were assessed by conditioning the specimens at different variations of temperatures: 10°C, 20°C, 30°C, 40°C, and 60°C under temperature control as shown in Figure 3.63. The sound performance was measured in terms of the absorption coefficient, including cases with 0%, 0.75%, and 1.50% CR by the dry process. Additionally, the effect of modified bitumen was investigated using two types of polymer-modified binders PMB 45/80-65 and high viscosity rubber-modified binder BMAVC.

Figure 3.63 shows the control of temperature in the oven. The asphalt mixture samples were subjected to thermal conditions and their temperature was monitored using a FLIR C2 thermography camera when the specimen reached the temperature of T°C in the oven, it was promptly placed into the impedance tube, which was preheated in a conventional oven to the required temperature T°C.

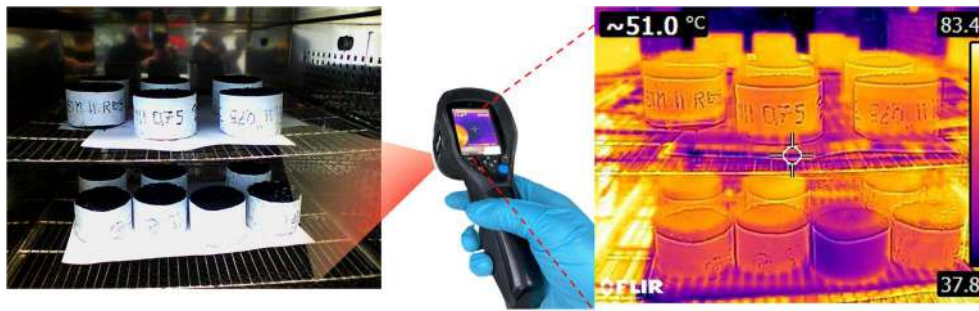


Figure 3.63: Thermal conditioning of specimens and control thermography. Source: Author's elaboration.

The average surface temperature of the specimen was obtained using FLIR tools analysis software. Initially, all samples were kept at a low temperature of 10 °C and then conditioned by specimens' groups until the desired temperatures of 20, 30, 40, 40, 50, and 60 °C (Figure 3.64). The thermal conditioning process was prolonged for 8 h for each temperature level and the temperature verification of the samples was accomplished by a thermographic camera.

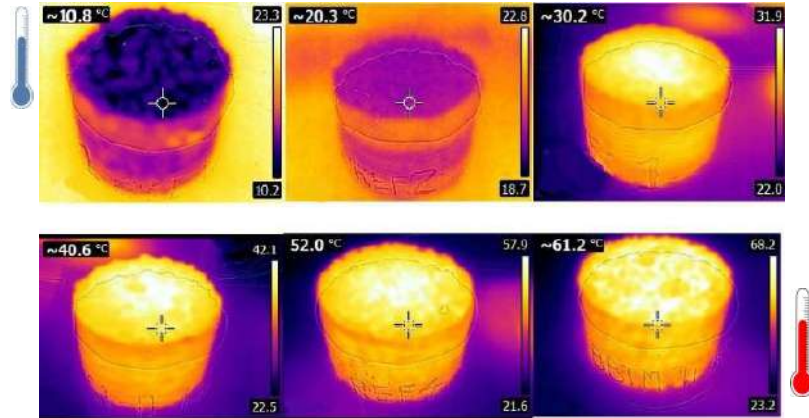


Figure 3.64: Conditioning samples and Thermographic imaging control (10 °C to 60 °C).

Source: Author's elaboration.

Subsequently, the entire assembly was introduced into the impedance tube at the specified temperature $T^{\circ}\text{C}$. After measuring the acoustic sound energy, the specimen was allowed to rest for 8 hours at ambient temperature. To ensure accurate measurement of the sound absorption coefficient, the temperature of both the impedance tube and the samples in the impedance tube is precisely controlled during the measurement process. This is illustrated in Figure 3.65.

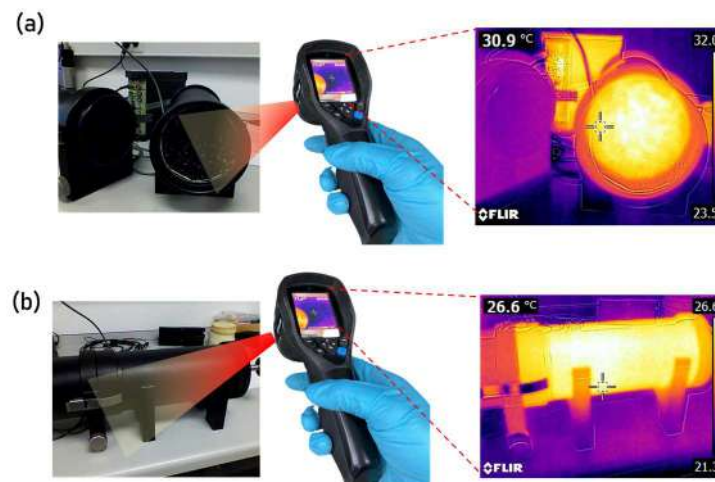


Figure 3.65: a) Control of the temperature of the specimen, b) Temperature measurement, of specimens inside of the impedance tube. Source: Author's elaboration.

Six specimens were tested for each combination of temperature, CR content, and type of asphalt mixtures accounting for a total of 540 values of sound absorption coefficient (a) obtained with the laboratory experiment described above.

b) Sound absorption analysis by Gaussian adjustment.

Using the Gaussian Fit (GF), three parameters were determined from the acoustic response spectrum: Peak (P), BandWidth (BW), and Area Under the Curve (AUC). Based on the parameters and the response spectrum analysis techniques, it is possible to characterize the absorption by Gaussian fitting (Lalanne 1984). All the fittings described in this subsection were carried out using the software Origin. The values of these parameters (P, BW, and AUC) are based on the general shape of the bell-shaped Gaussian function (Figure 3.66).

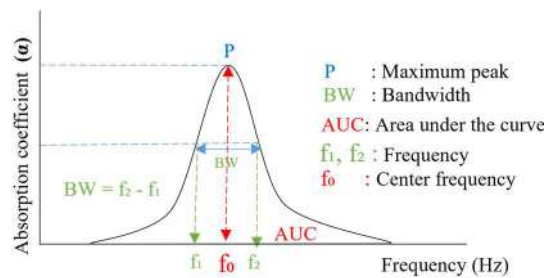


Figure 3.66: Geometric parameters for the characterization of the Gaussian fit. Source: Author's elaboration.

Figure 3.67 A shows a plot of the measured acoustic spectra for three types of asphalt mixtures (AC, SMA, and BBTM), and Figure 3.67B, shows the corresponding schemes of the parameters of the Gaussian fit: the fitted maximum peak, the fitted bandwidth and the fitted area under the curve for each type of asphalt mixture. The values characterized by the parameters of the Gaussian fit will be used to build correlation models with different volumetric characteristics of the asphalt mixtures, such as air void content, densities, permeability, and average depth of the surface texture, established from consecutive and statistically representative measurements for the different mixtures built with the asphalt mixtures studied.

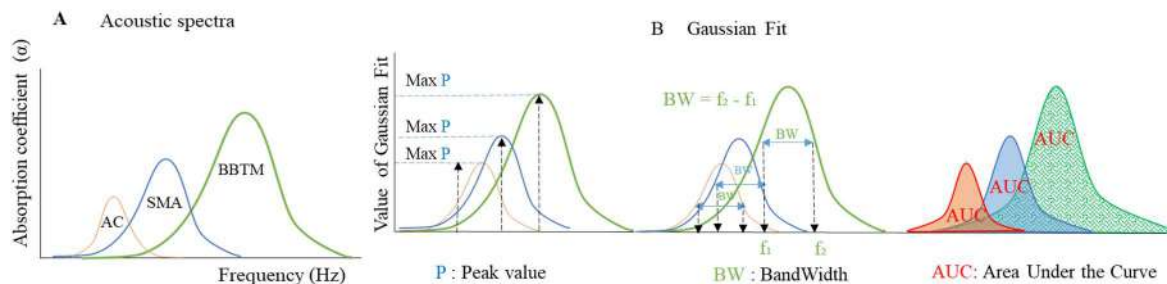


Figure 3.67: (A) Schematic of sound absorption spectra for three types of asphalt mixtures, (B) Schematic of the Gaussian fits describing the (ABS) for three types of mixtures. Source: Author's elaboration.

c) Statistical analysis

Statistical analysis was performed to evaluate the effect of temperature, CR content, and volumetric properties of the asphalt mixtures (independent variables) on the Gaussian fitting parameters of sound absorption, i.e. Peak (P), Bandwidth (BW), and Area Under the Curve (AUC).

Prior to this, a correlation analysis was carried out to check for possible links between the independent variables, which could give rise to multicollinearity problems.

The Pearson correlation coefficient (r) has a range between -1 and 1 (Akoglu, 2018). The higher the absolute value of the coefficient r , the stronger the relationship between the two variables studied. Conversely, the closer it is to 0, the weaker the association between the two variables. The Pearson correlation coefficient is calculated using Equation 18.

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad \text{Equation 18}$$

Where: n is the sample size, x_i and y_i are the sample points and $\bar{x}$ and $\bar{y}$ are the sample means.

The degree of correlation between volumetric characteristics, CR content, and sound absorption measurement temperature was established according to Pearson's correlation grading rules (r) (Akoglu, 2018) which are shown in Table 3.15. The sign of the coefficient indicates the direction of the relationship (positive or negative). A positive value (r) indicates that as one variable grows so does the other, while a negative value (r) means the opposite trend.

Table 3.15: Degree of correlation by Pearson's coefficient.

Classification rules	Degree of correlation
$r = 0$	No correlation
$0 < r \leq 0.19$	Very weak
$0.20 < r \leq 0.39$	Weak
$0.40 < r \leq 0.59$	Moderate
$0.60 < r \leq 0.79$	Strong
$0.80 < r \leq 1.00$	Very strong
$ r = 1$	Monotonic correlation

On the other hand, the effect of volumetric characteristics, CR content, and temperature on the peak Gaussian fit parameters (P), Bandwidth (BW), and area

under the curve (AUC) obtained from the acoustic spectra have been evaluated by means of a multiple linear regression analysis (MLR). Linear models have been estimated to predict the coefficients of the Gaussian fit P, BW, and AUC. The development of the linear regression model has been formulated according to Equation 19. The multiple linear regression model can be expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n \quad \text{Equation 19}$$

Where: y is the dependent variable (in this case P, BW, or AUC), and. x_1 to x_n are the independent or predictor variables (in this case CR content, temperature, void content, average texture depth, permeability, and apparent density), β_0 is the y-intercepts (constant term) and β_1 a β_n are the regression coefficients estimated to improve the model fit.

Air void content Va, CR content (%), and temperature (°C) were considered as potential predictors of Peak (P), BandWidth (WB), or Area Under the Curve (AUC) models, and the ordinary least squares (OLS) regression technique was used to estimate the regression coefficients. Model estimation was carried out using Statmodels, a Python library built specifically for statistical computing. A backward stepwise regression approach was used, with a significant level of $\alpha = 0.01$. First, all potential predictor variables were included in the models excluding those that showed collinearity. Next, non-significant predictors were excluded from the models, and the regression analysis was repeated. The procedure was stopped when the optimal model was identified after selecting the most appropriate and significant variables. Furthermore, the goodness of fit of the models was assessed by the coefficient of determination (R^2).

A linear regression analysis was performed to build up a relationship model of the sound absorption coefficient (α) and of the volumetric properties of the asphalt mixture, such as air voids (Va), specific bulk density (Gmb), permeability (Kv), Mean Texture Depth (MTD) and Mean Profile Depth (MPD). The coefficient of determination, R^2 , was used to assess the fitting goodness.

Thirty-six values of the absorption coefficient (α) were obtained through laboratory experiments, with six specimens tested for each of the dry processes, as previously described. Subsequently, an Analysis of Covariance (ANCOVA) was performed using stats models in Phyton.

In general, ANCOVA evaluates main and interaction effects of categorical variables on a continuous dependent variable while controlling for the influence of other continuous variables (covariates). This analysis to be the most appropriate

for evaluating the main effect of CR content and the type of mixture (categorical variable) their interaction (CR content and type of mixture) and main effect of air voids (continuous variable) on the sound absorption of asphalt mixtures. The main and interaction effect were evaluated at 99% significance level ($\alpha=0.01$).

3.7.2. Dynamic stiffness

It is appropriate to clarify the differences in dynamic stiffness in relation to other stiffnesses, such as the modulus of stiffness of an asphalt mixture, commonly known as "stiffness" or stiffness Modulus. The dynamic stiffness value should not be confused with material strength.

Dynamic stiffness has been related to the noise generation on the pavement according to (Vázquez et al., 2016) while in the acoustic applications, it is primarily used to describe the insulation properties of materials used under floating floors in dwellings to damping impact noise. According to the applicable standard, EN-29052-1:1994 (ISO 9052-1:1989), the aim is to determine the frequency of the fundamental vertical vibration (resonance frequency) of a mass-spring system, where the mass is the load plate, and the spring is the sample of the insulating material. The procedures for performing the test and subsequent analysis will be described below.

Dynamic stiffness characterization is essential both for optimizing pavement acoustics and for evaluating the intrinsic stiffness related to the elastic vibration behavior of asphalt mixtures. The measurement of the dynamic stiffness (Ds) was conducted using the non-resonance method. The assessment of Ds is similar to that carried out by (Li et al., 2016a), concerning the intricate interplay between the force vector and the velocity vector (Vázquez et al., 2020a; Vázquez & Paje, 2016). This is closely related to the evolution of mechanical impedance (Z) which is calculated by Equation 20:

$$Z = \frac{F}{v} \quad \text{Equation 20}$$

Where: Z is mechanical impedance, F is the force complex vector, and v is the complex velocity vector. However, the Ds assesses the complex relationship between the force vector and the displacement vector.

The stiffness is a key factor in pavement acoustic engineering and is usually used to characterize the force vibration energy transmission and energy dissipation properties on the pavement structure. Previous studies have reported that

tire/pavement noise may be affected by the dynamic stiffness in like manner a mechanical impedance (Czech & Gardziejczyk, 2020) which is related to amplification/reduction noise generation (Sandberg & Ejsmont, 2003). In asphalt specimens, is typically described by a single-degree-of-freedom (SDOF). The stiffness is calculated based on the ratio of mass displacement to shaker displacement by load and boundary conditions of the SDOF model require excitation with a fixed mass end (Vázquez, 2015; Vázquez et al., 2020b; Vázquez & Paje, 2016).

The dynamic stiffness (D_s) of asphalt mixtures is influenced by their intrinsic and elastic properties, as well as the damping (Ns/m) resulting from the dissipation of imposed dynamic forces. Dynamic Stiffness (D_s) is the structural property that characterizes the dynamic behavior of the pavement through the complex relation between the applied force (F) and resulting displacement (d), according to Equation 21.

$$D_s = \frac{F}{d} \quad \text{Equation 21}$$

The D_s method was used to determine the dynamic characteristics of the specimens.

Excitations on the upper face of the specimens were applied at frequencies in the range between 1 Hz and 1000 Hz using an impedance head (accelerometer and force sensors) as shown in Figure 3.68e. The Dynamic response of the samples was verified by spectra obtained using a Bruel & Kjaer 4809 vibration exciter (Figure 3.68b). The impedance head was located on the asphalt samples to register the force applied by the vibration exciter and motion of the surface (acceleration) (Vázquez et al., 2020b). Using the non-resonant method and Fast Fourier Transforms (FFT), the frequency domain response was obtained. The dynamic stiffness measurement system also includes an amplifier, a signal generator, and a data receiver which records the results using a multi-analyzer system as shown in Figure 3.68c.

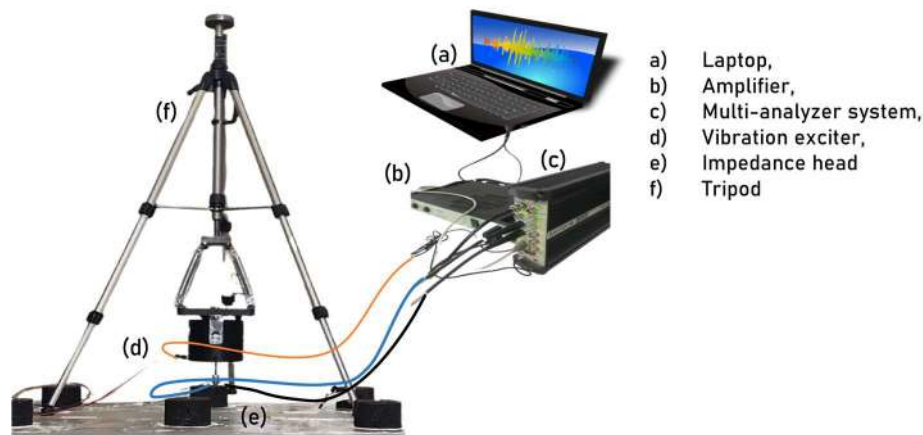


Figure 3.68: Dynamic Stiffness equipment. Source: Author's elaboration.

The dynamic response analysis setup for the dynamic stiffness measurement of bituminous samples can be seen in Figure 3.69. The setup includes a signal of the force and acceleration transducers (impedance head), produced by the vibration exciter, which is driven by a random and sweep sinusoidal vibration excitation signal generated and transmitted to the upper face of the sample asphalt mixture. Afterward, the force and vertical displacement measurements are obtained using the impedance head (Vázquez et al., 2020b). The process of the signal was analyzed using an FFT to determine the dynamic stiffness spectrum in (MN/m). Figure 3.70a. shows the manufacturing process. A connection plate in which the impedance head is attached is fixed on the upper surface of the specimens. The cylindrical specimens should be placed on the ground fixed to avoid movements that distort the transmission and reading of the signals in the laboratory. To ensure the correct application of signal vibrations a mass plate is supported by a tripod during the measurements (sweep and random), to stabilize the shaker during the test. More information on the measurement is included in (Vázquez et al., 2020a; Vázquez & Paje, 2016).

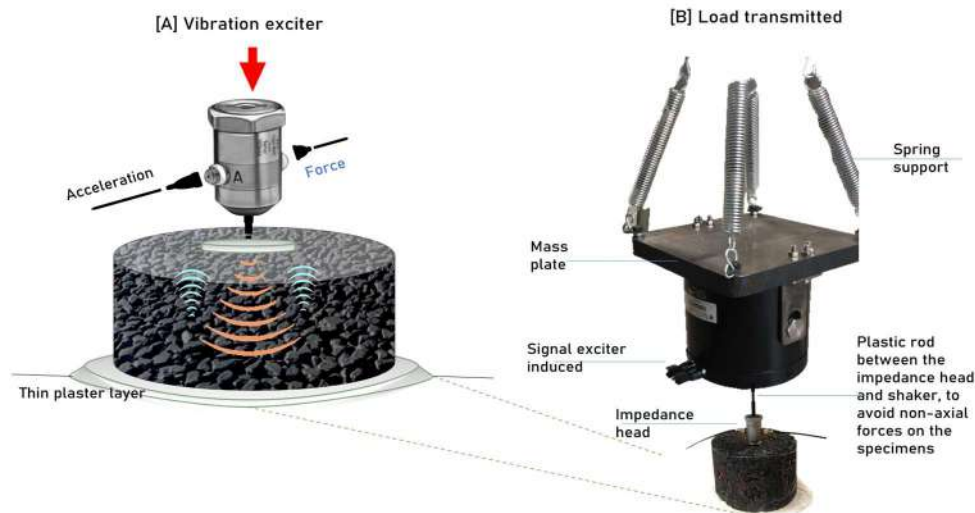


Figure 3.69: Signal exciter measurement of Dynamic Stiffness: A) Left schemes sample enabled impedance head, B) Parts of the set component to the measurement system.

Source: Author's elaboration.

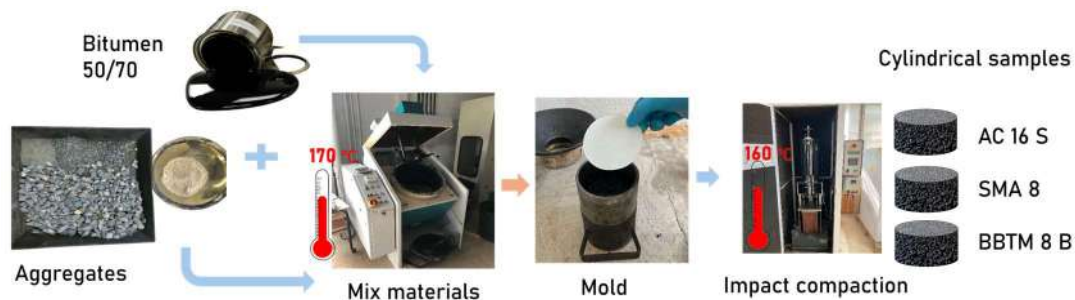


Figure 3.70: Schematic diagram of specimens, manufacturing. Source: Author's elaboration.

Precision and accuracy : Phase angle and coherence play a key role in determining the precision and accuracy of the dynamic stiffness test. These parameters provide valuable information about the internal integrity and behavior of the material. The phase angle ranges dynamically from 0° to 180° , serving as an indicator of the phase differential between the externally applied force and the consequent response within asphalt mixtures (Zhao et al., 2023). It serves as an indicator of the temporal relationship between the force exerted on the material and its resultant displacement or acceleration response. In examining the phase angle, researchers have understood it as a delay in the reaction of the material to an applied force.

Coherence, meanwhile, varies between 0 and 1 and quantifies the degree of the complex linear associated with two signals, typically the applied force and the system's response. It is used to assess the extent to which these signals are correlated or synchronized (Czech & Gardziejczyk, 2022). When coherence is high (1), it indicates an effective linear relationship relating the applied force and the system response. Conversely, a low coherence (0) suggests a weak or inconsistent relationship.

In order to find a relationship between void content (Va), bulk density (Gmb), and dynamic stiffness (Ds) values at different frequencies, the Pearson (r) linear correlation analysis between Va, Gmb, and Ds values has been performed through 1 Hz and 1000 Hz. Research in the field of acoustics has predominantly emphasized measurements at 400 Hz frequencies (Vázquez, 2015).

To evaluate Pearson's correlation coefficient (r), a scale ranging from -1 to 1 was used. A high absolute value of r signifies a closer relationship between the variables examined, while a value close to 0 denotes a lesser connection between the set of variables. Pearson's correlation coefficient was determined using Equation 22:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad \text{Equation 22}$$

Where: n is the sample size, x_i and y_i are the sample measurement values and $\bar{x}$ and $\bar{y}$ are the sample means.

Analysis of covariance (ANCOVA) was then performed. Similar to the of sound absorption, the objective of the analysis was to evaluate the main effects of CR content and type of mixture their interaction, and the main effect of air void content on the dynamic stiffness of asphalt mixtures. Details about the procedure of the analysis can be found in Section 3.71.

3.8. Piezoresistive characterization

The assessment of the contribution of CR to the piezo resistive measurement of asphalt mixtures was performed during the investigation. CR provides greater flexibility to asphalt mixtures by improving their ability to deform under load and recover. Additionally, it absorbs and dissipates mechanical stresses. This flexibility can improve the sensitivity of the electrical response.

Figure 3.71 illustrates the scheme of the evaluation program to measure the self-sensing of the asphalt mixtures tested in this research.

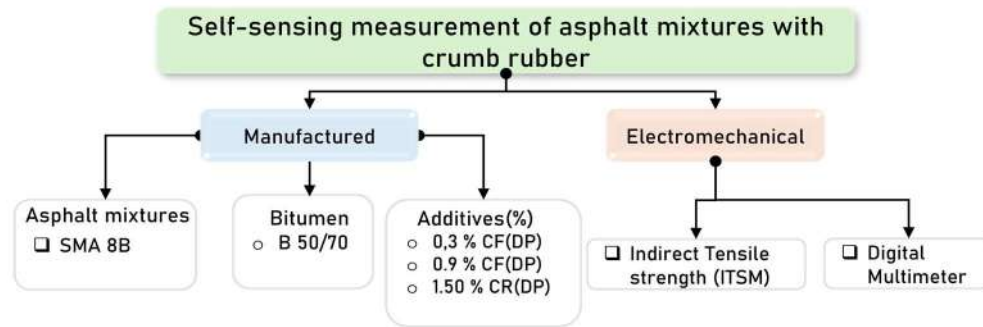


Figure 3.71: Schematic assessment of self-sensing.

3.8.1. Mixtures under study

To assess the impact of crumb rubber (CR) on the self-sensing capabilities of asphalt mixtures, various materials were employed at 1.50% CR, 0.3% carbon fibers (CF), and 0.9% CF by weight of the total aggregate of the asphalt mixture. Due to the differing specific weights and densities of CR and CF, a substitution principle was applied in volume.

When integrating CF into asphalt mixtures, a primary concern is its effect on conventional volumetric and mechanical properties, which are critical for ensuring the structural and functional performance of road pavements. The composition of the materials, including the replacement of the Electric Arc Furnace Slag (EAFS) in the fraction of 4mm to 0.063 mm, is outlined in Table 3.16. This consistency in replacement signifies an important aspect of the incorporation process and it has a potential impact on the properties of asphalt mixtures.

Table 3.16: Composition of materials.

Materials		Reference	Mod-1	Mod-2
	Size (mm)	%	%	%
Porphyry	11.2 -8	7	7	7
Porphyry	8 - 4	53	53	53
EAFS	4 - 2	10	9	8
EAFS	2- 0.5	13	11	9
EAFS	0.5 – 0.063	8	8	8
EAFS	0.063 -0.0	9	9	9
Bitumen		6	6	6
CR %		-	1.5	1.5
CF 0.3%		-	0.3	-
CF 0.9%		-	-	0.9
total weight (g)		1000	950	950

In this phase, a reference mixture, without CF neither CR was also fabricated for comparison purposes.

3.8.2. Manufacturing of the self-sensing asphalt specimens

Stone Matrix Asphalt (SMA) mixtures were studied to assess their capabilities, with dosages defined in Chapter 3.1.1, and its mechanical performance were evaluated. Various Marshall cylindrical asphalt mixture specimens, measuring 101.6 mm in diameter and approximately 60 mm in height, were manufactured in accordance with the procedure outlined in Figure 3.72.

All specimens were mixed at a temperature of 175°C. For conductive mixtures (CF-0.3% and CF-0.9% mixtures), first the selected quantity of carbon fibers (CFs) was hand-mixed with the bitumen for 5 minutes at a temperature of 170°C. second stage the crumb rubber (CR) was added to the aggregates at the same temperature, mixed for 2 minutes. And third, the binder (binder+ CF) was incorporated to the aggregates, at 160°C, followed by final mixing for 30 seconds at 170°C.

The digestion process of the CR involved keeping the mixtures before compaction in the oven at 160° for 90 minutes to allow the rubber particles to interact with the bituminous mixture. To ensure uniform thermal processing for all mixtures the reference mixture, without CR, overcame a parallel thermal process in the oven. Finally, compaction was carried out at 165°C using a Marshall hammer (EN 12697– 0:2004), with 50 blows applied on each side of the specimen.

The measurement of electrical resistance requires the incorporation of four copper wires (electrodes) embedded within the bituminous mix samples, which implies a modification of the manufacturing procedure described above. For this purpose, four small holes were drilled in the metal base of the Marshall mold 20 mm apart to accommodate the four copper wires (electrodes) in a vertical position, each with a length of 4 cm and a diameter of 2 mm (Figure 3.72a). The electrodes were securely fixed with a temporary metal support to prevent movement during the pouring phase (Figure 3.72b). After having introduced a part of the mixture into the mold (Figure 3.72c), the metal support was removed, and the rest of the mixture was added. Finally, the compaction phase was carried out(Figure 3.72d). After demolding the sample, the four electrodes were soldered to other more flexible copper wires to allow the electrical measurement (Figure 3.72e).

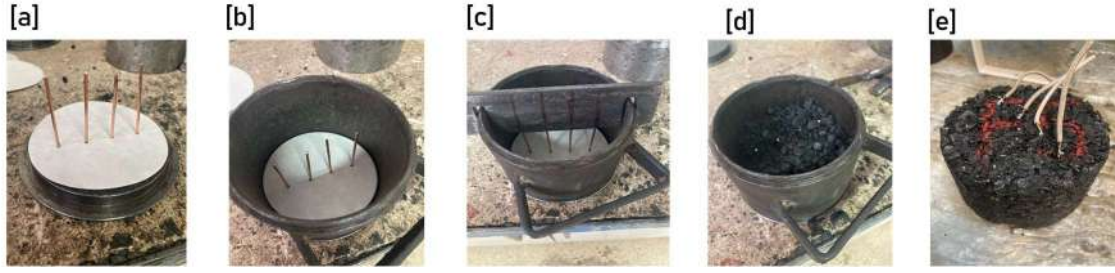


Figure 3.72: Manufacture of the asphalt mixtures samples for the assessment of electric response . Source Authors elaboration.

3.8.3. Volumetric characterization

The bulk density (G_{mb}) of the asphalt mixtures was estimated using the saturated surface dry (SSD) method (EN 12697-6:2012). This method, coupled with the determination of the maximum density (G_{mm}) (EN 12697-5:2012), allowed for the calculation of air void content (A_v) using Equation. 23 this methodology is explained in section 3.3.1.

$$v_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \quad \text{Equation 23}$$

For the mechanical characterization of the conductive asphalt mixtures, the Indirect Tensile Stiffness Modulus (ITSM) test was conducted in accordance with the EN 12697-26:2012 standard. ITSM measures the relationship between applied stress and maximum measured strain response. The test involved applying five haversine-shaped load waveform pulses with specific parameters to produce a target horizontal deformation. ITSM, expressed in MPa, was calculated using Equation 24, which accounts for factors such as maximum load (P), Poisson's ratio (ν), horizontal deformation (z), and specimen thickness (h).

$$ITSM = \frac{P \cdot (\nu + 0.27)}{zh} \quad \text{Equation 24}$$

Additionally, the Indirect Tensile Strength (ITS) was evaluated as per the EN 12697-23:2018 standard, conducted at 15°C. This test involved applying a constant deformation until specimen rupture, and ITS, in MPa, was calculated using Equation 25

$$ITS = \frac{2 \cdot P_{max}}{\pi \cdot d \cdot h} \quad \text{Equation 25}$$

Where: P_{max} is the peak load, in N, d is the diameter of the specimen, in mm, and h is the height of the specimen, in mm.

3.8.4. Electrical assessment of the mixtures

An electrical assessment of the asphalt mixtures samples was conducted to evaluate the piezoresistive properties of the asphalt mixtures, which involves assessing the capacity for electric resistance to change in response to applied strain. The piezoresistive response of EAFS+CF+CR asphalt mixtures was evaluated using cylindrical specimens under both static and dynamic assessment.

Mechanic assessment of self-sensing consisted of evaluating the change in electrical resistance of the asphalt mixtures resulting from the application of external stimuli. This is done using a configuration of the set of the dynamic tensile strength loads in a haversine pattern at 20°C, with amplitude across nine levels (100, 250, 500, 750, 750, 1000, 1500, 2000, 3000, and 4000 N). Each level includes 40 load cycles, recorded at a sampling rate of 100. Each load pulse lasted for 1 second, followed by a rest of 10 seconds.

Figure 3.73 shows the cycles of the load for two levels of charge (100 and 250N), the rest of the load levels are not shown for simplicity.

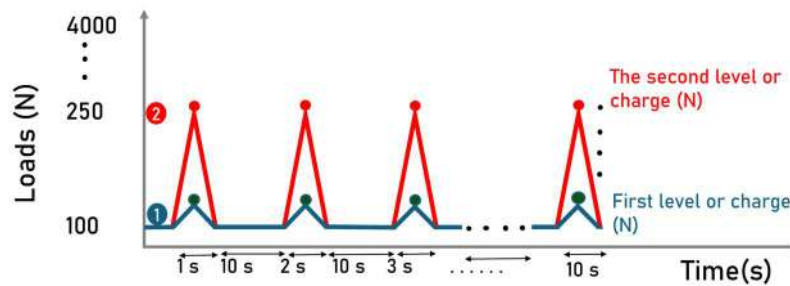


Figure 3.73: Loading pattern of the strain-sensing test. Source Authors elaboration

The asphalt specimen's measurement of electrical resistance R was measured with digital multimeter type Keysight 34465A Direct current (I) was applied to the two outer electrodes subjected to an electrical intensity, and the potential (V) was measured between the two inner electrodes (Buasiri et al., 2019), as represented in Figure 3.74.

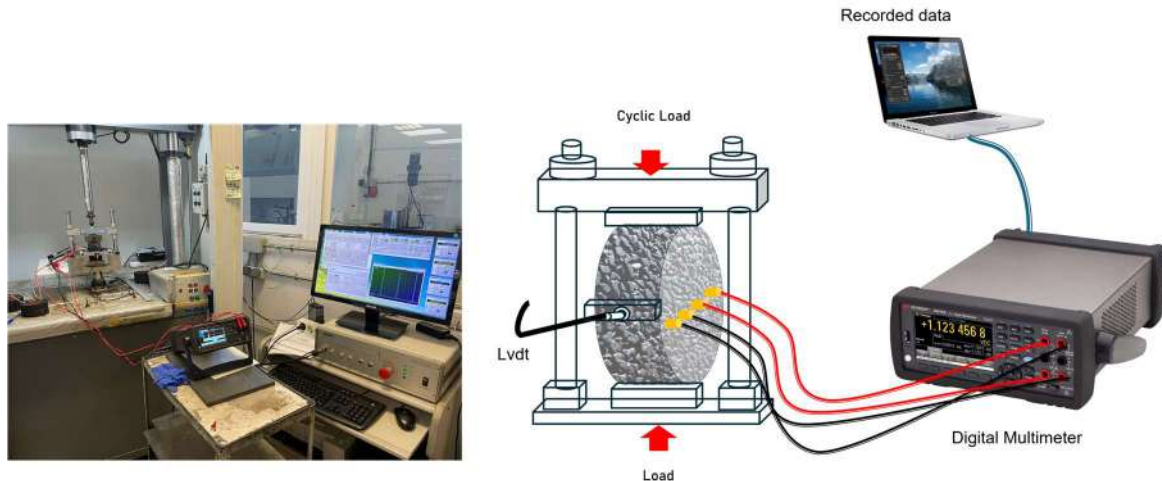


Figure 3.74: Piezoresistive experimental test. Source Authors elaboration.

The applied load charge of a haversian type of waveform was performed at a temperature of 20°C, with a rest period of 10s between successive applications of 1 second load. These configurations allowed for a comprehensive evaluation of the piezoresistive behavior of the asphalt mixtures under varying loads and frequency conditions. The specimens were subjected to 40 cycles of load strain.

The recorded dataset was analyzed through digital signal processing to evaluate the relationship between micro deformations units ($\mu\epsilon$) observed during the charge and discharge phases and the response to the fractional change of electrical resistance (FCR) of the specimen due to the effect of piezo resistivity. The experimental process is shown in Figure 3.75.

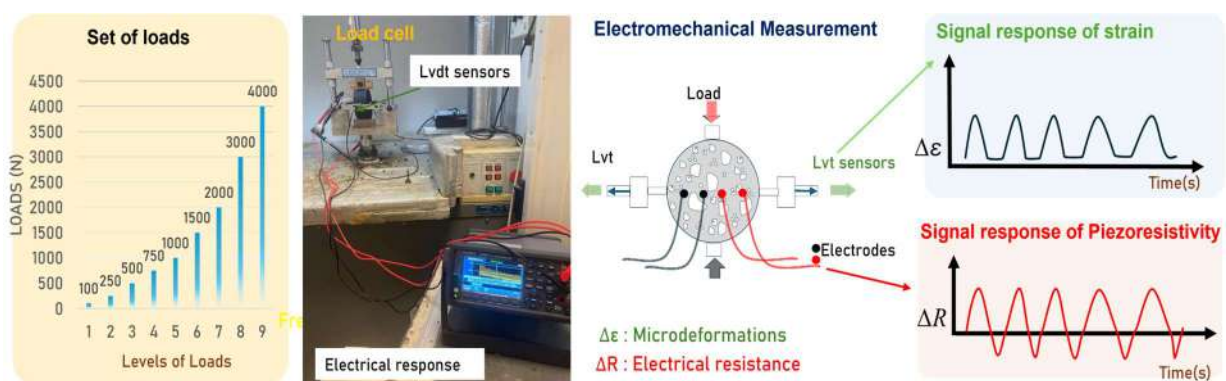


Figure 3.75: Experimental setup for the measurement of piezoresistive response.

To assess the piezoresistive properties, it is common to relate the concept between the change of electrical resistance produced by the strain ($R-R_0$) to the initial electric resistance (R_0), denoted as the fractional change of resistivity (FCR), and

expressed as a percentage. This relationship is typically represented as follows in Equation 26:

$$FCR(\%) = \frac{R-R_0}{R_0} \cdot 100 \quad \text{Equation 26}$$

In the analysis, both the signal of micro deformations ($\mu\epsilon$) and electrical resistance (FCR) exhibit varying behaviors in response to the applied external loads.

The second part of the analysis entails conducting linear regression analyses to establish the relationships between the amplitude of deformations of $\mu\epsilon$ and the FCR value associated. This step aims to assess the detection capabilities of the asphalt mixtures containing crumb rubber (CR), carbon fiber (CF), and Electric Arc Furnace Slag (EAFS).

4. Results and discussion

This section presents the most outstanding and significant results of the effect of crumb rubber on the volumetric, mechanical performance of the asphalt mixture. In addition, the relevant evaluation of the effect of crumb rubber on the characterization of the texture, skid resistances and the acoustic properties of the asphalt mixtures, as well as the piezoresistive response are included.

4.1. Volumetric and mechanical characterization

a) Apparent, maximum density and air void content

Table 4.1 shows the volumetric characteristics of asphalt mixtures with the addition of the CR by the DP.

Table 4.1: Volumetric characteristics for the dry process

Asphalt Mixtures	CR (%)	MT (°C)	DT (°C)	Gmm (g/cm ³)	Gmb (g/cm ³)	Va (%)
AC16S	0.00	170	160	2.526	2.406	5.27
	0.75	170	160	2.494	2.358	5.19
	1.50	170	160	2.472	2.304	6.72
SMA 8	0.00	170	160	2.511	2.385	4.86
	0.75	170	160	2.482	2.342	5.67
	1.50	170	160	2.457	2.296	6.73
SMA 11	0.00	170	160	2.516	2.345	6.66
	0.75	170	160	2.478	2.316	6.73
	1.50	170	160	2.443	2.282	6.56
BBTM 8B	0.00	170	160	2.557	2.220	16.84
	0.75	170	160	2.546	2.160	17.61
	1.50	170	160	2.463	2.137	18.16
BBTM 11B	0.00	170	160	2.559	2.278	18.50
	0.75	170	160	2.512	2.235	18.53
	1.50	170	160	2.511	2.208	18.65

CR: Crumb Rubber, MT: Manufacture Temperature, DT: Digestion Temperature.

The results of the effect of CR on the volumetric properties of the asphalt mixture present general trends for dry process mixtures as follows:

- Gmm decreases with the addition of CR, as crumb rubber has a lower bulk density than aggregates.
- Gmb also decreases with the substitution of aggregates for crumb rubber.
- Va it goes up slightly without no general rule for all mixtures.

Figure 4.1 shows the effect of the CR by the dry process on asphalt mixtures. It can be seen the reduction of the densities Gmm and Gmb and slight increase of Va respectively.

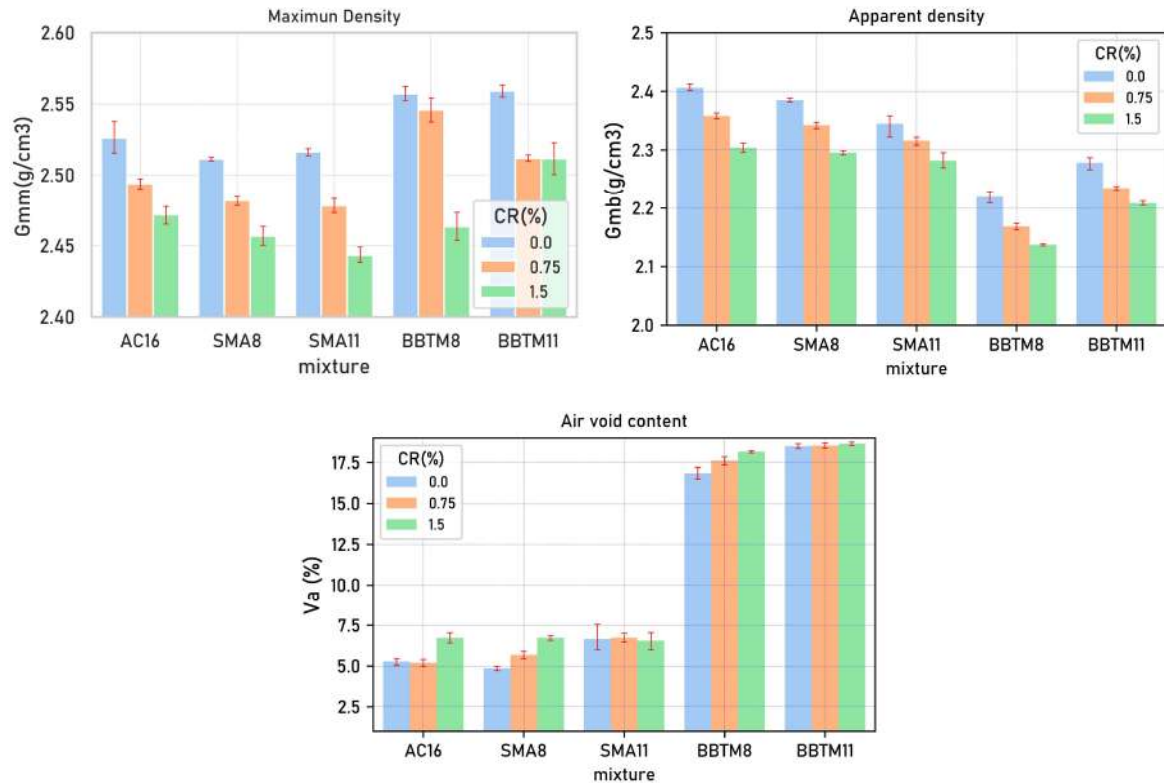


Figure 4.1: a) Maximum density, b) Apparent density, and c) Air void content behavior.

b) Permeability characterization

Table 4.2 presents results comparing the different asphalt mixtures in terms of drainage capacity.

Table 4.2: Permeability characteristics for the dry process

Asphalt Mixtures	CR (%)	MT (°C)	DT (°C)	Gmb (g/cm³)	Kv (m/s)
AC16S	0.00	170	160	2.406	(*)
	0.75	170	160	2.358	(*)
	1.50	170	160	2.304	(*)
SMA 8	0.00	170	160	2.385	0.00012
	0.75	170	160	2.342	0.00009
	1.50	170	160	2.296	0.00008
SMA 11	0.00	170	160	2.345	0.00019
	0.75	170	160	2.316	0.00011
	1.50	170	160	2.282	0.00016
BBTM 8B	0.00	170	160	2.220	0.00283
	0.75	170	160	2.169	0.00236
	1.50	170	160	2.137	0.00233
BBTM 11B	0.00	170	160	2.278	0.00176
	0.75	170	160	2.235	0.00150
	1.50	170	160	2.208	0.00052

(*) impermeable specimens

The impact of CR on permeability (K_v) is depicted in Figure 4.2. It's noteworthy that measuring K_v for AC (DP) was not feasible. The most significant observation is that CR by the dry process tends to decrease permeability. This result is in line with (Ren et al., 2021), the CR reduces the permeability performance of open-grade asphalt mixtures. This is related to the presence of CR in the tunnels inside the mixture.

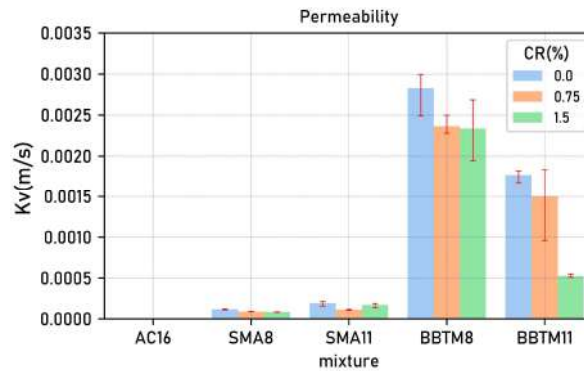


Figure 4.2: Permeability behavior.

c) Mechanical characterization

The result of Indirect tensile strength (ITS) and Indirect Tensile Strength Modulus (ITSM), with incorporation of CR by dry process is presented in Figure 4.3. The CR effect shows an increased ITS and ITSM.

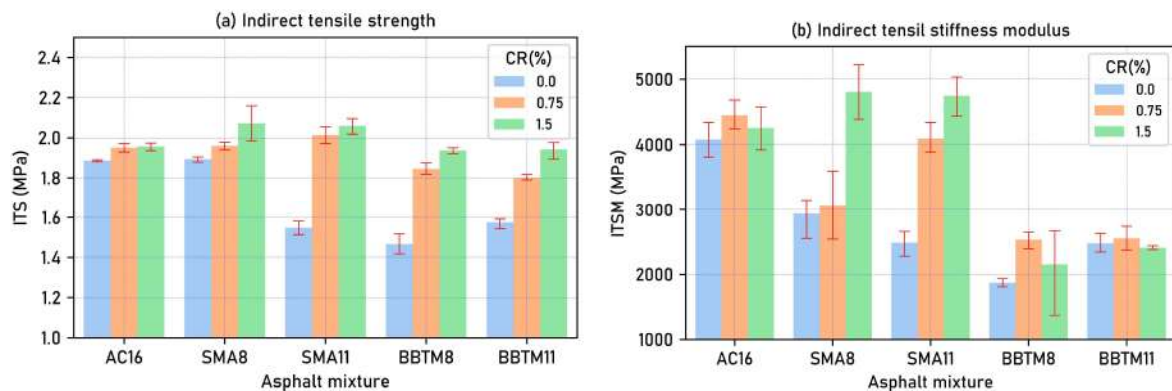


Figure 4.3: Mechanical properties for the dry process (DP) of the asphalt mixtures a) ITS, and b) ITSM.

Figure 4.4 shows the result of the Cantabro test for mixtures with crumb rubber by dry process. The general trend is a reduction of the particle's loss of asphalt mixtures specimens AC, SMA, and BBTM. These results are coherent with studies

of (Gardziejczyk et al., 2020) due to the fact that the increase of incorporation of crumb rubber slightly enhances their ability to resist degradation in the Cantabro abrasion loss test. The observed behavior, as noted by (Dueñas et al., 2009) is attributed to the capacity of crumb rubber (CR) to alter the viscosity of bitumen. This alteration leads to increased breaking strength, ultimately creating a protective coating on the aggregates with enhanced resistance to degradation. The absorption of aromatic oil by the crumb rubber particles in the asphalt binder results in the expansion of these particles CR, contributing to an overall increase in the asphalt binder's consistency (Z. Zhao et al., 2022).

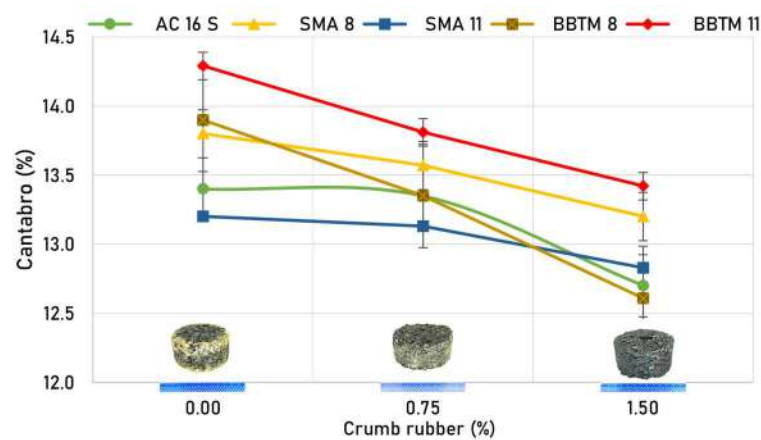


Figure 4.4: Effect of CR on the particle loss by Cantabro test.

Figure 4.5 shows the effect of the crumb rubber on resistance to degradation of particles of asphalt mixtures: AC 4.59 % (1.50 % CR) in SMA 8 4.24 % (1.50 % CR), SMA11 2.81 % (1.50 % CR), BBTM 8 B 9.03 % (1.50 % CR) and BBTM 11B 5.82 % (1.50 % CR) this is compared to reference mixtures.

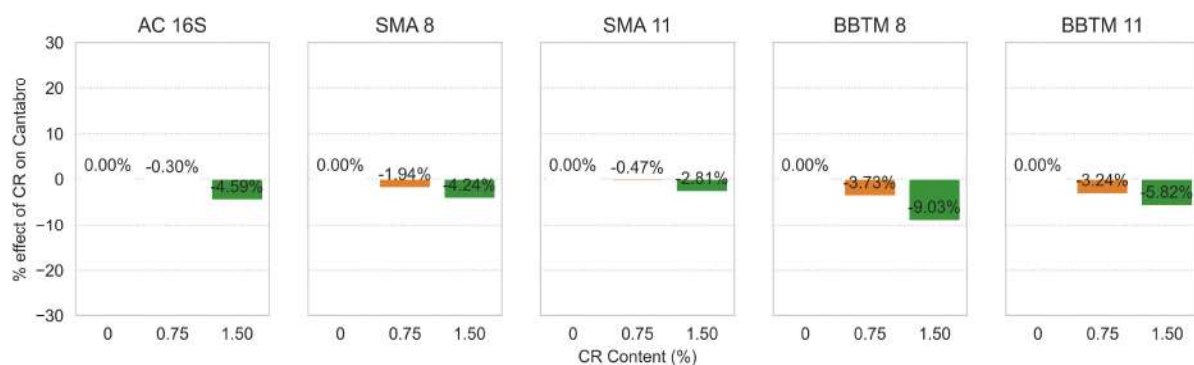


Figure 4.5: Effect of CR on the particle loss by Cantabro test.

4.2. Surface characterization.

The results of the surface characterization are mainly focused on the sand patch test (SPT) and the analysis of the profiles obtained through the laser texture scanner (LTS) on asphalt mixtures with the addition of the crumb rubber in different proportions over the weight of the mixture (0.0%, 0.75%, 1.50% CR). The texture is mainly determined by the aggregate gradation and the random interposition by the mineral particles during the construction.

The effect of CR on the mean depth texture (MTD) is illustrated in Figure 4.6. It is essential to emphasize the observed decrease in texture depth in all specimens with rubber by DP.

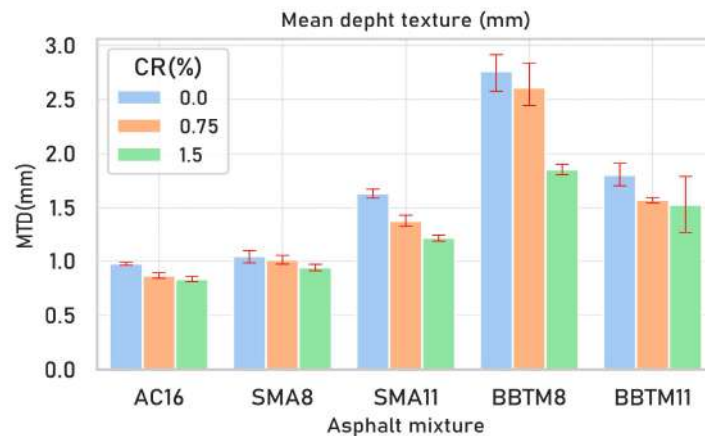


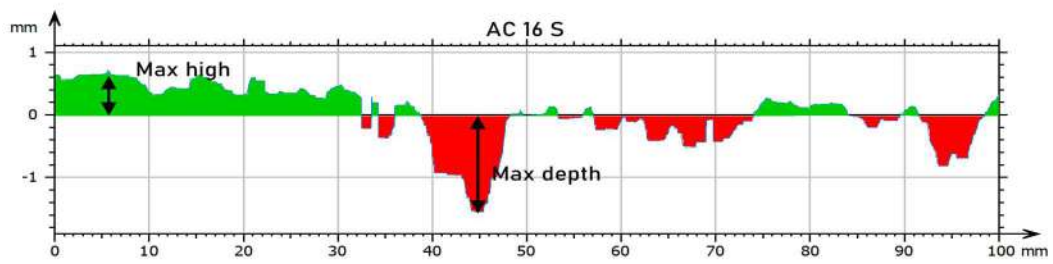
Figure 4.6: Comparison of MTD of the mixtures with rubber by dry process.

4.2.1. Profiles texture of the asphalt mixtures

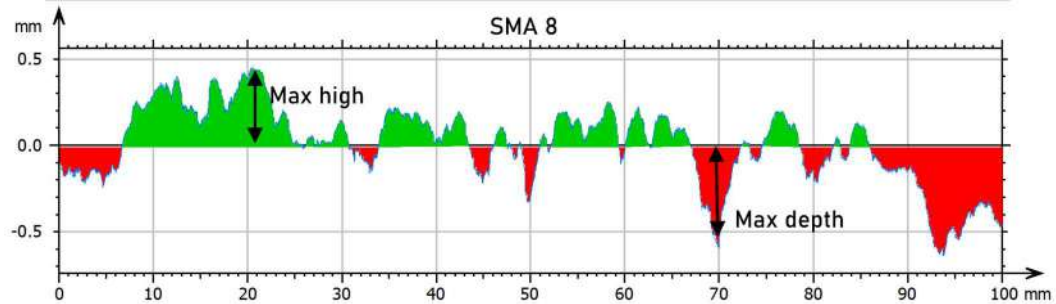
The profiles obtained by Laser Scanner Texturometer (LTS) for asphalt mixture (AC16S, SMA 8, SMA 11, BBTM 8B, and BBTM 11B) have allowed us to differentiate the sections of exposed valleys and peaks as shown in

Figure 4.7. Focusing in particular on the texture profiles of asphalt mixtures, this profile analysis shows that CR modifies the texture profiles, influencing the areas of peaks and valleys.

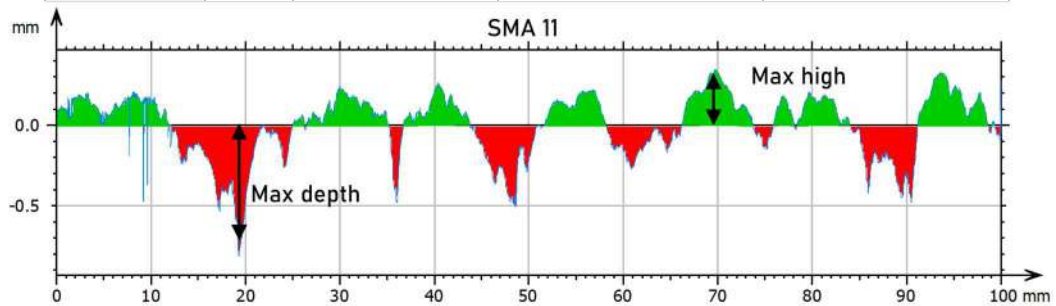
Figure 4.7 summarizes the changes in the profiles on AC and SMA due to the effect of the CR, where the parameters of the areas of valley and peak are reduced with the incorporation of 1.50 % CR. On the other hand, the maximum depth has also been modified by CR on specimens of AC, SMA, and BBTM presenting high differences.



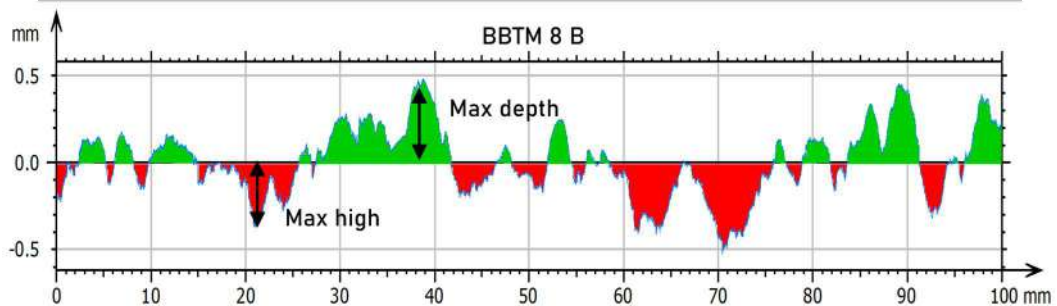
Parameters	Unit	AC 16 0 %CR	AC 16 0.75%CR	AC 16 1.50 %CR
Max depth	mm	1.547	▼ 0.719	▼ 0.623
Max Height	mm	0.713	▼ 0.606	▼ 0.447



Parameters	Unid	SMA8 0 %CR	SMA8 0.75%CR	SMA8 1.50 %CR
Max depth	mm	0.707	▼ 0.638	▼ 0.451
Max Height	mm	0.808	▼ 0.457	▼ 0.401



Parameters	Unid	SMA110 %CR	SMA11 0.75%CR	SMA11 1.50%CR
Max depth	mm	1.236	▼ 0.810	▼ 0.763
Max Height	mm	0.982	▼ 0.662	▼ 0.348



Parameters	Unid	BBTM8 0%CR	BBTM8 0.75%CR	BBTM8 1.50%CR
Max depth	mm	1.269	▼ 0.539	▼ 0.530
Max Height	mm	0.573	▼ 0.622	▼ 0.483

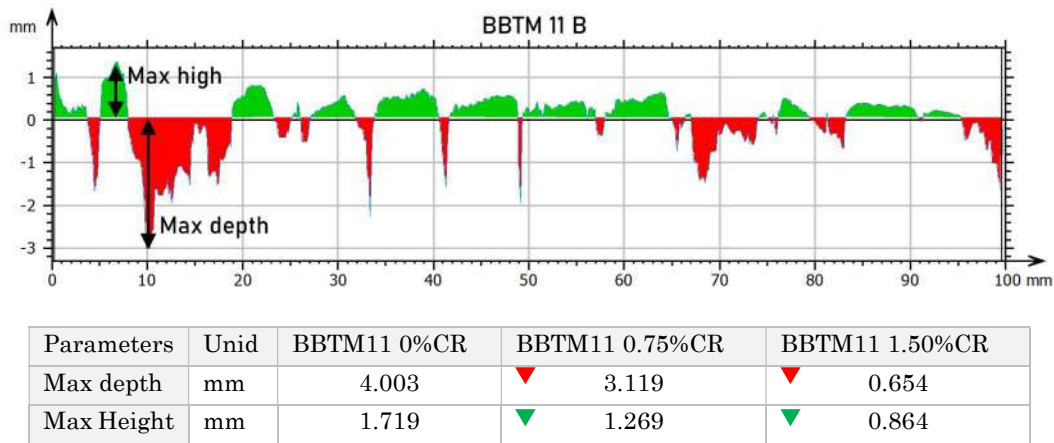


Figure 4.7: Effect of the crumb rubber on the parameters of the texture.

4.2.2. Tire/pavement contact surface.

Conditions of Contact Zones (CZ) describe contact surfaces between surface texture and tire tread. The 0 level is the line obtained as the average of peaks and valleys. The envelope base curve is the equidistant line between the highest peak and the 0 level (Δh). The envelope curve is defined as the surface of the peaks above the envelope curve. This envelope curve defines the contact zone, as shown in Figure 4.8.

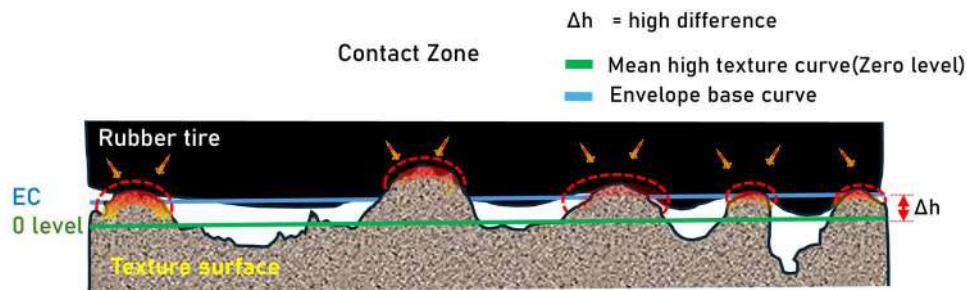


Figure 4.8: Scheme for describing contact zone. Source: Author's elaboration.

The contact determination of the contact zone is important to the study of the microtexture because it is just in these zones of contact where the rubber touches the pavement and the microtexture plays an important role. Figure 4.9 shows that the contact zones were identified by assigning a threshold in the intermediate dimension between the maximum peak and the 0 level in mm.

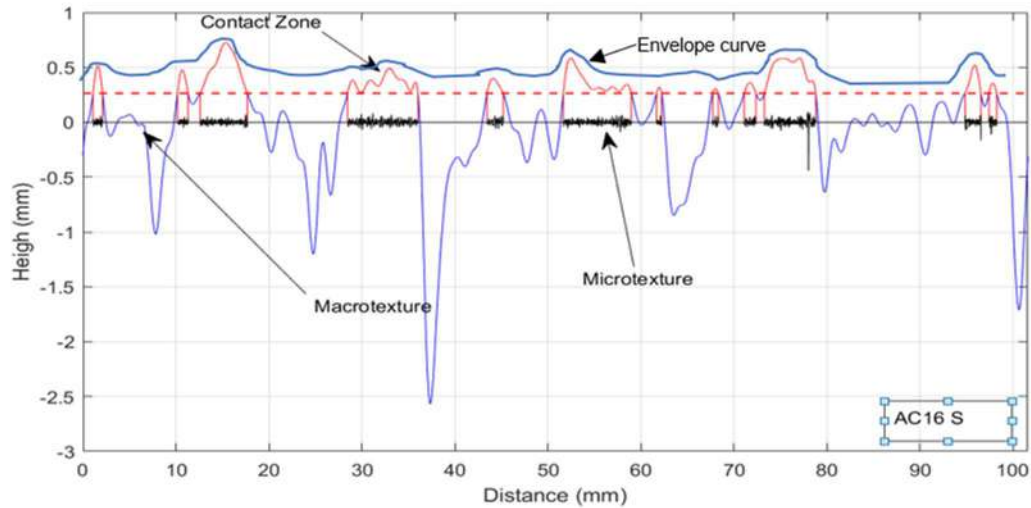


Figure 4.9: Identification of contact zones of AC asphalt mixtures. Source: Author's elaboration.

4.2.3. Characterization of texture on cylindrical specimens

In this section characterization of 3D MTD by volumetric Sand Path Test (SPT) and MPD 2D by laser scanner texturometer (LTS) were performed.

Figure 4.10a show the results of the average of six specimens, and the error bars represent the standard deviations of each type of asphalt mixture. The AC mixtures present a ranking by volumetric method of the MTD (3D) in the range of 0.9 to 0.8 mm. The semi-dense SMA 8 in 0.99 to 0.93mm, SMA11 in 1.6 to 1.2 mm, open-graded BBTM 8 B in 2.9 to 1.9 mm, and BBTM 11B present 3.0 to 2.7 mm. A ranking of the texture depth has been established, and this variation is linked to the predominant size of the aggregates of the mixtures.

Figure 4.10b shows the tendency of the effect of the CR on the behavior of the mean profile depth MPD (2D). The AC mixtures present in the range 0.59 to 4.3 mm, the SMA 8 in the range 0.76 to 5.6 mm, SMA11 in the range 1.0 to 0.7 mm, and open-graded BBTM 8 B in 1.04 to 0.85 mm BBTM 11B present 1.3 to 1.08 mm.

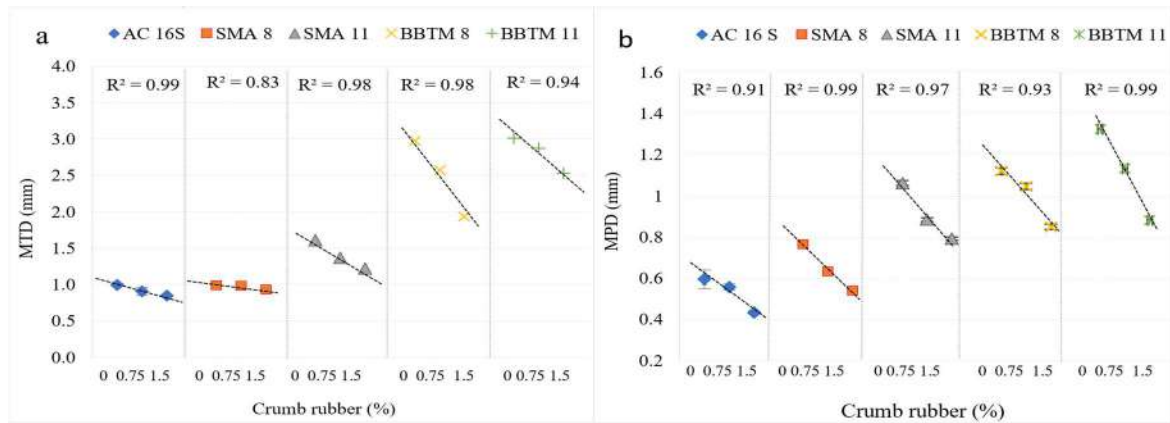


Figure 4.10: Effect of CR parameter on texture parameters a) MTD and b) MPD.

In addition, the effect of CR up to 1.50 % has been verified in Figure 4.11 showing a tendency to reduce the MTD for AC16 at 16.39%, in SMA 8 at 3.95%, SMA11 at 23.99%, BBTM 8B at 33.93% and BBTM 11B in 13.18%. This reduction in (%) is possibly explained due to the filling effect by the crumb rubber during the digestion time and clogging the texture valleys as shown in Figure 4.7, where the value max depth decrease as the CR content goes up. These results are coherent with those observed by (Hossain et al., 2018) who suggested that the addition of any additive can reduce MTD, and even increasing binder can have the same reduction effect on MTD.

Figure 4.11 shows the effect of the crumb rubber on the mean depth texture in percentages (%).

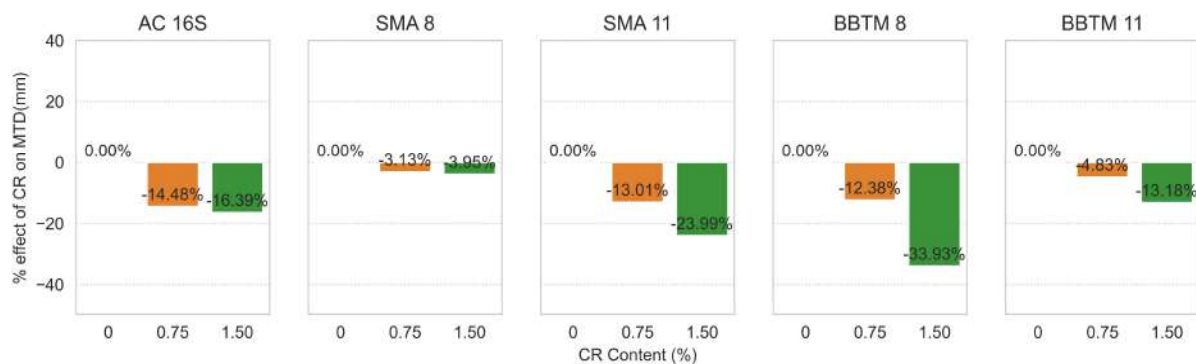


Figure 4.11: Effect of the CR on mean depth texture in asphalt mixtures.

The decrease in MPD 2D, observed with the addition of CR content in percentage, has been verified in Figure 4.12. The addition of 1.50% CR in AC results in a decrease of 24.26 %, SMA8 experiences a decrease of 23.87%, SMA11 sees a decrease of 2.21 %, BBTM 8 B decreases by 23.55 %, and BBTM11B decreases by

33.21 %. This trend is attributed to the CR covering the surface texture and reducing the depth and contours, as shown in Figure 4.12.

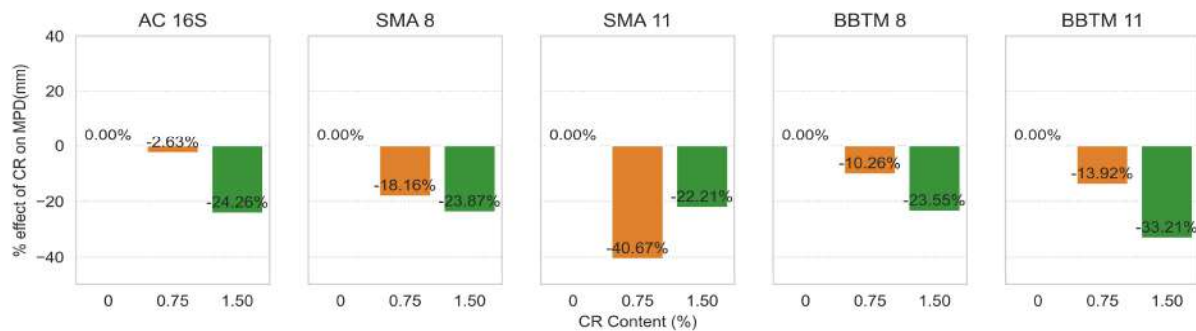


Figure 4.12: Effect of the CR on Mean depth texture in asphalt mixtures.

4.2.4. Correlation analysis between 2D and 3D methods

Both methods (contact MTD and non-contact MPD) describe the surface texture of the pavement, but in 3D and 2D respectively with different dimensions. The relationship between MPD and MTD has been displayed in Figure 4.13, showing a high correlation coefficient of $R^2 = 0.81$. In addition, higher values of MTD (mm) have been compared to MPD (mm). This could be explained by the higher accuracy of the 3D method in terms of the complete consideration of peaks and valleys of the texture, as it achieves contacts in all directions of sand during the assessment of sand patch test (SPT).

On the other hand, the 2D method has presented a reduction in measurements by focusing only on texture heights and directions. These results are also consistent with those found by (Praticò & Vaiana, 2015) who found a divergence between the results, which have highlighted that the volumetric method (MTD) produces higher values compared to the profile method (MPD).

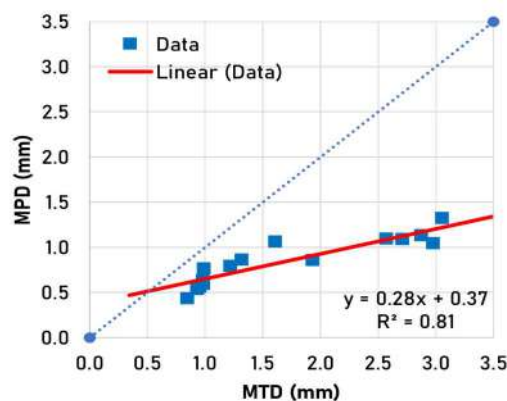


Figure 4.13: Correlations between 3D and 2D method.

4.2.5. Other characterization parameters with the 2D method

Figure 4.14 presents the result of estimated texture depth (ETD) and the statistical parameters describing the behavior of texture parameters, such as kurtosis (Rku), skewness (Rsk), and root mean square (RMS).

The addition of CR presents a different trend in texture parameters for all asphalt mix specimens due to the presence of crumb rubber (CR). The reduction in ETD and RMS, and the addition of crumb rubber 0.75 % and 1.50 % can fill the spaces between aggregates, thus reducing irregularities and roughness in the pavement surface. This translates into a decrease in the RMS value that may potentially impact skid resistance. RMS is a measure of pavement surface roughness. A reduction in RMS indicates a smoother and more uniform surface. the reduction of Rsk by the effect of crumb rubber 0.75 % and 1.50 % could result in a more uniform texture distribution along the road surface, which could contribute to a reduction in the asymmetry of the surface texture profile distribution.

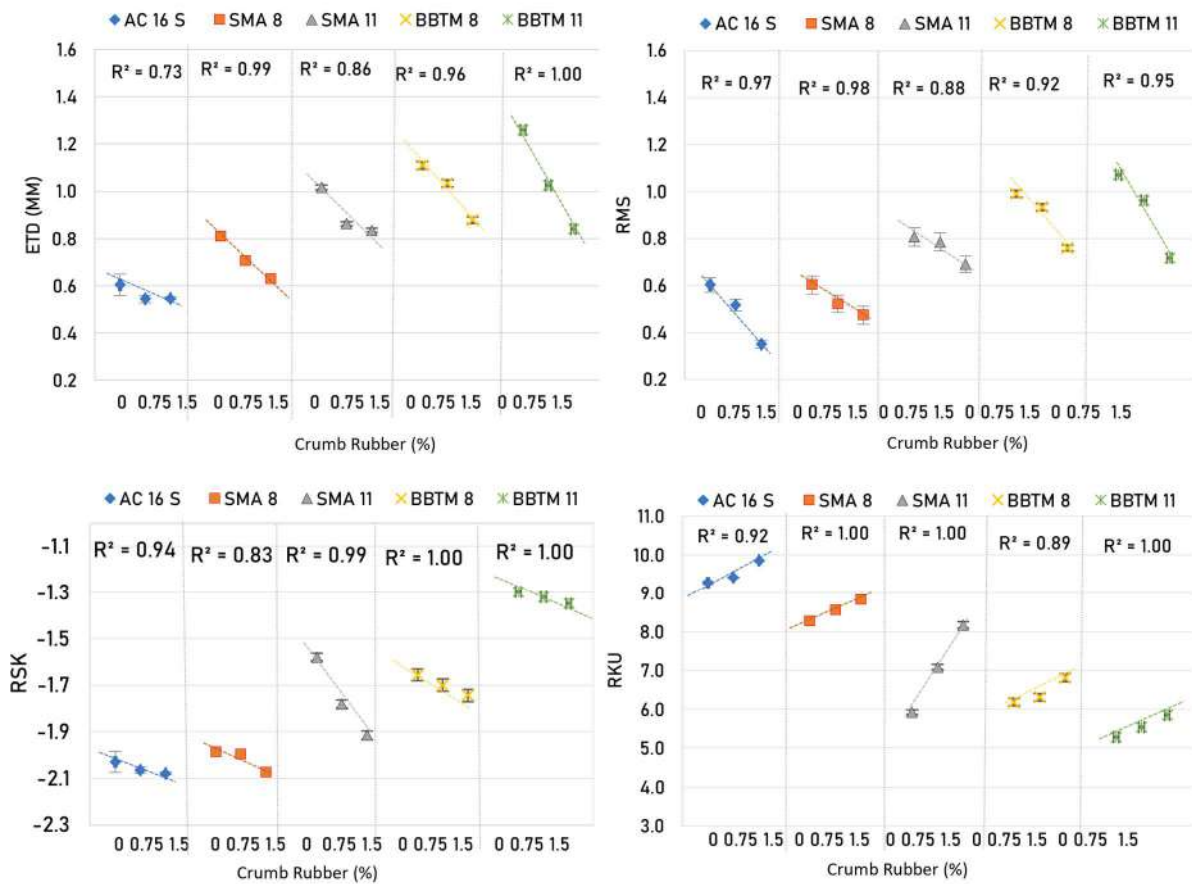


Figure 4.14: Texture parameters vs crumb rubber.

The increase in kurtosis due to the addition of CR content of 0.75 % and 1.50 % in asphalt mixtures may be associated with changes in the roughness, evenness, and adherence of the pavement surface texture. These changes may affect the distribution of data related to surface texture, which would be reflected in an increased kurtosis, meaning that the protuberances of the surface have wider tails. According to Figure 4.14, mixture AC16S is the mixture with longer tails and , for all the mixtures under study, the addition of rubber means longer tails of the protuberances.

4.3. Skid resistance.

4.3.1. Low-speed measurement by BPN

The evaluation of the BPN measurement at 10km/h and its evolution was carried out through an accelerated polishing process prototype Accelerated Polish Machine (APM) developed during this PhD Thesis with the objective of simulating traffic wear. Figure 4.15 shows the experimental scheme and the results detailed in this section.

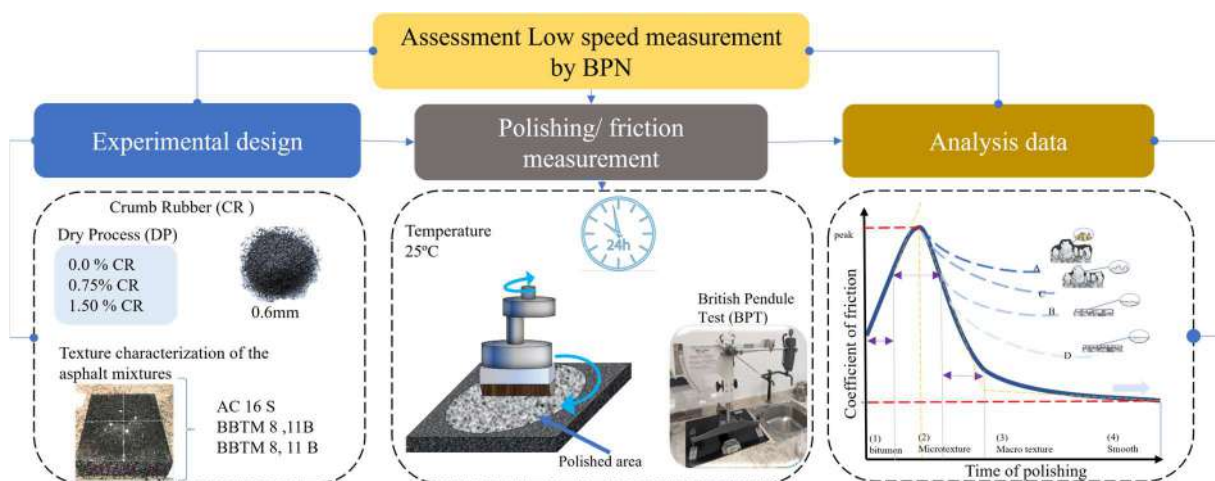


Figure 4.15: Scheme of experimental design for the polishing/friction process. Source: Author's elaboration.

4.3.2. Evolution of the BPN coefficient of friction of asphalt mixtures

Table 4.3 highlights the evolution of friction measured by the British Pendule Test BPT on asphalt mixtures characterized by initial friction levels, higher maximum levels of friction, and a decrease of friction value of British Pendule Number (BPN), measured at lower speeds at 10km/h with the BPT. The methodology procedure

was developed and described in Section 3.6.1 for polishing cycles, abrasion stages, and friction BPN measurement. The process involves five stages: 1) Unpolished test specimen, 2) Wear cycles using only a rubber cylinder, 3) Wear with rubber and coarse emery to accelerate the process, 4) Wear with rubber and fine emery to start polishing. And 5) Final stage wear using only rubber to simulate macrotexture polishing, representing medium to long-term skid resistance performance. Table 4.3 summarizes the BPN measured for each of the test specimens over the entire process of wear and polishing. The progressive values of friction obtained show an initial increase, followed by a long period of decreasing and a final stabilization. This result is in line with the (S. Zhu & Ji, 2022) similar trend observed.

Table 4.3: Laboratory test stages of result of British Pendule Number

Stages	Polishing cycles	AC16S-PBN			SMA8-BPN			SMA11-BPN			BBTM8B-BPN			BBTM11B-BPN		
		0	0.75	1.50	0	0.75	1.50	0	0.75	1.50	0	0.75	1.50	0	0.75	1.50
S-1	0	56	55	57	54	50	50	43	52	48	54	48	55	56	58	59
S-2	1	56	55	57	54	50	50	43	52	48	54	48	55	56	58	59
S-3	75	61	59	59	62	59	60	56	61	59	60	56	60	63	64	65
	150	64	64	62	69	71	71	69	70	71	68	65	66	69	71	71
	300	65	65	62	70	72	72	71	70	72	70	66	68	72	72	72
	450	66	66	64	72	73	73	72	71	73	71	67	69	72	73	73
	600	68	67	65	73	74	74	73	73	74	72	69	70	74	73	74
	750	68	68	66	73	75	75	74	73	74	73	70	71	75	75	75
S-4	900	68	69	67	74	75	76	74	74	75	71	71	73	73	71	73
	2400	67	66	66	75	75	74	75	75	70	70	70	71	70	69	69
	3900	63	61	61	72	73	68	70	70	67	61	70	70	57	55	57
	5400	56	54	54	69	72	59	65	67	57	57	60	58	55	54	56
	6900	51	51	51	59	57	57	55	55	54	53	55	56	51	53	56
	8400	48	50	50	54	54	53	53	52	51	50	51	54	49	48	50
S-5	9900	46	49	49	49	51	48	51	49	48	48	47	48	49	47	49
	11400	46	48	48	47	47	47	48	47	47	46	46	46	46	46	48
	12900	45	48	47	47	47	46	46	46	47	44	46	45	45	45	48
	14400	45	48	47	45	46	46	45	45	46	42	45	44	44	45	47

The evolution values of the BPN are shown in Figure 4.16. In this process, the loss of friction is produced by the change of asperities and roughness. This trend is observed in AC dense, SMA gap-graded, and BBTM open mixtures. The first changes are exhibited by continuous growth in friction until they reach their peak (aggregates undressing). Subsequently, the friction decreases as the number of wear cycles increases because of the decreasing of the macrotexture and the microtexture. This finding is consistent with the results reported by (Mahmoud et al., 2023), a decrease in friction is evidenced in relation to the number of wear cycles measured by the British Pendulum Test (BPT) at 10km/h. This observation is relevant because it provides a deeper understanding of asphalt mixtures and can contribute to the optimization of their performance under real-use conditions.

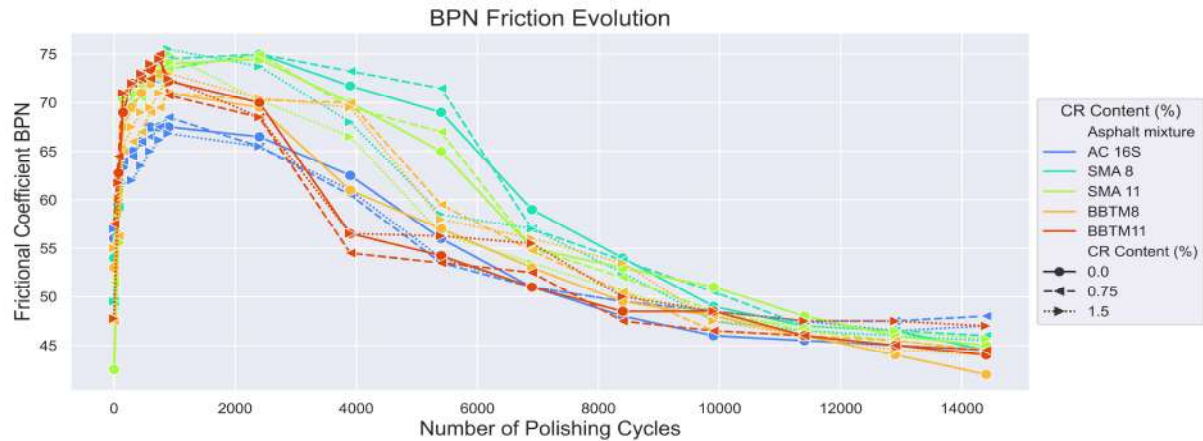
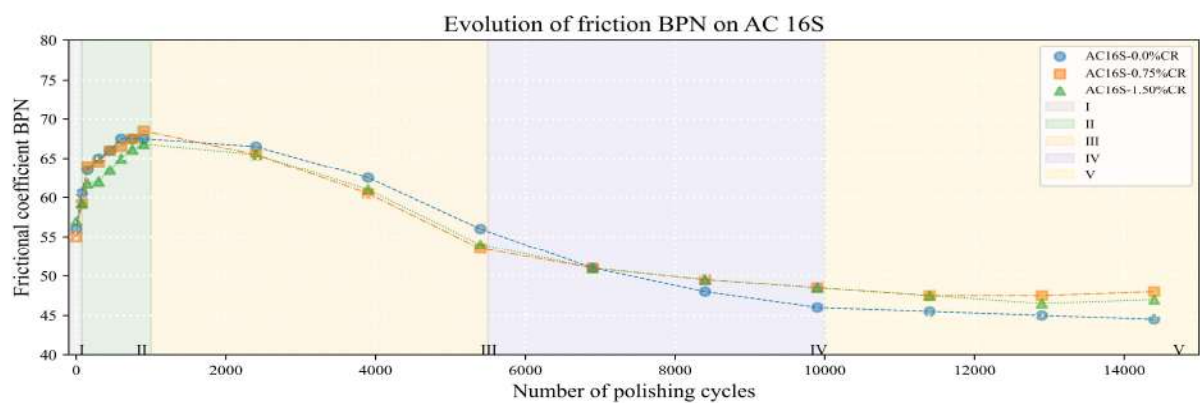


Figure 4.16: Characterization of the BPN on different asphalt mixtures.

The evolution of the BPN at different cycles of polishing is shown in Figure 4.17. It is important to note that this accelerated polishing procedure has provided evidence of the evolution of the binder stripping process in different asphalt mixtures. To understand the evolution of BPN at 10km/h we defined 5 stages: Stage I initial friction before polishing; Steady increase in friction has been observed, reaching its peak of the maximum friction coefficient BPN (Stage II). Subsequently, there is observed accelerated attenuation of friction BPN (Stage III), of friction initial stabilization of friction BPN (Stage IV), and the final stabilization is arrived at (Stage V).



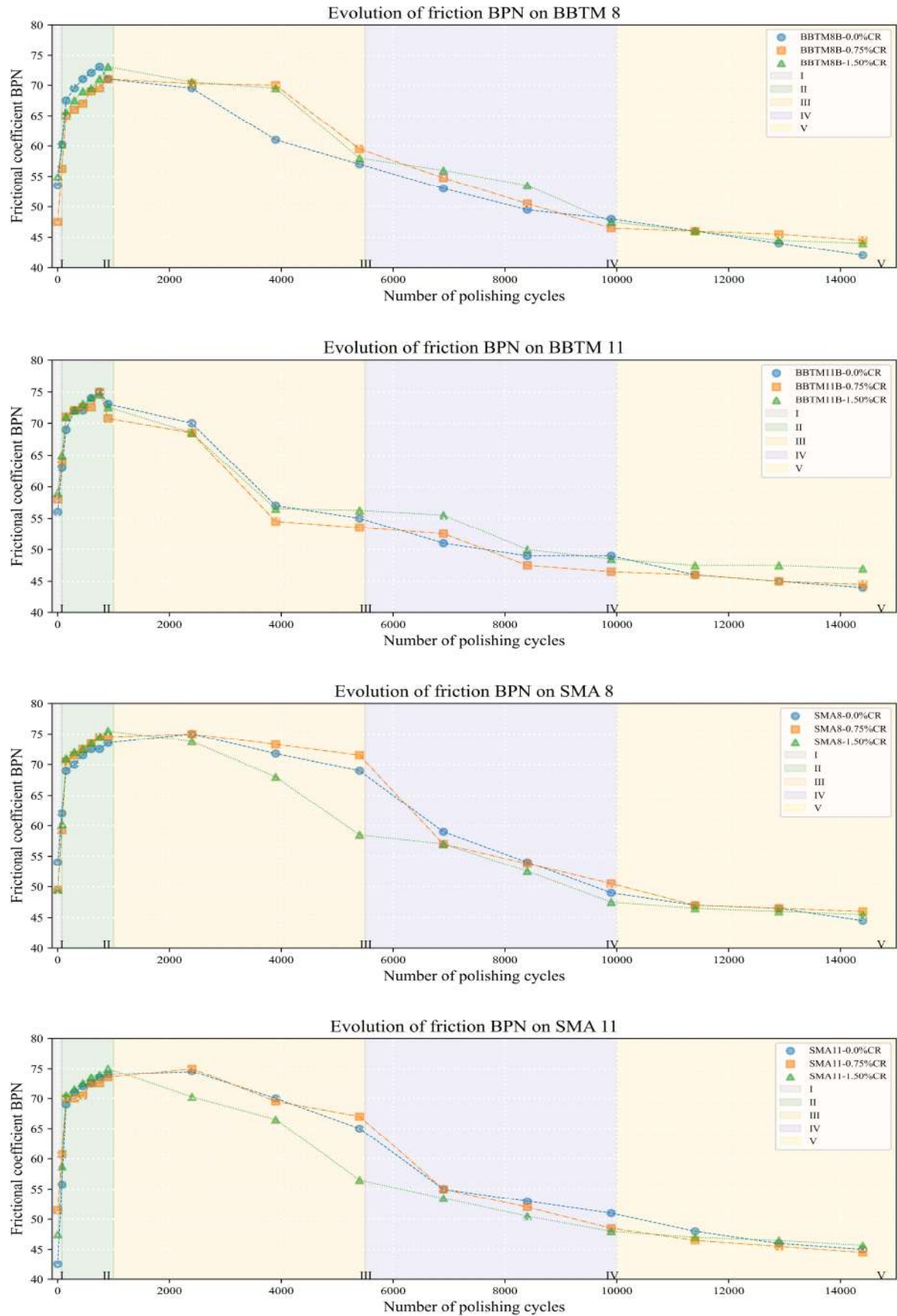


Figure 4.17: Evolution of the BPN for different asphalt mixtures.

The evolution of BPN and texture in 5 stages can be seen in Figure 4.18. From friction perspective: Stage 1 to stage 2 shows an increase in BPN results, indicates peak of BPN. Stage 2 to Stage 3 represents a decrease in BPN, and Stage 3 to Stage 4 continues to decrease until the stabilization of BPN. From Stage 4 to Stage 5, the BPN values stabilized for all asphalt mixtures.

In terms of texture behavior: Stage 1, characterized by a gradual loss of the bitumen film and exposed microtexture. Stage 2 starts with a rapid degradation of microtexture and part of macrotexture due to aggregate wear. Stage 3 reflects a degradation of macro texture. Stage 4 shows a transition phase where the polishing and stabilizes surface texture. Stage 5 represents final stabilization of the surface. It is a balance between the wear potential of the polishing machine and the resistance of the surface to polishing.

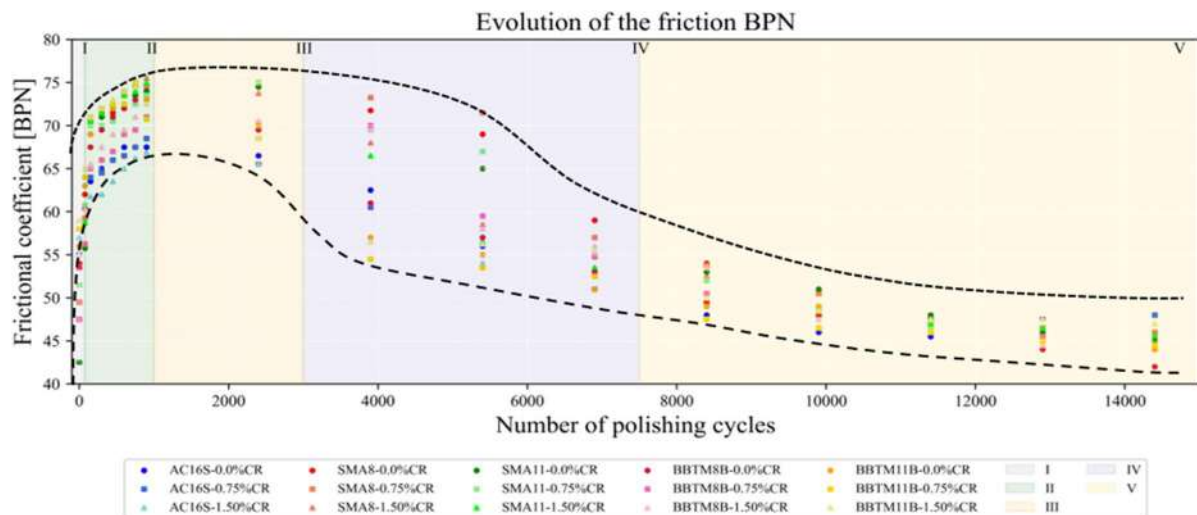


Figure 4.18: Categorization zone changes of BPN for different asphalt mixtures.

For all processes, various stages of polishing are depicted in Figure 4.19, showcasing a range of surfaces before and after weathering (stage 1 and stage 5) of asphalt mixtures after 14400 cycles of Accelerated Polishing Machine (APM). In this case of the AC mixture, it is evident that the contact areas of the surfaces are noticeably affected due to their exposure to tire rubber.

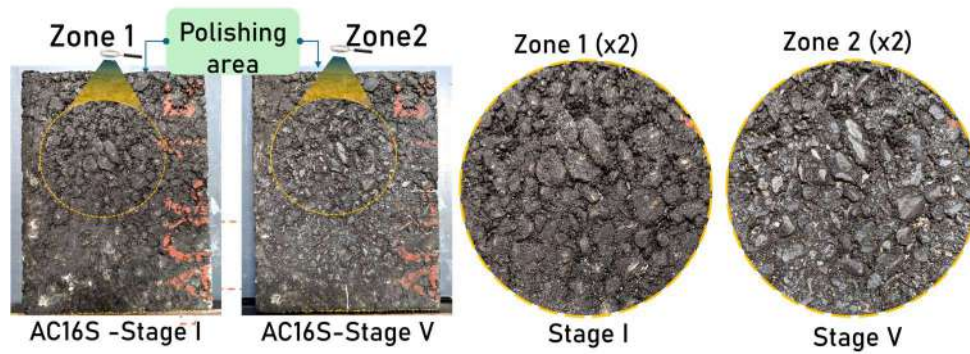


Figure 4.19: Unpolished and Polished state after 14400 Cycles by APM.

Figure 4.20, which depicts a comprehensive examination of the accelerated polishing process, gives important insights into how asphalt mixtures vary in mass loss particles (kg/m^2) and the influence of CR. A methodological procedure was developed and described in section 3.5.1. Each cycle of the APM polishing process produces distinct mass losses for various asphalt mixtures, indicating a steady trend. Throughout this progression, the effects of various pollutants and particles on asperity wear become apparent. Furthermore, the presence of crumb rubber helps to resist mass loss of particles from the surface roughness of asphalt pavement. The loss of particle mass can be explained as follows:

In stages [I-II], polishing occurs mainly due to the direct contact of the tires with the rough pavement surface.

In stages [II-III], the roughness is polished by using a coarse emery, generating friction between the rubber and the surface texture.

In stages [III-IV], micro-asperities are reduced by fine grinding.

Finally, in the stages [IV-V], the reduction of the asperities is carried out by the action of the tire rubber.

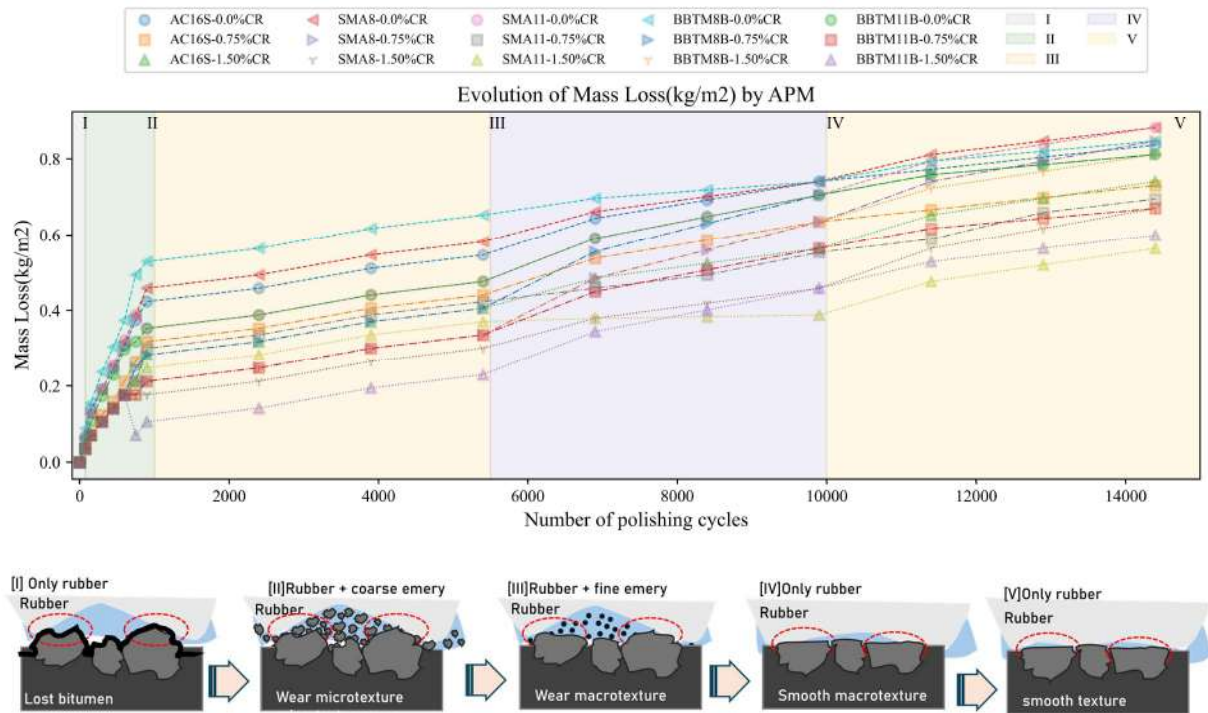


Figure 4.20: Evolution of the mass loss by APM of different asphalt mixtures.

a) Evolution of the mass loss by APM

The resistance to mass loss varies depending on the type of asphalt mixture. Figure 4.21 depicts the overall trend of mass loss at 14400 cycles of rubber pass on APM. The initial mass loss is significantly strong due to the tire stripping all loose particles from the pavement surface, including bitumen from the rubber contact zone. The plots all show the large loss of mass that occurs during the very early period simulating traffic (stage I-II). The stage (III-V) presents a small linear increase in mass loss relating to wear of the aggregate particles. This wear loss is related to rounding of individual particles and the loss of small particles embedded in the mastic binders. The smallest amount of loss mass was registered for specimens by 1.50 %CR reflecting its resistance to wear.

This could be explained by the rubberized mastic by CR covering the particles, which provides more consistency and strengthens the bonding of the aggregates to the surface. In contrast, no rubber mixtures are more prone to particle loss from mastic asphalt.

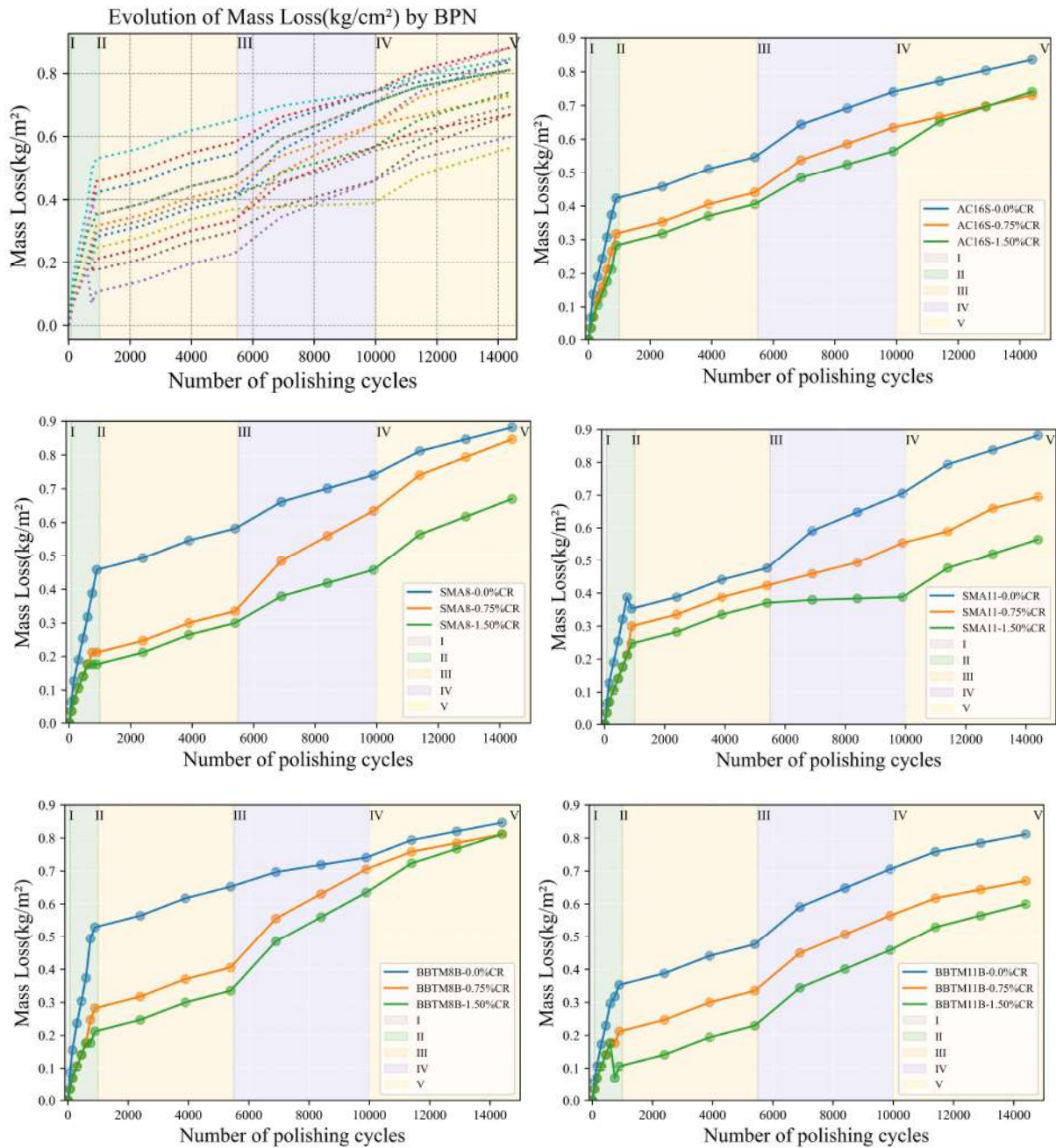


Figure 4.21: Evolution of mass loss by APM of the asphalt mixtures and Difference of polishing of conventional and rubberized asphalt mixture.

Figure 4.22 shows the effect of crumb rubber (1.50%CR) on the reduction of the mass loss on asphalt mixtures AC16 = 8.26%, SMA 8 = 22.41%, SMA 11 = 35.34%, BBTM 8 = 2.33% and BBTM 11 = 24.88%. This mass loss generated by APM is not necessarily related to friction loss. It is the result of texture loss in different wear cycles.

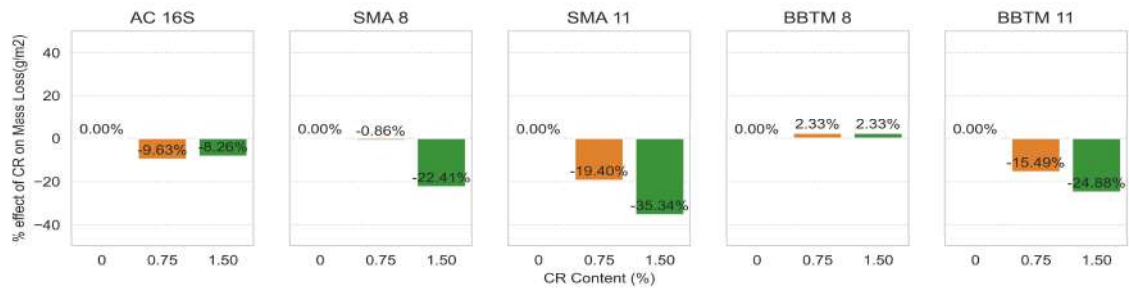


Figure 4.22: Compared of Mass loss by APM at 14400 cycles of the asphalt mixtures.

b) Analysis of the minimum threshold of BPN

In the comparison of the BPN performance of asphalt mixtures at 10 km/h, a threshold of 52 is equivalent to [CRT=50] (see section 3.6.1 d) and has been established according to the CRT for skid resistance by NLT-336 described by (Bustos & Echaveguren, 2006). Figure 4.23 shows the BPN values over the progressive stages of wear and polishing. Concerning Stage I (S-I), initial BPN measurements do not meet the established threshold. For this reason, the PG-3 specifications recommend starting measurements months after opening to traffic. Stage II (S-II) exceeds the minimum requirement for all asphalt mixtures, as well as Stage III (S-III). BPN friction is progressively lost, and Stage VI (S-VI) shows the beginning of the stabilization or BPN values. Finally, Stage V (S-V), usually reaches lower BPN values than the threshold.

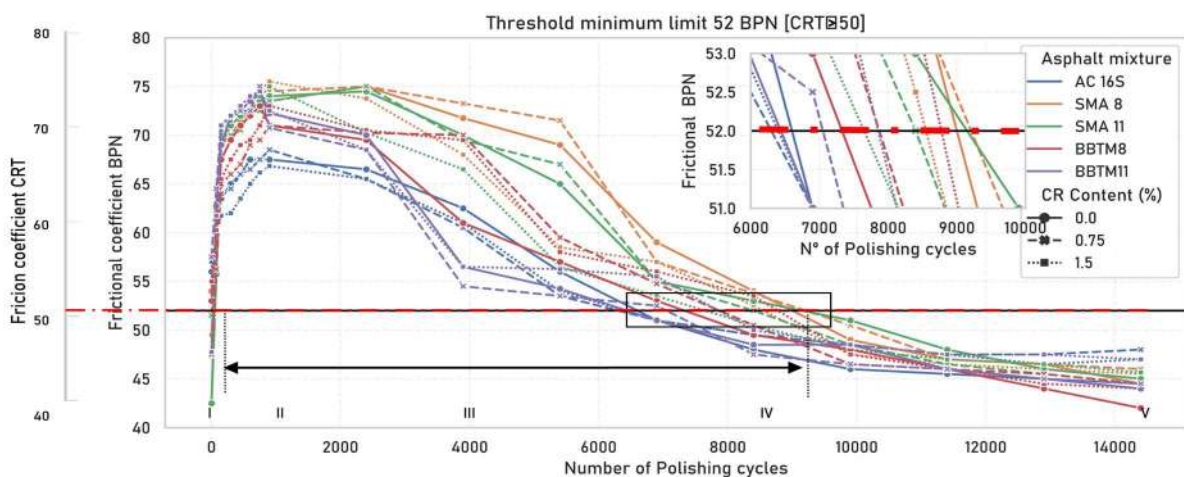


Figure 4.23: Thresholds of the BPN to control asphalt mixtures.

Figure 4.24 shows the number of cycles needed to reach the criterion BPN = 52. The AC mixtures require only fewer cycles to reach this threshold (≈ 6500 cycles), while SMA 8 and SMA 11 exhibit a great tendency (≈ 9100 cycles) the BBTM 8 exhibit ($\approx$

7300 cycles), and the BBTM11 lower behavior exhibit (≈ 6400 cycles). It is worth noting that using crumb rubber up to 1.50% reduces the number of cycles required to achieve the threshold 52, in AC, SMA8, and SMA 11 compared to reference specimens. While the BBTM 8 B and BBTM11B require more cycles to achieve the threshold BPN = 52. This could be explained by an improvement in the mastic envelope of the aggregates since the CR provides greater protection to the external structure of the texture of asphalt mixtures BBTM B , whose aggregate are more prone to move due to the limited mastic in the mixture.

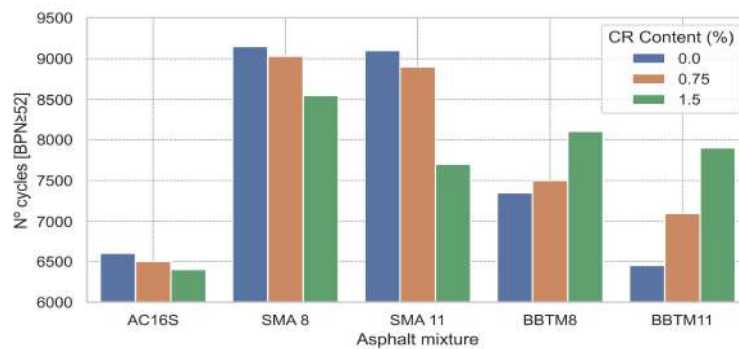


Figure 4.24: Number of cycles to achieve the BPN= 52 threshold.

Nevertheless, the effect of CR content, in the AC, SMA 8 and SMA 11 mixtures, it reduction of the number of cycles number of cycles needed to reach the 52 BPN friction threshold. It can be due to the fact that rubber particles partially digested fill the valleys of the texture, as previously commented to the additional reinforcement of bonding of the superficial aggregates, since in these mixtures the mastic is abundant.

The effect of CR observed on the achievement of the threshold BPN=52 is shown in Figure 4.25 indicating a minimal influence for AC mixtures, with a decrease of up to 3.03 % observed with 1.50 % CR. SMA 8 and SMA 11 revealed differences in reduction, showing decreases of 6.56 % and 15.38%, respectively, with 1.50 % CR. Conversely, in the case of BBTM 8B an increase of 10.20% and BBTM 11B, an increase of 22.48 %, respectively, was observed with the presence of 1.50 % CR.



Figure 4.25: Effect of CR on the threshold of BPN=52.

Figure 4.26 depicts variations behavior of BPN development under the influence of CR. The AC, SMA, and BBTM mixtures show friction behavior from favorable behavior conditions between Stage 1 to Stage 3, with acceptable friction coefficients and friction decrease in Stage 4 to Stage 5. From the threshold of BPN = 52.

c) Evolution of the BPN by stages of polishing

At stage 1, it appears that the asphalt mixtures SMA have difficulties achieving the threshold of BPN=52 when open to traffic. Furthermore, in stage 4, none of the measurements reach the threshold of BPN=52. Therefore, intervention is necessary to establish skid resistance characteristics in this stage. This change in the frictional coefficient BPN is shown in Figure 4.26.

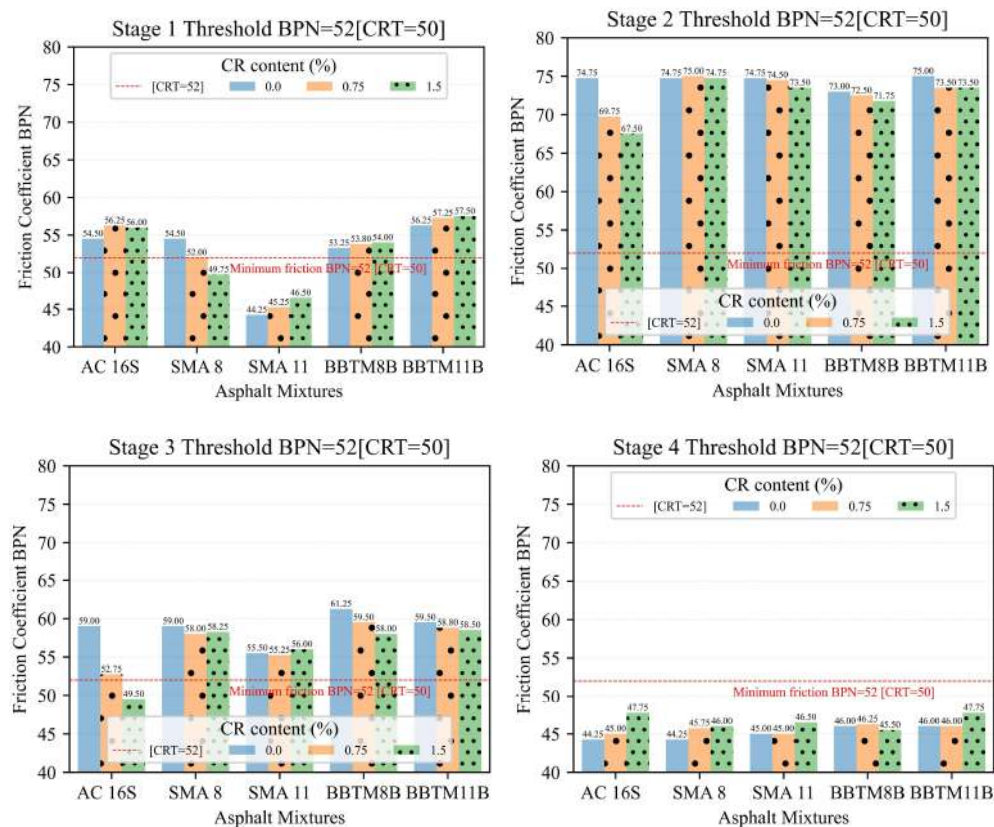


Figure 4.26: Effect of crumb rubber on the evolution of BPN of asphalt mixtures.

Table 4.4 shows a significant difference in the friction coefficient BPN at a low speed of measurement 10km/h for asphalt mixtures (analyzed at stage 5), with $F(4,8)=34.2004$ and $p\text{-value}=0.004$. This explains the significant variance in BPN friction at low speeds on different asphalt mixtures.

The effect of CR content on the friction BPN (at 10km/h) performance of asphalt mixtures was found to be non-significant. Table 4.5 shows $F(2,8) = 0.7551$, $p\text{-value} = 0.5007$. This result shows that even with existing differences in asphalt pavements, no differences due to different content of % CR were confirmed statistically. Table 4.6 shows no significant difference by the addition of CR, only having the effect that a few percentages increased the frictional BPN, while no improvements were observed in terms of frictional BPN capabilities as shown in Figure 4.27. No difference was observed between the individual CR addition amounts.

Table 4.4: Effect of asphalt mixtures on friction BPN (low speed)-ANOVA output.

	SS	Df	Mean square	f	p-value
Asphalt mixture	37.1302 ^a	4	9.2825	34.2004	0.0004
Error	2.17133	8	0.27142		
Total	39.3015	12			

^a $R^2 = 0.995$ (Adjusted $R^2 = 0.994$)

SSQ: sum of squares, Df: degrees of freedom, MS: Mean Squares, f: fisher ratio, p-value: probability value.

Table 4.5: Effect of CR content on friction BPN (low speed)-ANOVA output.

	SS	Df	Mean square	f	p-value
CR content %	0.4099 ^a	2	0.2049	0.7551	0.5007
Error	2.1713	8			
Total	2.5812	10			

^a $R^2 = 0.995$ (Adjusted $R^2 = 0.994$)

SSQ: sum of squares, Df: degrees of freedom, MS: Mean Squares, f: fisher ratio, p-value: probability value.

Table 4.6: Effect CR content by T-student post doc.

	A	B	Parametric	T	p-value
CR content %	0.0	0.75	True	-0.1397	0.08957
CR content %	0.00	1.50	True	1.1469	0.3153
CR content %	0.75	1.50	True	0.8038	0.466

p-value: probability value.

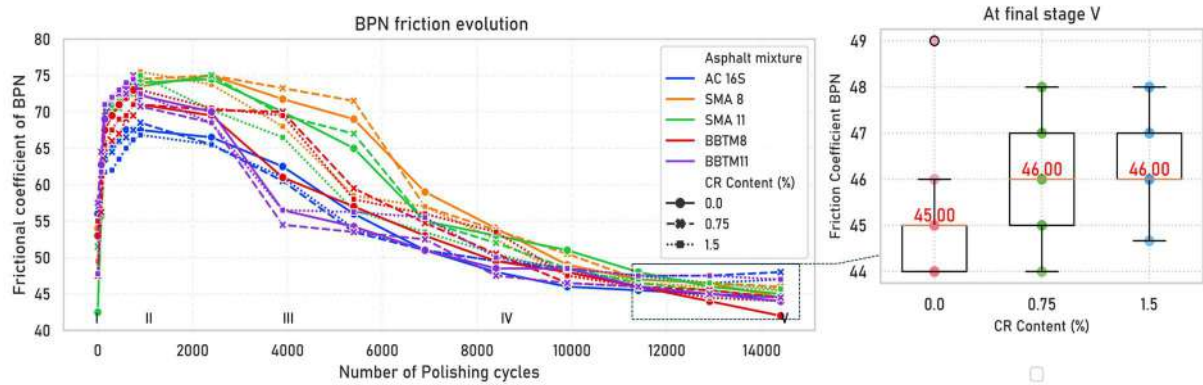


Figure 4.27: Effect of crumb rubber on the evolution of friction BPN at final Stage-V.

d) Analysis of the evolution of texture parameters

The evolution of the texture parameters was analyzed using profiles created with a laser texture scanner (LTS). To assess the evolution of the texture three principal asphalt mixtures AC16S, SMA 11, and BBTM 11B with different content (0.0 %, 0.75 %, 1.50 % CR) were selected and evaluated for the texture evolution. Figure 4.28 illustrates the texture evolution by the arithmetic average roughness (Ra): a) Ra of microtexture, b) Ra of macrotexture, c) estimated depth texture (ETD) and Mean profile depth (MPD) of asphalt mixtures. This comprehensive comparison allows a thorough assessment of how the texture parameters change concerning the development of polishing in different asphalt mixtures.

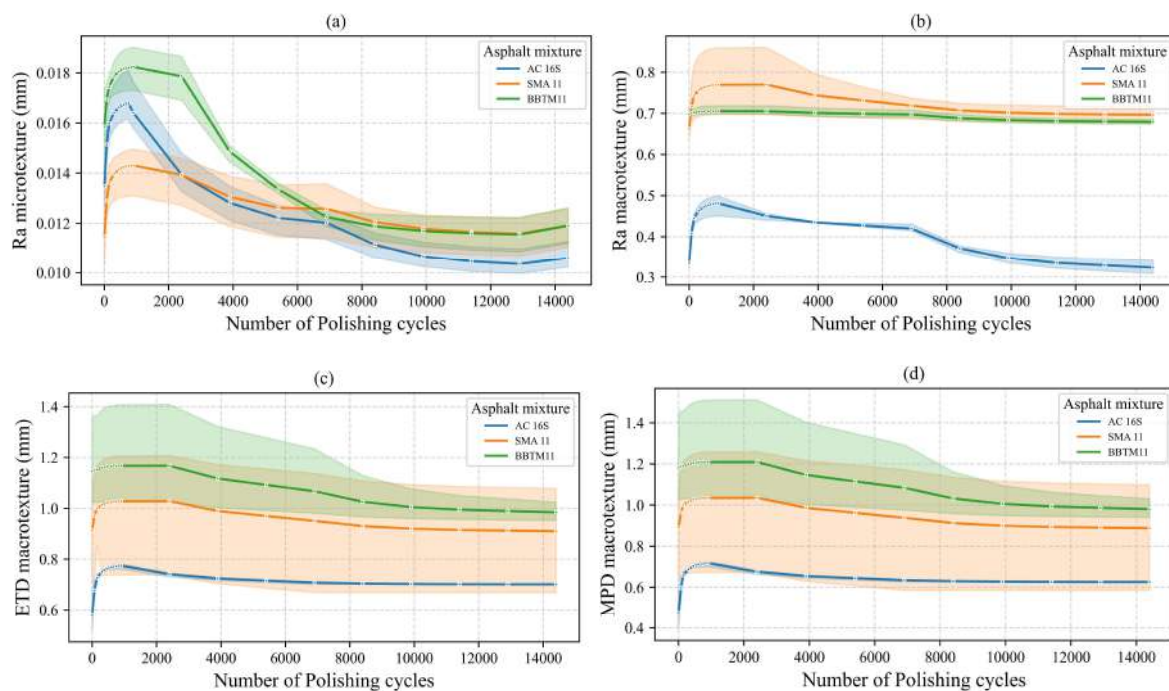


Figure 4.28: Evolution of texture parameters of asphalt mixtures: a) Ra microtexture, b) Ra macrotexture, c) ETD, and d) MPD macrotexture.

Table 4.7, Table 4.8, and Table 4.9 show texture parameters computed in average values of AC dense, SMA11 semi-dense, and BBTM11B open-grade asphalt mixtures that have been observed in this research.

Table 4.7: Result of surface properties of AC 16S (9 mixtures x 17 degrees of polishing)

Wear Set	AC 16 S								
	0% CR			0.75% CR			1.5% CR		
	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)
1	0,354	0,014	56	0,326	0,014	55	0,322	0,013	57
2	0,403	0,016	61	0,411	0,015	59	0,411	0,014	59
3	0,427	0,017	64	0,453	0,016	64	0,455	0,015	62
4	0,439	0,018	65	0,474	0,016	65	0,477	0,016	62
5	0,445	0,018	66	0,484	0,016	66	0,488	0,016	64
6	0,448	0,018	68	0,490	0,016	67	0,494	0,016	65
7	0,450	0,018	68	0,492	0,016	68	0,497	0,016	66
8	0,451	0,018	68	0,494	0,016	69	0,499	0,016	67
9	0,441	0,015	67	0,454	0,014	66	0,456	0,013	66
10	0,435	0,013	63	0,434	0,013	61	0,435	0,012	61
11	0,433	0,013	56	0,424	0,012	54	0,425	0,012	54
12	0,431	0,012	51	0,414	0,012	51	0,414	0,011	51
13	0,375	0,011	48	0,377	0,012	50	0,361	0,011	50
14	0,347	0,011	46	0,359	0,011	49	0,335	0,010	49
15	0,333	0,010	46	0,350	0,011	48	0,322	0,010	48
16	0,326	0,010	45	0,345	0,011	48	0,315	0,010	47
17	0,320	0,010	45	0,341	0,011	48	0,309	0,010	47

Table 4.8: Result of surface properties of SMA 11(9 mixtures x 17 degrees of polishing)

Wear Set	SMA 11								
	0% CR			0.75% CR			1.5% CR		
	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)
1	0,690	0,010	43	0,639	0,013	52	0,659	0,011	48
2	0,776	0,013	56	0,695	0,014	61	0,678	0,012	59
3	0,818	0,014	69	0,724	0,014	70	0,688	0,013	71
4	0,840	0,014	71	0,738	0,015	70	0,693	0,013	72
5	0,850	0,015	72	0,745	0,015	71	0,695	0,013	73
6	0,856	0,015	73	0,749	0,015	73	0,696	0,013	74
7	0,858	0,015	74	0,750	0,015	73	0,697	0,013	74
8	0,860	0,015	74	0,751	0,015	74	0,697	0,013	75
9	0,860	0,015	75	0,752	0,014	75	0,697	0,013	70
10	0,796	0,014	70	0,744	0,013	70	0,692	0,012	67
11	0,764	0,014	65	0,740	0,013	67	0,689	0,011	57
12	0,732	0,014	55	0,737	0,013	55	0,687	0,011	54
13	0,724	0,013	53	0,717	0,012	52	0,681	0,011	51
14	0,720	0,012	51	0,706	0,012	49	0,678	0,011	48
15	0,718	0,012	48	0,701	0,012	47	0,677	0,011	47
16	0,717	0,012	46	0,699	0,012	46	0,676	0,011	47
17	0,717	0,012	45	0,697	0,013	45	0,676	0,011	46

Table 4.9: Result of surface properties of BBTM11B (9 mixtures x 17 degrees of polishing)

Wear Set	BBTM 11 B								
	0% CR			0.75% CR			1.5% CR		
	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)	Rama (mm)	Rami (mm)	BNP (%)
1	0,712	0,017	68	0,697	0,014	58	0,684	0,016	52
2	0,713	0,018	68	0,698	0,017	65	0,692	0,017	62
3	0,712	0,018	68	0,698	0,018	71	0,695	0,017	71
4	0,716	0,018	70	0,698	0,018	72	0,697	0,017	72
5	0,717	0,018	70	0,699	0,019	73	0,698	0,017	73
6	0,718	0,018	71	0,699	0,019	73	0,699	0,017	74
7	0,718	0,018	72	0,699	0,019	75	0,699	0,017	75
8	0,719	0,018	71	0,699	0,019	71	0,699	0,017	73
9	0,719	0,018	69	0,698	0,019	69	0,699	0,017	69
10	0,713	0,015	55	0,697	0,015	55	0,693	0,014	57
11	0,710	0,014	54	0,696	0,013	54	0,690	0,013	56
12	0,708	0,013	49	0,696	0,012	53	0,688	0,012	56
13	0,696	0,012	48	0,687	0,011	48	0,681	0,012	50
14	0,690	0,012	48	0,683	0,011	47	0,677	0,012	49
15	0,688	0,012	45	0,681	0,011	46	0,675	0,012	48
16	0,686	0,012	44	0,680	0,011	45	0,675	0,012	48
17	0,685	0,013	43	0,679	0,011	45	0,674	0,012	47

Table 4.10, Table 4.11, Table 4.12 present details of the estimated multiple linear regression models for AC, SMA, and BBTM mixtures, respectively. Equations 27, 28, and 29 show the expression that estimates the BPN values as a function of CR, Rama, and Rami. The models fitted for each type of mixture enable predictions for new BPN observations based on the microtexture, macrotexture, and crumb rubber content.

Table 4.10: Estimates of the BPN model for the AC mixture.

Variable	Unstandardized β	Std. Error	Standardized β	T	p-value
Constant	9.235	2.562		3.605	<0.001
Rami	1899.789	228.851	0.603	8.301	<0.001
Rama	54.348	9.847	0.401	5.519	<0.001
R ²	0.901				
R ² adj	0.897				
RMSE	2.54				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value.

$$BNP(AC) = 9.235 + 1899.789 \text{ Rami} + 54.348 \text{ Rama}$$

Equation 27

Table 4.11: Estimates of the BPN model for the SMA mixture.

Variable	Unstandardized β	Std. Error	Standardized β	T	p-value
Constant	-91.573	13.586		-6.740	<0.001
CR	10.938	1.611	0.595	6.790	<0.001
Rami	6547.885	792.930	0.761	8.258	<0.001
Rama	81.599	23.355	0.407	3.494	<0.001
R2	0.822				
R2adj	0.811				
RMSE	4.94				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value

$$BNP(SMA) = -91.573 + 10.938 CR + 6547.885 Rami + 81.599 Rama \quad \text{Equation 28}$$

Table 4.12: Estimates of the BPN model for the BBTM mixture.

Variable	Unstandardized β	Std. Error	Standardized β	T	p-value
Constant	-194.201	41.840		-4.641	<0.001
CR	4.787	0.906	0.264	5.282	<0.001
Rami	2926.585	226.568	0.747	12.917	<0.001
Rama	296.675	63.277	0.333	4.689	<0.001
R2	0.947				
R2adj	0.943				
RMSE	2.67				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value.

$$BNP(BBTM) = -194.201 + 4.787 CR + 2926.585 Rami + 296.675 Rama \quad \text{Equation 29}$$

All the coefficients obtained in the models (Equations 27, 28, and 29) had positive signs, meaning that Rami, Rama, and CR content tend to increase the BPN value. To assess the sensitivity of the BPN value to changes in the explanatory variables within the observed intervals and to compare these sensitivities to the values of the standardized beta coefficients, Table 4.10, Table 4.11, Table 4.12 can be checked. As the asperity of the aggregates (Rami) or the surface macrotexture (Rama) of the asphalt mixture increases, the BPN value increases, as expected. This is consistent with the findings of other authors (Kouchaki et al., 2017; Qian & Meng, 2017; Serigos et al., 2016a) (Kanafi et al., 2015b) who have demonstrated that both macrotexture and microtexture positively contribute to the increase in friction (Adresi & Lacidogna, 2021).

Also, the CR tended to increase the BPN in the SMA and BBTM mixtures. However, its influence on the AC mixtures was not significant ($p > 0.001$). This could be due to the fact that the AC mixtures have a lower macrotexture, and therefore

there is more mortar on the surface, composed mainly of bitumen and sand, which minimizes the influence of the CR additive.

For all types of mixtures, the variable associated with microtexture, Rami, had a more significant impact compared to the one related to macrotexture, Rama. In the case of AC mixtures (Table 4.10), the standardized β for Rami and Rama were 0.603 and 0.401, respectively. For SMA (Table 4.8), the difference in standardized β was more pronounced, with values of 0.761 for Rami and 0.407 for Rama. Finally, BBTM mixtures (Figure 4.11) exhibited the most substantial difference in terms of the impact of the two variables, with values of 0.747 for Rami and 0.333 for Rama. It is also worth noting that for both SMA and BBTM mixtures, the CR content is also important in predicting BNP, with standardized β of 0.595 and 0.264 respectively (Table 4.12). This is in line with (Liu et al., 2009) and confirms that the CR can be considered as a complementary skid resistance additive. The impact of the macro and microtexture on the skid resistance at a lower speed of measurement at 10km/h is summarized in Figure 4.29. Moreover, the same figure shows the impact value of CR on the skid resistances.

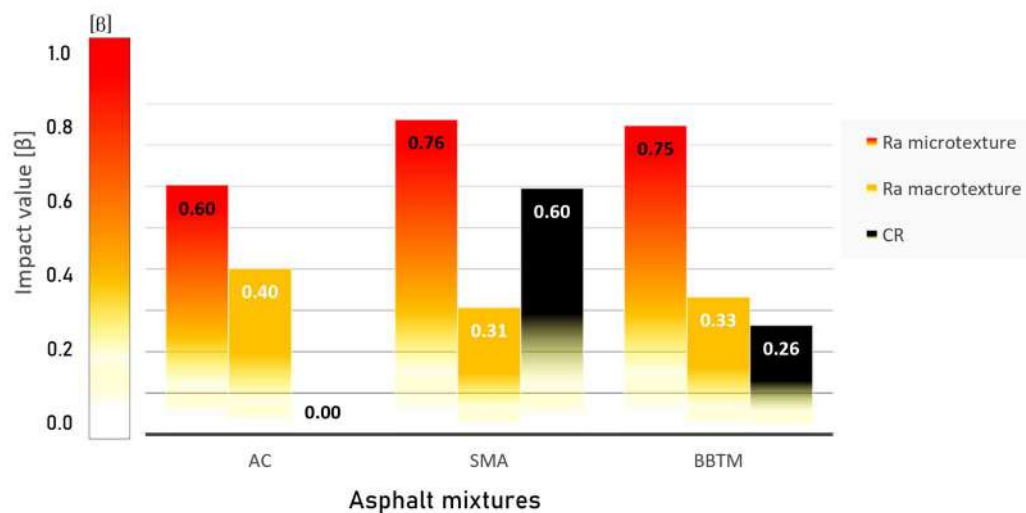


Figure 4.29: Impact value of the texture parameters and the CR content on the prediction models for BPN.

In order to demonstrate the predictive capability of the multivariate linear regression models, a validation process is conducted by comparing the data predicted by the model with the laboratory-measured data. After fitting a linear model to the data for each type of mixture, the prediction error by Root Mean

Square Errors (RMSE) as shown in Figure 4.30, were obtained for AC mixtures (2.54%), SMA mixtures (4.94%), and BBTM mixtures (2.67%) as shown in the Table 4.10, Table 4.11, Table 4.12. This indicates that, on average, the model predictions have an error of approximately less than 5 units concerning the actual average values of the BPN.

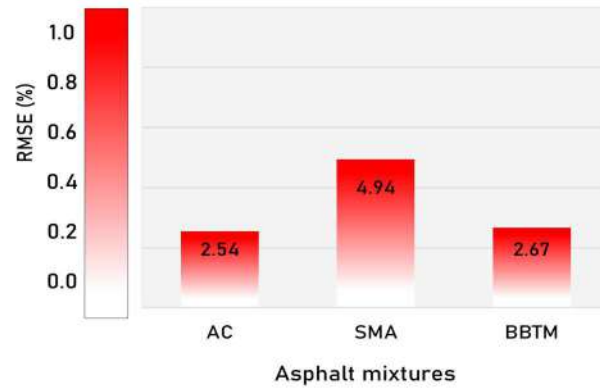


Figure 4.30: Evaluation of model prediction error RMSE.

A criterion for considering a good model fit based on RMSE is that its value should not exceed 10% (Karunasingha, 2022). Therefore, the model's fit can be considered acceptable. The models exhibit a linear fit to the experimental values of BNP with quite robust correlation coefficients for AC mixtures ($R^2 = 0.91$) and BBTM mixtures ($R^2 = 0.95$). On the other hand, the SMA sample shows a slightly lower correlation coefficient ($R^2 = 0.82$) but still demonstrates a significant correlation as shown in Figure 4.10, Figure 4.11, Figure 4.12. The grey line in Figure 4.31 shows the 45-degree line, which stands for the total coincidences of a model with the experimental data. A model is considered better when more data points approach this line. In this case, the models fit quite well.

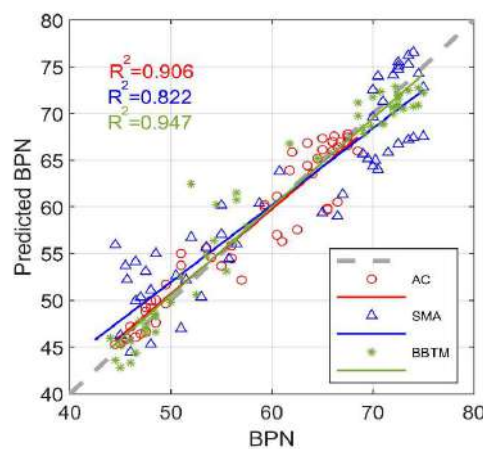


Figure 4.31: Comparison between Predicted BPN and measured BPN.

4.3.3. High-speed measurement by Wehner/Schultze.

The assessment of friction at high speed 60 km/h by Wehner/Schultze (W/S), as well as the process conditioning and polishing of specimens are shown in Figure 4.32.

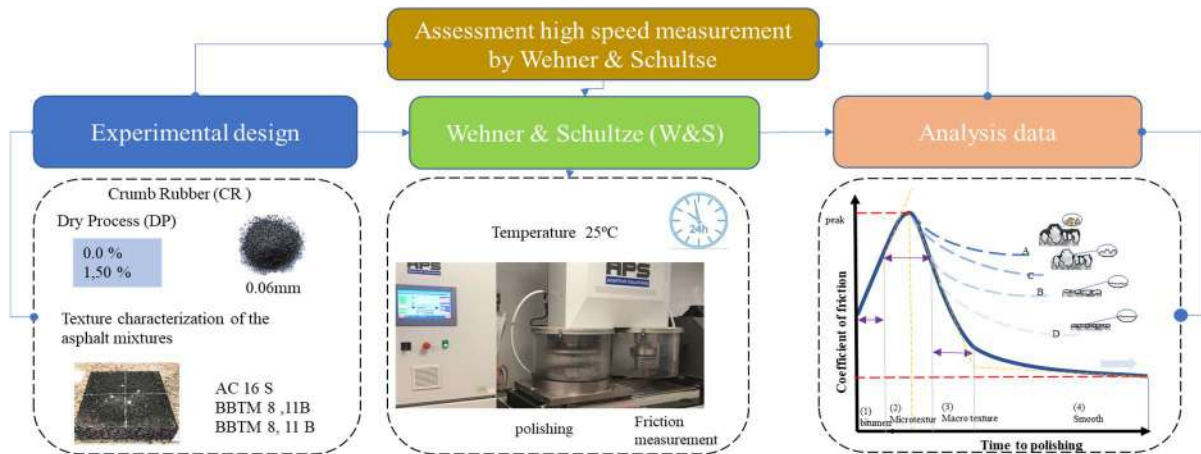


Figure 4.32: Wehner & Schulze test polishing and friction measurement. Source: Author's elaboration.

4.3.4. Evolution of the W/S coefficient of friction.

Figure 4.33 shows the development of skid resistance W/S. In this case, the content of rubber added were (0.0 % and 1.50 % CR) four points are observed: (1) A low coefficient of friction is observed at the beginning, followed by an increase with of polishing, reaching a peak value (2). Subsequently, the coefficient of friction decreases (3) until it stabilizes (4). This pattern is consistent with previous research (Do et al., 2014b, Do & Marsac, 2002) and indicates a consistent behavior across studies regarding the effects of CR on asphalt mixture polishing.

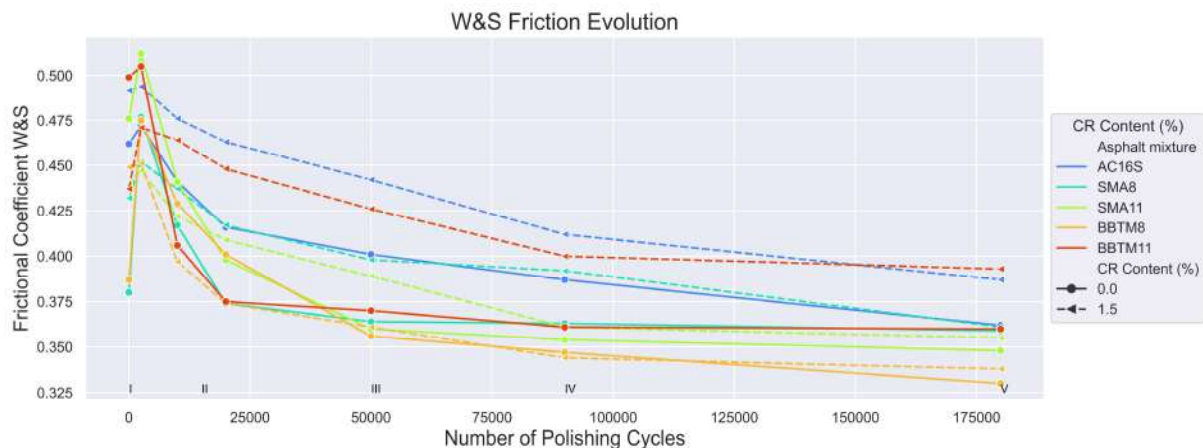


Figure 4.33: Behavior of the friction coefficient W/S for asphalt mixtures.

The decreasing trend of the friction coefficient culminates in a stabilization zone, which is particularly noticeable at an average speed of 60 km/h. This finding provides valuable information about the dynamic behavior of asphalt mixtures during different polishing cycles.

a) Impact of crumb rubber on the evolution of W/S results.

The evolution of friction coefficient by W/S at 60km/h in different asphalt mixtures is shown in Figure 4.34. It is possible to distinguish different stages (I, II, III, IV, and V). At the initial stage I when traffic is open, operating at high speeds of 60 km/h, the addition of crumb rubber appears to increase skid resistance. In stage II maximum skid resistance is achieved due to surface texture. In stage III the decreasing of the skid resistance gets a more moderate slope. From stage IV to V a stabilization of skid resistances at 60km/h. is observed.

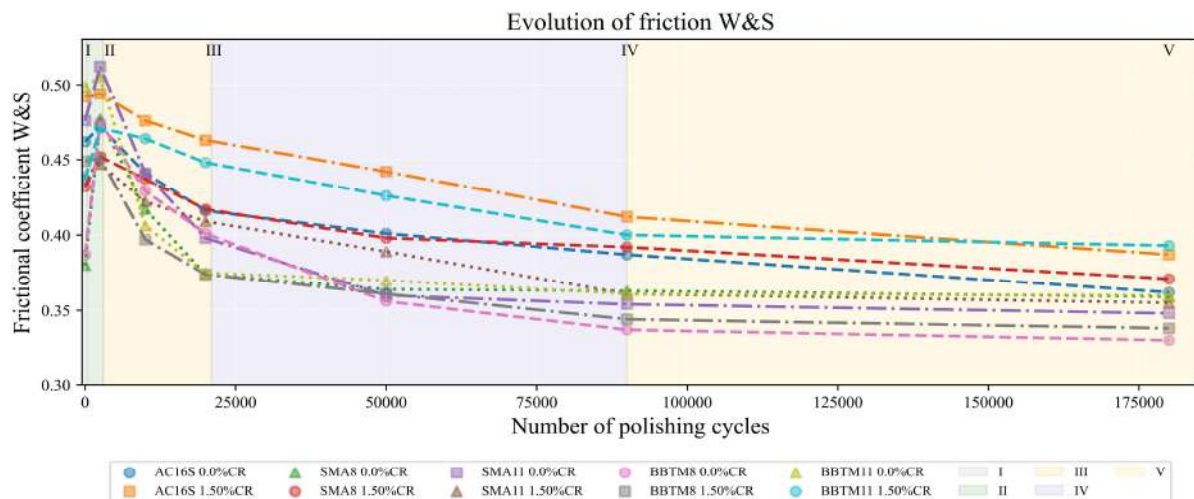


Figure 4.34: Evolution of the friction of W/S.

Figure 4.35 illustrates the effect of CR on stage II (maximum skid resistance) and stage V (stabilization skid resistance) on the evolution of friction. In stage II, a consistent increase trend is observed by the influence of the CR (0.00%, and 1.50%), with the maximum skid resistances for AC at 2.49 %, SMA 8 at 5.53 %, SMA 11 at 5.41%, BBTM 8 at 5.32%, and BBTM 11 at 5.11 % higher than the references without crumb rubber.

In the stabilization stage V, there is a notable decrease in the skid resistances of all mixtures. Regarding the influence of rubber in this of stage of polishing. It can be observed a slight CR decrease in AC at 1.28%, SMA 8 at 1.95 %, SMA 11 at 0.72 %, BBTM 8 at 1.74 %, and BBTM 11 at 3.48 %. It is convenient to keep in mind that these measurement of skid resistance with the W/S device performed at

60Km/h, instead of the BPN measurement, carried These findings highlight the effect of CR at 60km/h of measurement by W/S.

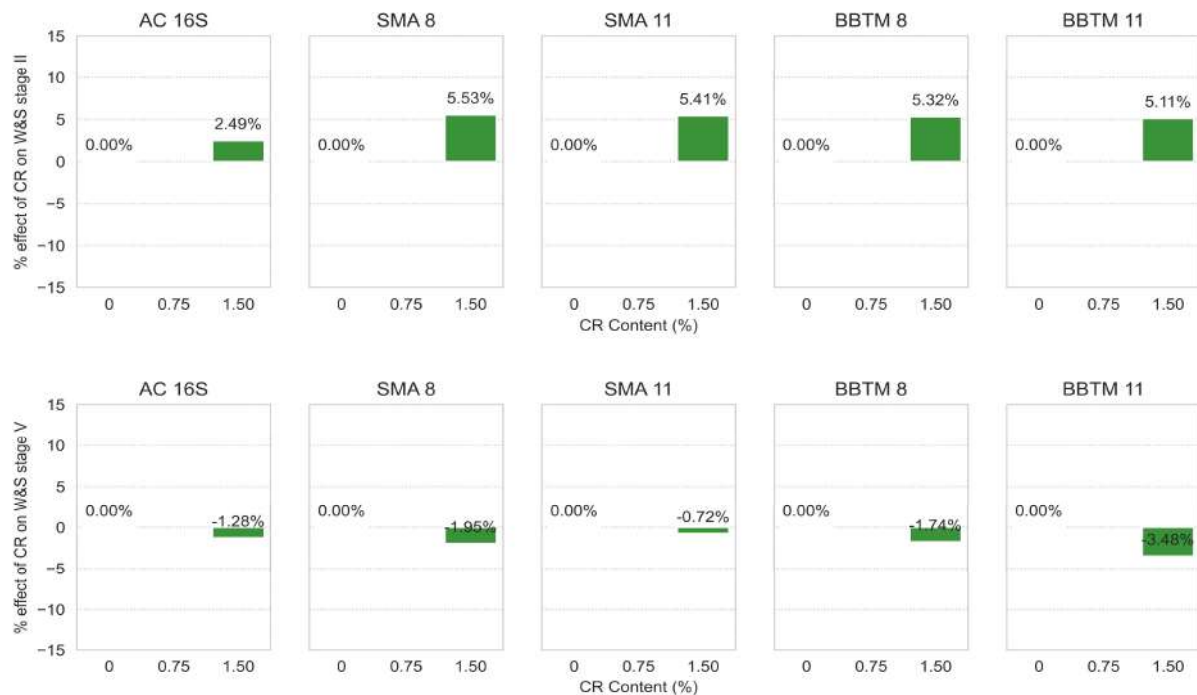
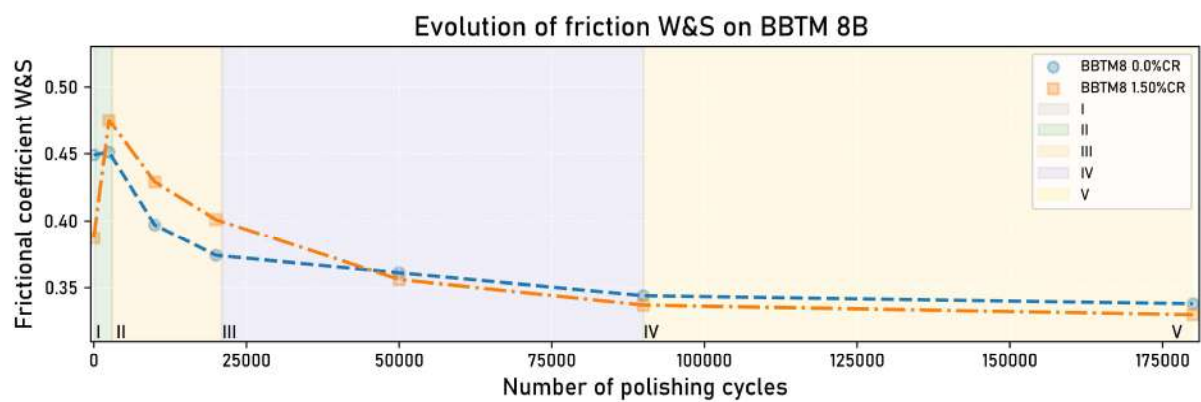
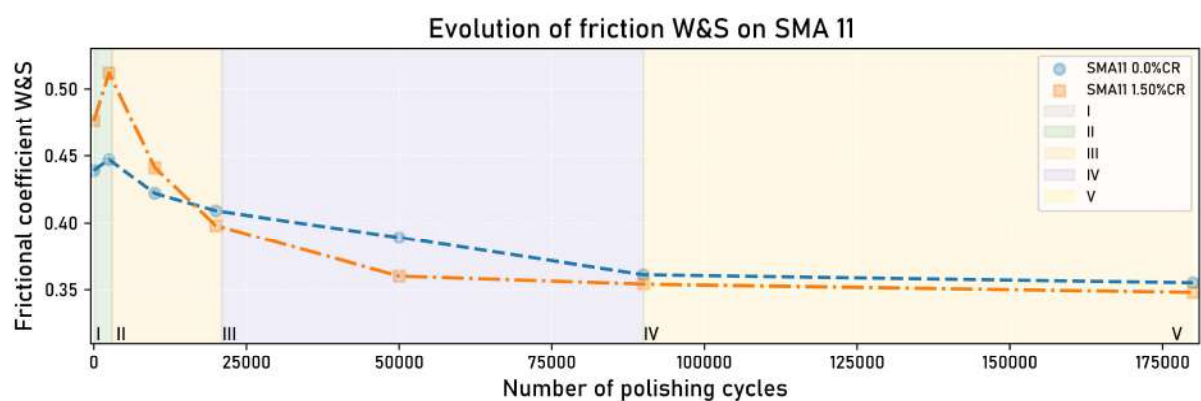
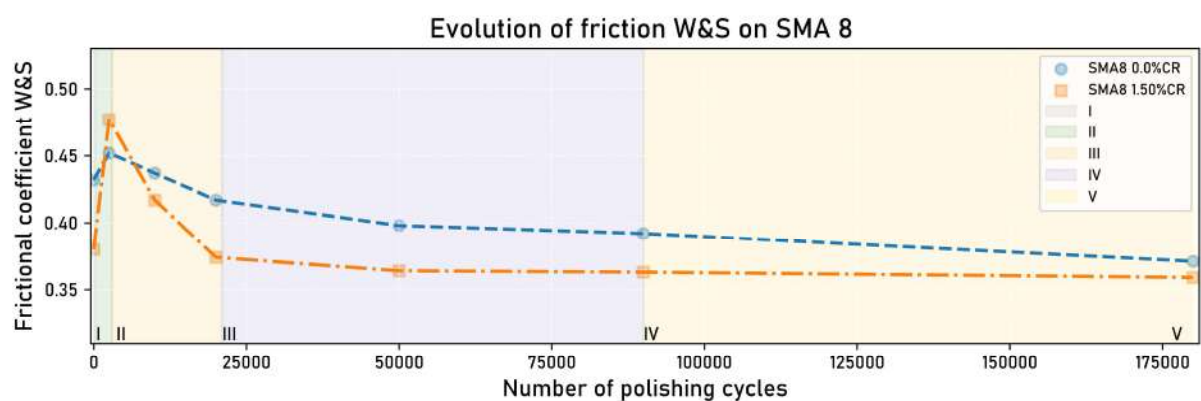
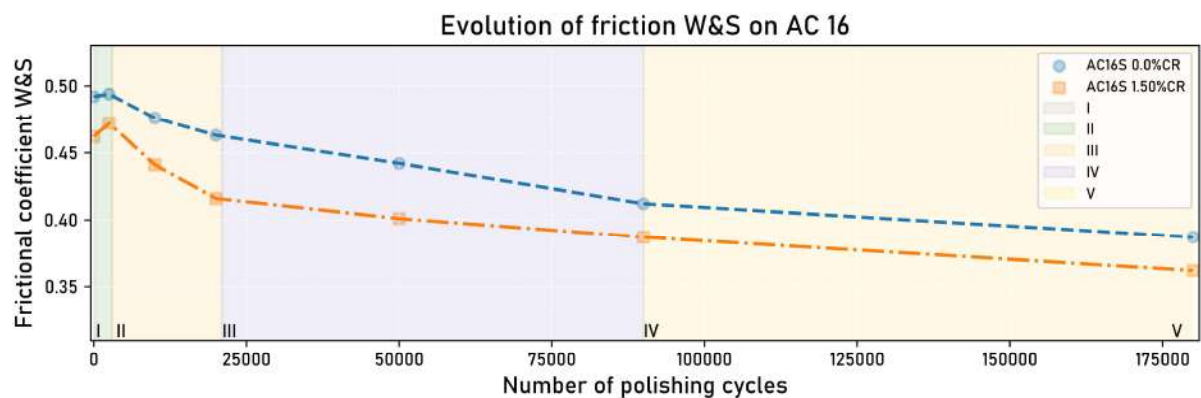


Figure 4.35: Effect % of CR on stages on II, and V (W/S) of asphalt mixture.

Figure 4.36 shows the evolution of the coefficient of friction over the W/S wear cycles for the mixtures under study. In general terms, all the specimens show a similar trend of rapid increase, reaching the maximum constant friction coefficient in all the asphalt mixtures at 2500 cycles. A reduction of the coefficient is observed from 250 to 9000 cycles, at which time the friction stabilization begins, remaining constant until reaching 180000 cycles. The frictional behavior of the reference asphalt mixtures exhibits inferior behavior compared to mixtures with 1.50% CR. On the other hand, AC mixtures show a significant difference in frictional behavior with the effect of CR, as do the SMA 8 mixes which exhibit superior performance. However, the CR effect of SMA 11 mixes shows a slight variation in frictional behavior. The BBTM 8 B mixtures show a similar behavior to the reference mixtures, while the BBTM 11B mixtures show a superior behavior due to the effect of CR. This means that the effect of CR results in a slight increase in the W/S friction stored as a response, with significant variations in the frictional behavior observed in the different mixtures and additions of CR.



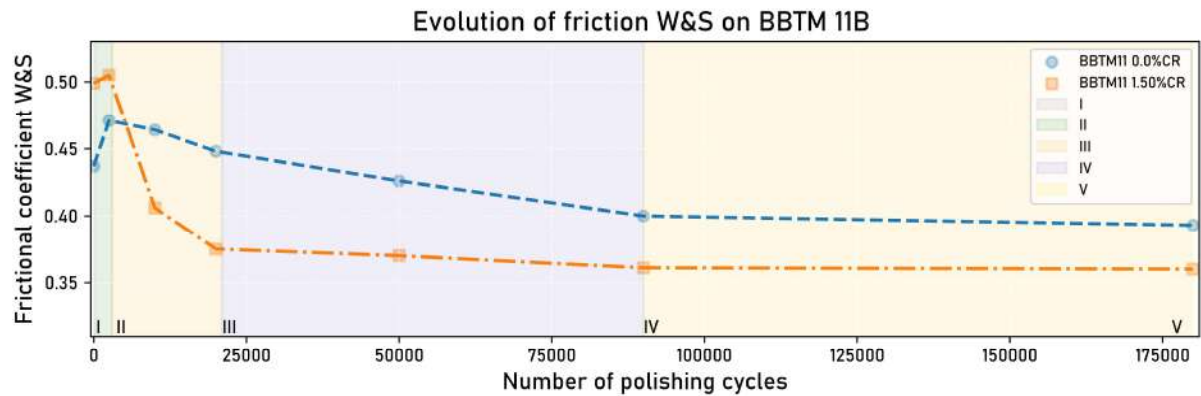


Figure 4.36: Comparison of the average of the coefficient friction W/S of asphalt mixtures.

b) Analysis of the threshold by W/S

A threshold of 0.46 in the W/S machine is equivalent to [CRT=50] (see section 3.6.2.1 a) and has been established according to the CRT for skid resistance W/S by NLT-336 described by (Bustos & Echaveguren, 2006). Figure 4.37 shows the W/S values concerning Stage I (S-I). Initial W/S measurements just meet this threshold for AC 16S, SMA11, and BBTM 11B mixtures, but SMA 8 and BBTM 8 B do not accomplish established threshold of 0.46. Stage II (S-II) considered the maximum peak of the skid resistances achieved the threshold requirement for AC reference and AC 1.50%CR and BBTM 11B reference and BBTM11B 1.50%CR asphalt mixtures. While Stage III (S-III), Stage VI, and Stage V are observed all samples are below the threshold. These stages are considered the stabilization of “equilibrium levels of W/S values”, usually lower than the threshold.

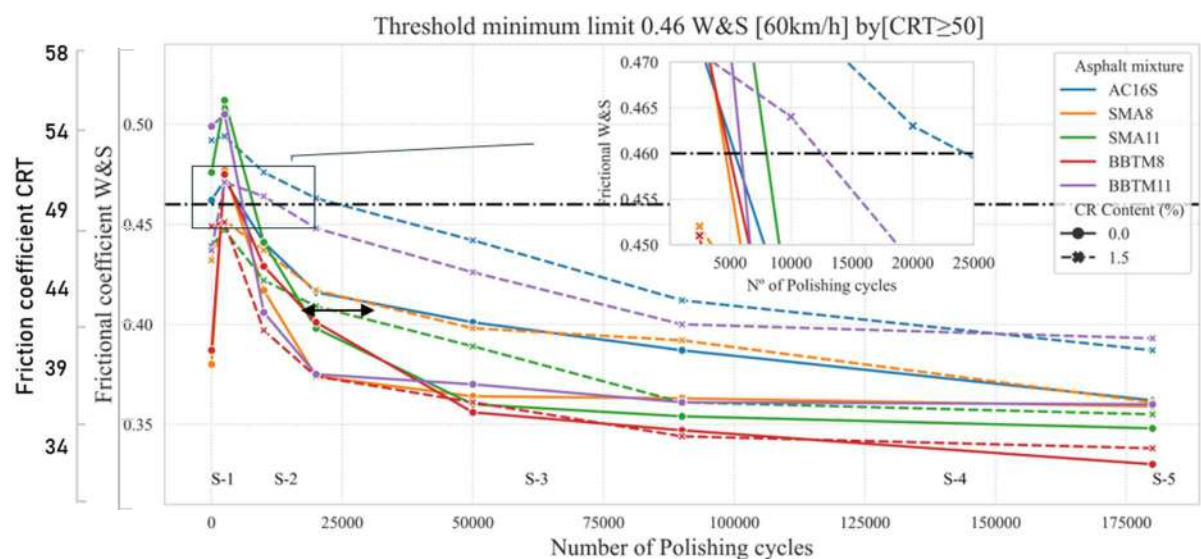


Figure 4.37: Evolution of the skid resistances at high speed at 60km/h by W/S.

Figure 4.38 illustrates the number of cycles required to reach the threshold $W/S = 0.46$. The AC 16S reference mixtures require approximately 6000 cycles, while AC with 1.50% CR requires approximately 24000 cycles to achieve the threshold. Similarly, SMA 8 requires approximately 4000 cycles, SMA 11 approximately 8000 cycles and BBTM 8, approximately 5000 cycles are needed, but with CR, the minimum threshold is not achieved. The BBTM 11 reference requires approximately 6000 cycles, whereas BBTM 11 B with 1.50% CR requires approximately 13500 cycles.

It is worth noting that using crumb rubber up to 1.50% requires a greater number of cycles to achieve the threshold of 0.46. This could be due to the maximum aggregate size of 16 mm in dense mixes and 11 mm in open mixtures, which is explained by an improvement in the integrity of the mastic envelope. The CR provides greater protection to the external envelope structure of the surface texture of asphalt mixtures.

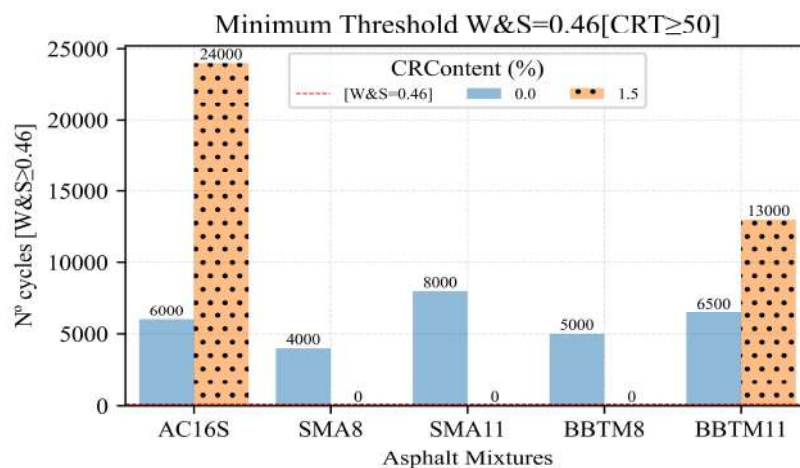


Figure 4.38: Effect of crumb rubber to achieve the threshold $W/S = 0.46$.

c) Evolution of the W/S for stages of polishing.

Figure 4.39 shows a comparison at threshold 0.46 for 5 stages. In stage I, seems that the asphalt mixtures SMA 8 and BBTM 8B have difficulty achieving the threshold of $W/S = 0.46$ when open to traffic. In stage II the reference mixtures fulfill the threshold 0.46 W/S . Nevertheless, by the effect of CR only AC 16S and BBTM 11B meet the threshold. At stage III only AC16S +1.50%CR and BBTM11B +1.50%CR meet the minimum threshold. At stage VI and stage V none of the texture achieve the minimum threshold.

Differences in the skid resistance measured by W/S have been observed. In relation to the results obtained from the mixtures studied. In general, they do not coincide with the classification that result from the BPT equipment. This could be due to the accelerated polishing intensity, resulting from the W/S procedure. Additionally, the equivalent CRT = 50 to W/S = 46 is not totally proven, and it is necessary to admit that this uncertainly could change some of the comments above on the accomplished of the safety threshold by the W/S laboratory performed in this investigation.

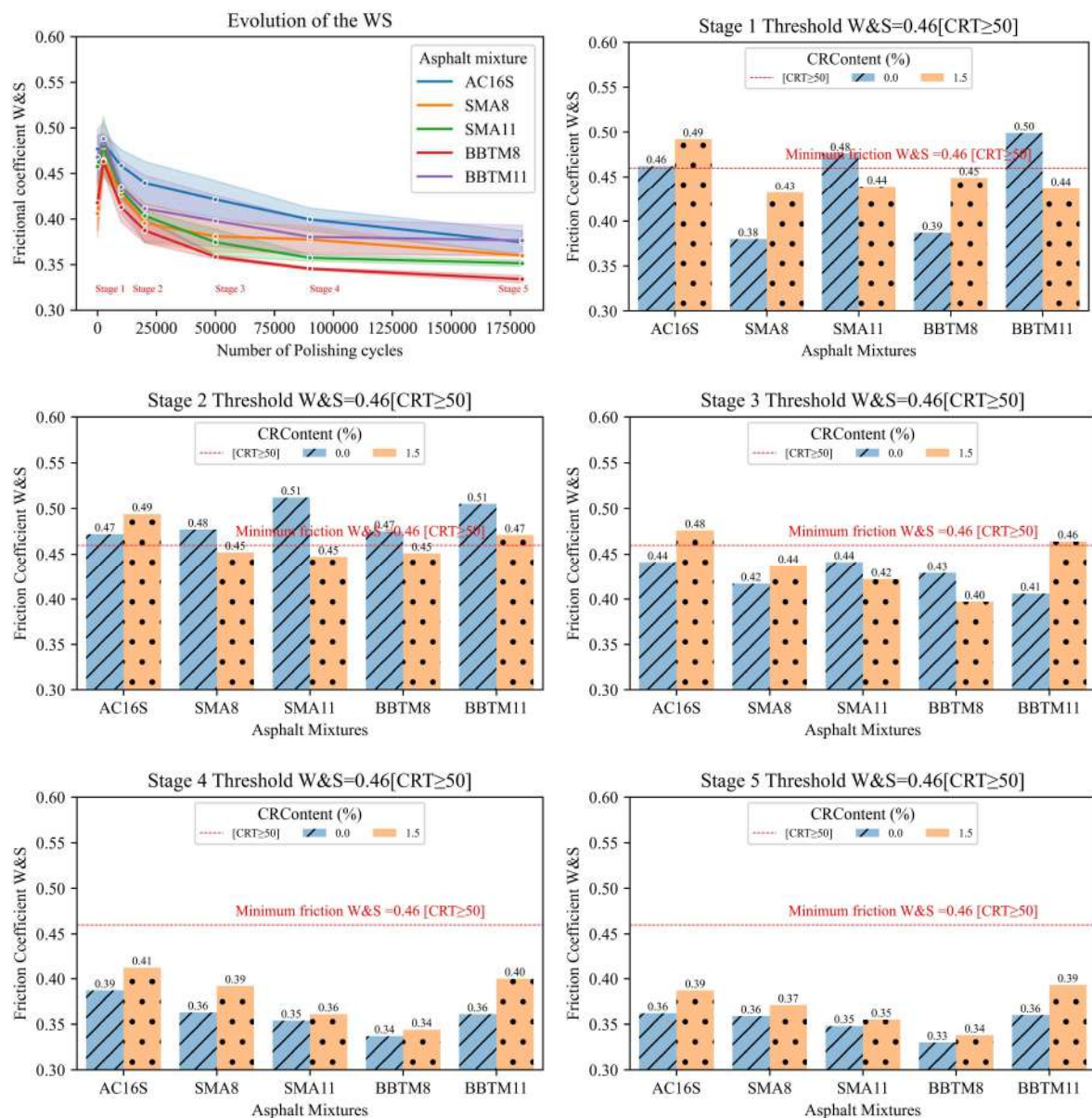


Figure 4.39: Comparative by the threshold W/S= 46 (CRT≥50).

Table 4.13 provides a summary of the effect of crumb rubber content on W/S skid resistance. The difference between reference and CR mixtures is present in AC mixtures while the SMA and BBTM dot exhibits significant differences as shown in Table 4.13. This behavior is shown in Figure 4.40 the group of samples of reference mixtures shows a greater dispersion of W/S, while the group of samples with CR decreased dispersion and shows a slight increase in W/S. Although a slight increase in W&S is observed, statistically there is no significant difference between the mixtures.

Table 4.13: Estimates of T-student for the asphalt mixture.

	AC 16S		SMA 8		SMA 11		BBTM 8 B		BBTM 11B	
Variable	0.00	1.5%CR	0.00	1.5%CR	0.00	1.5%CR	0.00	1.5%CR	0.00	1.5%CR
Mean	0.442	0.413	0.410	0.392	0.397	0.412	0.378	0.391	0.396	0.434
Variance	0.002	0.002	0.001	0.002	0.001	0.003	0.002	0.003	0.003	0.001
P-value	0.006		0.152		0.309		0.087		0.060	

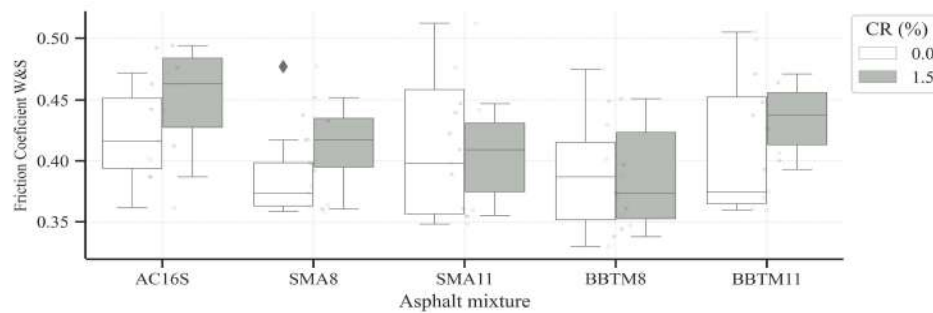


Figure 4.40: Effect of the crumb rubber on the friction coefficient W/S.

Figure 4.41 shows the average influence of CR on the Wehner & Schulze (W/S) for high-speed measurements. It shows a slight difference in the average values in the last stage V (cycles between 90000-180000). The median value in the last phase with 1.50% CR is 0.36 and thus exceeds the reference mixtures (0.37 W/S). This indicates a relatively constant trend in W/S development, which is positively influenced by CR, especially at high speeds in the last polishing cycles. But statistically no present differences (p-value =0.1527) as shown in Table 4.14 below.

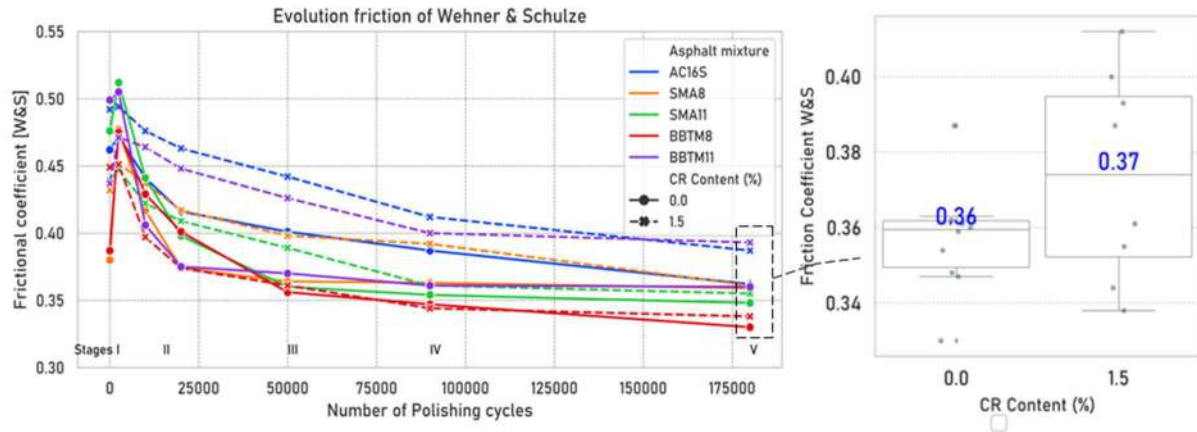


Figure 4.41: Effect of CR on the final stage of the friction coefficient W/S.

The factor of asphalt mixtures does not offer any significant changes in the friction coefficient W/S at high speed. Table 4.14 presents $F(4,4) = 3.0517$; $p\text{-value} = 0.1527$. The influence of CR content on the coefficient of friction W/S (at 60 km/h) of asphalt mixtures was not found to be significant present $F(1,4) = 1.3985$, $p\text{-value} = 0.3025$ as shown in Table 4.15. This result shows that even if there are differences in the asphalt pavements, there are no differences due to the different percentage content of CR. The addition of CR only had the effect of a few percent increased the friction W/S, while no improvements were observed in terms of friction W/S. The post-hoc analysis compared two specific CR levels (0.0 and 1.50 %CR. The P-value showed no significant difference between these CR additions (Table 4.16).

Table 4.14: W/S friction in asphalt mixture (high speed)-ANOVA output.

Variable	SS	Df	Mean square	F	p-value
Asphalt mixture	0.0025 ^a	4	0.0006	3.0517	0.1527
Error	0.0008	4	0.0002		
Total	0.0033	8			

^a $R^2 = 0.995$ (Adjusted $R^2 = 0.994$)

SSQ: sum of squares, Df: degrees of freedom, MS: Mean Squares, f: fisher ratio, p-value: probability value.

Table 4.15: Effect of CR content on friction coefficient at high-speed W/S -ANOVA output.

Variable	SS	Df	MS	f	p-value
CR content %	0.0003 ^a	1	0.003	1.3985	0.3025
Error	0.0008	4			
Total	0.0011	5			

^a $R^2 = 0.995$ (Adjusted $R^2 = 0.994$)

SSQ: sum of squares, Df: degrees of freedom, MS: Mean Squares, f: fisher ratio, p-value: probability value.

Table 4.16: Effect CR content by T-student post doc.

Variable	A	B	Parametric	T	p-value
CR content %	0.0	1.50	True	-1.1826	0.3025

p-value: probability value.

4.3.4.1. Texture evolution by W&S.

Figure 4.43 shows visually the evolution of mean texture depth (MTD) over successive polishing cycles, emphasizing the noteworthy distinction between MTD and texture profile (MPD) parameters, particularly evident after 180000 polishing cycles. Notably, MTD measurement brings light differences among asphalt mixtures, with BBTM 8 and 11 along with SMA 11, demonstrating comparable depth values. In contrast, AC16S and SMA 8, exhibit lower values compared to SMA 11, BBTM 8B - 11B. The examination of the MPD reveals significant variation, showcasing considerable differences in results across specimens. Both MTD and MPD texture parameters elucidate the dynamic changes in the texture characteristic during the polishing cycles. Assessing the influence of the CR, Figure 4.42 and Figure 4.43 provides a summary of average values for MTD and MPD across different asphalt mixtures. CR exerts a discernible effect on both texture depth and profile. The reduction of these parameters by CR is consistently noticeable, particularly when compared to 60 km/h by standard PG-3. Remarkably, MTD values meet satisfactory standards, while MPD falls short of the minimum threshold required. This result highlights the nuanced influence of CR on texture characteristics and emphasizes the need for a comprehensive evaluation of MTD and MPD parameters to better understand the performance of asphalt mixtures during polishing cycles.

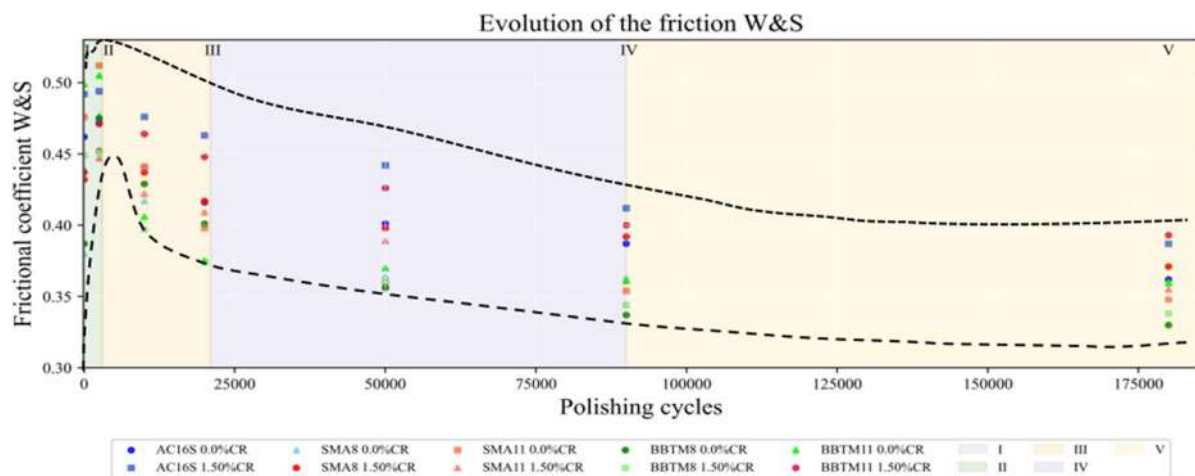


Figure 4.42: Evolution band of skid resistance W/S of asphalt mixtures.

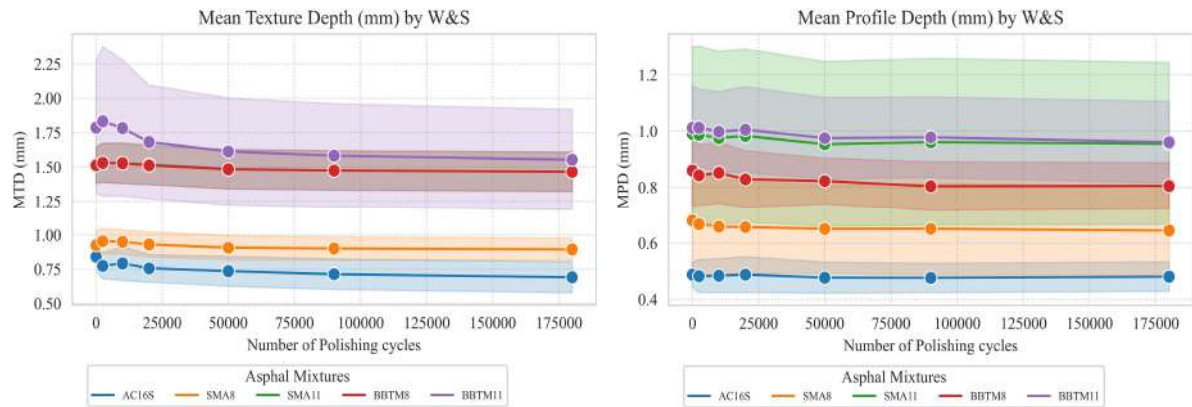
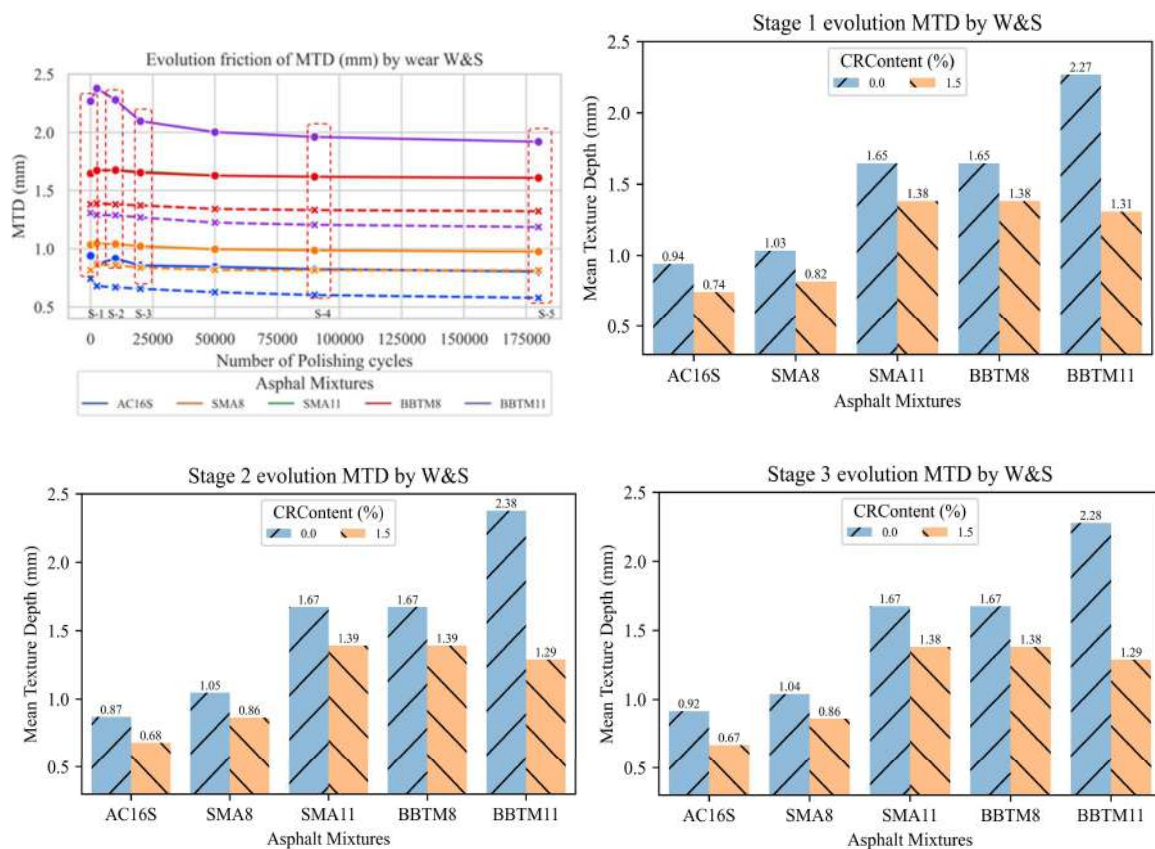


Figure 4.43: Evolution of the MTD and MPD along the polishing procedure.

In Figure 4.44 the evolution of texture parameters MTD and MPD is depicted, providing a visual representation of the changes in texture characteristics across four distinct stages. Notably, throughout all stages, AC 16 S, SMA 8, SMA11, BBTM 8B, and BBTM 11B decrease texture parameters.

The influence of CR is evident in its reducing effect across all asphalt mixtures, emphasizing a consistent trend polishing of texture parameters associated high speed of polishing 500 r.p.m.s equivalent to 17km/h.



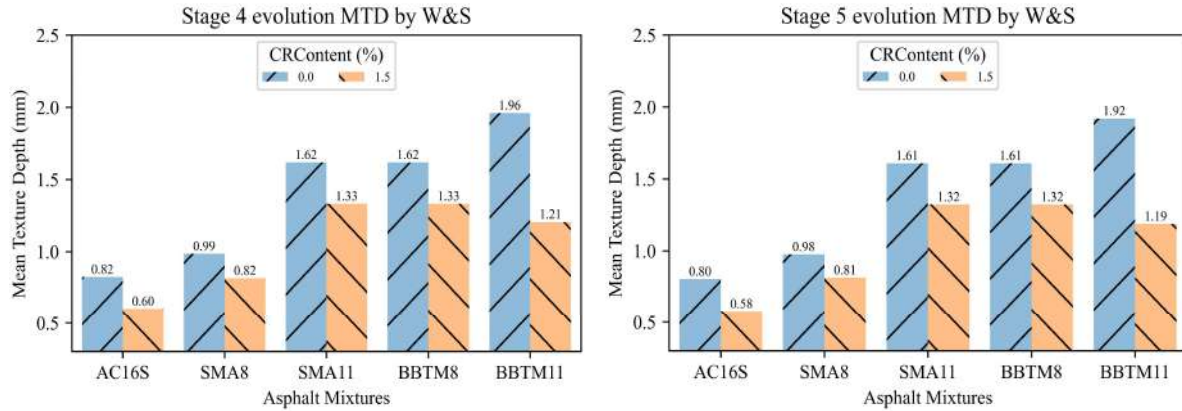


Figure 4.44: Effect of the crumb rubber on the texture parameters.

These observations underscore the differential impact of crumb rubber on texture characteristics in various asphalt mixtures and emphasize the importance of considering the evolving trends across different stages for a comprehensive understanding of the influence of crumb rubber on texture evolution. Table 4.17, Table 4.18, and Table 4.19 present details of the estimated multiple linear regression models for AC, SMA, and BBTM mixtures, respectively. Equations 30, 31, and 32 show the expression that estimates the W/S values as a function of CR, Rama, and Rami. The models fitted for each type of mixture enable predictions for new observations based on the microtexture, macrotexture, and crumb rubber content.

Table 4.17: Estimates of the W/S model for the AC16S mixture.

Variable	Unstandardized β	Std. Error	Standardized β	t	p-value
Constant	-0.9686	0.2104		-4.6035	<0.001
CR	-0.1034	0.0207	-1.948	-4.994	<0.001
Rami	25.641	7.674	2.052	3.341	<0.010
Rama	4.4921	0.822	0.603	5.462	<0.001
R2	0.87				
R2adj	0.82				
RMSE	0.017				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value

$$W/S[AC] = -0.969 + 25.641 Rami + 4.492 Rama + 0.103CR \quad \text{Equation 30}$$

Table 4.18: Estimates of the W/S model for the SMA11 mixture.

Variable	Unstandardized β	Std. Error	Standardized β	t	p-value
Constant	-2.3927	0.3747		-6.388	<0.001
CR	0.8101	0.1092	12.876	7.414	<0.001
Rama	3.3072	0.4430	12.788	7.464	<0.001
R2	0.861				
R2adj	0.831				
RMSE	0.020				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value

$$W/S [SMA] = -2.393 + 3.307 Rama + 0.810CR \quad \text{Equation 31}$$

Table 4.19: Estimates of the W&S model for the BBTM 11B mixture.

Variable	Unstandardized β	Std. Error	Standardized β	t	p-value
Constant	-0.818	0.3171		-2.5813	<0.001
CR	0.0462	0.0127	0.798	3.6341	<0.005
Rama	1.3921	0.3631	0.756	3.8332	<0.004
R2	0.684				
R2adj	0.613				
RMSE	0.0298				

Std: Standard deviations, β : coefficient beta, t: student test :p-value: probability value.

$$W/S [BBTM] = -0.819 + 1.392 Rama + 0.046CR \quad \text{Equation 32}$$

All the coefficients obtained in the models (Equations 30, 31, and 32) had positive signs, meaning that Rami, Rama, and CR content tend to increase the W/S value (except CR in AC mixture). To assess the sensitivity of the W/S value to changes in the explanatory variables within the observed intervals and to compare these sensitivities to the values of the standardized beta coefficients, Table 4.17, Table 4.18, and Table 4.19 can be checked. As the asperity of the aggregates (Rami) or the surface macrotexture (Rama) of the asphalt mixture increases, the W/S value increases, as expected. This is consistent with the findings of other authors (Arampamoorthy et al., 2011b; Friel et al., 2013; Kane et al., 2013c).

The CR seems to increase the W/S in the AC and SMA and BBTM mixtures with significant ($p > 0.001$). with higher coefficient correlations R^2 , as show in the Figure 4.45.

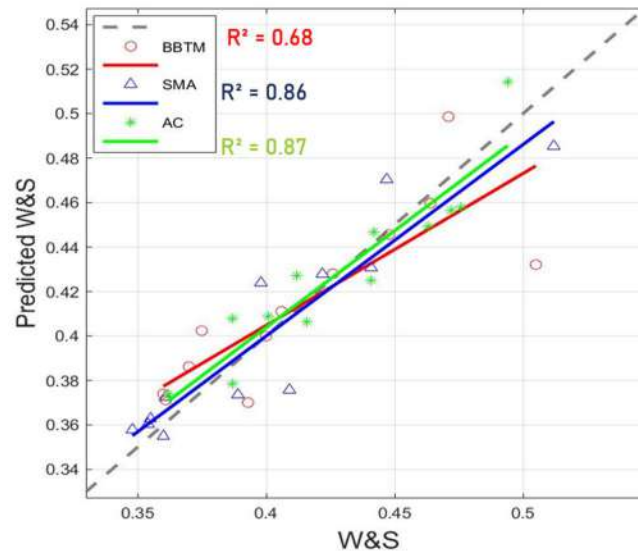


Figure 4.45: Comparison between Predicted W/S and measured W/S.

Figure 4.46. shows that for all mixtures, the variable Rama associated with macrotexture had a significant impact compared to the microtexture Rama. In

particular, the Rama showed significant participation in the AC mixtures compared to SMA and BBTM as shown in Table 4.17. The standardized β for Rama is 2.052 for AC, 0.603 for SMA and 0.76 for BBTM respectively. The CR content impact on the AC, SMA and BBTM mixtures exhibits significant influence, consistent with the findings of (Daskova & Kudrna, 2012).

In general, the variable with most impact on the skid resistance measurement by W/S at 60km/h is macrotexture.

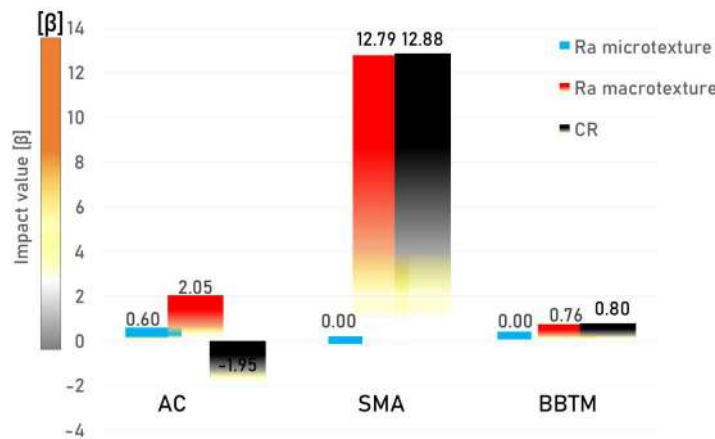


Figure 4.46: Impact of the texture parameters and CR content on the W/S friction value.

It is worth noting that even the CR has not significant influence on the W/S results considering at once the three mixtures, it has demonstrated to have significant effect on the W/S values of the mixtures when considering each mixture separately, including the effect of Rama, Rami and CR content.

4.3.5. Tangential friction resistance (T2R)

The tangential stress resistance test was conducted using the Tribometer T2R apparatus with the methodological procedure that was described in section 3.5. The experimental workflow for the tangential stress resistance test is visualized in Figure 4.47, which also describes the procedures needed in acquiring data and analyzing the results by the asphalt mixtures AC 16S, SMA 11, and BBTM 11B.

This comparative feature adds another level of study to help in the comprehension of how additives might affect the asphalt mixtures' resistance to tangential stresses. The results are more comprehensive when the chosen mixtures and the impact of additives are included. This enables a thorough evaluation of the

tangential stress resistance and the possible impact of additives in the context of various asphalt combinations.

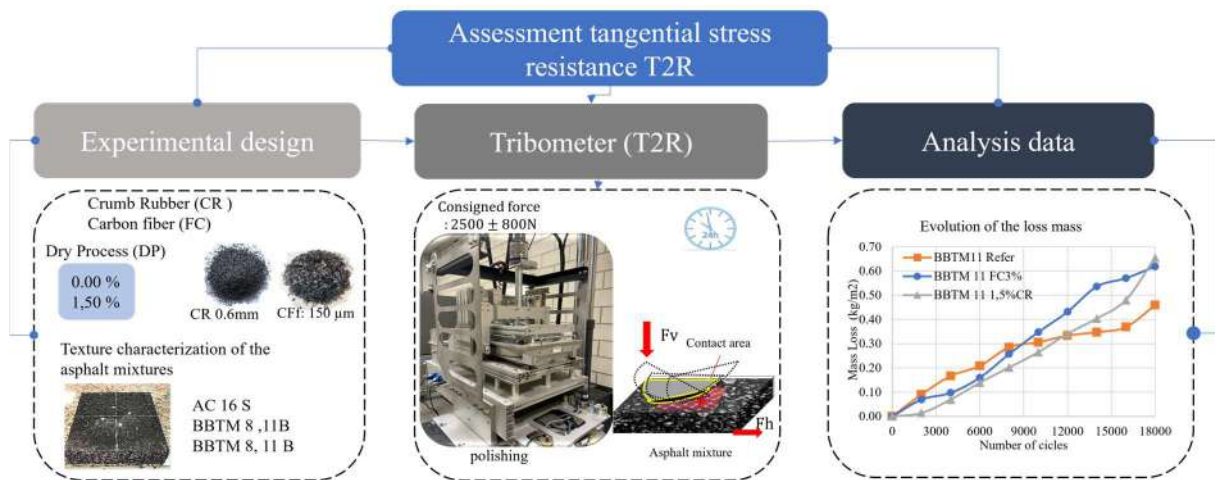


Figure 4.47: Scheme of the experimental of tangential stress resistance. Source: Author's elaboration.

The progression behavior for various types of asphalt mixtures is shown in Figure 4.48. Notably, the maximal mass loss at 18000 cycles for BBTM is 1.09 kg/m², for SMA it is 0.17 kg/m², and for AC it is 0.09 kg/m². The difference in mass loss between the asphalt mixtures can be attributed to changes in their exposed surface texture and surface degradation. These differences in the mass loss for each asphalt mixture are due to the internal structure and surface texture properties of the asphalt mixtures.

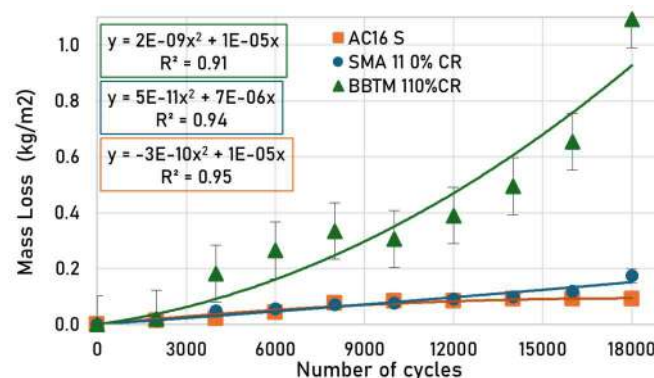


Figure 4.48: Evolution of the tangential stress resistances for asphalt mixtures under study.

In the investigation context, Figure 4.49a highlight a significant difference in mass loss among various asphalt mixtures. Notably, BBTM mixtures exhibit high mass loss, while semi-dense SMA and AC dense mixtures show the lowest losses. This

observed difference in mass loss can be attributed to the internal structure of the asphalt mixtures, as depicted in Figure 4. 50b. AC and SMA mixtures exhibit a more compact granulometry, characterized by a lower content of internal voids, even reaching a range of 5-6% Va. On the contrary, BBTM open mixes display fewer contact points and higher void contents, reaching up to 18 % of Va. The phenomenon can be associated with the ability of more compact mixtures to generate a higher number of contact points, contributing to better grip compared to more open mixtures with fewer contact points. Granulometry and internal void distribution emerge as crucial factors influencing the skid resistance of asphalt mixtures. The ability to generate sufficient contact points appears to enhance grip and, additionally, reduce mass loss during the tangential stress resistance test.

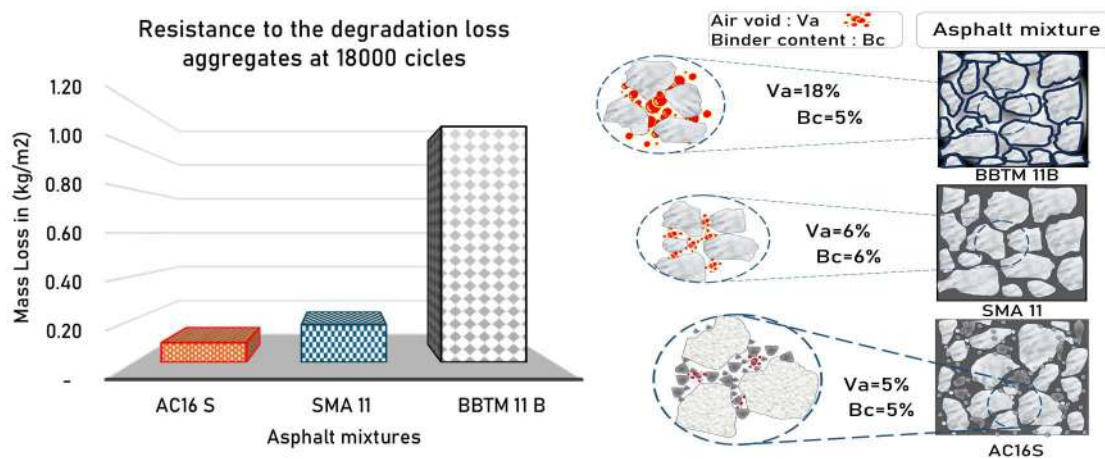


Figure 4.49: a) Ranking of mass loss, and b) Characteristic of the asphalt mixtures.

Source: Author's elaboration.

4.3.5.1. Effect of the additives on the resistance to the mass loss

Figure 4.50a show the behavior of the additives on the mass loss by the T2R test and Figure 4.50 b) shows the percentages of the influence of the additives CF 0.3% and 1.5%CR on the mass loss of the pavement surface after the T2R test. The AC mixtures exhibit a differentiated behavior in terms of mass loss and the addition of 0.3% long carbon fiber (CFL) shows a reduction in mass loss by 38.46 %. While 1.50% CR shows a -22.60 % mass loss compared to the reference mixtures. In contrast, the SMA mixtures show an increase in mass loss by 24.0 % by CFL and an increase by 64.0% by CR in terms of mass loss. The BBTM mixtures show a great reduction of mass loss, with 80.89% by CFL and 75.16% by CR reduction respectively compared to the reference mixtures. Since BBTM mixtures have an

open gradation, the CFL and CR could be accommodated in to their void space, allowing them to better perform during mixing and compacting. This behavior could be due to the fact that the cohesive properties of the CR are improved due to its elastic components.

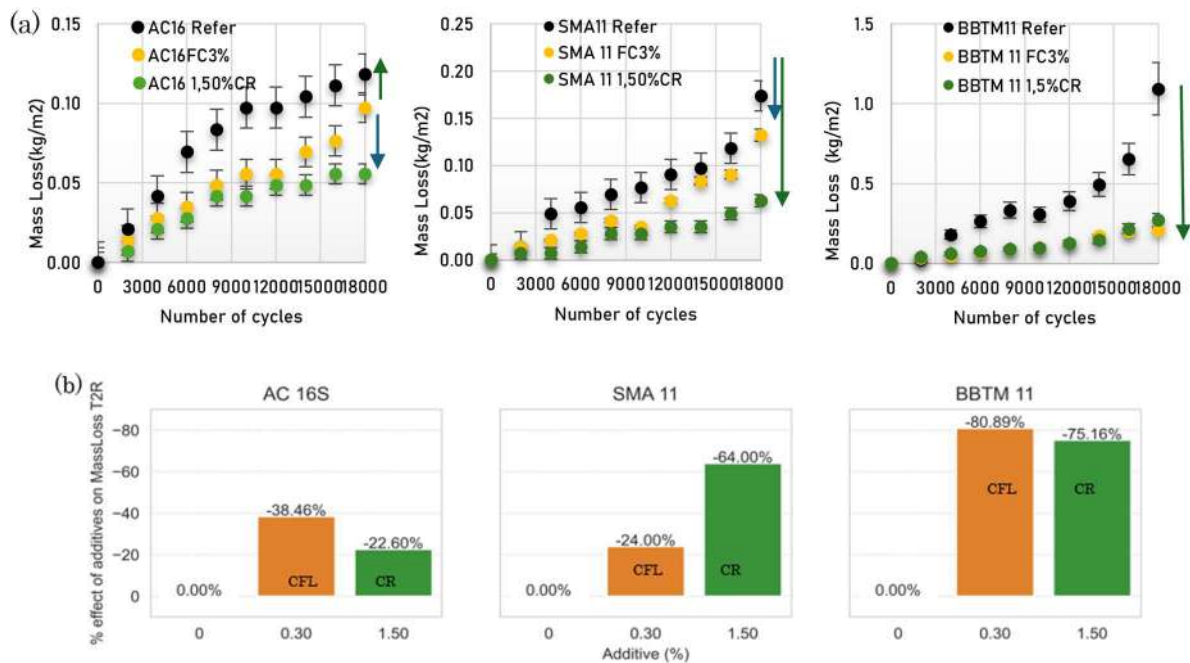


Figure 4.50: a) Spectra of the evolution and b) % influence of the type of additives on mass loss of asphalt mixtures.

Figure 4.51 categorizes the mass loss for asphalt mixtures including 0.3 % CFL and 1.50 % CR. It is observed that the effect on mass loss reduction of the AC, SMA, and BBTM asphalt mixtures. In particular, in the BBTM 11B mixtures, a remarkable mass loss reduction around of 80 % is observed, this being a significant percentage considering the total loss in the reference mixtures. This contribution of additives is crucial given that open mixtures, such as BBTM, tend to present more problems of disintegration and detachment of materials, a concern that has been pointed out by several researchers in the past (Kayhanian and Harvey 2020) (Hamlat et al., 2007).

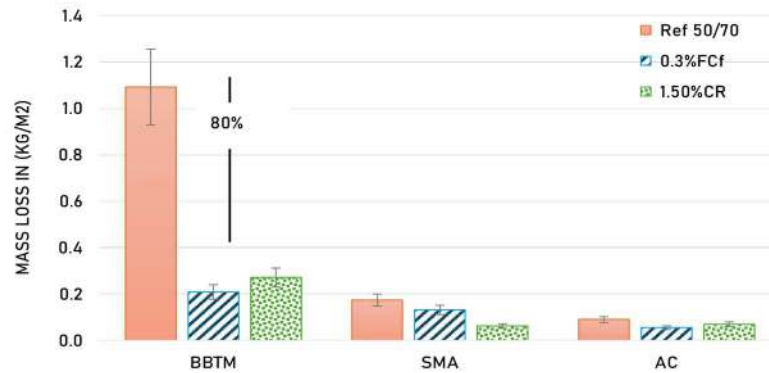


Figure 4.51: Comparison of mass loss for all asphalt mixtures.

From a physical perspective, mass loss can be interpreted as the degradation of the surface exposed aggregates. Figure 4.52 provides a visual comparison of surface losses between losses of 1.09kg/m² (BBTM 11B), 0.17kg/m² (SMA 11), and 0.09kg/m² (AC 16S).

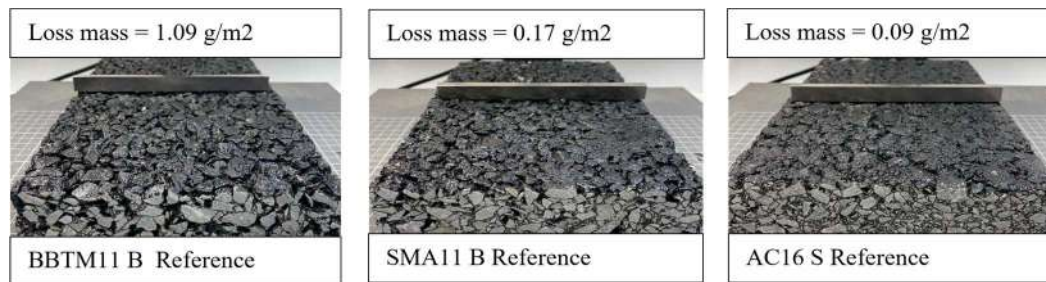


Figure 4.52: Mass loss after 18000 cycles by tribometer T2R.

AC asphalt mixtures exhibit an increase in mass loss, influenced by the effect of CR, while the effect of CFL tends to reduce mass loss. In contrast, SMA mixtures show a decrease in mass loss due to the presence of CR, as well as to the CFL (Figure 4.53). In the case of BBTM mixtures, a significant reduction in mass loss influenced by both CR and CFL is observed. Despite the effects of CR and CFL on mass loss, no great changes in the surface condition of the AC and SMA specimens were observed. Furthermore, mass loss is characterized as a relatively slow stripping process, especially in the presence of CR, with values of 0.06 and 0.13 kg/m², respectively.

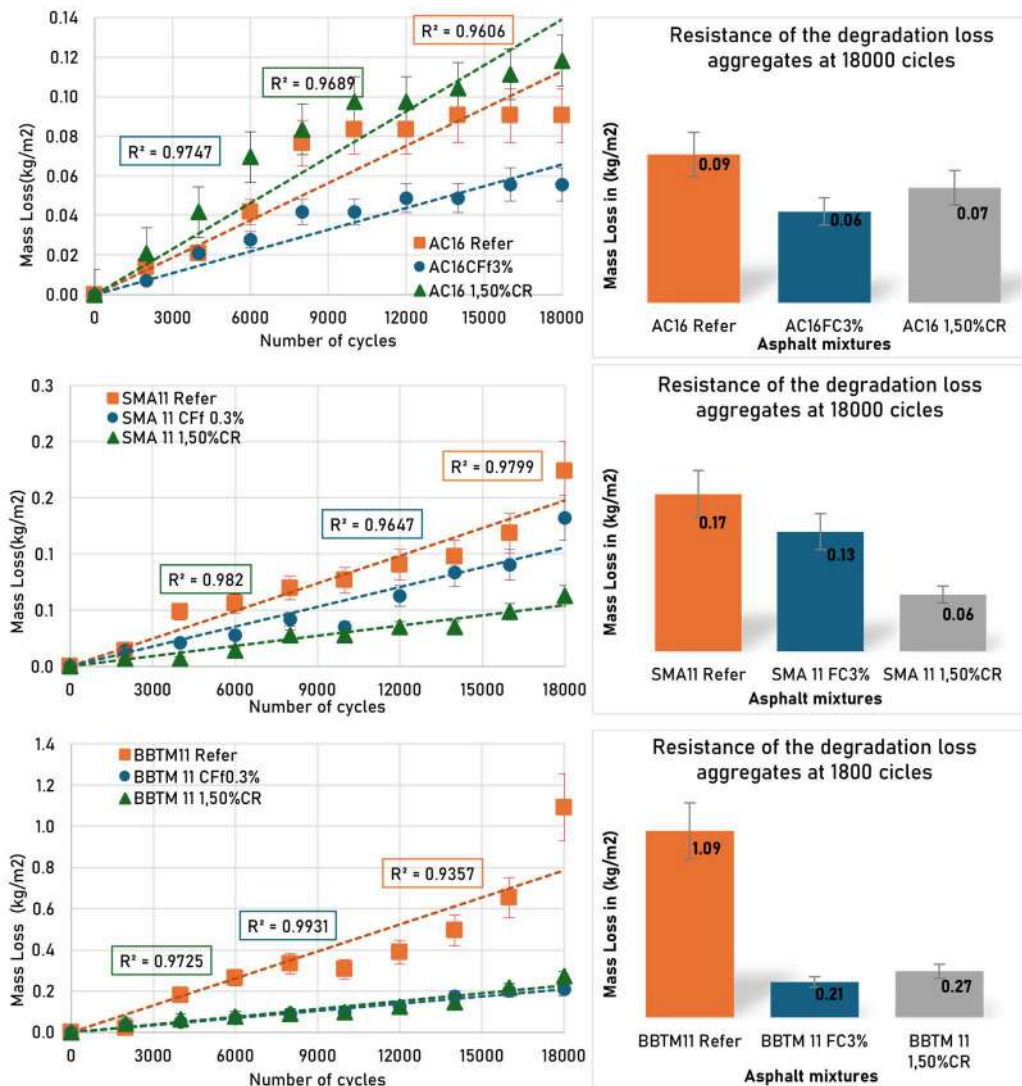


Figure 4.53: Categorization of tangential stress resistance.

In contrast, the BBTM mixtures show surface alterations with aggregate displacements. On the other hand, surface gradual degradation is observed by the presence of 1.50 % CR, and the addition of 0.3 % CFL exhibits moderate degradation, with loss rates of 0.21 kg/m² and 0.27 kg/m² respectively. These findings offer important insights into the influence of different additions of CR and CFL on the stability and durability of asphalt mixtures, highlighting the importance of considering both the type and proportion of the materials used in the asphalt mixtures.

4.3.5.2. ImageJ processing analysis

A novel analysis of processing surface degradation is applied after the repetitive stress transmission by T2R in asphalt mixtures. It was proposed to use the surface

information processing technique through image processing. This approach of T2R was carried out in the laboratories of Gustave Eiffel University, specifically in the Duriez Laboratory - France. Measurements were collected through images captured before and after performing 18000 cycles using the T2R tribometer equipment. To extract physically meaningful data from the corresponding pictures, the methodological procedure described in section 3.07 uses image comparison concerning the reference images. Using **ImageJ** can be extracted data from 2d images of the surface texture. This is demonstrated in the following based on a tracer in experiment test result by T2R Figure 4.54.

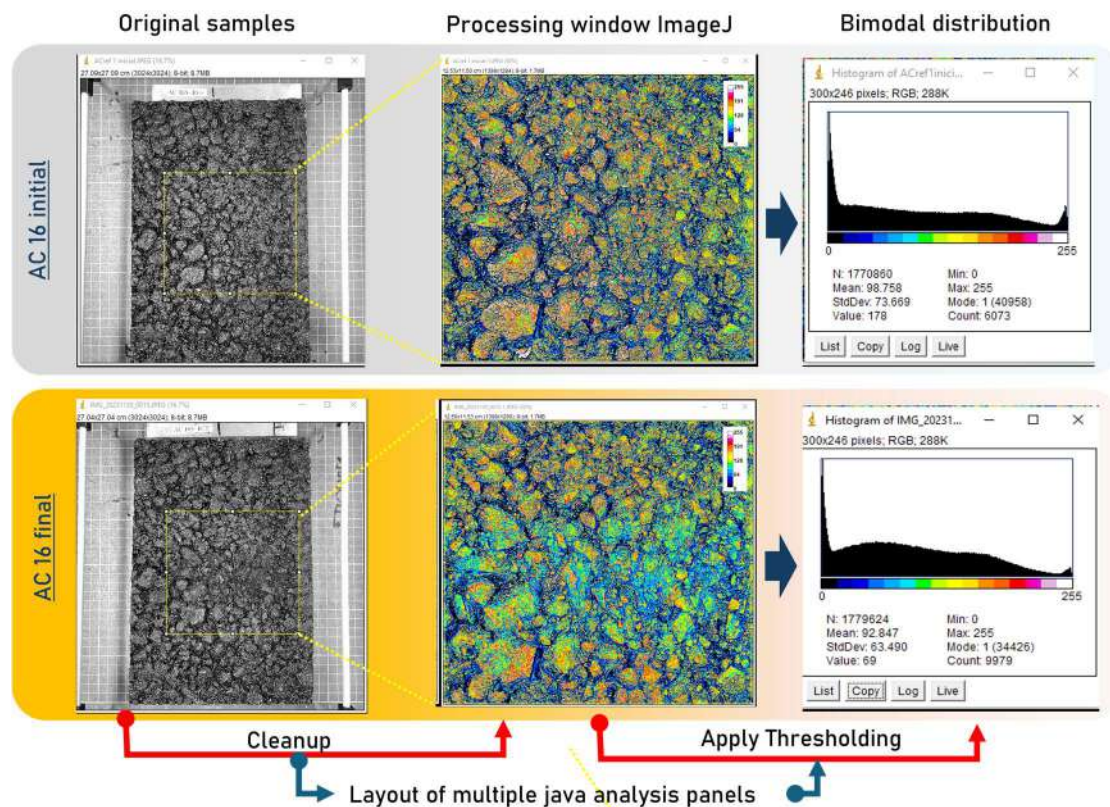


Figure 4.54: Tracer Experiment with zoom in ZOI before and after the T2R test.

To extract physically meaningful data from processed images using **ImageJ** and corresponding photographs, it is feasible to compare them with respect to a reference image. This comparison is conducted before and after testing the degradation surface by T2R, enabling the examination of tracer concentration. In order to correlate a monochromatic signal intensity (in this case, grayscale) to the actual tracer concentration, a linear conversion is selected. This conversion

necessitates the determination of suitable, scaling parameters. For instance, Figure 4.55 shows the effect of crumb rubber on the tracer experiment by ImageJ.

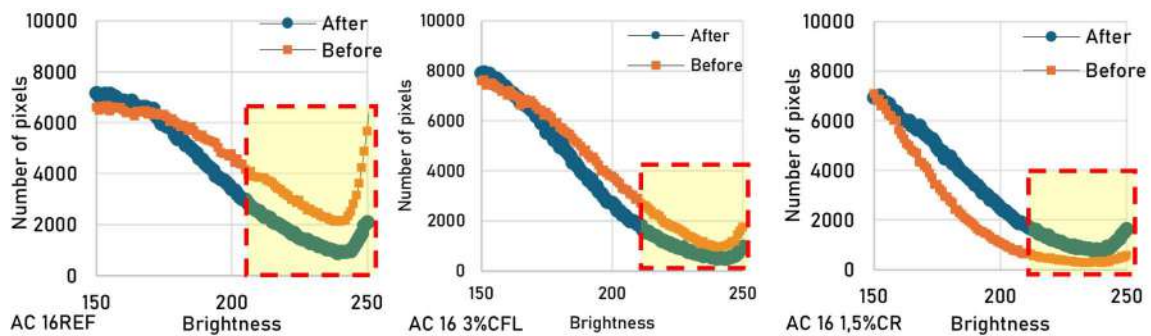


Figure 4.55: Effect of crumb rubber on tracer experiment by ImageJ.

Figure 4.56 presents comparatively the effect of CR and CFL additives after ImageJ processing. A decrease in intensity has been observed in the area of interest corresponding to mass loss in the AC, SMA, and BBTM asphalt mixtures.

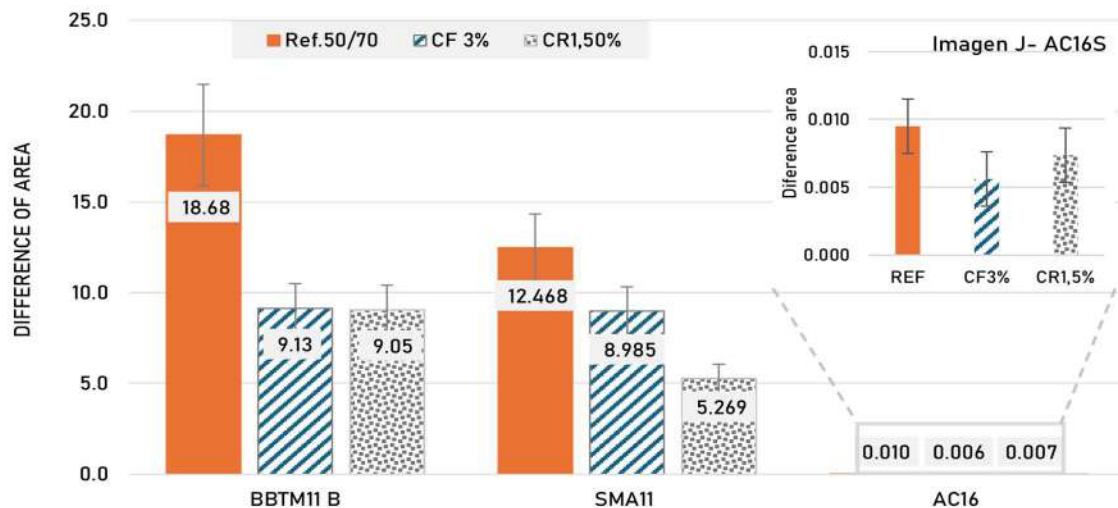


Figure 4.56: Effect of carbon fiber large and crumb rubber by ImageJ.

The correlations observed in terms of the areas of interest align with the findings observed by the T2R equipment, as depicted in Figure 4.57. Concerning the resistance to degradation by T2R, it is evident that BBTM mixtures exhibit the highest losses, SMA demonstrates an intermediate level of loss, and AC displays the lowest loss. These measurements are determined by the differences in areas of interest as assessed through ImageJ. The coefficient of correlations reveals robust values, with coefficients in the range of $R^2 = 0.92-0.96$. This indicates a strong

correlation between the variables under consideration, signifying a high degree of association between the measured quantities.

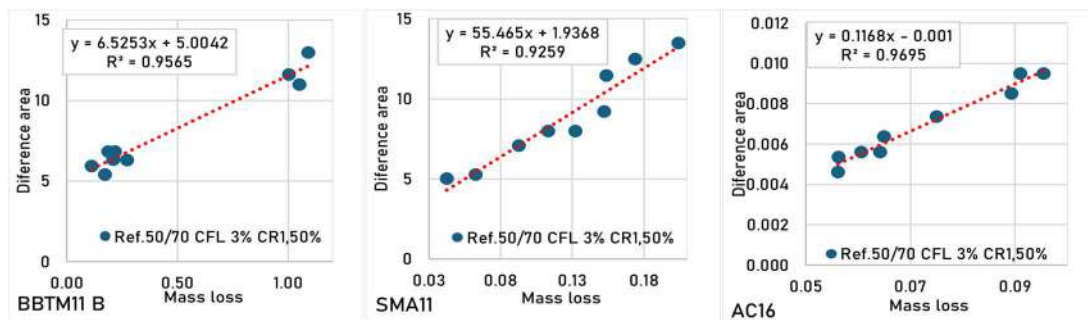


Figure 4.57: Correlation between result by ImageJ and T2R.

4.3.5.3. Effect of additives on the cohesion Test

Figure 4.58 shows the result of the cohesion characterization revealing distinctive response behaviors at different temperatures. In particular, reference binders 50/70 additives with fine carbon fiber (CF ϕ), exhibit an increased cohesion. Notably, the addition of large carbon fiber (CFL) particles significantly enhances the maximum cohesion, while CR also demonstrates elevated cohesion values. This phenomenon is likely attributable to the higher modulus of carbon fiber and the elastic component present in the CR structure.

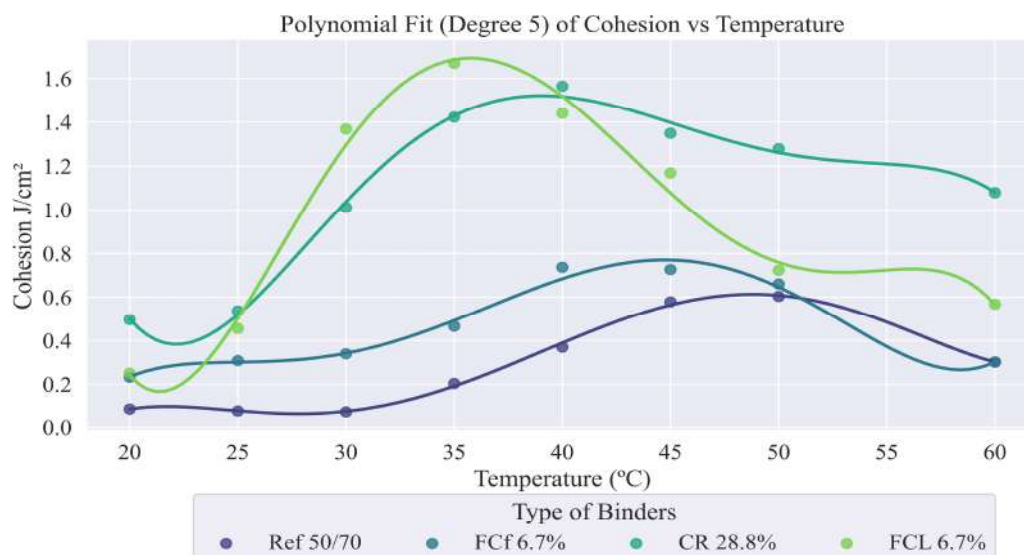


Figure 4.58: Cohesion characterization of binders.

A closer look at Table 4.20 also shows characteristics of maximum cohesion at different temperatures.

Table 4.20: Characteristics of cohesion test of binders

Asphalt binders	Maximum Cohésion J/cm² (EN13588)	Temp °C	Penetration test EN 1426 (1/1 mm) at 25°C
Ref 50/70	0.6	50	63.6
FCf 6.7%	0.74	40	50.1
CR 28.8 %	1.56	40	18.9
FCL 6.7%	1.67	35	16.2

The low temperatures on asphalt binders cause them to become stiffer and more brittle, leading to increased susceptibility, to cracking and a transition to a brittle state, increasing the risk of cracking in the pavement. Research has shown that this brittle behavior at low temperatures increases susceptibility to load fracture and thermal changes, leading to cracking (Wang et al., 2017).

The effect of the additives on the maximum cohesion is shown in Figure 4.59. Remarkably, both CR and CFL have significantly higher values of cohesion than the reference binder 50/70 at 20°C and 25°C. This is relevant considering that asphalt mixtures tend to crack at this temperature and lower ones, indicating excellent performance at intermediate temperatures.

CR and CFL binders show the greatest cohesion at 30 °C and 40 °C. Physically, this can be explained by the fact that the binder shows increased flexibility under the influence of heat, which is due to the elastic component of CR and the fiber network by CFL. This improvement in maximum cohesion is significant and persists at higher only by CR at 50 °C and 60 °C, with cohesion being three times higher compared to reference binders of 50/70.

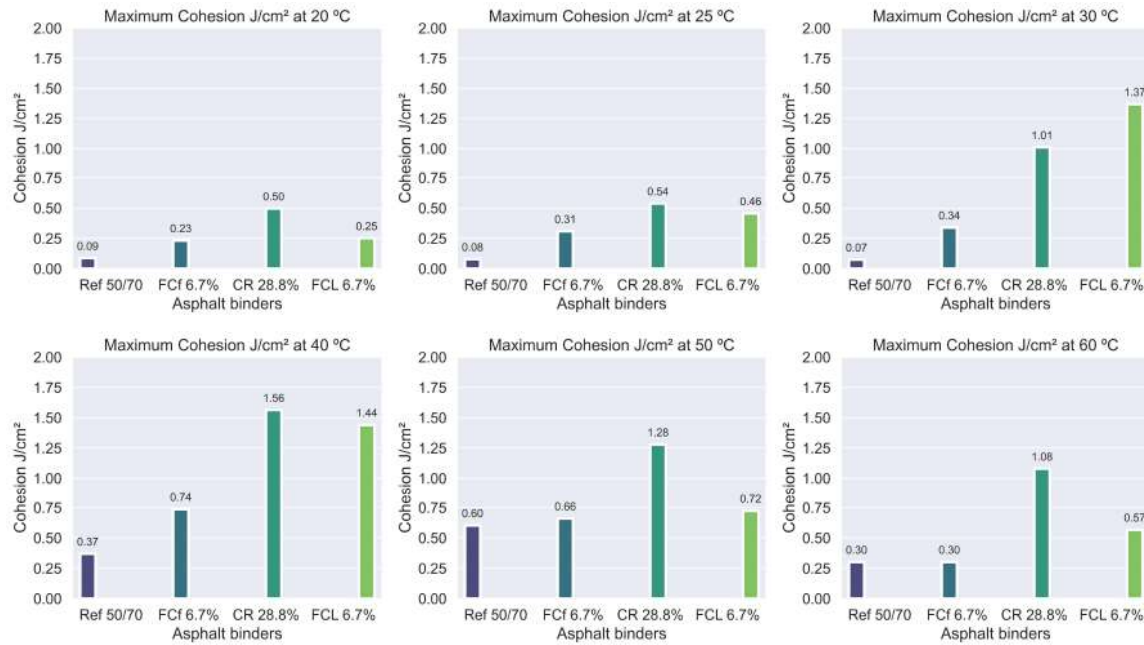


Figure 4.59: Effect of the temperature on the maximum cohesion.

The maximum cohesion is plotted as a function of temperature, considering the physical behavior of the binder. Maximum cohesion is critical not only at low temperatures but also at high temperatures as it reflects the performance of the binder under changing environmental conditions. Road surfaces are exposed to temperature fluctuations during their lifetime, with morning temperatures often ranging from 10 to 20 degrees Celsius and maximum temperatures reaching up to 60 degrees Celsius in the afternoon in warm climates.

Figure 4.60 shows that the cohesion of CR binders consistently has a higher maximum cohesion compared to other binders, particularly in the temperature range between 40 °C and 60 °C. This suggests that the CR binder exhibits improved cohesion across a wider range of high temperatures, making it particularly noteworthy for pavement applications exposed to varying thermal conditions. A remarkable point has been observed that the CR controls the susceptibility to temperature changes better than the reference binder.

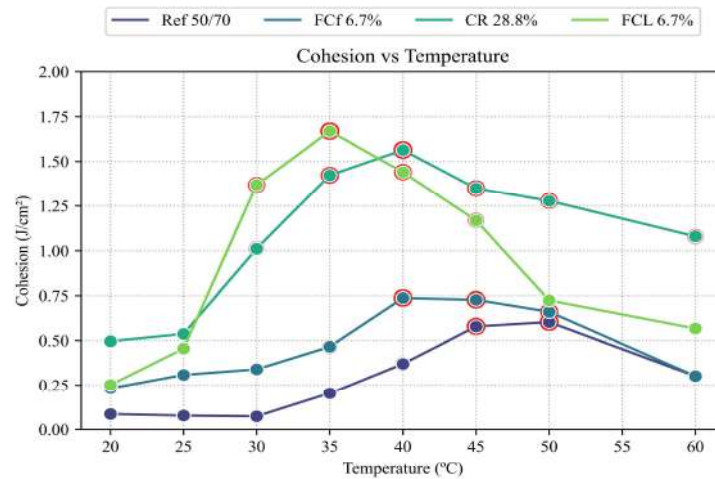


Figure 4.60: Effect of CR on the behavior of maximum cohesion binders at high temperature.

Figure 4.61 provides information on the difference in the central trend between median cohesion values and as well as the ranking based on statistics of the binders. The reference binders present a difference of 0.3 (J/cm²), CFf has a difference of 0.4 (J/cm²), CFL has a difference of 0.9 (J/cm²) and CR has strikingly high values with a median cohesion difference of 1.2 J/cm² as shown in Figure 4.61a. This is due to the crumb rubber. A thicker rubber bitumen mastic had formed around the particles, reinforcing their cohesion. The fiber and bitumen specimens show a higher cohesion capacity than the base binders, probably due to the network of fibers, especially large fibers CFL.

This result is significant as it emphasizes the substantial increase in cohesion attributable to the presence of CR. Figure 4.61b, shows the ranking of the higher cohesion values provided by CR, that indicates a superior ability to resist internal forces and maintain the integrity of the binder, highlighting its effectiveness in improving the overall cohesion of the asphalt mixture.

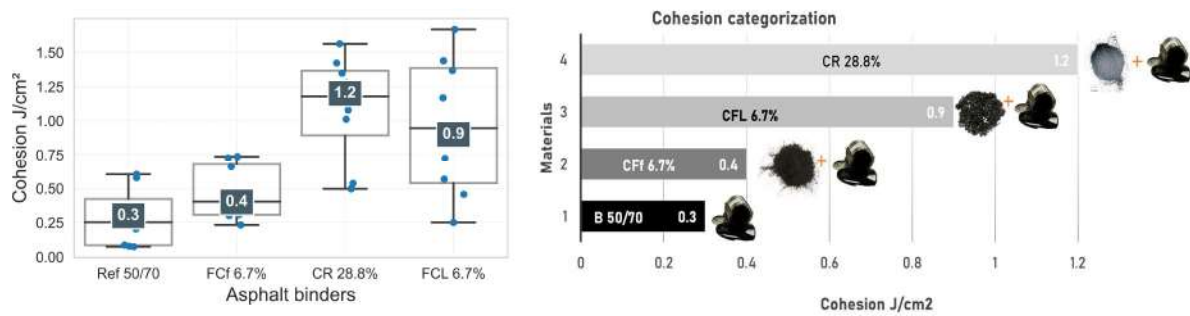


Figure 4.61: Comparison of cohesion test and ranking of additives.

Figure 4.62 shows the maximum cohesion of binders. This is a remarkable result of the CR and CFL with high differences at 40 °C and 35 °C, (1.56 -167 J/cm² energy cohesion respectively). In comparison, the reference binders 50/70 and CFF at 40 °C - 50 °C showed lower values (0.74 and 0.60 J/cm² energy cohesion respectively).

The minimum cohesion is observed for each binder at different temperatures. The CR presents a high difference at 20 °C (0.50 J/cm²), compared to CFL and CFF at 23-25 °C (0.23-0.25 J/cm²), and the reference binders 50/70 at 30 °C (0.07 J/cm²). It is noteworthy that CR consistently exhibited higher cohesion at both thermal conditions.

On the other hand, at temperatures below 20 °C, asphalt mixtures tend to become more rigid and less flexible. This can make the pavement more prone to fracture, as it loses its ability to deform and absorb stress caused by vehicular loads and thermal changes. Unfortunately the equipment at the laboratory did not allowed us to perform test at temperature lower than 20°C, although it would be very interesting to characterize of binder under study at low service temperature.

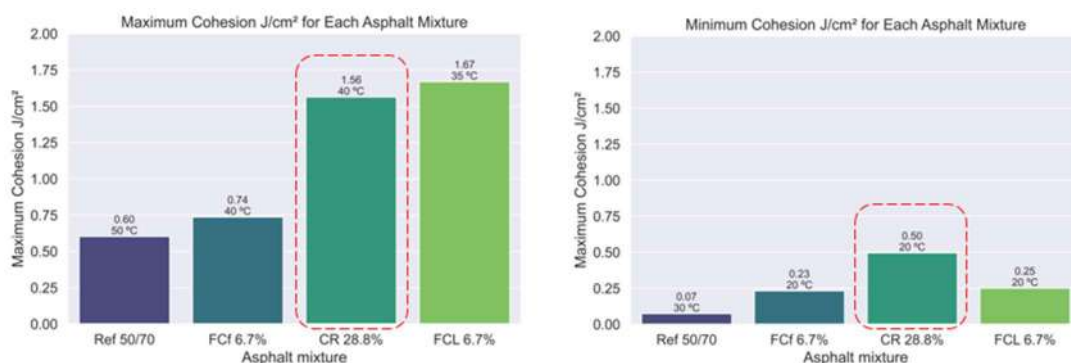


Figure 4.62: Temperature for the maximum and minimum cohesion of binders.

Figure 4.63 shows the effect of the additives on the maximum and minimum cohesion, when compared with the reference binder. The maximum behavior of the CR presents a 160% increase and CFL 178.33 %. Furthermore, in the minimum cohesion, CR showed a 471.38% increased, and the CFL presented an increasing of 189.30%. In-depth, CR provides elastic components and allows the binder to be more resistant to intermediate temperatures compared to CFL and reference binders. It could be attributed to CR providing greater resistance to fracture with higher cohesion in high and medium temperatures.

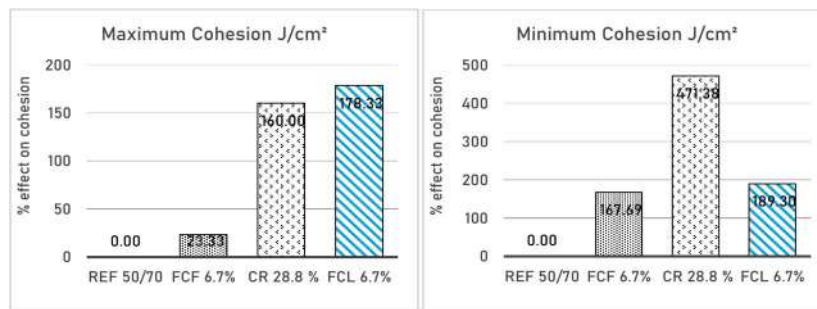


Figure 4.63: The effect of additives on maximum and minimum cohesion.

4.4. Acoustic characterization

4.4.1. Sound absorption characterization

The results obtained with the impedance tube at 20°C are shown in Figure 4.64. In this case, the use of CR by the DP was crucial to evaluate the basic properties of the asphalt specimens, as explained in section 4.2.1. The study focused on sound absorption properties and evaluated the acoustic contribution of CR to acoustic properties. A total of 90 specimens (5 mixtures x 3 crumb rubber contents x 6 specimens) were produced and tested in this section 4.4.1.

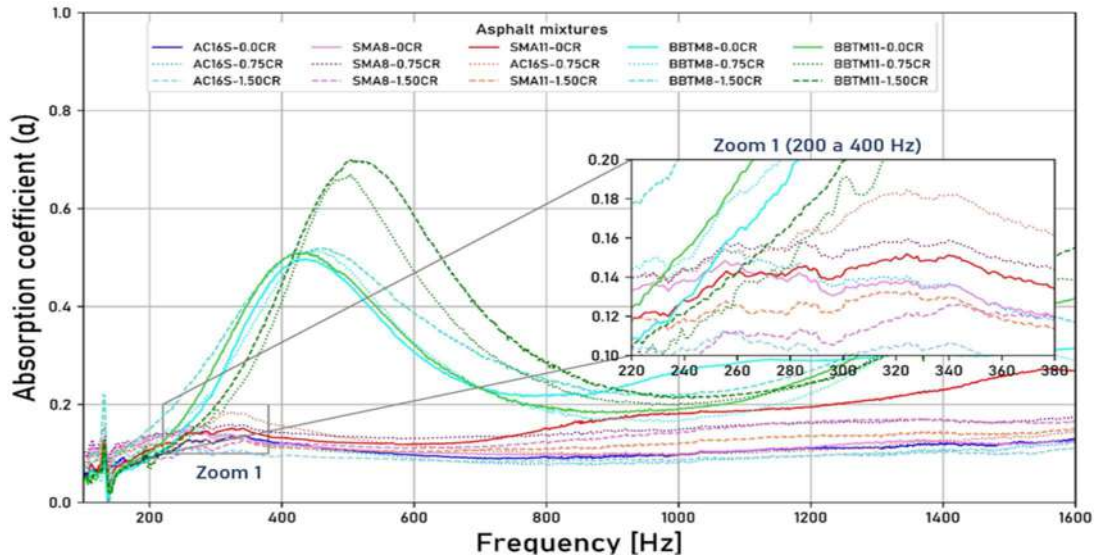


Figure 4.64: Sound absorption spectra of asphalt mixtures.

The acoustic absorption spectrum of AC, SMA, and BBTM asphalt mixtures with 0.0 % (reference), 0.75 % and 1.50 % CR were determined. The average of six specimens was recorded to show the average spectrum of the asphalt mixtures at each frequency. The measurement spectra are displayed between 100 Hz and 1600 Hz. Initially, there is a slight difference in sound absorption between the asphalt specimens, with the spectra differences increasing until the maximum absorption coefficient is reached.

Based on the outcomes, the AC 16 S, SMA 8, SMA 11, BBTM 8 B, and BBTM 11 B compositions demonstrated different acoustic responses (α) across the percentage of sound absorption, as illustrated in Figure 4.65. The small effect of the CR in terms of the acoustic properties can be observed as well. The frequencies corresponding to the attainment of the highest absorption peaks are detailed in Table 4.21.

Table 4.21: Peak absorption coefficient from the absorption spectra in the frequency domain.

Asphalt Mixtures	CR content (%)	Max. Peak (α)	Std. Dev.	Frequency [Hz]
AC 16 S	0.00	0.13	0.008	276-278
	0.75	0.16	0.018	240-250
	1.50	0.15	0.014	175-245
SMA 8	0.00	0.16	0.007	265-265
	0.75	0.14	0.031	180-275
	1.50	0.14	0.032	320-450
SMA 11	0.00	0.16	0.009	305-375
	0.75	0.19	0.021	320-370
	1.50	0.14	0.020	250-265
BBTM 8 B	0.00	0.51	0.014	440-455
	0.75	0.59	0.010	435-465
	1.50	0.51	0.003	490-520
BBTM 11 B	0.00	0.60	0.021	505-540
	0.75	0.69	0.016	610-645
	1.50	0.71	0.020	570-605

Std. Dev: Standard Deviation, CR: Crumb Rubber.

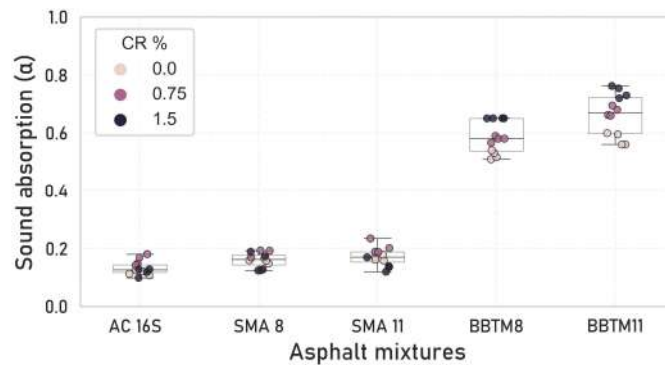


Figure 4.65: Categorization of the sound absorption of asphalt mixtures.

Table 4.22 shows the results of the one-way ANCOVA, showing the possible effects of the CR content, type of asphalt mixture, air void content (V_a), and the type of asphalt mixture, on the maximum absorption coefficient (α).

Table 4.22: Result of the ANCOVA analysis of the factor CR content.

Variable	Coefficient	Standard error	t	p-value > t	[0,025	0,095]
Intercept	0.0569 ^a	0.092	-0.617	0.539	-0.241	0.127
Mixture[T.BBTM11]	-0.0569	0.241	-0.791	0.431	-0.670	0.289
Mixture[T.BBTM8]	-0.1904	0.213	-0.121	0.904	-0.449	0.398
Mixture[T.SMA11]	-0.0257	0.049	1.687	0.096	-0.015	0.181
Mixture[T.SMA8]	0.0019	0.039	0.049	0.961	-0.076	0.080
CR	-0.0393	0.033	-1.183	0.240	-0.105	0.027
CR:mixture[T.BBTM11]	0.0839	0.043	1.946	0.055	-0.002	0.170
CR:mixture[T.BBTM 8]	-0.0154	0.040	-0.381	0.070	-0.096	0.065
CR:mixture[T.SMA 11]	-0.0226	0.044	-0.511	0.611	-0.111	0.065
CR:mixture[T.SMA 8]	0.0036	0.041	0.088	0.930	-0.077	0.084
Va	0.0373	0.018	2.116	0.038	0.002	0.072

^a R² = 0.863 (Adjusted R² = 0.864), F-statistic = 49.82, p-value = < 0.001. No observations = 90, Df residual = 79.

Df Model = 10, t : Test student, F: fisher ratio, p-value: probability value.

The overall performance of the ANCOVA is significance, $F = 49.82$, $p\text{-value} < 0.001$, mean that the model explains a substantial portion of the variability in the dependent variable compared to the intercepted-only model. The model had a coefficient of determination of $R^2 = 0.863$ and adjusted $R^2 = 0.864$, showing robust performance.

The result of the models showed that the only factor affecting the sound absorption was air voids, $t = 2.116$, $p\text{-value} < 0.038$, while other factors, such as CR content, mixture and the interaction between CR content and mixture, were not significant.

To better clarify this concept, Figure 4.66 illustrates the influence of crumb rubber (CR) on the maximum absorption coefficient of the asphalt mixtures investigated. It can be observed that the use of CR in asphalt mixtures does not have a direct effect on sound absorption, as this phenomenon can be rather related to the internal structure of the mixture, void and interconnected voids and channels.

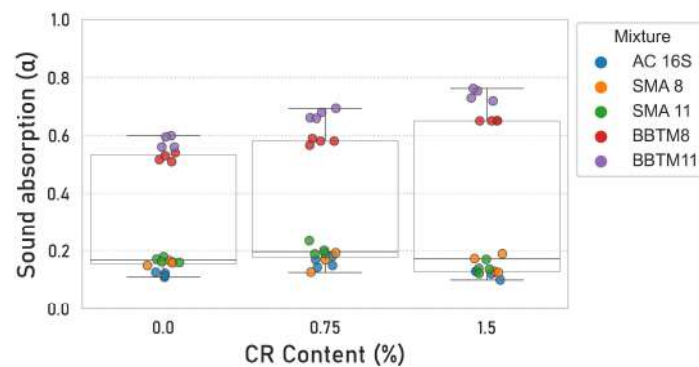


Figure 4.66: Effect of crumb rubber on sound absorption.

Figure 4.67 shows the effect of mixtures on the sound absorption. Despite evident differences can be observed between BBTM (8 and 11), mixtures and against the other mixtures, the statistical analysis revealed that the factor affecting the sound absorption is not the type of mixture but instead the air void (V_a), AC and SMA mixtures showed lower sound absorption. This is due to the fact that these are dense mixtures with low void content (between 5 and 7%), that prevent the entrance of sound waves into the mixture.

On the other hand, BBTM mixtures revealed the best sound absorption properties. This is probably due to their high air void content. Noise is incident through their high negative texture and the air voids so that noise is attenuated within the interconnected air channels. Other researchers have also confirmed this evolution of the sound absorption coefficient and have related it directly to the air void content (Alber et al., 2018; Alauddin Ahammed and Tighe, 2011).

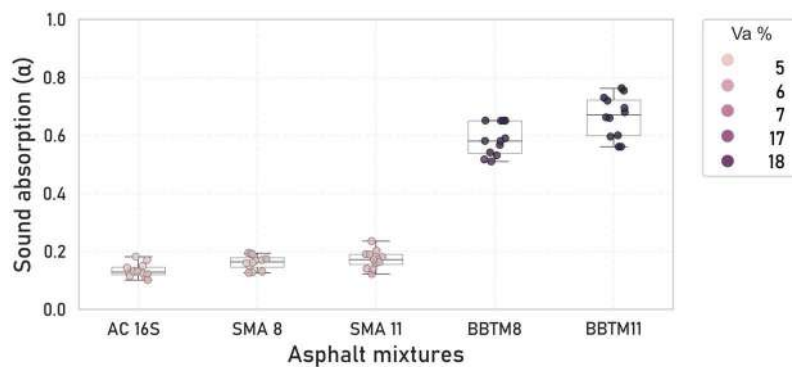


Figure 4.67: Effect of the sound absorption on type of mixture.

4.4.2. Predicting the sound absorption coefficient

Figure 4.68 A linear regression analyses carried out to model the maximum sound absorption coefficient (α) as a function of the volumetric and surface properties of asphalt mixtures, (air void content (V_a), apparent density (G_{mb}), permeability (K_v), Mean Texture Depth (MTD), and Mean Profile Depth (MPD)). This assessment was conducted in the frequency range between 100 and 1600 Hz, concerning all the asphalt mixtures under study.

Figure 4.68a shows the relationship between V_a and the maximum sound absorption coefficient (α vs. V_a), presenting a strong correlation $R^2 = 0.94$. Therefore, the coefficient indicates that for each unit increase in the percentage of air void content the maximum sound absorption increases by 0.04. (slope of the linear approach).

The relationship between bulk density (G_{mb}), and the maximum coefficient of sound absorption, is shown in Figure 4.68b (α vs. G_{mb}). The fitting between maximum sound absorption coefficient and bulk density strongly correlates with $R^2 = 0.91$, implying a strong relationship. Furthermore, it means that as the maximum coefficient absorption decreases, G_{mb} increases (negative slope = -1.11). However, the bulk density of the asphalt mixtures is directly involved in the calculation of the air void content and is negatively correlated with (α).

The relation between the maximum sound absorption test and permeability (K_v) is presented in Figure 4.68c (α vs. K_v). The mixtures with higher void content show effective communication between internal air voids, as verified by the drainage tests. The coefficient of determination $R^2 = 0.91$, indicates a positive trend of α as a function of K_v . The prediction equation explains that for each unit increase in K_v (m/s), the maximum coefficient absorption is expected to increase by 0.17. The intercommunication of pores through the tunnels allows a good absorption process.

The air void content (V_a), theoretical maximum density (G_{mm}), and bulk density (G_{mb}) are related by Equation 1 of section 4.1, so they are expected to have a similar relationship with sound absorption. On the other hand, G_{mm} and G_{mb} depend on the specific weight of the aggregates, which varies from project to project. This is, voids represent the most realistic internal volumetric characteristics of asphalt mixtures and allow for more realistic comparisons between different projects. Therefore, V_a would, in principle, be more suitable for fitting in prediction models than the G_{mm} and G_{mb} parameters.

Figure 4.68 d shows that the addition of CR has a correlation coefficient $R^2 = 0.002$, which means that the presence of rubber does not have an influence on sound absorption.

However, the type of granulometry composition of the bituminous mixtures defines the mean profile depth (MPD) and mean texture depth (MTD) of the surface. The influence on the sound absorption is shown in Figure 4.68e (α vs. MTD) which shows that the MTD presents a strong correlation ($R^2 = 0.84$), meaning that MTD increase leads to an increase in α by 0.25. On the other hand, the model in Figure 4.68f (α vs. MPD) shows a moderate to slightly positive correlation between the MPD and α , with an $R^2 = 0.50$, and according to the regression Equation, it is explained that for every unit (in mm) increase in MPD, the maximum absorption peak increase by 0.63.

Therefore, the average depth of the texture MTD seems to have an important effect on the maximum coefficient of sound absorption, while in the case of the mean profile depth MPD, it has a moderate to low influence on the maximum sound absorption coefficient. Both tests show a positive correlation. Distinct levels of texture depth could be related to the maximum peak sound absorption since the determination of the MTD is volumetric (3D) while the MPD is in profile (2D).

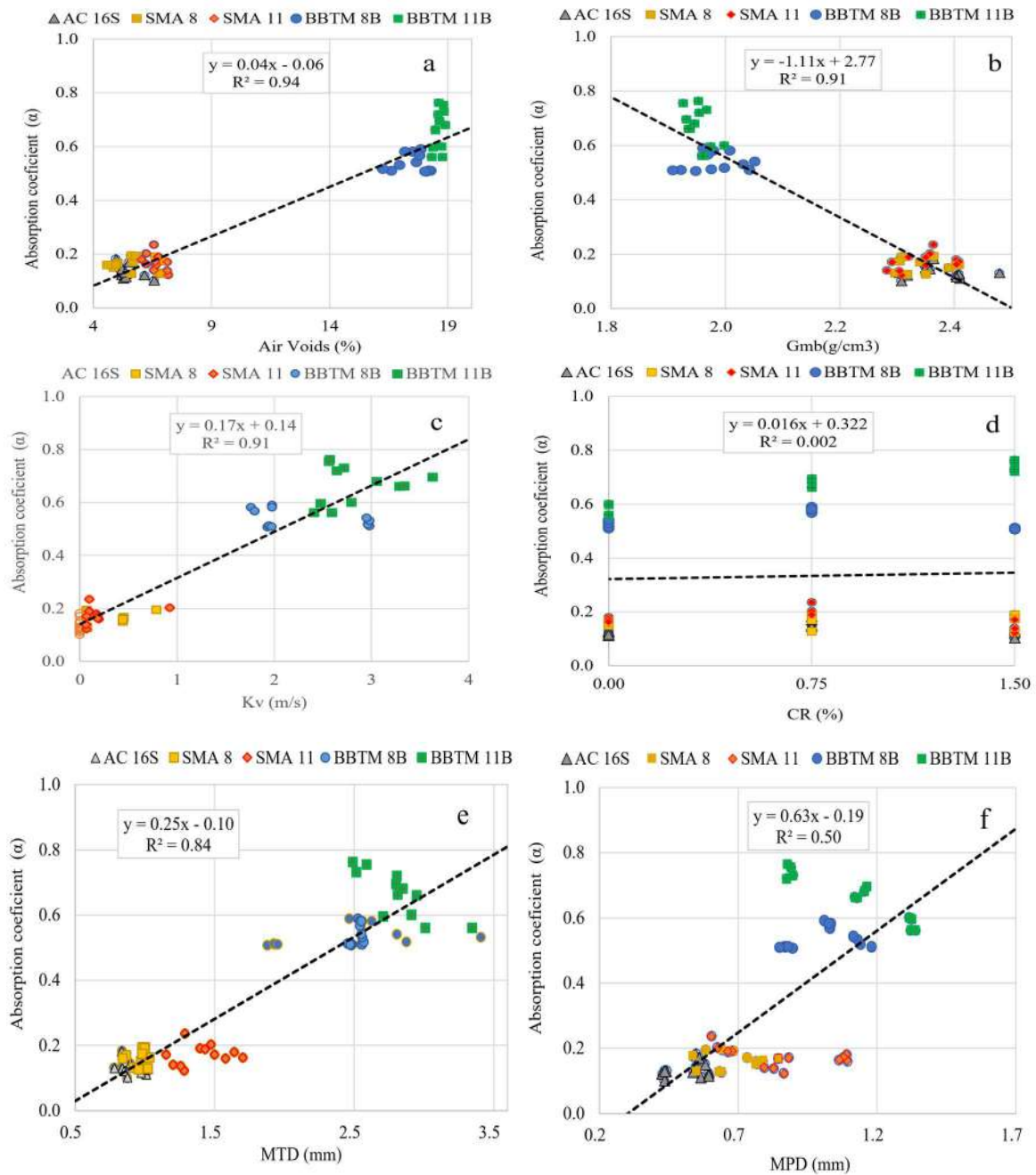


Figure 4.68: Overall correlation model a) α vs. Va, b) α vs. Gmb, c) α vs. Kv, d) α vs. CR, e) α vs. MTD, f) α vs. MPD.

Figure 4.69 shows the correlation values of the volumetric, and texture parameters, and CR content versus the sound absorption coefficient. The highest R^2 values are presented by the relationship (α , V_a). It is true that G_{mb} , K_v , and MTD also present high R^2 coefficients with absorption.

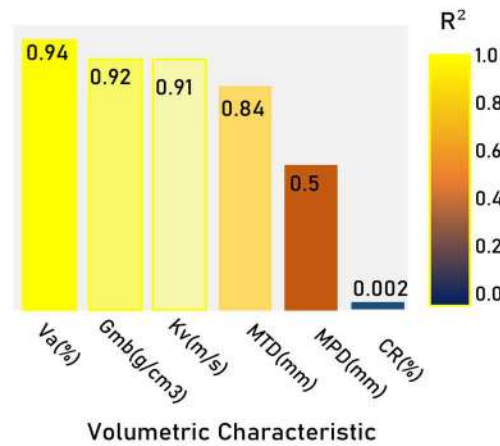


Figure 4.69: Comparison of R^2 coefficient for different variables influencing the acoustic absorption of the mixture.

However, all of them are strongly related to V_a and, therefore, the most simplified and direct expression is the one relating V_a to absorption. This confirms the idea that the sound absorption response of asphalt mixtures is mainly related to the air void content (Alber et al., 2018). Increasing the air voids (%) of the mixture allows for an increase in the maximum peak of sound absorption coefficient (α) (Figure 4.70). The best regression model can be expressed as follows:

$$\text{Sound absorption coefficient } (\alpha) = 0.038 \cdot V_a - 0.075 \quad R^2 = 0.95 \quad \text{Equation 33}$$

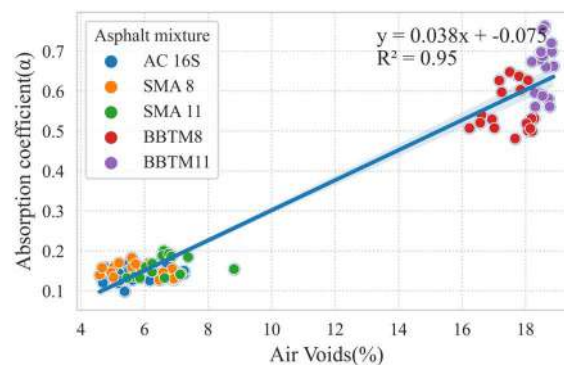
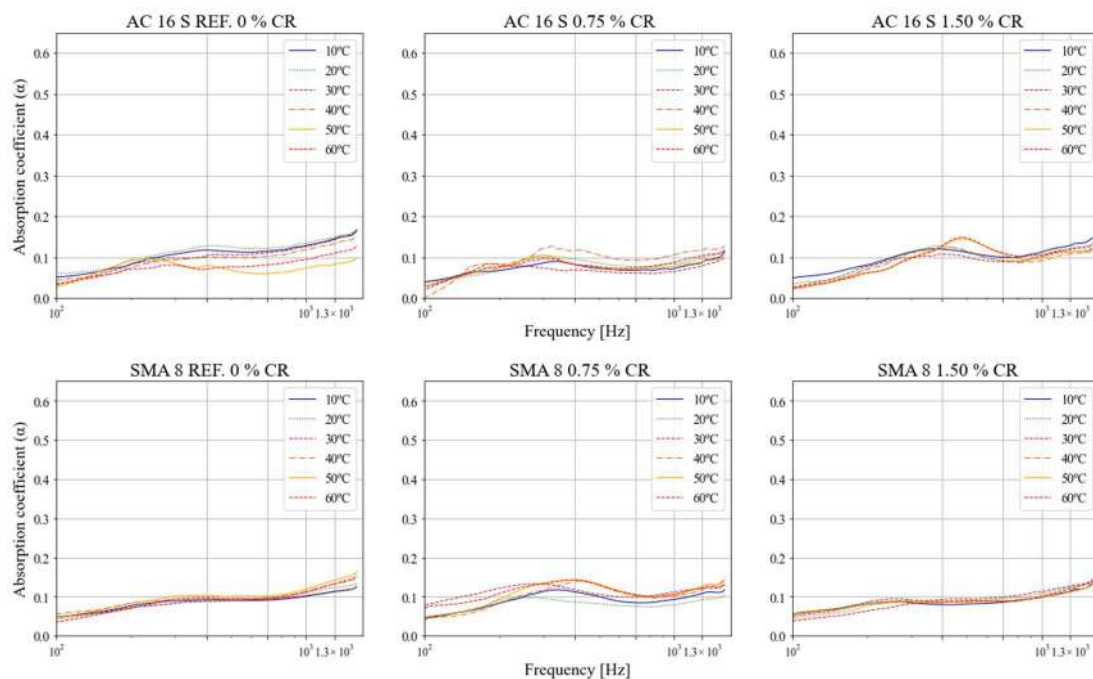


Figure 4.70: Model prediction of sound absorption

4.4.3. Effect of temperature on acoustic absorption of asphalt mixtures with crumb rubber

Figure 4.71, shows that as the temperature increases, the levels of the maximum sound absorption coefficient also increase in the discontinuous BBTM mixtures. However, the changes in the maximum absorption coefficient in the dense AC mixtures due to the increasing effect of temperature are not so clear. Nor do the results obtained for the SMA mixtures show a differential behavior regulated by the effect of increasing temperature.

On the other hand, it is interesting to mention the behavior of the maximum sound absorption recorded in the BBTM mixtures, which show a positive behavior of the spectra and peaks of maximum sound absorption with slight improvements of the sound absorption at higher frequencies. However, it is necessary to conclude that for practical purposes the measurement temperature has little influence, except for the BBTM mixture, where at 60 ° C the sound absorption seems to be approximately 10 % higher than at 10 ° C. As for the influence of the CR content, it seems to have little influence on sound absorption at every temperature. The statistical significance of these variables will be analyzed in the following paragraphs.



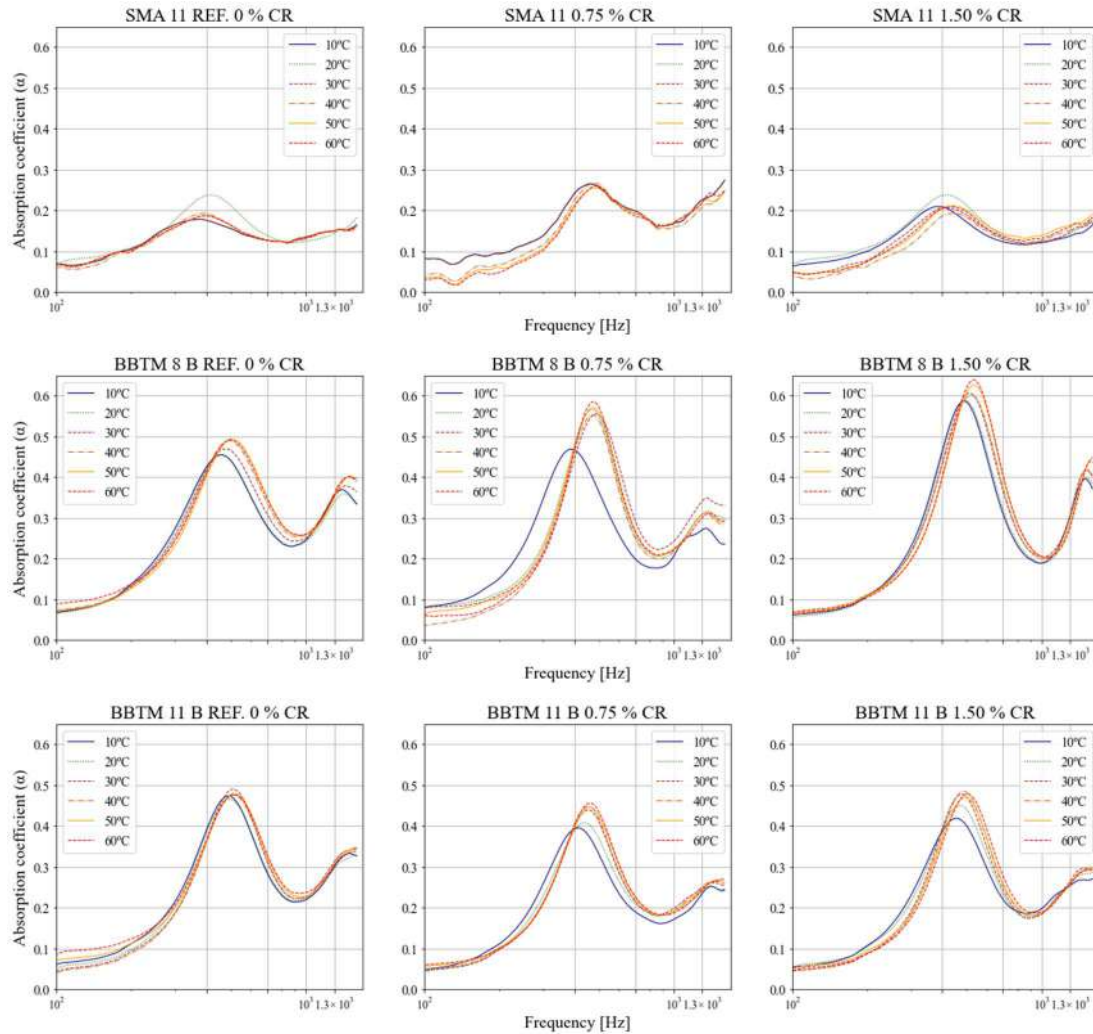


Figure 4.71: Sound absorption coefficient of the asphalt mixtures studied at different temperatures.

a) Analysis of the shape of the spectra of the sound absorption

The sound absorption results were obtained by using an impedance tube, and a thermostatic chamber to control the samples' temperature, as described in the methodology section 3.7.1.

The acoustic results were processed by Gaussian fitting (GF) for each sound absorption spectrum, discretizing them into Peak (P), Area Under the Curve (AUC), and BandWidth (BW). The methodological procedure was described in section 4.1.5. The results obtained were subjected to statistical analysis, which allowed the establishment of models that correlate the characteristics of asphalt mixtures and sound absorption. Model of the potential predictors (air void content V_a , absorption measurement temperature, and CR content), and the process were

iterated to obtain optimized models with statistically significant predictors. Table 4.23, Table 4.24, and Table 4.25 show the significance of all predictor variables used for the prediction models of P, AUC and WB. In the peak model it has been observed that the CR content and temperature variables do not show high significance, while, for the bandwidth and area under the curve models, only temperature does not show significance.

Table 4.23: Peak (P) model.

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	t	p-value	Lower bound	Upper bound
Intercept	-0.0301	0.028	1.055	0.292	-0.026	0.086
Air Voids (%)	0.0708	0.002	44.611	< 0.000	0.068	0.074
CR content (%)	-0.0061	0.015	-0.396	0.693	-0.036	0.024
Temperature (°C)	0.0005	0.001	0.919	0.358	-0.001	0.002
No. Observation	540					
R ²	0.788					
Adjusted R ²	0.787					

Degrees of freedom = 539, R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value

Table 4.24: Band Width (BW) model.

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	T	p-value	Lower bound	Upper bound
Intercept	416.770	11.341	36.748	< 0.000	394.495	439.053
Air Voids (%)	-10.650	0.811	-13.126	< 0.000	-12.242	-9.055
CR content (%)	79.450	7.864	10.103	< 0.000	64.004	94.900
Temperature (°C)	-0.352		-1.180	0.239	-0.941	0.235
No. Observation	540					
R ²	0.327					
Adjusted R ²	0.323					

Degrees of freedom = 539, R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value

Table 4.25: Area Under the Curve (AUC) model

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	T	p-value	Lower bound	Upper bound
Intercept	18.504	2.931	6.314	< 0.000	12.747	24.261
Air Voids (%)	8.157	0.210	38.907	< 0.000	7.745	8.569
CR content (%)	-5.921	2.032	-2.914	0.004	-9.913	-1.929
Temperature (°C)	0.1338	0.077	1.734	0.084	-0.018	0.285
No. Observation	540					
R ²	0.740					
Adjusted R ²	0.738					

Degrees of freedom = 539, R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value

Once the significant predictor variables have been determined (see section 2.4), the results of the optimized models for Peak (P), BandWidth (BW) and Area Under the Curve (AUC) based on the 540 data set (5 mixtures x 3 CR contents x 6 measurement temperatures x 6 specimens) were obtained and are shown in Tables 9, 10 and 11, respectively.

Table 4.26: Statistical parameters of the Peak model (P)

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	t	p-value	Lower bound	Upper bound
Intercept	0.0424	0.020	2.164	0.031	-0.004	0.081
Air Voids (%)	0.0708	0.002	44.720	< 0.001	0.068	0.074
No. Observation	540					
R2	0.788					
Adjusted R2	0.788					

R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value.

Table 4.27: Statistical parameters of the model BandWidth (BW)

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	t	p-value	Lower bound	Upper bound
Intercept	416.77	11.341	36.748	< 0.001	394.495	439.053
Air Voids (%)	-10.65	0.811	-13.126	< 0.001	-12.242	-9.055
CR content (%)	79.45	7.864	10.103	< 0.001	64.004	94.900
No. Observation	540					
R2	0.325					
Adjusted R2	0.322					

R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value.

Table 4.28: Statistical parameters of the Area Under the Curve (AUC) model

	Coefficients		Statistics		95% confidence interval for β	
	β	Standard Error	t	p-value	Lower bound	Upper bound
Intercept	18.504	2.931	6.314	< 0.001	12.747	24.261
Air Voids (%)	8.157	0.210	38.907	< 0.001	7.745	8.569
CR content (%)	-5.921	2.032	-2.914	0.004	-9.913	-1.929
No. Observation	540					
R2	0.738					
Adjusted R2	0.737					

R²: correlation coefficient, β : estimated correlations coefficients, t: t-student, p-value: Probability value.

In the Peak (P) model in Figure 4.26, the variables temperature and CR content were found to be non-significant and were therefore excluded from the prediction model (Equation 34). The model has a coefficient of determination $R^2 = 0.788$. The only significant variable was air voids content (V_a), and the coefficient is positive, meaning that an increase in air voids in the asphalt mixtures leads to a higher peak sound absorption (P). More specifically, each one-unit change in the air void content of the mixtures corresponds to an increase in peak (P) by a factor of 0.0708.

The fitted line and the relationship between air void content (V_a) and Gaussian peak (P) are shown in Figure 4.72, and the model can be expressed as Equation 34:

$$Peak(P) = 0.0424 + 0.0708 \cdot (V_a)$$

Equation 34

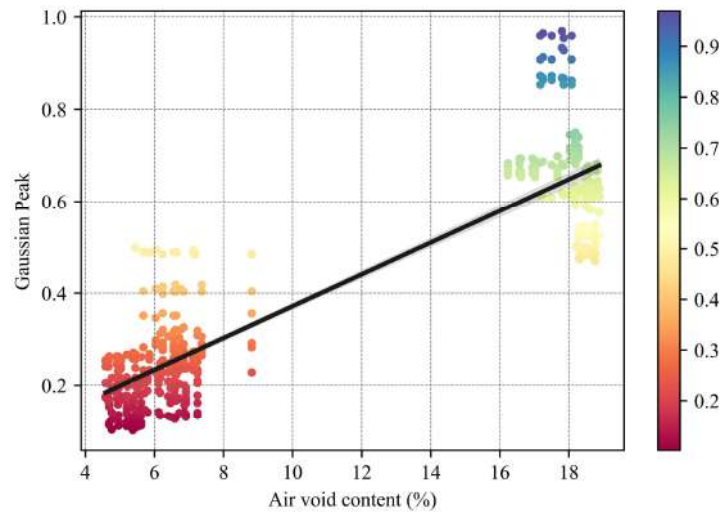


Figure 4.72: Linear correlation analysis of void content (V_a) and peak (P).

It should be noted that the model obtained is valid in the range of air void content considered in this study ($5 \% < V_a < 19 \%$).

In the BandWidth (WB) regression model, two significant variables were identified, V_a and CR content (%). On the other hand, the temperature of the mixtures was found to be non-significant as seen in Figure 4.73, and was therefore excluded from the prediction model (Equation 35). The coefficient of determination R^2 of the model was quite low, equal to 0.325, which means that the model can only explain 32.5 % of the WB variability. The sign of the air void content (V_a) was negative ($\beta = -10.648$), which means that an increase in air voids could produce a decrease in the Bandwidth (BW). In other words, a narrower bandwidth concentrates more sound energy absorption in the frequencies that are most easily attenuated in the network of tunnels formed by the interconnected voids.

On the other hand, the rubber content (CR) showed a positive coefficient, which means that the addition of CR tends to increase the WB. That is, it widens the range of frequencies that sound waves are absorbed by asphalt mixture. Since the coefficient is high ($\beta = 79.452$) the effect is noticeable despite the small range of variation in crumb rubber content.

Figure 4.73 shows a 3D visualization of the multiple regression model, for a better interpretation of the relationship between air voids, CR content, and WB. This model obtained falls within the limits of the void contents studied in this project ($5 \% < V_a < 19 \%$). This relationship can be expressed as:

$$\text{BandWidth}(WB) = 416.77 - 10.648 \cdot V_a(\%) + 79.452 \cdot CR\text{content}(\%) \quad \text{Equation 35}$$

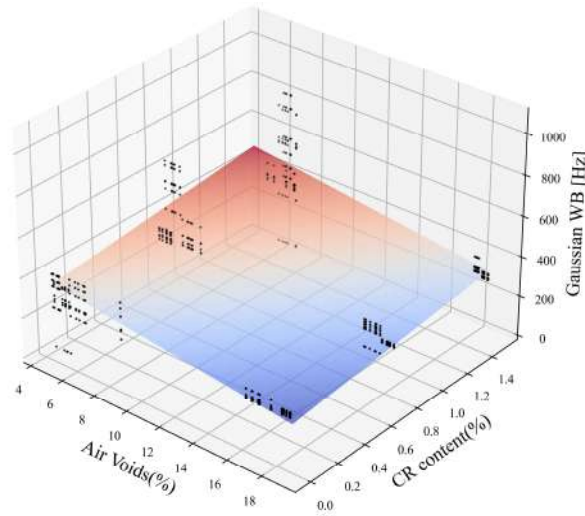


Figure 4.73: Multiple linear correlation analysis of void content and, CR content, to the bandwidth (WB) of absorption.

Finally, in the area under the curve (AUC) model, two significant variables, V_a and CR content, were found. Again, temperature appears not to affect the acoustic response of the asphalt mixture, is not significant, and is excluded from the prediction model (Equation 36). The coefficient of determination of the model was equal to $R^2 = 0.74$, representing a strong relationship between the predictors and the dependent variable AUC. The coefficient of the air void content (V_a) was positive, meaning that an increase in air voids in the mixture results in an increase in the AUC. Each one-unit change corresponds to an increase in AUC by a factor of 8.157 when the other predictor variable (CR content) is held constant. This was also confirmed in several studies, where the importance of the air void content and its influence on the sound absorption coefficient is highlighted (Sun et al., 2022).

On the other hand, CR content exhibited a negative coefficient, meaning that its effect is to reduce AUC (). This means that taking into account a wide range of frequency, the rubber makes the mixture to absorb less sound in all Figure 4.74 shows the combined effect of air void content V_a and CR content on the AUC. The model, neglecting, the non-significance influence of temperature can be expressed as:

$$\text{Area Under Curve}(AUC) = 18.504 + 8.157 \cdot V_a(\%) - 5.921 \cdot CR\text{content}(\%) \quad \text{Equation 36}$$

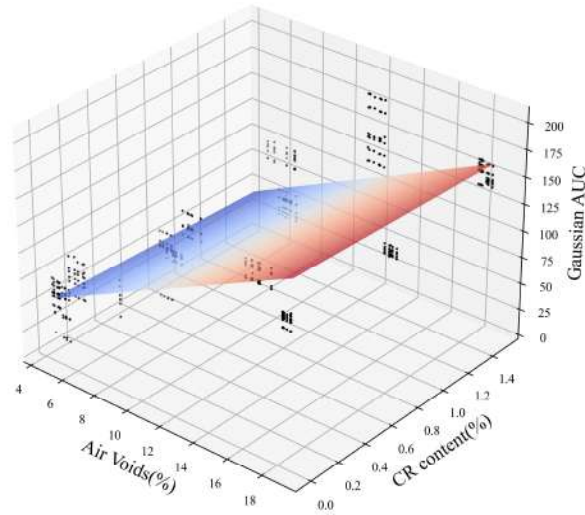


Figure 4.74: Multiple linear correlations between void content, CR content, and area under the AUC.

The best correlations between the different volumetric properties and the Gaussian fitting parameters of the sound absorption have been obtained using the peak (P) and area under the curve (AUC) models. The developed models showed a coefficient of determination $R^2 = 0.788$, and $R^2 = 0.738$ respectively, and relate the void content (Va) to the peak P and the area under the curve AUC.

4.4.4. Dynamic stiffness characterization

The main results of dynamic stiffness are shown in Table 4.29. The addition of CR produces a reduction in the dynamic stiffness (Ds) of the asphalt mixtures. The greater the amount of CR, the greater the reduction (Ds) which is considered beneficial for noise reduction.

Table 4.29: Maximum values of the dynamic stiffness, coherence, and angle phase at 100, 400, and 1000 Hz of the dynamic stiffness spectra.

Asphalt Mixture (CR)	(Ds at 100Hz) (MN/m)	(Ds at 400 Hz) (MN/m)	(Ds at 1000 Hz) (MN/m)	Coherence	Angle phase. (°)
AC16S (0.00)	18.775	27.367	31.997	1.00	180.00
AC16S (0.75)	12.758	15.481	18.278	1.00	180.00
AC16S (1.50)	9.575	14.438	15.737	0.99	179.99
SMA8 (0.00)	16.075	19.386	23.371	1.00	180.00
SMA8 (0.75)	16.025	18.736	22.169	1.00	180.00
SMA8 (1.50)	12.575	15.732	20.193	0.99	179.99
SMA11 (0.00)	15.675	22.701	30.755	1.00	180.00
SMA11 (0.75)	11.825	21.452	31.697	1.00	180.00
SMA11 (1.50)	8.774	20.049	28.317	1.00	179.99
BBTM8 (0.00)	6.935	26.305	48.500	1.00	180.00
BBTM8 (0.75)	5.265	15.826	28.500	1.00	180.00
BBTM8 (1.50)	4.825	12.823	15.649	0.99	179.99
BBTM11 (0.00)	9.325	13.268	17.820	1.00	180.00
BBTM11 (0.75)	7.315	10.413	13.549	1.00	179.97
BBTM11 (1.50)	4.215	6.011	12.324	0.99	179.99

Figure 4.75, shows the results of the dynamic spectra. There are differences between each type of mixture, with the reference AC16 S mixture exhibiting the highest dynamic stiffness. This is possibly due to the dense structure of the mixture, which contains voids in the range from 4 % to 6 %. In the case of the SMA 8 and SMA 11 mixtures, both show a lower Ds than the AC16 S mixture. This is probably due to the slightly increase of voids in the range between 4 % and 7 % Va. Finally, the mixtures with the lowest dynamic stiffness are BBTM 8 and BBTM 11. A notable difference is observed in comparison with the dense AC 16 mixtures, which is explained by the reduction of the fine fraction, which allows for obtaining higher voids in the range between 16 % and 18 % Va. These differences can also be seen in Table 4.29, which displays the average values for the comparison of dynamic stiffness for each mixture. Furthermore, the effect of crumb rubber on dynamic stiffness can be observed. This reduction effect is proportional to the increase of crumb rubber content, and it is a generalized behavior observed across all evaluated mixtures. The accuracy of these results was validated using the coherence parameter, which indicated values close to 1 for all results. Furthermore, the angular phase behavior of the spectrum exhibited exact values of 180 ° for the reference mixtures. However, the addition of 1.50 % CR showed a phase angle value of 179.99 °, which is very close to 180 °.

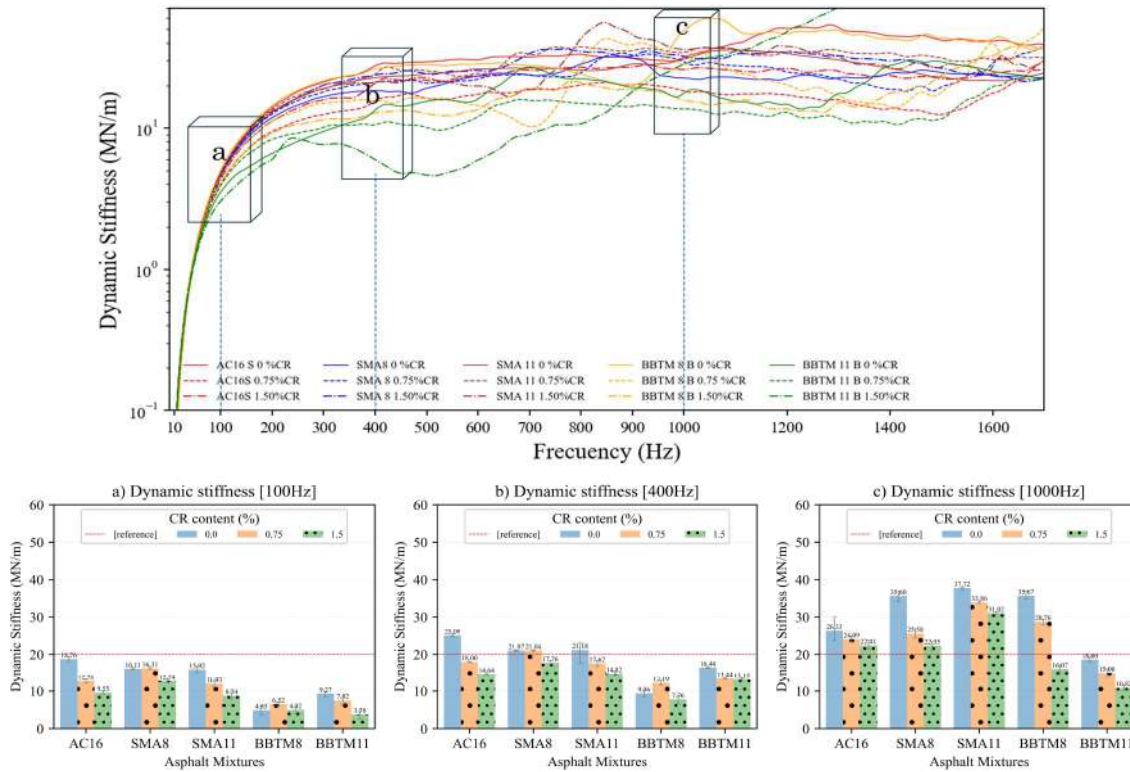


Figure 4.75: Dynamic stiffness of the bituminous mixtures studied.

Figure 4.76 represents the Ds behavior response after applied excitation force, the coherence, and the phase angle obtained. Each line represents the average result of the dynamic response of six specimens. The Ds generally decrease with the addition of the CR with the preload constant of 20 MPa. A similar trend of Ds, coherence, and phase angle behavior has been observed for all asphalt mixtures due to the effect of CR shown in Figure 4.76. This effect of CR has previously been observed in different asphalt mixtures (Vázquez & Paje, 2016b).

In terms of consistency and precision of the result, the coherence represents a relationship between applied force and the signal response that has been observed at values close to 1.0. The angle phase value of the different asphalt mixtures of AC, SMA, and BBTM with 0.0 (Reference), 0.75, and 1.50 % of CR was approximately 180° at 100 Hz of the Ds spectra. The average of six specimens has been taken and plotted as the average result of every study of the asphalt mixture types.

Comparing these results with those obtained by other authors with asphalt mixture specimens (Vázquez et al., 2020a, Pavoni Belli et al., 2003; Schiavi et al., 2005), similar values of dynamic stiffness Ds and reduction of the factor Ds' were obtained. Therefore, this confirms the assumption that the intrinsic stiffness

properties of asphalt mixtures are a reasonable approximation to force vibration and energy transmission in asphalt mixtures.

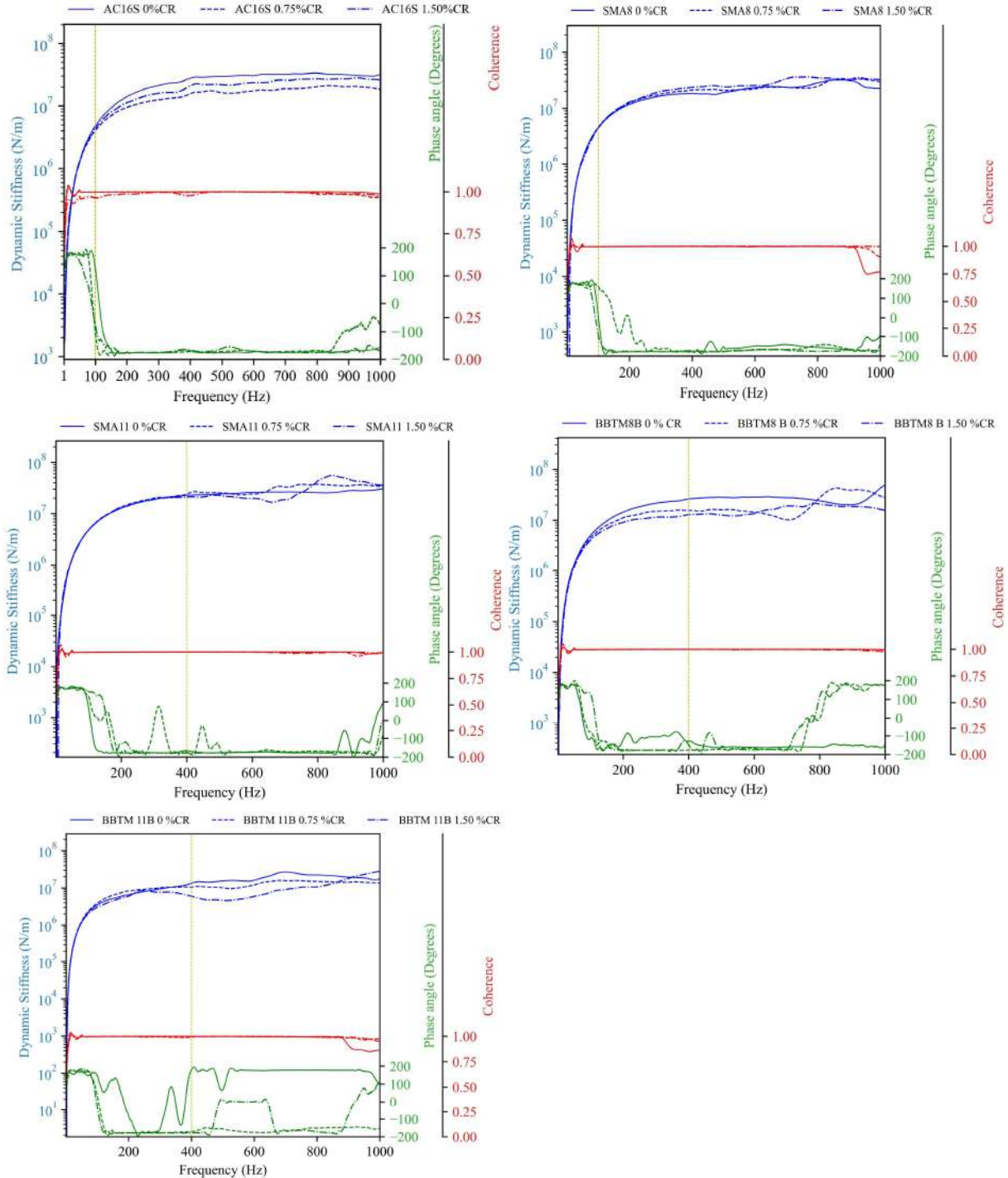


Figure 4.76: Dynamic stiffness, coherence, and phase angle spectra of asphalt mixtures
a) AC 16 S, b) SMA 8, c) SMA11, d)BBTM 8 B, and e)BBTM 11B.

The effect of the crumb rubber on the angle phase and coherence factors are interrelated parameters. Moreover, coherence results present the linear relationship between two signals (force and displacement) (H. Zhao et al., 2023).

Figure 4.77 exhibits a high level of coherence in their responses indicating a significant level of consistency and precision of the measurements and the dynamics stiffness test procedure. This high coherence is a favorable characteristic as it enhances the accuracy of Ds response. Moreover, the small differences in coherence, which hover around 0.99, among the asphalt mixtures with different CR percentages (0.0 %, 0.75 %, and 1.50 %), align with findings from other studies (Czech & Gardziejczyk, 2022). It is noteworthy that the trend for all CR additions is a slight decrease in coherence as expected, indicating consistent behavior in line with expectations.

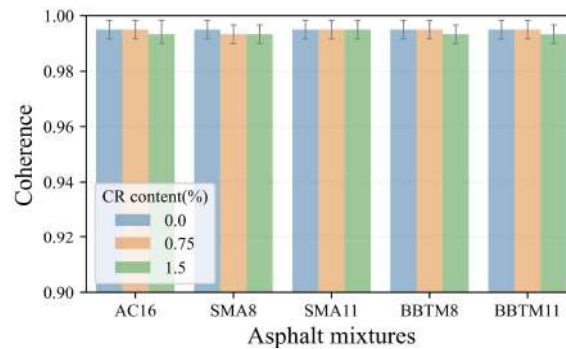


Figure 4.77: Coherence of measurement of the dynamic stiffness asphalt mixtures and with/without crumb rubber.

a) Influence of the volumetric properties on Dynamic stiffness

To determine the parameters that control noise generation by means of the dynamic stiffness Ds, a correlation analysis between the volumetric parameters of the asphalt mixes was carried out. To explore possible predictions models of dynamic stiffness as a dependent variable of various volumetric features in the context of pavement engineering. By considering volumetric parameters such as voids, densities, permeability, texture, and the content of CR. The application of this technique would allow a systematic evaluation of how different combinations of these features affect the dynamic stiffness of the pavement.

In summary, bulk density stands out as an indicator highly correlated with dynamic stiffness, providing a direct measure of mixture compactness. This relationship is in line with that observed in the work (Vázquez & Paje, 2016). In addition, volumetric characteristics such as void content and aggregate size, along

with mechanical properties such as dynamic modulus and indirect tensile strength, also play significant roles in influencing pavement dynamic stiffness. These findings offer valuable insight into the optimization and design of asphalt mixtures with specific dynamic stiffness properties.

In order to evaluate the relationship between the variables air void (Va), apparent density (Gmb), and dynamic stiffness (Ds), a preliminary comparison was conducted through the frequency span between 10 Hz to 900 Hz as shown in Figure 4.78. It has been observed that in both cases exists a specific range of frequencies that exhibit hard correlations between the dynamic stiffness and the Gmb, as well as between the dynamic stiffness and the Va. These findings indicate that the relationship not limited to a specific frequency range, but it extends to a wider spectrum. This highlights the need for comprehensive investigations through various frequencies to fully understand the correlation between apparent Gmb, Va and Ds in acoustics. First and foremost, this analysis revealed that frequencies associated with high Pearson linear correlations, in the range from $r = 80$ to $r = 90$ between the volumetric variables (Va and Gmb) and the dynamic stiffness (Ds), were located at frequencies f 70, f 80, f 90, f 100, f 200, f 300, and f 400. Based on these observations, and according to Figure 4.82 the frequency of 100 Hz has been selected as the optimum frequency for further detailed evaluation and statistical analysis in the subsequent sections of this study.

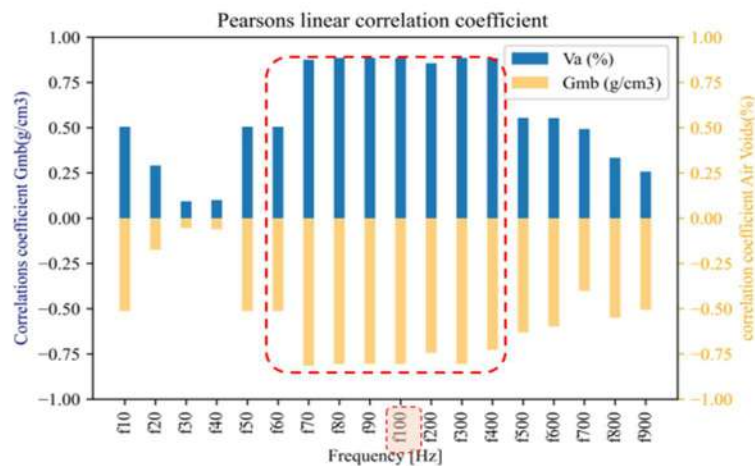


Figure 4.78: Correlation frequency of the volumetric properties with dynamics stiffness.

Figure 4.79a show a linear correlation between the air void content (Va) and the dynamic stiffness (Ds) with R^2 of -0.80. Similarly, Figure 4.79b shows a strong linear correlation between the apparent density (Gmb) and Ds with an R^2 of 0.89. The

robust negative correlation between V_a and D_s is attributed to the grading curve of aggregate, with different V_a values: between 4 – 6% V_a (for AC16 mixtures), less than 9% V_a for SMA 8 and SMA11 mixtures, and more than 16% -18% V_a for BBTM 8 and BBTM 11 mixtures. While the air void content could play a crucial role in the dynamic stiffness, other design features could also contribute to these results.

In addition, bulk density shows a positive linear correlation with dynamic stiffness at a frequency of 100 Hz, indicating a strong relationship between G_{mb} and D_s . The high R^2 coefficient of 0.89 indicates a high degree of correlation and emphasizes a strong relationship between the variables and their tendency to move in the same direction. These results are consistent in predicting the dynamic response and highlight the significant role of bulk density in the behavior of the different asphalt mixtures (Alber et al., 2018).

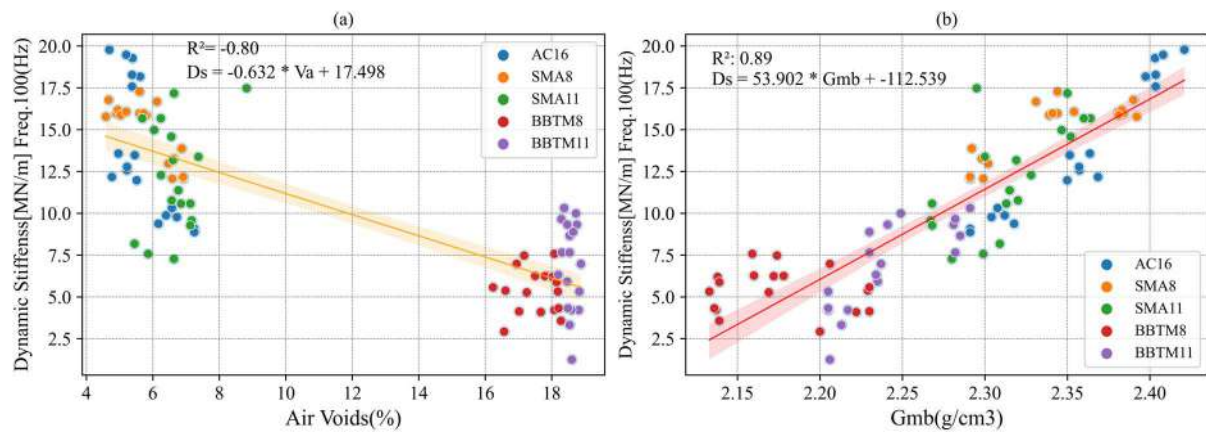


Figure 4.79: 3D Linear correlations analysis of dynamic stiffness at frequency 100 Hz, a) air void, and b) apparent density.

Table 4.30 provides the ANCOVA analysis, relative to the effect of CR content, type of mixture and air void content (V_a) on D_s .

Table 4.30: ANCOVA analysis

Variable	Coefficient	Standard error	t	p-value > t	[0,025	0,095]
intercept	22.0407 ^a	2.069	10.652.	<0.001	17.922	26.159
Mixture[T.BBMT11]	-15.0100	5.394	-2.783	<0.007	-25.992	-4.273
Mixture[T.BBMT8]	-19.6593	4.768	-4.123	<0.001	-29.151	-10.168
Mixture[T.SMA11]	-4.2451	1.102	-3.150	<0.001	-6.438	-2.052
Mixture[T.SMA8]	-2.7630	0.877	-9.995	0.002	-4.509	1.017
CR	-7.4364	0.744	-9.995	<0.001	-8.917	-5.956
CR:mixture[T.BBTM11]	5.1839	0.966	5.366	<0.001	3.261	7.107
CR:mixture[T.BBTM 8]	5.9429	0.904	6.577	<0.001	4.144	7.741
CR:mixture[T.SMA 11]	3.2307	0.991	3.259	0.002	1.258	5.204
CR:mixture[T.SMA 8]	4.6205	0.910	5.080	<0.001	2.810	6.431
V_a	0.4854	0.395	1.230	0.222	-0.300	1.271

^a $R^2 = 0.892$ (Adjusted $R^2 = 0.879$), F-statistic = 65.53, p-value = <0.001. t: Test student; F: fisher ratio, p-value: probability value.

The overall performance of the ANCOVA is significant, $F = 65.53$, p-value < 0.001, and the model had a coefficient of determination of $R^2 = 0.892$, and R^2 adjusted = 0.879, showing good performance.

The ANCOVA showed that the CR has a statistically significant impact on the dynamic stiffness, $t = -9.995$, p-value < 0.001. This difference is also observable in Table 4.30. The addition of CR tends to reduce the D_s , as observed in Figure 4.80.

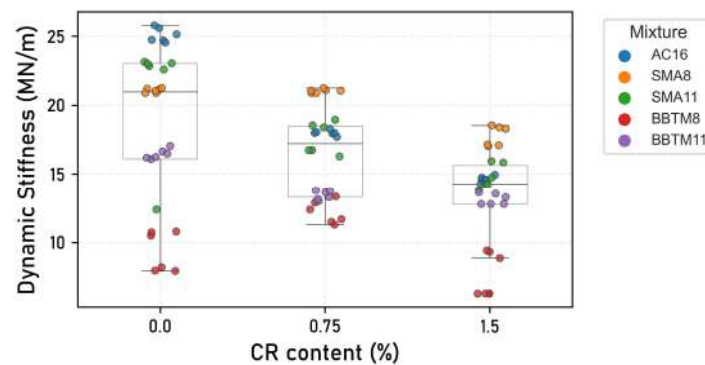


Figure 4.80: Effect of crumb rubber on the dynamic stiffness.

Based on these findings, a small content of CR on the asphalt mixtures may produce slight dynamic stiffness variations compared to the reference mixture without CR. This means that larger CR quantities are required to obtain greater D_s differences. With the addition of 1.50 % CR in the mixture, significant variations in the behavior of the dynamic stiffness can be observed. This is consistent with the results obtained by (Lee et al., 2013) and (Ucar & Basdogan, 2018) who reported that the higher the amount of CR added to the mixtures, the greater the difference in dynamic stiffness. This also agrees with other authors, who observed that the effect of CR in mixtures produces a significant decrease in dynamic stiffness in poroelastic mixtures (M. Li et al., 2016b).

The ANCOVA showed that the V_a has not a statistically significant impact on the dynamic stiffness, $t = -1.230$, p-value < 0.222.

The type of mixture was found to significantly affect dynamic stiffness. These differences are observable in Figure 4.81, where AC and SMA mixtures exhibited higher D_s , while BBTM mixtures, and in particular BBTM 8, showed the lower D_s values.

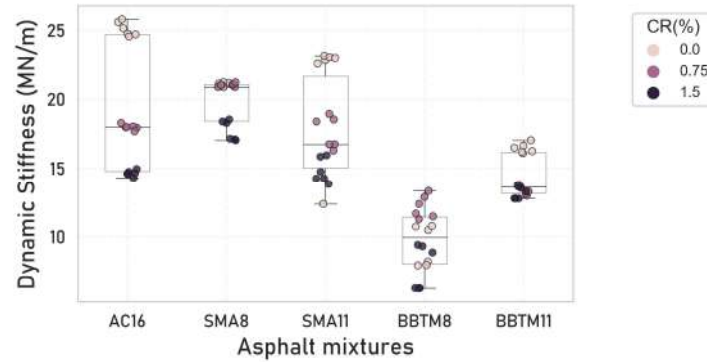


Figure 4.81: Effect of type of mixtures on the dynamic stiffness.

This behavior could be explained by the internal structure of each type of mixture. the AC mixtures are characterized by a dense structure, while the SMA 8 and SMA11 mixtures have a semi-dense structure. Therefore, a higher value of the dynamic stiffness is associated with a higher density in the asphalt mixture specimens. This densification in the asphalt structure can promote the efficient transfer of stresses and strains resulting in a more compact structure and higher dynamic stiffness response in dense mixtures.

In contrast, BBTM 8B and BBTM 11B mixtures exhibited lower dynamic stiffness values compared to AC and SMA mixtures. This is likely due to their lower density. A lower density had lower dynamic stiffness (Vázquez et al., 2020a; Vázquez & Paje, 2016). These investigations highlight the interaction between material density and, how density significantly affects dynamic stiffness (Ds).

Meanwhile, the reduced dynamic stiffness values observed from the BBTM 11 B with 3.776 (MN/m) could be justified for the apparent density (G_{mb}). Minor G_{mb} values lead to lower dynamic stiffness values as for the influence of CR when comparing the result for the reference specimens of mixtures. A lower density indicates a higher void content and a less solid structure, which can result in lower stress and strain transfer. Therefore, mixtures with a low G_{mb} will have lower Ds. In similar behavior, the AC mixture presents high values of G_{mb} and high values of Ds. As mentioned in section 2, the low dynamics stiffness response is beneficial, since the structure may dissipate tire/pavement vibration, and therefore, the noise generation (Sandberg, 1987, 2001; Ulf Sandberg, 1999).

One of the components that confer elasticity to rubber is butadiene, which transfers improved elasticity to the rheological properties of the pavement.

Figure 4.82 shows the effect of the CR on the asphalt mixtures. The mixtures SMA 8 and BBTM8 B do not present differences with 0.75 % of CR (regarding 0 % of CR), but with an addition of 1.50 % CR, these mixtures present low values of D_s . AC 16, SMA11, and BBTM11 B present a similar trend, with a reduction of D_s when the CR increases from 0 % to 1.50 %. This result could be explained since the CR has a low dynamic stiffness due to its ability to deform and recover its original shape under dynamic loads. The hyperelastic properties of rubber should be used in the reduction of the dynamic stiffness (Zhang & Markert, 2016) and improved by the addition of CR since the dynamic stiffness reduces as CR increases (Cong et al., 2013). It can be attributed to the fact that CR has a decreased modulus and stiffness than asphalt.

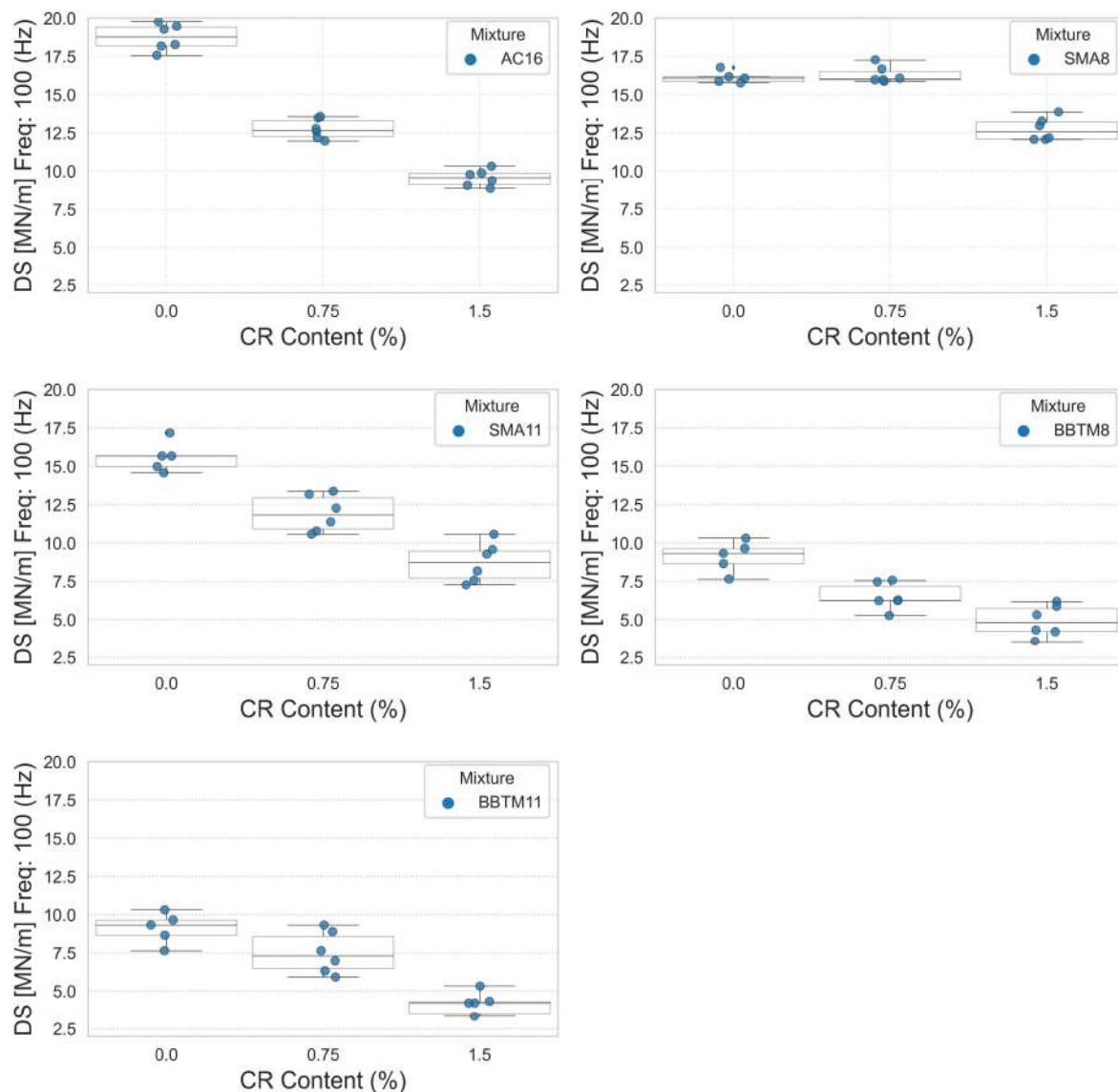


Figure 4.82: Comparison of dynamic stiffness by the effect of CR on each asphalt mixture

Figure 4.83 shows the trend of decrease attributed to CR in AC at 21.11%, SMA 8 at 14.60%, SMA 11 at 30.03%, BBTM 8 at 19.82%, and BBTM 11 at 12.81%. CR has a greater influence on the reduction of dynamic stiffness in semi-dense SMA and dense AC mixtures. This could be attributed to the fact that CR produces a denser and more elastic mastic within the internal structure of the mixtures. On the other hand, BBTM open mixtures have more internal voids, and the CR develops within these pore cavities, leading to a reduction in dynamic stiffness.

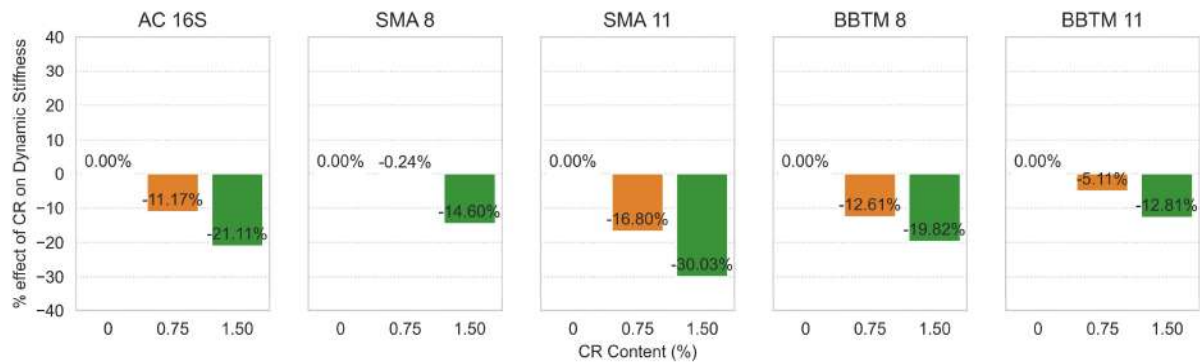


Figure 4.83: Effect of crumb rubber on the dynamic stiffness of asphalt mixtures.

Several studies by (Sandberg, 2001, Sandberg & Ejsmont, 2003, Ejsmont et al., 2014) have observed that the stiffness of pavement is related to the generation of rolling noise, where stiffer materials generate greater amounts of noise, as opposed to fewer stiffness pavements that reduce noise generation. Figure 4.84 illustrates the linear relation between the result of sound absorption and dynamic stiffness of the asphalt mixtures.

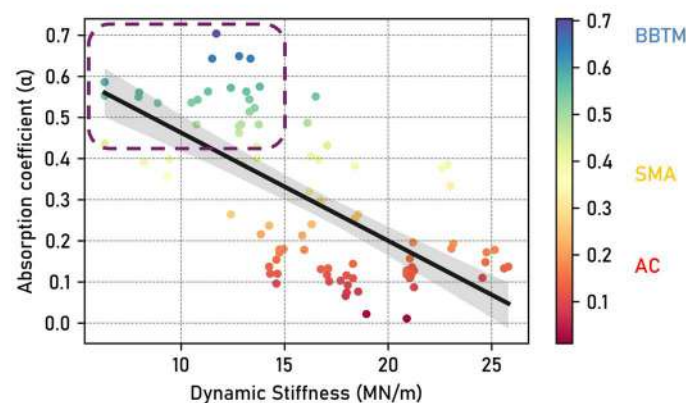


Figure 4.84: Relations of dynamic stiffness and sound absorption coefficient.

In summary, the open-grade mixtures, specifically BBTM play a crucial role in developing quieter and more eco-sustainable roads. These mixtures contribute to

driver comfort and by the reduction of the ambient noise in residential and urban areas. BBTM mixture are promising candidates for the construction of roads with improved low noise generation and high sound absorption. The addition of crumb rubber helps reducing dynamic stiffness, reducing noise generation and slightly increase sound absorption. Future research is expected to optimizing and refine these mixtures to achieve even better performance in terms of eco-suitable asphalt mixtures.

4.5. Contribution of crumb rubber to self-sensing capability of asphalt mixtures

4.5.1. Mechanical characterization

The impact of carbon fiber (CFL), and crumb rubber (CR) on mechanical properties is depicted in Figure 4.85 that presents the result of the Indirect tensile strength (ITS). Indirect tensile stiffness modulus (ITSM) is shown in Figure 4.86. Each value represents the average of four specimens, and the error bars represent the standard deviations.

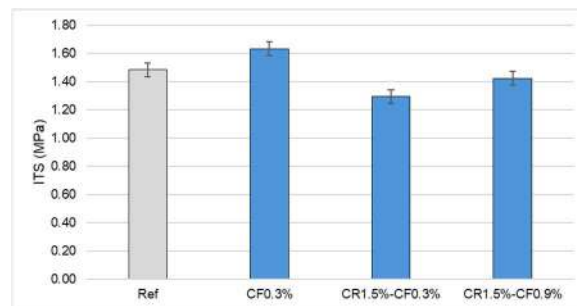


Figure 4.85: Indirect tensile strength ITS mixtures with carbon fibers and crumb rubber.

The incorporation of carbon fibers (CF) into the asphalt mixtures resulted in an increase in the Indirect Tensile Strength (ITS) compared to the reference mixtures with no CF. The increase in ITS reached 1.60 MPa when the percentage of CF was 0.3%. Conversely, the incorporation of CR results in a reduction in ITS, going down to 1.20 -1.40 MPa with 0.3% and 0.9% CF respectively, compared to the reference asphalt mixtures, which have an ITS of 1.50 MPa without CR and CF. This increase in ITS can be attributed to the resistance of fibers, that help prevent and retarding cracks.

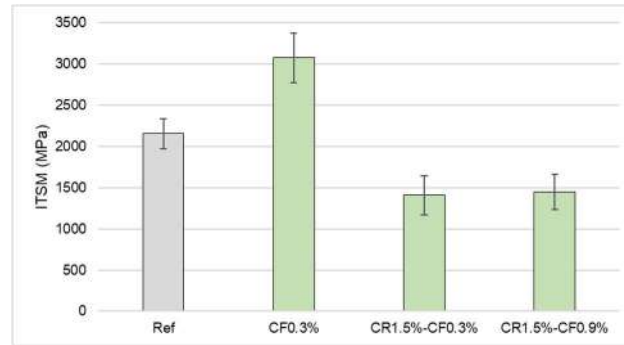


Figure 4.86: Indirect Tensile Stiffness Modulus ITSM mixtures with carbon fibers and crumb rubber.

Regarding the indirect tensile stiffness modulus, in the case of CR, the reduction in stiffness can be attributed to the modulus of CR. Furthermore, CR exerts a beneficial effect on the recovery asphalt mixtures, preventing permanent deformations, as reported by (Chavez et al., 2019)

The addition of CF 0.3% into the asphalt mixtures resulted in an increase in the Indirect Tensile Strength Modulus (ITSM) reaching 3076 MPa when CF was added. Conversely, the incorporation of CR results in a reduction in ITSM, reaching 1410 MPa with 0.3% CF compared to the reference asphalt mixtures, which have an ITSM of 2154.5 MPa without CR and CF. This increase in ITSM can be attributed to the CF, which has a tensile module of 240 GPa.

4.5.2. Self-sensing Capacity of the asphalt mixtures

Electromechanical measurements of asphalt mixture specimens with several compositions CF-0.3%, CR-1.50%, CR-1.50%,+CF0.3% and CR1.50% + CF-0.9% were carried out. Figure 4.87 shows only an example of the electric and strain response by the mixture with CR-1.5% and CF-0.3% for a frequency of 1Hz and different loads (100N, 250N, 500N, 750N, 1000N, 2000N, 3000N, and 4000N). Micro deformations induced by applied loads result in changes in the electrical properties of the materials. The application of stress causes a modification of the morphology of the conductive network within the material. This alteration causes the fractional change in resistance (FCR).

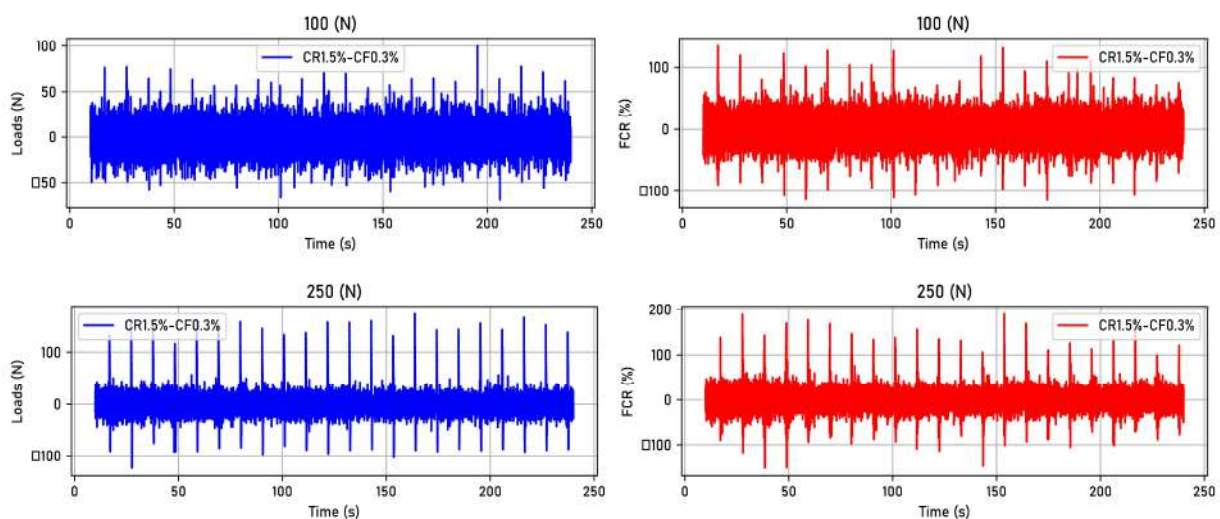
In addition, the electrical response of the material may reflect the viscoelastic properties of the asphalt mixture. Under load, the deformation does not recover instantaneously. Part of the deformation (viscoelastic component) is recoverable over time, while another part (plastic component) does not recover. This finding is

of significant importance for self-monitoring applications since FCs-0.3% mixtures can autonomously provide data regarding their strain level. However, the FC-0.3% +1.50%CR specimens showed an increase in the range of micro-deformations to imposed stresses Figure 4.87, and this was also reflected in the wider range of the FCR.

During the charging phase, as loads are applied indirect tensile deformations occur in the perpendicular plane within the specimens, where the electrodes are located resulting in an increase in electrical resistance. This increase is due to the transference of loads internally within the specimens. Upon discharge, the contact of carbon fibers is reestablished, leading to a reduction in the electrical resistance of the specimen.

The most notable results are observed at a frequency of 1Hz with the CR-1.50%, + CF-0.3% composition, where the electrical resistance response exhibits a consistent trend. The viscoelastic properties of the asphalt mixtures contribute to the fact that deformations do not fully recover immediately, requiring additional time for complete recovery. The effect of CR on the electrical resistance seems to contribution of the component flexibility (deformations and recovery) to asphalt mixtures Figure 4.87, resulting in a wider range of electrical resistance measurements, especially in the case of CR 1.50% - CF 0.3% , as showed in Figure 4.87.

For the CF-0.9% composition, an increase of the electrical resistance, this is observed due to piezo resistivity effect, but higher variations in the response are noted after the discharge phase. This could be attributed to the higher CF content leading to increased stiffness in the asphalt mixtures.



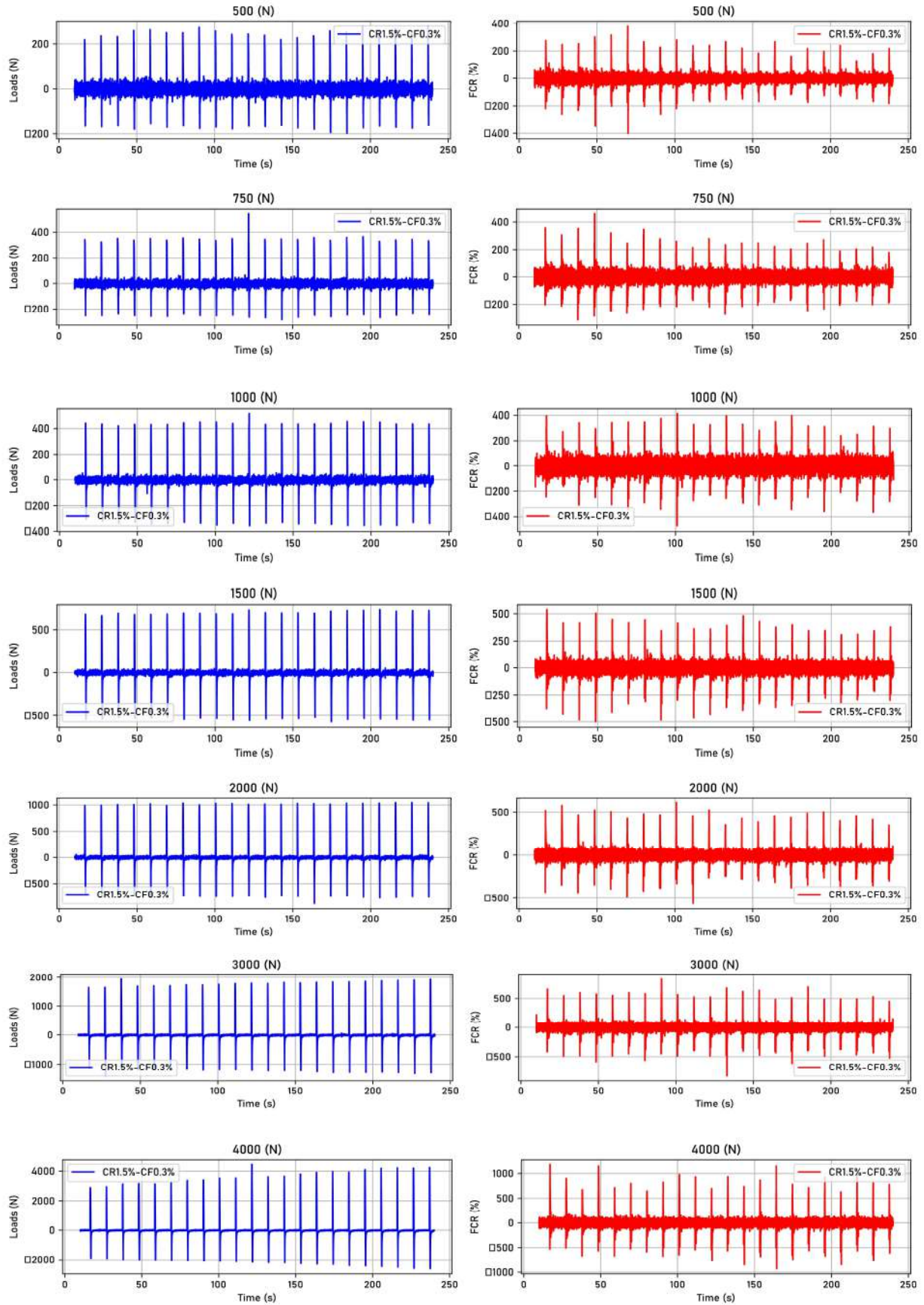


Figure 4.87: Strain and electrical response of CR-1.5%+CF-0.3% asphalt mixture.

Figure 4.88 shows the result of the analysis of the polynomial regression between the variation in FCR and variation in deformation, generated imposing to the mixture samples diametral loads in the range 100-4000N, a previously stated in Figure 4.89. The CF presents a high coefficient correlation value of R^2 . In the case of CF-0.3%, $R^2=0.95$, due to the influence of the CF, while in the case when additionally incorporates CR in 1.50% the value of $R^2 = 0.97$, is probably due to the presence of the CR that provided the mixture with enhanced elastic properties maximizing of the recovery after loads applications. Anyway, the coefficients are very high in both cases.

The CR-1.50% + CF-0.3% presents good linearity up to 800 micro deformations. Additionally, in terms sensibility of electrical change response by imposed micro deformation, CR-1.50%+CF-0.3% mixture us advantageous as the range of ΔFCR goes from 0 to 80% , while ΔFCR by mixtures at CF-0.3% and CF-0.3+CF-0.9% go up to 20% and 40%, respectively.

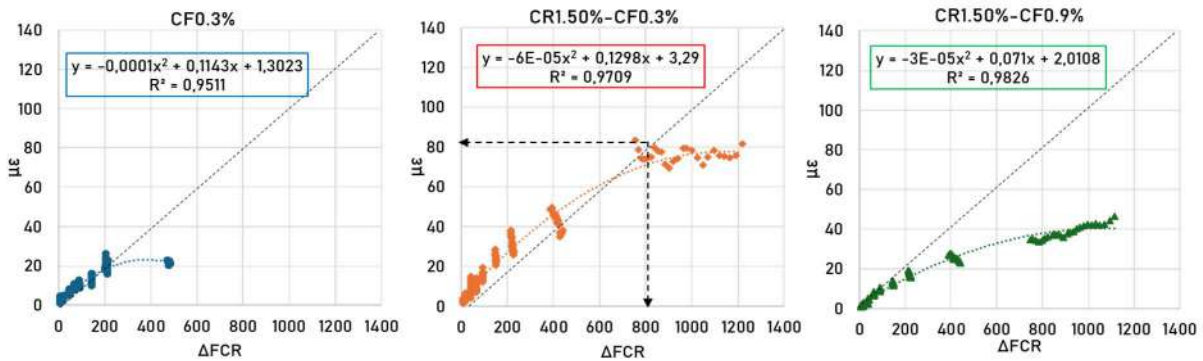


Figure 4.88: Relationship between ΔFCR and $\mu\epsilon$.

Figure 4.89 illustrates linear correlation of the sensitivity ΔFCR of cylindrical specimen to strain in microdeformations ($\mu\epsilon$), and the vertical axis represents the fractional change in resistances (ΔFCR) when the three mixtures under study are subjected to different strain levels.

The trend for improving the range of ΔFCR variation is observed with CR-1.50% + CF-0.3%, with the proportional effect measured by FCR when the same micro deformations $\mu\epsilon$ are applied.

In the case of CR-1.50%+CF-0.9%, it presents a high R^2 , but a lower range of ΔFCR what is not advisable regarding practical applications of self-sensing in any type of material. Moreover, the reference mixtures with CF-0.3% display a lower behavior in terms of micro deformations $\mu\epsilon$ and ΔFCR .

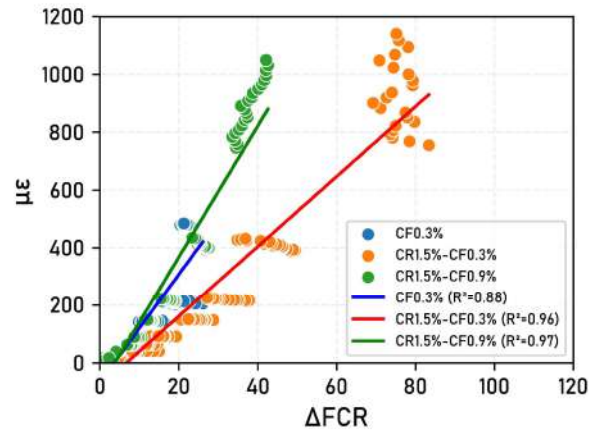


Figure 4.89: Strain-sensitivity of the performance of CR asphalt specimens.

To further quantify the sensitivity of micro deformations, linear regression analysis has been conducted to model the relationship between $\mu\epsilon$ and ΔFCR as shown in Equation 37. This analysis provides a quantitative assessment of the micro deformation sensitivity.

Figure 4.90 demonstrates a linear relationship for the addition of only 0.3% CF and crumb rubber at 1.50%CR ($R^2 = 0.96$) between the strain and the electrical response, represented by the ΔFCR . This linear relationship ensures the reliability of the strain monitoring performance. Specifically, Equation 37 relating these two variables, suggesting a higher sensitivity in the detection of micro deformations in this composition being proportional to the fractional change of the electrical resistance.

$$Strain(\mu\epsilon) = 12.132 \cdot FCR(\%) + 81.482 \quad \text{Equation 37}$$

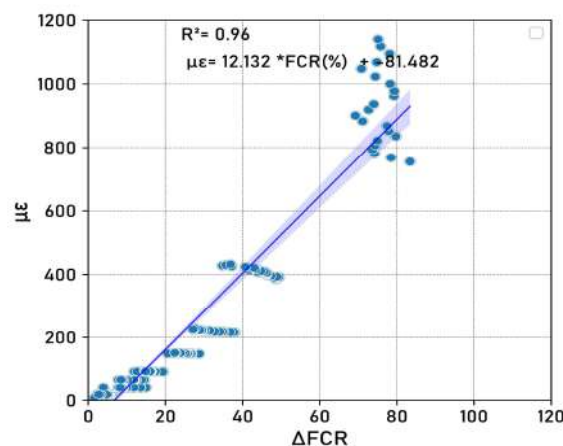


Figure 4.90: Strain-sensing performance of CR-1.50%+CF-0.3% asphalt mixtures.

Carbon fiber possesses sensing properties that are crucial for incorporating sensory capabilities into asphalt mixtures. These properties enable the pavement to sense structural capacities and detect deterioration effectively. However, due to the high cost of carbon fiber, approximately 30 Euros/kg, it is currently not a viable option for constructing high-volume asphalt pavements. Nevertheless, it is feasible to use carbon fiber in specific sectors of construction to enable sensing and self-monitoring of the pavement. This approach allows for the reception of important datasets regarding the real state of the pavement, contributing to the self-health monitoring of the pavement structure.

5. Conclusions and Future lines of research

This thesis contributes to road pavements engineering by investigating the incorporation of crumb rubber in asphalt mixtures, with a focus on its impact on volumetric properties, surface texture, skid resistance at high and low speeds, sound absorption performance, and self-sensing capability. The goal is to contribute to the development of eco-sustainable and digitalized pavements.

5.1. Conclusions

The study explores the utilization of rubber tires at the end of its life and employs conventional and non-conventional tests (acoustic and electrical assessment) within the realm of road asphalt mixtures.

In this section, we will discuss the accomplishments of the research goals outlined in Section 2.7. The objectives primarily focused on thoroughly examining the impact of Crumb Rubber (CR) by the dry process (DP) on various asphalt mixtures for the development of mechanical, functional, and Eco-suitable asphalt pavements. The research aimed to address four specific objectives, each targeting different gaps in our current understanding: the impact of the crumb rubber on the volumetric, mechanical, evolutions of the skid resistances, acoustical skid resistances and piezoresistive properties of five distinct asphalt mixtures: Dense (AC), semi-dense (SMA 8 and SMA11) and open mixtures (BBTM 8B and BBTM 11B). Two formulas incorporating CR, at 0.75% and 1.50 % content over the weight of the mixture were manufactured and testing for comparison purposes.

5.1.1. Volumetric and mechanical properties.

The first research objective of this thesis was to study the effect of the interaction between CR by DP and the volumetric and basic mechanical properties of asphalt mixtures. Thesis focuses on delving into the impact of CR on the volumetric characteristics of asphalt mixtures, including dense (AC), semi-dense (SMA), and open mixes (BBTM), which are the most used mixtures in the construction and maintenance of pavement for streets, rural and highways.

- There was a decrease in apparent densities on the all mixtures by presence of crumb rubber.

- Additionally, there was a decrease in the apparent density G_{mb} with the incorporation of CR.
- Nevertheless, the air voids content (which depends on G_{mm} and G_{mb}) did not change in the same way. A tendency to increase (1-2%) was observed in the AC 16, SMA 8 and BBTM8 mixtures. Nevertheless, SMA 11 and BBTM 11 mixtures showed these mixtures to suffer difficulties during compaction due to the rubber particles or the increased viscosity of the bitumen partially modified by the digestion of the rubber.
- BBTM mixtures showed higher permeability, although with decreasing values as the content of CR increased. The role of crumb rubber in lining the internal tunnels of the BBTM mixtures was confirmed, leading to a reduction in permeability. SMA mixtures showed a very low permeability.

In dense AC mixtures, no permeability was observed, even with no rubber.

Generally speaking, lower permeability means that the mixture is more resistance to water penetration, which is positive for preventing water related damage such as erosion and weakening of the pavement. Whereas in BBTM mixtures the reduction of permeability would be detrimental for draining, since these mixtures are usually selected for rain water drainage. For this reason, when designing an asphalt mixture with permeability for drainage purpose, the effect of CR must be considered.

On the other hand, the effects of the incorporation of crumb rubber on the mechanical properties of dense (AC), semi-dense (SMA), and open grade (BBTM) asphalt mixtures have revealed an important contribution to their mechanical characteristics. These improvements were verified through indirect tensile strength (ITS) and indirect tensile stiffness modulus (ITSM), carried out on Marshall-type samples.

- A slight improvement in indirect tensile strength is observed in AC mixtures due to the presence of CR. Moreover, the increase was more pronounced in SMA and BBTM mixtures. This difference could be since SMA and BBTM mixtures have less sand than the AC mixture, being more benefited by the modification by the CR addition. In deeds SMA and BBTM mixtures use to be manufactured with polymer modified binders.
- Because of the same reason, a drastic in the stiffness modulus of SMA mixtures with CR contributes more to the structural capacity of the

pavement. Nevertheless, the stiffness modulus of AC mixtures have a compact structure, with a higher modulus, which have a high content of air voids, that makes it no easy to increase the stiffness modulus by adding rubber.

- In the Cantabro test, an improvement in fragmentation resistance and particle loss is observed in AC, SMA and BBTM mixtures.

A reduction in particle loss suggests that the addition of crumb rubber improves the durability of the mixtures. This is important in pavements subjected to heavy traffic and adverse weather conditions, where wear resistance is crucial to extend the service life of the pavement, especially for open graded mixtures, more prone to this type of failure.

5.1.2. Texture and skid resistance at low and high speeds

5.1.2.1. Effect of the CR on the texture of the asphalt mixtures

Regarding the influence of CR on the texture, as a rule, the addition of CR to the asphalt mixtures under study decreases the macrotexture and the microtexture. The understanding of this effect on the macrotexture, was possible thanks to the mean texture depth (MTD) obtained from the Sand Patch Test (SPT). The study of the macro and micro texture was carried out by the Laser Texturometer Scanner (LTS), which allowed to obtain the mean profile depth (MPD), and the roughness average (Rama for macrotexture and Rami for microtexture). The parameters MTD, MPD, Rama and Rami decreased with the addition of CR for the five asphalt mixtures under study. This result must be considered to accomplish the texture requirements in road. In some cases, it would be advisable a shift change in the grading curve during the design to counteract the effect of CR on the surface texture.

5.1.2.2. Effect of crumb rubber on the evolutions of friction at low speeds (10 km/h)

The skid resistance at low speeds (10 km/h) was studied by the British Pendulum Test (BPT). The accelerated polishing effect was performed by the Accelerated Polishing Machine (APM), a prototype developed during this Doctoral Thesis. The Accelerated Polish Machine (APM) present a great capacity to polished asphalt mixtures and simulated the evolution of the surface due to the traffic in the road.

During the test, the evolution of the macro and micro texture parameters was monitored as well as the evolution of skid resistance.

With this procedure it has been proven that the presence of rubber in the mixtures AC and SMA shorten the period of service to reach the minimum threshold of skid resistance under current standards. Nevertheless, for mixtures BBTM this period is longer, which is positive in terms of management and maintenance.

This could be explained by an improvement in the mastic envelope of the aggregate, since the CR provides greater protection to the external structure of the texture of asphalt mixture BBTM B, whose aggregate are more prone to move due to the limited mastic in the mixture.

Nevertheless, the effect of CR content in the AC 16, SMA 8 and SMA 11 mixtures, is the reduction of the number of cycles needed to reach the BPN friction threshold. It can be because rubber particles partially digested fill the valleys of the texture. This effect results predominant in these mixtures compared to the additional reinforcement of bonding of the superficial aggregates, since in AC and SMA mixtures the mastic is abundant.

Regarding the final value of BPN, as a rule, mixtures with rubber showed a bit better skid resistance at the end of the experiment.

Remarkable aspect of this study was to establish skid resistance prediction models for different asphalt mixtures AC, SMA, and BBTM. CR has a positive influence on the skid resistance of SMA and BBTM mixture, combined with the average roughness of micro (R_{mi}) and macro (R_{ma}) textures. Nevertheless, for the AC mixture CR did not show a significant influence, as the skid resistance was depending only on R_{ma} and R_{mi} , being R_{mi} the most influential parameter.

In practical terms, it can be said that to improve the skid resistance at low speeds of SMA and BBTM mixtures, the mix formula has to include CR, and at the same time, to keep high values for R_{mi} .

5.1.2.3. Effect of Crumb rubber at high speeds of 60 km/h:

Part of the evaluations of the evolution of the skid resistance was measured at 60 km/h by Wehner Schulze (W&S).

The final values of friction, as a rule, were a bit higher when the mixtures under study included CR. Nevertheless, the addition of crumb rubber does not present a significant difference to the skid resistance at the end of the evolution

measurements in the final stage of the investigation, when the mixtures were analyzed all together.

To better understand the effect of the crumb rubber on skid resistance, texture parameters were analyzed during the polishing progress, as these reflected changes in the texture profile, including roughness and asperities.

Remarkable aspect of this study was to establish skid resistance prediction models for different asphalt mixtures AC, SMA, and BBTM. CR has a positive influence on the skid resistance of AC, SMA and BBTM mixtures, combined with the average roughness of macrotexture (R_{ma}). Nevertheless, for the AC mixture R_{mi} showed influence.

In practical terms, it can be said that to improve the skid resistance at high speeds of asphalt AC, SMA and BBTM mixtures, the mix formula must include CR, and at the same time, to keep high values for R_{ma} and R_{mi} .

5.1.2.4. Effect of Crumb rubber on resistance of tangential stress by T2R :

The resistance to surface degradation of pavements has been evaluated using AC, SMA and BBTM mixtures with different rubber contents (0%, and 1.50% of crumb rubber by dry process). This test allows for quantification of surface degradation under simulated traffic conditions, especially during vehicle acceleration, deceleration, and concerning :

- The resistance to tangential stress T2R corroborated the results of the resistance to tensile degradation of the pavement surface. It was observed that the conventional BBTM mixtures presented a higher loss of particles due to detachment and surface degradation, with the dense and semi-dense mixtures showing a lower loss in comparison. This is because the dense mixtures have a more densified structure, which more mortar, which better secures the aggregates.
- The reduction in mass loss by addition of 1.50 % CR showed trends in all asphalt mixtures, compared to conventional asphalt mixtures, with no rubber. This improvement in the efficiency against surface degradation substantially improved the resistance to surface traction generated by vehicles, especially in turns, accelerations, and decelerations in curves.
- On the other hand, the effect of carbon fiber (0.3 % FCL) showed significant differences similar to those observed with CR. This indicates that additives

such as fibers can reduce the mass loss of exposed aggregates on the pavement surface.

Additionally, the cohesive properties of the binders have been verified with different types of additives such as crumb rubber (1.50 %CR), long carbon fiber FCL (0.3%FCL), fine carbon fiber (0.3%FCf) added to bitumen 50/70 respectively. Regarding the characterization of cohesion, the laboratory procedure for estimating the energy loss of the Vialit cohesion was carried out.

- Binder Cohesion Efficiency: Although conventional 50/70 bitumen has a limited cohesion. However, a suitable modification can improve these cohesive properties and optimize the performance of the evaluated binder.
- Cohesion Improvements with Modifiers: Fine Carbon Fibers and Long Carbon Fibers increase in cohesion of the conventional binder.
- Crumb Rubber increases in cohesion at intermediate temperature (20°C) when added to conventional asphalt binder.
- The advantage of CR at high temperature (60°C) over the performance of no rubber binders, is greater. At this temperature, even compared to CF modified binders, the CR addition is more beneficial, a high cohesion.

This suggests that incorporating crumb rubber improves cohesive properties to conventional bitumen, resulting in better performance at medium and high temperatures.

5.1.3. Sound absorption

The acoustic evaluations of the sound absorption by the impedance tube on the AC, SMA and BBTM asphalt mixtures with CR by DP were carried out. And the noise generation was evaluated by Drynamic stiffness (DS). From the result of the experiments, it can be said:

- The influence of the volumetric parameters is crucial to understanding of sound absorption of the asphalt mixtures. According to this case of study the air void content (V_a) and the permeability (K_v). Are the best predictors of sound absorption. This is due to to role of internal tunnels to attenuate noise by a better absorption.
- The influence of the Mean Macrottexture Depth (MTD), by the volumetric method, was found to be highly influence on the sound absorption.

- The addition of crumb rubber at concentrations of 0.75% and 1.50% did not show a significant influence on sound absorption.
- No differences were observed in the effect of temperature (10, 20, 30, 40, 50, and 60 °C) on sound absorption of the asphalt mixtures.

The acoustic results were processed by Gaussian fitting (GF) for each sound absorption spectrum, discretizing them into Peak shapes (P), Area Under the Curve (AUC), and Band Width (BW). Further correlations were studied to predict the three Gaussian parameters. As a result, the CR does not affect the pic of absorption, but widen the bandwidth and makes lower the area under the curve of absorption.

Additionally to the absorption, the generation of noise in the wheel-tire contact was studied by the dynamic stiffness D_s .

As a rule, the addition of CR reduces the dynamic stiffness of the mixtures. This means that the generation of noise in the wheel-pavement contact is attenuated by the presence of rubber, which is a beneficial effect of CR on the acoustic pollution.

In practical terms, the acoustic results of this investigation clearly show that the most silent asphalt mixture, among the investigated here, is BBTM. This mixture has a larger sound absorption coefficient and a lower dynamic stiffness. The value of dynamic stiffness is further reduced with the addition of CR, meaning a low generation of noise, and a great absorption, the best combination for a silent pavement.

5.1.4. Self-sensing

The present research focused on evaluating the self-sensing properties by piezo resistive mechanism of the asphalt mixtures, by means of mechanical and electrical characterization tests, dosing the SMA mixture with carbon fibers and crumb rubber.

According to the results of this investigation, the crumb rubber improves the magnitude of the piezo resistive response by conferring deformability and elastic recovery to the asphalt mixture. When compared with the the reference mixture, with no CR, the rubberized mixture developed greater amplitude of strain, so the internal network of electrical contacts undergoes a greater change, easier to be detected and measured by electrical instruments. This improvement of the self-

sensing capacity or asphalt mixtures by the addition of CR is positive and can contribute to the spreading of this technology. The present research can be considered as a starting point for the development of rubberized pavement with detection systems based on self-sensing asphalt pavements.

5.2. Future lines of research

Progress towards the development of eco-sustainable pavements is essential for a more sustainable future in transportation. Although significant progress has been made, more research is still required to achieve fully sustainable solutions. The results of this thesis can be an important starting point for improving the properties of eco-sustainable pavements, especially in terms of acoustics and skid resistance.

Future lines of investigation on skid resistance in pavements with CR:

- Evaluation of different incorporation methods: in addition to the dry process used in this study, other ways of incorporating CR, such as pellets or pretreated CR, by semi-wet or wet methods could be investigated. This would allow for a more complete evaluation of the functional capabilities of asphalt mixtures incorporating CR.
- Large-scale studies: It is important to validate the results obtained at in real conditions of large-scale paved roads. This would provide a better understanding of CR performance in low-traffic areas and encourage its application in such contexts.

Future lines of research in acoustic improvements with CR could consider the following aspects:

- Evaluation of different incorporation methods: in addition to the dry process used in this study, other ways of incorporating CR, such as pellets or pretreated CR, by semi-wet or wet methods could be investigated. This would allow for a more complete evaluation of the acoustic performance of asphalt mixtures incorporating CR.
- Full-scale evaluations: Although the results are promising, it is crucial to perform evaluations in real conditions to better understand the acoustic performance on different types of pavements.

Annexes I.

Scientific Publications

The main findings of the present study have been used for the scientific communications of papers in international journals, indexed in the journal citations reports (JCR).

SP1. Freddy Richard Apaza Apaza, Victoriano F,Vázquez, Santiago Paje , Federico gulisano, Leticia Saiz, Juan Gallego. **The potential effect of crumb rubber on the maximum sound absorption performance of asphalt mixtures.** Construction and Building Materials. DOI: [10.1016/j.conbuildmat.2023.131789](https://doi.org/10.1016/j.conbuildmat.2023.131789) [May 2023 JCR Journal Impact Factor 7.4 Journal Citation indicator 1.43 Engineering Civil Q1]

SP2. Freddy Richard Apaza Apaza, Victoriano F,Vázquez, Santiago Paje , Federico gulisano, Valerio Gagliardi, Leticia Saiz, Juan Gallego. **Towards Sustainable Road Pavements: Sound Absorption in Rubber-Modified Asphalt Mixtures.** MDPI Infrastructures Sustainable and Digital Transformation of Road Infrastructures. DOI: [10.3390/infrastructures9040065](https://doi.org/10.3390/infrastructures9040065) [March 2024 JCR journal Impact Factor 2.6 Journal Citation indicator 2.4 Engineering Civil Q2].

SP3. Freddy Richard Apaza Apaza, Rafael Jurado, Rodrigo Diaz-Torrealba, Federico gulisano, Gustavo Boada, Juan Gallego. **Texture and skid resistance of asphalt mixtures with crumb rubber.** Taylor&Francis International Journal of Pavement Engineering. DOI: <https://doi.org/10.1080/10298436.2024.2378335> [July 2024 JCR Journal Impact Factor 2.6 Journal Citation indicator 2.4 Engineering Civil Q2].

SP4. Federico Gulisano, Mohammadmahdi Abedi Rafael Jurado-Piña, Freddy Richard Apaza Apaza, Mohammad Jawed Roshan, Raul Fangueiro, Antonio Gomes Correia, Juan Gallego. **Stress and damage-sensing capabilities of asphalt mixtures incorporating graphene nanoplatelets.** Elsevier Sensor and Actuators A. Physical. DOI: [10.1016/j.sna.2023.114494](https://doi.org/10.1016/j.sna.2023.114494) [June 2023 JCR Journal Impact Factor 4.6 Journal Citation indicator 4.3 Engineering Civil Q1].

Scientific Collaborations-Publications

SP5. Federico Gulisano, Thanyrat Buasiri, Freddy Richard Apaza Apaza, Andrezej Cwirzen Juan Gallego Automation in Construction, **Piezoresistive behavior of electric arc furnace slag and graphene nanoplatelets asphalt mixtures for self-sensing pavements** Elsevier Sensor and Automation in construction DOI: [10.1016/j.autcon.2022.104534](https://doi.org/10.1016/j.autcon.2022.104534), [August 2022 JCR Journal Impact Factor 10.3 Journal Citation indicator 8.6 Engineering Civil Q1].

Scientific communications

The main results of the present study have been used for scientific communications papers in international conferences:

- SC1.** Freddy Richard Apaza Apaza, Victor F.Vázquez, Santiago E.Paje, Roberto Perez Aparicio , Leticia, Saiz Rodriguez, Juan Gallego. **Characterisation of the sound absorption of bituminous mixtures modified with rubber from end-of-life tires..** International conference Rubberised Asphalt -Asphalt binder -Malaga- Spain 2022.
- SC2.** Freddy Richard Apaza Apaza, V.F Vázquez, S.E. Paje Federico Gulisano , Gustavo Boada , Juan Gallego. **Dynamic stiffness analysis of asphalt mixtures for nondestructive pavement performance assessment.** Conference 12734 Earth Resources and Environmental Remote Sensing/GIS Applications XIV Sensor + Imaging – Amsterdam 2023 .
- SC3.** Freddy Richard Apaza Apaza, Victor F.Vázquez, Santiago E.Paje, Roberto Perez Aparicio, Leticia, Saiz Rodriguez, Juan Gallego. **Caracterización de la microtextura y macrotextura de pavimentos bituminosos modificados con polvo de caucho NFVU.** International conference Congreso Ibero- Latinoamericano del Asfalto -Granada Spain 2024.
- SC4.** Freddy Richard Apaza Apaza, Federico Gulisano, Damaris Cubilla, Rafael Jurado-Piña, Gustavo Boada-Parra, and Juan Gallego. **Diseño de mezclas bituminosas auto-sensorizadas.** International conference Congreso Ibero- Lantinoamerciano del Asfalto -Granada Spain 2024.
- SC5.** Freddy Richard Apaza Apaza, Victor F.Vázquez, Santiago E.Paje, Roberto Perez Aparicio , Leticia, Saiz Rodriguez, Juan Gallego. **The acoustic performance of bituminous mixtures with wet and dry process incorporations.** International conference Eurasphalt & Eurobitumen – Budapest-Hungary 2024.

Awards

- A1:** First accesit of the founders' award of the Ibero-Latin American Asphalt Congresses with the technical-scientific work: Design of self-sensing asphalt mixes. XXII Congreso Ibero latinoamercano del Asfalto (CILA), - Granada Spain-2024. - Freddy Richard Apaza Apaza, Federico Gulisano, Damaris Cubilla, Rafael Jurado-Piña, Gustavo Boada-Parra, and Juan Gallego.
- A2:** Dynamic stiffness analysis of asphalt mixtures for non-destructive pavement performance assessment” 12734-33. selected winner of \$700 for airfare and/or lodging, as well as a registration fee waiver to the SPIE Sensors + Imaging 2023 conference. Amsterdam -2023: Freddy Richard Apaza Apaza, V.F Vázquez, S.E. Paje, Federico Gulisano , Gustavo Boada , Juan Gallego
- A3:** Nominated for the award within the 10 best business ideas in the competition and creation of companies with the proposal PaveUP pavements sensorsados in the Actua-UPM 2022 Program. Federico gulisano, Juan gallego, Rafael Jurado, Luis gustavo, Freddy richard Apaza Apaza.

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