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Department of Civil, Construction and Environmental Engineering

DESIGN AND VERIFICATION OF ASPHALT BLENDS MADE WITH MARGINAL MATERIALS

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ABSTRACT

Desing and verification of asphalt blends made with marginal materials.

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Gas emissions from the production of asphalt mixtures are a factor that greatly contributes to Greenhouse Gas (GHG) emissions. To reduce GHG from the production of asphalt mixtures, several strategies can be implemented. Increased use of Recycled Asphalt Pavement (RAP) and Plastic Waste (PW) in new asphalt mixtures is also one of the proposals from this study. The use of these marginal materials not only reduces waste but also lowers the demand for new raw materials. Designing and verifying asphalt mixtures made of marginal materials involves a systematic approach to ensure the resulting asphalt mix meets the desired performance and durability standards. From there, the aim of this study was divided into a laboratory part: identifying optimum solutions with six asphalt mixtures structured with alternative materials, RAP and PW, and involving them in the design and verification of pavement stratigraphy. This part of the study found that Mix virgin limestone MOD had optimal performance, showing a fatigue cracking |DC| of 0.86 and rutting [$\boldsymbol{\delta p}$] of 0.61. Incorporating modified binder improved fatigue |DC| and rutting resistance. Mix Cold PW 8.5% cem was promising, with comparable fatigue cracking |DC| and increased rutting [$\boldsymbol{\delta p}$] resistance due to higher cement content. This phase was carried out through the integration of methodological, structural, and performance analysis with Building Information Modelling (BIM) tools. Finally, the second part had as its goal to design a complete decision support tool (algorithm) about twenty-four maintenances on the pavements on the basis of discriminating variables appropriately integrated with a sufficient level of detail in the specific BIM semantics of the roads, such as the mechanical performance of the mixtures. As some results showed, the mechanical behaviour of the asphalt mixtures structured with RAP and PW obtained satisfactory performance in relation to the traditional asphalt mixtures. The algorithm developed is totally meaningful for engineers in terms of decision-making in relation to the maintenance list available in the algorithm designed for every asphalt mixture designed for the binder layer of the pavement structure. Using RAP and PW in asphalt mixtures make them have a mechanical behaviour comparable to traditional mixtures. It reduces reliance on natural aggregates, promoting sustainability by utilizing more marginal materials effectively. Considering potential impacts, decision-makers and road managing bodies can gain from utilizing the developed methodology to meet future requirements for BIM and Minimum Environmental Criteria (MEC).

Keywords: Asphalt mixtures, RAP. Plastic Waste. Fatigue. Rutting. BIM.

RESUMO

Projeto e verificação de misturas asfálticas feitas com materiais marginais.

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As emissões de gases provenientes da produção de misturas asfálticas são um fator que muito contribui para as emissões de Gases de Efeito Estufa (GEE). Para reduzir os GEE provenientes da produção de misturas asfálticas, diversas estratégias podem ser implementadas. O aumento do uso de *Reclaimed Asphalt Pavement* (RAP) e Resíduos Plásticos (PW) em novas misturas asfálticas, também, é uma das propostas deste estudo. O uso desses materiais marginais não apenas reduz o desperdício, mas também reduz a demanda por novas matérias-primas. Projetar e verificar misturas asfálticas feitas de materiais marginais envolve uma abordagem sistemática para garantir que a mistura asfáltica resultante atenda aos padrões de desempenho e durabilidade desejados. A partir daí, o objetivo deste estudo foi dividido em uma parte laboratorial: identificar soluções ótimas com seis misturas asfálticas estruturadas com materiais alternativos, RAP e PW, e envolvê-las no projeto e verificação de uma estratigrafia de pavimento. Esta parte do estudo revelou que a mistura asfáltica Mix Virgin limestone MOD teve um desempenho ótimo, mostrando um rachamento por fadiga |DC| de 0,86 e afundamento de trilha de roda (ATR) [$\boldsymbol{\delta}$p] de 0,61. Incorporando ligante modificado melhorou a fadiga |DC| e resistência ao ATR. A mistura asfáltica Mix Cold PW 8,5% Cem mostrou-se promissor, com igual resistência à fadiga |DC| e maior resistência ao ATR [$\boldsymbol{\delta}$p] devido ao maior teor de cimento. Esta fase foi realizada através da integração da análise metodológica, estrutural e de desempenho com ferramentas de *Building Information Modelling* (BIM). Finalmente, a segunda parte teve como objetivo projetar uma ferramenta completa (algoritmo) de apoio à decisão cerca de vinte e quatro manutenções nos pavimentos com base em variáveis discriminantes adequadamente integradas com um nível de detalhe suficiente na semântica BIM específica das estradas, como o desempenho mecânico das misturas. Como alguns resultados mostraram, o comportamento mecânico das misturas asfálticas estruturadas com RAP e PW obteve desempenho satisfatório em relação às misturas asfálticas tradicionais. O algoritmo desenvolvido é totalmente significativo para os engenheiros em termos de tomada de decisão em relação à lista de manutenção disponível no algoritmo projetado para cada mistura asfáltica projetada para a camada aglutinante da estrutura do pavimento. O uso de RAP e PW em misturas asfálticas faz com que tenham um comportamento mecânico comparável às misturas tradicionais. Reduz a dependência de agregados naturais, promovendo a sustentabilidade utilizando materiais mais marginais de forma eficaz. Considerando os impactos potenciais, os tomadores de decisão e os órgãos de gestão de estradas podem se beneficiar da utilização da metodologia desenvolvida para atender aos requisitos futuros de BIM e Critérios Ambientais Mínimos (MEC).

Palavras-chave: Misturas asfálticas. RAP. Resíduos plásticos. Fadiga, ATR. BIM.

ZUZAMMENFASSUNG

Entwurf und Überprüfung von Asphaltmischungen mit Randmaterialien.

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Gasemissionen aus der Herstellung von Asphaltmischungen sind ein Faktor, der wesentlich zu den Treibhausgasemissionen (THG) beiträgt. Um die Treibhausgasemissionen bei der Herstellung von Asphaltmischungen zu reduzieren, können verschiedene Strategien umgesetzt werden. Der verstärkte Einsatz von *Reclaimed Asphalt Pavement* (RAP) und Kunststoffabfällen (PW) in neuen Asphaltmischungen ist ebenfalls einer der Vorschläge dieser Studie. Der Einsatz dieser Randmaterialien reduziert nicht nur den Abfall, sondern senkt auch die Nachfrage nach neuen Rohstoffen. Die Planung und Überprüfung von Asphaltmischungen aus Randmaterialien beinhaltet einen systematischen Ansatz, um sicherzustellen, dass die resultierende Asphaltmischung die gewünschten Leistungs- und Haltbarkeitsstandards erfüllt. Von dort aus wurde das Ziel dieser Studie in einen Laborteil unterteilt: die Identifizierung optimaler Lösungen mit sechs Asphaltmischungen, die mit alternativen Materialien, RAP und PW strukturiert sind, und deren Einbeziehung in die Gestaltung und Überprüfung einer Pflasterschichtung. Dieser Teil der Studie fand heraus, dass Mix Virgin Limestone MOD eine optimale Leistung zeigte, wobei ein Ermüdungsriss |DC| von 0,86 und ein Rutting [$\boldsymbol{\delta}$p] von 0,61 zeigte. Mit modifiziertem Bindemittel verbesserte Ermüdung |DC| und Spurtreue. Mix Cold PW 8,5% cem war vielversprechend, mit vergleichbarem Ermüdungsriss |DC| und erhöhter Rutting [$\boldsymbol{\delta}$p] Beständigkeit aufgrund eines höheren Zementgehalts. Diese Phase wurde durch die Integration von methodischen, strukturellen und Performance-Analysen mit Building Information Modelling (BIM) Tools durchgeführt. Schließlich hatte der zweite Teil das Ziel, ein komplettes Entscheidungsunterstützungstool (Algorithmus) zu entwerfen Etwa vierundzwanzig Wartungen auf den Gehwegen auf der Grundlage von diskriminierenden Variablen, die angemessen mit einem ausreichenden Detaillierungsgrad in die spezifische BIM-Semantik der Straßen integriert sind, wie z. B. die mechanische Leistung der Mischungen. Wie einige Ergebnisse zeigten, erreichte das mechanische Verhalten der mit RAP und PW strukturierten Asphaltmischungen eine zufriedenstellende Leistung im Vergleich zu den traditionellen Asphaltmischungen. Der entwickelte Algorithmus ist für Ingenieure in Bezug auf die Entscheidungsfindung in Bezug auf die Wartungsliste, die in dem Algorithmus verfügbar ist, der für jede Asphaltmischung entwickelt wurde, die für die Binderschicht der Pflasterstruktur ausgelegt ist, völlig bedeutungsvoll. Die Verwendung von RAP und PW in Asphaltmischungen führt zu einem mechanischen Verhalten, das mit herkömmlichen Mischungen vergleichbar ist. Es reduziert die Abhängigkeit von natürlichen Aggregaten und fördert die Nachhaltigkeit durch die effektive Verwendung von marginalen Materialien. Unter Berücksichtigung potenzieller Auswirkungen können Entscheidungsträger und Straßenbetreiber von der Verwendung der entwickelten Methodik profitieren, um zukünftige Anforderungen an BIM und Minimum Environmental Criteria (MEC) zu erfüllen.

Schlüsselwörter: Asphaltmischungen. RAP. Kunststoffabfällen. Fatigue. Rutting. BIM.

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1 INTRODUCTION

1.1 Background

The roads have an essential contribution to the socio-economic development of emerging countries. Road construction is often regarded as one of the most significant industries globally from several perspectives, such as economic, political, and military. The insufficiency of a road infrastructure network has wide-ranging implications for the agricultural sector, national integration, security, and economic development, among other factors. Hence, the acquisition of information pertaining to the road system is seen as a crucial determinant in the pursuit of optimal performance by individuals in the contemporary globalised economy.

The term "pavement" refers to a constructed structure composed of numerous layers that has the ability to endure the detrimental effects caused by vehicular traffic and environmental factors. The physical and mechanical characteristics of the pavement's constituent layers are just one of many factors that affect its performance. The surface layers consist of components that are somewhat expensive and hence need specific attention. Several variables may impact the performance of an asphalt layer, including the qualities of the materials used, the dosage of these elements, the compaction conditions during construction, the construction process itself, and the management of maintenance and restoration activities.

The degradation of pavement is an unavoidable consequence of the extensive use of roads, mostly attributed to the substantial traffic volume on overloaded roadways. This excessive traffic load leads to an expedited deterioration of the various layers comprising the pavement structure. Therefore, the primary objective of pavement restoration is to adequately prepare the structural and surface layers to withstand the effects of climatic variations and the demands imposed by traffic loads over its renewed lifespan. This ensures that drivers experience enhanced safety, comfort, and cost-effectiveness throughout this new era.

An exacerbating element in the context of highways is the substantial use of primary resources, which is necessary for the implementation of various interventions, including both maintenance activities and the establishment of new infrastructure. The primary constituents of pavements in their original state are aggregates and bitumen. When considering aggregates, it is important to note that although the sources of materials are many, they are ultimately limited in quantity. Materials of high quality that are easily accessible have a tendency to deplete rapidly. Additionally, environmental regulations, land use laws, and the phenomenon of urban expansion further restrict the availability of natural aggregate sources. In this context, while these materials remain accessible, their availability is progressively diminishing.

The increased recognition of the proper utilisation of natural resources, the need for environmental conservation, and the need to decrease pollutant emissions have prompted the exploration of eco-friendly alternatives to traditional paving methods. When addressing environmental concerns, it is essential to consider factors such as the longevity and maintenance of roadways. By doing so, the effectiveness of these approaches may be evaluated and compared to conventional tactics. As a result, the use of pavement recycling techniques has garnered endorsement from governing bodies and the general public, since they are seen as technically feasible options that align with political correctness and provide economic feasibility when effectively utilised. Therefore, measures about climate change and the ecological emergency were adopted by many national and international organisations in all their fields of action to integrate sustainability and the Sustainable Development Goals. In this way, the attention to the sector of building and construction sustainably is definitely growing. This sector represents one of the most demanding natural resources (raw materials and energy) and contributes to a huge amount of Greenhouse Gas (GHG) emissions and solid waste production. Due to the fact, the New Green Deal has been developed to be a strategy adopted by the European Union (EU) to become a zero-GHG emission area and become carbon neutral in a few decades through a competitive resource-efficient economy.

As it is known, gas emissions from the production of asphalt mixtures are also a factor that greatly contributes to GHG emissions. These emissions mainly come from the energy-intensive process of producing asphalt and the use of fossil fuels. Some of the key sources of greenhouse gas emissions in the production of asphalt mixtures are energy consumption. The production of asphalt mixtures requires a significant amount of energy, primarily for heating and mixing the raw materials. Energy is often obtained from fossil fuels, such as natural gas or oil, which release carbon dioxide (CO_2) when burned; emissions from raw materials, which means the extraction and transportation of raw materials used in asphalt production, such as aggregates (sand, gravel, and crushed stone) and bitumen (a petroleum-based binder), can result in emissions. The energy used in these processes and the combustion of fuels in transportation contribute to emissions. Process emissions, during the mixing and heating of asphalt, there can be emissions of volatile organic compounds (VOCs), which can react in the atmosphere to form ground-level ozone, a potent greenhouse gas. These processes may also result in other air pollutants; and transportations, The transportation of raw materials to the asphalt plant and the transportation of the finished asphalt mix to construction sites can generate emissions, especially if diesel or gasoline-powered vehicles are used.

To reduce greenhouse gas emissions from the production of asphalt mixtures, several strategies can be implemented. The improvement of the energy efficiency, for example, of asphalt plants can be achieved by optimising heating and mixing processes, using more efficient equipment, and incorporating technologies like heat recovery systems. The alternative binders, exploring and adopting alternative binders, such as bio-based or recycled materials, to reduce the environmental impact of bitumen production. Other strategies for renewable energy include transitioning asphalt plants to use renewable energy sources, like solar or wind power, to reduce the carbon footprint of the production process. In addition, increase the use of recycled asphalt pavement (RAP) and plastic waste (PW) (both materials used in this research as well) in new asphalt mixtures. This not only reduces waste but also lowers the demand for new raw materials. Also, optimise the efficiency of transportation logistics to minimise the distance materials and finished products need to travel. This can reduce emissions associated with transportation. Furthermore, invest in research and development to find more sustainable and lower-emission technologies and materials for asphalt production. And for sure, the implementation of emissions control technologies to capture and reduce volatile organic compound (VOC) emissions from the production process.

By adopting measures and promoting sustainable practices in asphalt production, it is possible to reduce greenhouse gas emissions associated with the manufacturing of asphalt mixtures and contribute to a more environmentally friendly construction industry. With the aim of reducing this emission of these pollutants, the knowledge of the characteristics and the use of alternative materials in the asphalt blends can be an alternative to these reductions of emissions. Likewise, the design of asphalt mixtures for highways is a big contributor to minimise GHG emissions.

Designing and verifying asphalt mixtures made of marginal materials involves a systematic approach to ensure the resulting asphalt mix meets the desired performance and durability standards. Marginal materials typically refer to materials that may not meet the traditional specifications for asphalt construction but can be used with appropriate adjustments. In other words, these marginal materials are typically materials that are not suitable for use in their natural state but can be improved or stabilized for use in asphalt mixes. Ergo, conducting comprehensive material characterization tests are of paramount importance to understand, e.g., their properties, including gradation, plasticity, moisture content, and chemical composition. In addition, the mix design, as well as the testing and verification are in the same way crucial in production processes of asphalt mixtures, and likewise to minimized GHG emissions.

In relation to the mixture design (5.2.1), it is necessary to select a suitable methodology for the mixing project. The Superpave method is frequently employed in the design of asphalt mixes. Hence, it is crucial to ascertain the appropriate characteristics of the asphalt binder, such as the performance grade (PG), as well as the air voids and aggregate gradation, in order to achieve the desired mix qualities. It is necessary to perform a mix design in order to determine the most effective combination of substandard materials, virgin aggregates, and asphalt binder to attain the specified qualities of the mixture. The successful completion of this task may necessitate the implementation of several iterative blending attempts. However, the verification process will involve conducting a series of laboratory experiments in reason to validate the performance of the asphalt blend. The tests that may be included are as follows: (I) The Marshall Stability Test is conducted to assess the load-bearing capability and deformation characteristics of asphalt mixtures. (II). The Indirect Tensile Strength (ITS) Test (5.2.2) is conducted to evaluate the tensile strength of the asphalt mixture. Additionally, the Indirect Tensile Stiffness Modulus (ITSM) (5.2.3) is determined to assess the elastic stiffness of the asphalt. (IV): Analysis of Asphalt Content and Gradation: It is important to verify that the mixture satisfies the prescribed criteria for binder and aggregate content and gradation. (V). Test for Moisture Sensitivity: This test assesses the ability of the mixture to withstand damage caused by moisture. The topic of discussion is rutting and fatigue, specifically in relation to section 5.3.3. Experimental Evaluation: Evaluate the capacity of the mixture to withstand enduring deformation and cracking when subjected to vehicular stresses.

In addition, to conducting necessary tests on mixes to assess their behaviour, the implementation of changes and optimization measures is crucial in achieving desirable mechanical characteristics in asphalt blends. The major modifications and enhancements are derived from the findings of the field experiment, whereby any required modifications to the composition design, building techniques, or used materials are made, and similarly, the mixture is refined to enhance its performance.

It is important to note that the successful design and verification of asphalt blends made up of marginal materials require a thorough understanding of local conditions, materials, and the specific project requirements. Collaboration with experienced engineers, material suppliers, and contractors is crucial in achieving a durable and cost-effective solution. Additionally, compliance with local regulations and specifications is essential throughout the process.

The utilisation of this particular classification of materials in the design of asphalt mixes can serve as a viable approach for achieving cost efficiency and promoting sustainability in the field of road construction. The incorporation of cost savings and sustainability is of utmost importance in the realm of road construction. The implementation of efficient solutions in these domains has the potential to not only yield cost savings but also mitigate the environmental consequences associated with construction activities. Several strategies can be employed to achieve cost savings and promote sustainability in road construction. One such strategy involves optimising the design of roads, which entails investing in comprehensive planning and design processes to minimise material waste and decrease construction time. Additionally, considering various factors such as traffic volume, soil quality, and climate can contribute to the development of roads that have a longer lifespan, thereby reducing maintenance costs. In addition, the utilisation of recycled materials and locally sourced materials, such as RAP and recycled concrete aggregates, serves to mitigate the demand for fresh resources. Conducting life-cycle cost studies is crucial in order to make informed/conscious decisions on road construction, as it allows for a comprehensive evaluation of the overall cost encompassing upkeep and operational expenses during the road's entire lifespan. The implementation of strategic approaches can enhance the cost-effectiveness and environmental sustainability of road construction projects, thereby yielding advantages for both the community and the environment.

1.2 Problem statement

The highway, especially the pavement, due to its importance for transport and socioeconomic activity over the long term, should permanently present satisfactory performance. This satisfactory performance is reflected in the offer to the user of traffic conditions that are safe, comfortable, and economical - given the precepts of optimising the total cost of transportation.

Acknowledging such a need that civilization has for this intermediate process comes from the reasoning that it is vital to socioeconomic development to create conditions under which transport can be done so that their productivity can be optimized. Furthermore, there is a real need to provide infrastructure to enable people and products to travel around the planet harmoniously from a social and economic point of view. The consumption of approximately 1.52 billion tonnes of virgin aggregate and 80 million tonnes of bitumen for the production of 1.6 billion tonnes of asphalt around the world shows the importance of an environmentally sustainable approach in terms of reducing environmental effects and natural resource consumption. The spread of pavement recycling has the potential to create about a billion $/year in economic value worldwide. This will only be possible with the application of correct processes to waste material, not wasting it, and using effective techniques. Thus, the resulting effects of environmental and natural resource consumption in production processes will be minimised [1].

When dealing with the economic and environmental aspects of the reuse of materials, waste material reuse has great potential to meet these needs. The asphalt material derived from the milling of the pavements is another material that needs to be studied because tonnes of this material are deposited along the highways for every maintenance of a road stretch, often without an appropriate destination. The correct use of this material serves as an alternative to the consumption of natural aggregates now widely used on the design of asphalt mixtures on pavements.

The research intends to structure an analytical procedure, duly validated with analysis of laboratory experiments, that returns design solutions for bituminous mixtures for base layers and road superstructure binders that comply, on the one hand, with the mechanical requirements indicated in the current Special Tender Specification and Technical Regulations of the sector for the control of road materials and, on the other hand, those of an environmental nature for the return of an eco-sustainable final product. The research pursues strategies for the prevention of natural resources, with the production of asphalt blends and mastics at hot and cold temperatures with alternative materials as solutions for milled products, integrating waste from industrial processing processes and/or from construction and demolitions of civil engineering works in the optimisation procedures of mastics and asphalt mixtures, in favour of solutions with high and low thermal inertia with a reduced quantity of raw material to be used and consequently waste to be sent to landfills.

Furthermore, the research was developed on a three-year basis as part of this Ph.D. programme and has as its objective the formulation and validation of a methodological procedure, as transversal as possible, which is supported by experimental laboratory phases functional to the definition of feasibility and efficiency of possible intervention scenarios for the alternatives to reduce the environmental impacts mentioned above, introducing the alternative materials via the use of technologies studying the different phases for the composition of an asphalt blend. At the end of it all, the creation of an automatic digital system involving the Building Information Modelling (BIM) and laboratory phases of the same scheme will be performed. This aims to create a complete decision support tool that can return, based on discriminating variables, appropriately integrated with a sufficient level of detail in the specific BIM semantics of the roads, such as the performance of the bituminous mastics and mixtures (i.e., mechanical performance, environmental sustainability and social, costs).

As described above, this fully complies with the objectives formulated by the European Union in the field of Circular Economy (COM 302, 2003; COM / 2015/0614), as well as the deadlines set by the Decree of the Ministry of Infrastructure and Transport No. 560 of 2017, which binds technicians to use electronic methods and tools in the management of all infrastructural works starting from January 1st, 2025.

1.3 Research aims and objectives

The aim of this research is to evaluate the feasibility of using a more sustainable asphalt pavements for roads which maximizes the recycling and re-use of potential waste by incorporating the maximum amount of it for the design of a bituminous mixture. The asphalt technology will be designed in order to be a cost-effective solution which maximizes the amount of recycled materials and minimizes the overall environmental impact. For this purpose, the first part of this work is aimed at developing procedures and strategies to better understand the role of this waste materials within the mastic and asphalt mixtures. The second part of this work aims at developing a comprehensive framework for modelling road engineering into the BIM.

Among the numerous problems that have emerged by analysing the literature concerning the road materials sector and the evolution of BIM applied to road works, as reported in the next paragraph, the major criticalities that need to be addressed in the present research are:

I. Correct and accurate assessment of the feasibility of reuse of each selected waste starting from environmental compatibility, in line with what is specified in annex 3 of the Ministerial Decree February 5, 1998, where the need for a transfer test is declared in accordance with appendix A to the UNI 10802 standard, which however refers to the waste as it is and not to its inclusion in the mixture which, in fact, it is intended to elaborate while looking for a guiding protocol, in line with what is currently available for the other fields, advancing corrective hypotheses and additional tests for the specificity of the material treated and studied in this work;

II. Studying the alternative materials from an environmental point of view; validation of a procedure for the characterization of the specific waste in terms of compliance as aggregates and fillers obtained from natural and recycled materials for use in bituminous mixtures, with specific geometric requirements, physical, and chemical composition;

III. Studying the rheological properties of the asphalt blends containing alternative materials in terms of elasticity, viscosity and plasticity, in order to know about the deformation behaviour and flow of these materials submitted to a stress/strain that will be applied on the mastic and the asphalt mixture. The dynamic of the mixtures will be initiated with the optimization: granulometric curve individualization, optimum bitumen content, statistic and dynamic (Stiffness Test, Double Wheel Tracking Test, Water Sensitivity Test, Tensile Strength Ratio Test);

IV. Analysing the relation between the mastics and asphalt mixtures. Identifying the optimum solution with alternative material and involving it into the design and verification of a pavement stratigraphy. This phase will be carried out with particular attention through the integration of methodological, structural and performance analysis with BIM tools;

V. In addition to all of this, this research also proposes a framework for effective calculation and analysis of the pavement structure, which integrates Revit, Dynamo, and other supporting techniques such as program Python programming language and MEPDG (Mechanistic-Empirical Pavement Design Guide). The framework will be described in setting parameters, implementation association of pavement structural analysis with design parameters, and realising the integration of pavement structural design and analysis. The framework will be able to provide information on structure analysis results based on the designed 3D visualization pavement model and the corresponding parameters. The subsequent segment will explain, in the development of this research, the structure and the contents of the solutions provided in this framework in detail:

- Setting of variable parameters;
- Implementation of the predictive model;
- Association of pavement structural analysis with design parameters;
- Realising the integration of pavement structural design and analysis.

VI. Digitalization of the road pavement design and management process, in compliance with the Ministerial Decree n ° 560 of 2017, or that the use of electronic methods and tools will be mandatory for all public construction and infrastructural works starting from January 1, 2025. The research aims at the drafting of digital plans for the structuration of asphalt blends of the superstructure road in the BIM environment, an aspect that is currently still little explored in the field of road infrastructures. The main methodological advancement necessary to achieve this goal is the integration of BIM with data management and information management, essential for managing the work's life cycle;

VII. The ultimate goal is to design a complete decision support tool that it can return, on the basis of discriminating variables appropriately integrated with a sufficient level of detail in the specific BIM semantics of the roads, such as the performance of the mixtures (i.e., mechanical performance).

1.4 Outline of the thesis

Chapter One: Introduction with an overview and background information about the recycling of asphalt pavements. Also includes the problem statement associated with the emission of pollutants by the production of asphalt mixtures and detailing the research aims and objectives.

Chapter two: Presents an up-to-date literature review of the topics discussed in this thesis. These topics contributed to understanding the research field and included: experimental works with asphalt pavement, RAP, and plastic waste; sustainable asphalt pavement in relation to the cold mixture asphalt; a BIM study; and an investigational assessment of the incorporation of marginal components into asphalt mixtures.

Chapter three: Description of the current practice of the reemployment of Rap and PW into asphalt mixtures according to legislative framework; explanation of Life Cycle Assessment in road infrastructure projects; Minimum Environmental Criteria and legislative utilisation of BIM in roads.

Chapter four: In this chapter, the material study is realised. These materials are the plastic waste, for example: the Polyethylene (HDPE), the Polypropylene (PP), and the Polyethylene Terephthalate (PET); the reclaimed asphalt pavement, and the binders that structured all asphalt blends. The findings derived from this section will be utilised in Chapter 5.

Chapter five: Illustrates the methodology programme. This part included a comprehension of the binder rheology in relation to the asphalt mixtures. Also, it describes the methods used in this research for testing recycled binders and mixtures. These tests access conventional and rheological properties of binders and performance-related properties of binders and mixtures by means of complex/stiffness modulus, permanent deformation (rutting), fatigue, and water sensitivity. Furthermore, this chapter explains to software to analyse the stress and strain in a pavement structure.

Chapter six: Emphasises the experimental work programme as an essential step to achieve the goal of this thesis. Laboratory work included the optimisation of asphalt blends made with PW, the optimal aggregate size, cement content, bituminous emulsion and water. Moreover, this chapter demonstrates the advanced characterization of mechanical properties and the design and verification of the best sustainable flexible pavement solutions, in relation to both software, the rutting and fatigue cracking law verification, and finally, elucidating the identification of the optimal thickness pavement payers. The results obtained from this chapter are to be used in Chapter 7.

Chapter seven: On this part, the creation of pavement information models in the BIM environment was of paramount importance to achieving the objectives of this thesis. This phase was divided into information template definition, the development and addition of properties to sets, and the design of analytical tools to draft a Performance Management System (PMS). It means the creation of a complete and reversible decision support algorithm based on discriminating variables appropriately integrated with a sufficient level of detail in the specific BIM semantics of the roads, such as the performance of the mixtures.

Chapter eight: Presents all results obtained during all experiments carried out on this study, and afterwards the final chapter.

Chapter nine: In this chapter, the main conclusions and recommendations for future research are introduced.

2 LITERATURE REVIEW

Existing in all parts of the world, the waste materials quantity generated annually is about of 4 billion tonnes approximately, according to the most recent investigation from the International Solid Waste Association. About this waste production, half of the waste is urban, while the other half is special waste generated by industrial and production activities.

2.1 Experimental works on the asphalt pavement

The conduct of experimental studies on asphalt pavement serves a crucial role in the advancement and enhancement of the infrastructure of roads. These studies may be undertaken either in laboratory settings or in field environments, with a primary emphasis on investigating different facets of asphalt mix design, building methodologies, and pavement maintenance. The objective of these trials is to improve the longevity, security, and efficiency of asphalt pavements. There are a multitude of domains for investigation and research within this particular topic.

The need to convert current consumption and lifestyles has emerged with increasing vigour in the last twenty years, inevitably also involving the scientific world. Already during the World Summit on the sustainable development of production and consumption models, the need was highlighted "to reverse as quickly as possible the current trend of the degradation of natural resources", favouring a better destination in terms of the environment, considering the technological possibilities and socio-economic aspects. The exponential growth of the urban population, which marked a turning point in forecasting trends, requires the search for innovative solutions capable of responding to current challenges, most and foremost that of coping with climate change and reducing the need for fossil resources.

It is clear that the transition towards an environmental sustainability paradigm must take place through approaches and methods appropriate to the complexity of the elements at stake. In other words, it is necessary to abandon logics and approaches that allow partial solutions in favour of a global vision and of a system capable of grasping the relationships that are generated between the elements, recognising their complexity, and identifying tools and methods to support the action of knowledge necessary for the definition of possible solutions and achievable objectives. This perspective pushes towards the definition of new methodologies, towards the adaptation of traditional intervention tools, and towards the identification of solutions that are oriented towards well-being and sustainability.

In the current situation to develop solutions for the environmental sustainability paradigm, several actions and policies, such as the New Green Deal and the Circular Economy Action Plan are rowing in the direction of the importance of a product's "green design", saving raw materials, and waste prevention oriented along the entire life cycle of a product. Another action, it is the European Green Deal (EGD), which proposes an aim for Europe to become the world's first carbon-neutral continent by 2050 and, through this aim, strengthen European cohesion [2]. Only with a shift in the economy applied to a new development path can the EGD be successful, generating broad political and social support from the beginning. In Europe, this necessitates tangible enhancements in living standards across all socioeconomic strata and religious affiliations. Furthermore, these progresses must be rationalised in terms of how climate policy can incentivize a shift towards an alternative trajectory of development. [3, 4]. Furthermore, also reflecting the principles of the circular economy within the field of pavement study, recycling of plastic waste is primarily intended for the manufacture of new and innovative polymers, designed to modify pure bitumen or to be used as an alternative aggregate and/or filler.

To make a major reduction to the environmental impact of construction, at the beginning and at the end of the materials' life, an efficient use of these materials plays an important role [5]. This benefit would be achieved mainly by a depletion reduction of finite natural resources and an increase in dependence on landfills. Construction and buildings are responsible, in the EU, for about 40% of the total energy consumption and about 36% of the greenhouse emissions [6]. However, the transport sector, in accordance with the European

Commission, is one of the main sectors responsible for air pollution in cities, and regarding Europe's GHG emissions, it is responsible for about 25% [7, 8], mainly because of road transport to perform the transport of freight and people [9, 10]. Transportation is the primary need on human beings and developing sustainable transportation facilities is of main concern. At the EU level, it is recognised that there is a need for improved use of natural resources and more sustainability in the construction industry through the Raw Material Initiative [11]. Asphalt pavement manufacturing is an industrial sector in which material production, construction, service, maintenance, and end-of-life are those phases where energy consumption and GHG emissions occur. About 1.6 billion metric tonnes of asphalt were produced worldwide in 2007 [5], which resulted in 14.4×10^{6} m3 of fuel, 1.28×10^{4} GWh of electrical consumption, and 46.08 million tonnes of CO_2 emissions, accounting for 0.15% of global CO_2 emissions. The situation referred to reflects the challenging goal established to rise across the EU: the recycling and recovery of Construction and Demolition Waste (CDW). Thus, the sustainability of pavement assets is triggered by the ideal balance among economic, engineering (performances), and environmental factors, as shown in Figure 1.

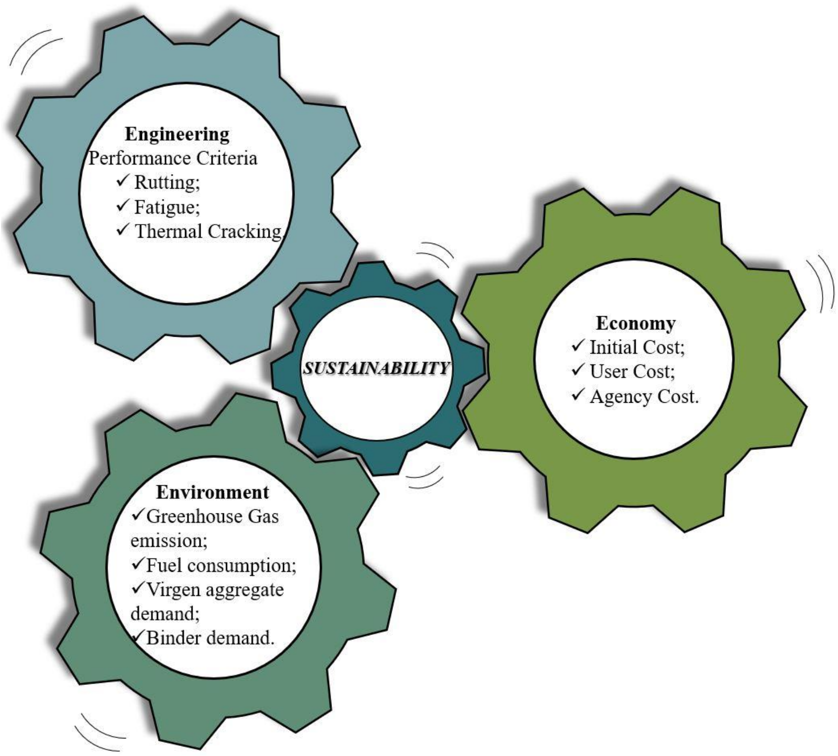


Figure 1 – Pavements Engineering Sustainability.

According to different research studies, the recovery and recycling aggregates can be used for several construction purposes. In view of the internal structure parameters of asphalt mixtures, the CDW is excellent, meeting the mix design standard model for heavy traffic and reducing GHG emissions, based on the characterization and behaviour knowledge of the material [5]. Besides that, according to Fatemi et al. [12], the thickness of the asphalt layer can be reduced when an appropriate percentage of recycled aggregates is used in the mix design, resulting in a reduction of road construction total costs and an environmental impact. Pederneiras et al. [13] elucidates the potential to consider a suitable mixture, establishing coarse natural aggregates and about 30% of recycled aggregates for paving. The decrease in energy consumption and GHG emissions, life cycle extension, and better serviceability can be achieved by the exploitation of waste materials, such as reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), and crumb rubber modifier (CRM), and/or the adoption of warm mix asphalt (WMA) technologies.

About the temperatures and the reduction from gas emissions, the WMAs present benefits important to the environment since this typology of asphalt mixtures decreases GHG emissions and fuel consumption. Due to less harmful emissions, the WMAs mixtures improve the working conditions for paving crews, the binder ageing is also reduced, hauling distance can be increased, the field densities can be potentially increased, it means better compatibility, and the paving season can be extended [14].

The durability of the bituminous layers of road pavements is significantly influenced by the mastic, based on its nature and composition. Playing a fundamental role in bituminous mixtures, the filler is a mineral aggregate that fills the interstices between the larger aggregates, improving the consistency of the bitumen and increasing the bonds between the larger particles. The main effect of the mineral filler is to stiffen the bitumen and, consequently, to improve the mechanical properties of the bituminous mixture. The mastic's stiffening effect stays in the mixture from the time it is built until it is used up. This affects the flooring's ability to withstand permanent deformations at high temperatures, fatigue phenomena at intermediate temperatures, and brittle breaking strength at low temperatures. Numerous researchers have studied the stiffening effect of the fillers, and their findings [15] demonstrate that the mastics exhibit reduced sensitivity to permanent deformations at any test temperature and level of applied load compared to the corresponding bitumen. The results from the analysis of mastics containing products deriving from coal combustion by Bautista et al. [16] affirm that the rheological behaviour of mastics depends on an interaction between the filler and the bitumen, but they suggest investigating the nature of this interaction with consequent quantification of the filler-bitumen ratio.

The rheological properties of bitumen are influenced by the materials used as filler. Many researchers investigated the rheological properties of asphalt mixtures containing waste filler in substitution of the traditional one with the aim of obtaining improvements in performance. Stiffening the bitumen is the principal effect of the filler; therefore, the mechanical properties of asphalt mixtures are enhanced. The studies conducted by Bautista et al. [16], Cardone et al. [17], Rieksts et al. [18], and Liao et al. [19] elucidate that the stiffness of the mastics is affected by the filler shape, size distribution, void space, surface area, and texture, such as physical characteristics and volume concentration, of mineral fillers, together with the physical-chemical synergy between the bitumen and filler.

Rieksts et al. [18] carried out a laboratory analysis regarding the effect of three types of mineral fillers (Jelsa Granite, Portland Cement, and Aggersund Limestone) and how they could highly influence the rheological properties. These fillers were assessed according to some common filler characteristics. A better stiffening effect is shown by results about the limestone filler, indicating in most cases lower values of non-recoverable compliance (J_{nR}), and it doesn't give a high stiffening potential, but performance is very similar when compared with mastics produced with cement. Also, this type of filler indicated, regardless of the temperature conditions, the highest recovery percentage. Explained the crucial role of fillers in asphalt mixtures, for a better understanding of the asphalt mixtures, their mechanical characterization is fundamental in relation to common asphalt pavement distresses.

A material that also influences the rheological properties is bio-oil in the production of bio-binders. The bio-oils from different resources can have other functions with regards to the effect on asphalt binder performance [20, 21]. According to Woldekidan et al. [22], the asphalt binder can have an improvement in the performance of bio-oils originated from waste cooking oils. Also, the viscosity and softening point of aged asphalt binder can be considerably reduced by the addition of waste cooking oils [23]. Furthermore, the use of waste oils to make asphalt mixtures is a sustainable way to dispose of this kind of waste material.

Nascimento et al. [24] wrote that the stress-strain curve parameters from the ITS test are compared with the permanent deformation results from a French wheel tracker. Using SUPERPAVE and Marshall mix designs, this study was conducted on six different varieties of asphalt concrete with a focus on airport applications. As results, for determining the rutting resistance of an asphalt mixture, the instrumentation of specimens with strain gauges for observing the deformation during the indirect tensile strength test was effective. Because of this, the research on the indirect tensile strength test of how tensile and compression work together can be used to figure out the shear strength, which will change how the mixture deforms over time.

A different study on the ITS test from [25] uses the main aggregate structure porosity and the ITS criteria to come up with a way to find the right amount of bitumen for a certain foamed bitumen mix. The aggregate gradation is broken down into three aggregate structures—oversize, primary, and secondary—using packing theory ideas. The primary aggregate structure's initial bitumen content is chosen using a maximum value for porosity of 50%. In addition, it is advised that this bitumen content be refined using a minimal indirect tensile strength standard. This method lets a bitumen content value be set before any experiments are done because porosity is based on physical factors like the specific gravity of the aggregate and binder and the gradation of the aggregate that are known before the mix design process. Whenever the indirect tensile strength is calculated in the lab, the bitumen content is later refined. With this approach, less time and material could be needed to complete the mix design process.

A research from Islam et al. [26] highlighted the ITS test's laboratory equivalence to field ageing due to the test's ease of use and variety of applications in assessing the performance of asphalt concrete (AC). To estimate the ITS value and flow number, cylindrical samples were compressed in the lab, aged there and in the field, and then loaded diametrically. Six sets of compacted samples were tested using the ITS method after being aged in a laboratory oven for 1, 5, 10, 15, 20, and 25 days at 85 °C, and 11 sets of compacted samples were tested after being aged in the field for 1, 2, and up to 12 months. A third set of specimens, whose loose mixtures had been aged in an oven for 8, 16, 32, 48, 72, and 100 hours at 135 °C, also underwent the ITS tests. As anticipated, the ITS of laboratory-aged samples (both compacted and loose) and field-aged samples rises while the flow number falls over time. This study discovered that, when assessed in terms of ITS value, one day of laboratory ageing is equivalent to around one year of outdoor ageing. The ITS value grows during the conditioning time, reaches a peak, and subsequently declines during the conditioning phase, according to the results of loose mix aging. Overall, as ageing intensity grows, the flow number drops, meaning that brittleness rises with age. The asphalt mixture dynamic modulus ($|E^*|$) is widely recognised as the essential mechanical feature that has a significant impact on the quality and operational life of asphalt pavement. One of the most essential inputs in mechanistic-empirical (ME) pavement analysis and design is also the dynamic modulus of asphalt mixes. Several models based on mixture volumetrics and material characteristics have been developed to estimate the dynamic modulus.

A study from Al-Tawalbeh [27] aims to calibrate and evaluate two regularly used models for forecasting the dynamic modulus of asphalt mixes in Qatar (the Hirsch model and the Alkhateeb model). The Hirsch model was shown to have a strong prediction performance of asphalt mixture moduli before calibration, with a coefficient of determination (R2) of 87.2% between predicted and measured values, based on the study results. This value of R2 increased slightly after calibration to 89.2%, whereas the Alkhateeb model had a determination coefficient of 78.8% before calibration, which improved to 89.2% after calibration. This study used the Hirsch model moduli predicted after and before calibration to do a mechanistic-empirical investigation of the performance of several common pavement sections in Qatar. The percentage change in anticipated fatigue damage owing to the employment of the calibrated Hirsch concept reached more than 50%, including an average value of 17.33%, while the percentage change in rutting reached 14% with an average value of 3.65%. These findings emphasise the need to adopt locally calibrated dynamic modulus models to enhance performance forecasts.

Ground penetrating radar (GPR) technology is indeed a promising tool for determining asphalt pavement material information. Its application is backed by research into the link between GPR waveform characterizations and metrics characterising asphalt pavement condition. Nevertheless, it is rarely used to forecast the dynamic modulus of an asphalt mixture. To address this gap, a research from Cui et al. [28] focused on building the appropriate dynamic modulus prediction approach using GPR data. The suitability of the ϕ 38 mm × h 110 mm small-scale specimen encompassing a wide range of air void content in the uniaxial compression test was first investigated. The empirical and artificial neural network (ANN) dynamic modulus prediction models were then created, taking the dielectric constant of the asphalt mixture into consideration. Finally, the two suggested models were evaluated in the field using four asphalt mixture lanes. The test faults of small-scale specimens were found to be less than 15%, and the statistical difference in dynamic moduli and phase angles determined from full-size and small-scale specimens was shown to be negligible at the 95% confidence level, indicating that the size influence may be ignored. The verification experiment revealed that the suggested empirical model and ANN model could produce acceptable results with average prediction errors of 19.3% and 24.8%, respectively. As an alternative to the current methods for finding out the dynamic modulus of an asphalt mixture on-site, the two presented predictive models should be used when combined with GPR data.

The study of [29] about the stiffness of asphalt mixes subjected to short-term and long-term ageing was the topic of this work. Asphalt mixes are subjected to this sort of ageing during manufacture, laying, and compaction, as well as throughout service. The study was conducted on asphalt mixture test samples AC11 50/70 and AC11 PMB 45/80-75 for the asphalt pavement wearing course. The conditioning of loose mixtures approach was used to expose the asphalt samples to the impacts of short-term and long-term ageing. Following that, the stiffness modulus of asphalt mixes at 20 °C was evaluated using the EN 12697-26 IT-CY technique. The stiffness modulus values obtained for the combination with paving-grade bitumen 50/70 were greater. The stiffness modulus difference was greatest for original asphalt mixes. Furthermore, an increase in the stiffness of the combination owing to ageing was noted, which was more obvious in the case of the mixture containing the polymer-modified bitumen PMB 45/80-75. Gradual ageing alters the characteristics of asphalt mixes, which are critical for road resilience.

The noteworthy growth of reuse and/or recycling of waste in asphalt mixtures has unleashed in less waste being dumped in landfills and more environmentally friendly asphalt mixtures. The Life Cycle Assessment (LCA) is the most often used approach in the asphalt mixes sector of the road building industry. According to Oreto et al. [30], numerous research focus on the LCA of various asphalt mixes comprising waste to evaluate the improvement from a mechanical viewpoint as well as from an environmental perspective when the waste is used as a replacement for primary resources. The energy consumption and accompanying GHG emissions over the lifespan of the pavement could be assessed using the LCA, and these emissions were larger than those generated during the building period [31].

2.1.1 Reclaimed Asphalt Pavement (RAP)

The Recycled Asphalt Pavement (RAP) pertains to the utilisation of recovered or recycled asphalt material in the establishment or upkeep of novel asphalt pavements. Asphalt pavements, which are often seen on roadways, motorways, and parking areas, are comprised of a composite blend of asphalt binder and aggregate substances. Over the course of time, the condition of these pavements may degrade as a result of many causes, such as weathering, vehicular activity, and the natural process of ageing. The RAP presents itself as a viable and economically efficient approach, whereby the deteriorated asphalt elements are repurposed for the construction of fresh road surfaces, circumventing their disposal in landfills.

The potential worth of the materials found in aged asphalt pavements persists, even when reaching the termination of their operational lifespans. The recognition of the inherent worth of aggregate and asphalt resources has led to a greater use of RAP in the construction of new asphalt pavements. Moreover, there has been a significant surge in interest surrounding the utilisation of RAP due to the recent escalations in crude oil prices and the overall energy sector. The demand for new materials is greatly reduced when the use of asphalt recovered and aggregate from deteriorated pavements is practised, consequently, it results in a minimisation in respect to the cost about to pavement improvement. Moreover, several studies have shown that asphalt mixes using RAP exhibit comparable performance to virgin mixes while simultaneously mitigating the environmental footprint [32].

In respect of the asphalt mixture, the advantage of the use of RAP can be in the potential of replacement of aggregates and virgin binder into this mixture [33]. The advantages associated with the utilisation of RAP are linked to the potential to replace natural aggregates and virgin binder in an asphalt concrete mixture. This substitution helps to mitigate the adverse consequences arising from the production process of HMA while minimising any detrimental effects on the desired mechanical properties. There is currently no universally accepted protocol for the optimisation and validation of a mixture that includes RAP. However, there is a significant need for such a technique.

In a study conducted by Sangiorgi et al. [34]., an examination was carried out on the dynamic as well as static mechanical properties of bituminous mixtures. The focus was on the utilisation of cold reclaimed asphalt (CRA) at 100% of reclaimed asphalt pavement (RAP) for the base layer of pavement. The researchers found that this approach did not have a detrimental impact on the performance of the mixture, its susceptibility to water, or its sensitivity to thermal conditions, when compared to hot mix asphalt (HMA).

Lyu et al. [35] conducted experimental studies to identify an effective method for incorporating Crumb Rubber Modifier (CRM) into bituminous mixes. The study focused on analysing several attributes, including high temperature performance (at 60°C), moisture stability (evaluated using Marshall Stability and Indirect Tensile Strength Ratio), and fatigue damage. The mixture consists of 3.8% emulsified asphalt, 2% cement, and 80% reclaimed asphalt pavement (RAP).

In their study, Arshad et al. [36] examined the impact of incorporating cementitious road additives (CRA) into recycled concrete aggregates (RCA) inside the base/subbase layer of a flexible pavement. The authors observed that the inclusion of RAP concentration ranging from 0 to 50% resulted in an augmentation of both the robust modulus and confined modulus. Furthermore, the mechanical characteristics of cold bituminous mixtures incorporating 100% Construction and Demolition Waste Aggregates (CDWA) were assessed by Gómez-Meijide and Pérez [37]. Their study revealed that the Indirect Tensile Strength (ITS) of these mixtures increased by up to 12.8% or more when compared to a conventional Hot Mix Asphalt (HMA), with the addition of 15% water and 5% bitumen based on the weight of dry aggregates. Numerous investigations have been dedicated to investigating the characteristics of the curing process of CRA mixtures [38]; [39]; [40]; [41].

2.1.2 Plastic Waste (PW)

As an escalating environmental crisis, the plastic waste is a trouble that plagues our planet. The plastic pollution has reached such a catastrophic level, due to the fact that it has a non-biodegradable nature and prolific use, that threatening ecosystems, our human health and also the very essence of sustainable living. Being affordable, versatile and durable, an ubiquitous product have the plastic become in our daily lives. A vast amounts of fossil fuels is needed to the production of plastic, what also contributes to the GHG emissions, exacerbating the climate change.

About the reduction of the production of plastic, and consequently plastic waste, a multifaced approach is essential to combat this crisis. The recycling is one crucial component of this solution. The development of innovative recycling technologies, such as chemical recycling, can break down plastics into their original components, allowing for a more efficient and sustainable use of plastic waste.

Several are alternatives that integrated into different areas can be the solution to tackle the problem with the plastic waste. Regarding to the road construction, the incorporation of PW into the design of asphalt mixtures is a solution of paramount of importance that do its part for the environmental.

The plastic waste re-use point of view, many investigations in the field of this typology of material have, shown an improvement in the binder properties when the waste plastic is adopted to modified it. A significant aspect of the analysis of the waste plastic for asphalt mixes is that 10% of the weight of asphalt binder having particles less than 2 mm in size is the appropriate amount of plastic to replace asphalt binder [42].

The recycling of plastic waste is of the utmost importance, as much from an economic standpoint as from sustainable factors. In addition to reducing the exploitation of natural resources, it reduces the level of environmental pollution, saves energy and resources, and contributes to modifying the properties of some engineering construction materials, such as concrete buildings and asphalt [43].

Polyethylene (PE) is the easiest and most generally used synthetic polymer [44]. The use of abbreviations such as PE for polyethylene, PS for polystyrene, PVC for polyvinyl chloride, and PET for polyethylene terephthalate is often referenced. In the same study mentioned above, it assessed the use of a very common and widely available flexible plastic for bitumen modification, Low Density Recycled Linear Polyethylene (R-LDPE). In the road sector, blends of R-LDPE base and modified bitumen were compared for enforceability using thermal, rheological, chemical, and physical evaluations. As conclusions, this study showed that as much as 3% of recycled flexible plastics have been estimated to be suitable for bitumen alteration, and over 6% of the bitumen viscosity was severely impacted by recycled soft plastics. Furthermore, the improvement in rutting strength (MSCR test) has been acknowledged with an increase in plastics, and the monitored sources of plastic waste have been identified as suitable for bitumen modification.

A research by Abed et al. [45] was carried out to examine the influence of Nano-High Density Polyethylene (Nano-HDPE) particles and Styrene-Butadiene-Styrene (SBS) on the rheological properties of modified asphalt binders and the performance of modified asphalt concrete blends. The research studied how the base asphalt binder of the PG (64–16) grade was modified with Nano-HDPE and SBS polymers at concentrations of 3% and 5% by weight of the total asphalt binder content. As results, the viscosity of modified binders with SBS is considerably greater than that of modified binders with NHDPE and base asphalt especially at a SBS concentration of 5%. In addition, superpave rheological properties results clearly demonstrate that according to the small strain Linear Visco-elastic (G*/sind), the SBS-use obtains a greatly better PG grad than that of HDPE at an equivalent polymer concentration in the asphalt base. The wheel tracking test results, on the other hand, conclude that 5% SBS in the base asphalt binder performed worse than 3% of the Nano-high density polyethylene (Nano-HDPE). The results of rutting, although they have a positive influence on the permanent deformation resistance of modified trigged by the SBS and Nano-HDPE, the effects are not related to alterations qualified by the G*/sind. There is, therefore, an additional need for attention regarding G*/sind in reaching decisions on the selection of the modifier for rutting resistance.

A research conducted by Almeida et al. [46] analysed the applicability of the LDPE flakes as aggregates arising from urban waste in the structuring of the hot mix asphalt implemented in surface layers. Subsequently, the behaviour was assessed considering the unaged and aged mixtures mentioned by testing for fatigue, rutting, and stiffness resistance. The results of the research elucidated that mixtures structured with 6% LDPE by the total weight of the bitumen led to an average resistance reduction of about 7% with respect to the reference mixture structured with limestone and gneiss (1 million cycles), with 5% Optimum Bitumen Content (OBC) and 16 mm as the maximum size, in other words, a low fatigue-cracking resistance. However, alternatively, enhancement of the resistance to rutting, with up to a 66% increase in the reference mixture, allows the possibility for an additional 30% reduction when aged.

The engineering and construction endeavours explore potential applications for repurposing polyethylene terephthalate (PTP) waste polymers, such as its use in road pavement construction. In addition, there is consideration of strategies aimed at enhancing the characteristics of asphalt mixes and asphalt binder. Hence, the primary aim of El-Naga et al. [47] was to examine the impact of using PTP on enhancing the characteristics and functionality of asphalt pavements. The primary objective of this study was to assess and measure the notable benefits associated with modifying asphalt in the pavement infrastructure. The laboratory conducted tests on an asphalt binder that had been changed and prepared in a clean manner. The findings indicated a propensity for enhanced strength in asphalt mixes upon the introduction of this modification. The maximum achieved efficiency of asphalt mixes is 12%, with the subsequent utilisation of the optimised proportion of PTP. The results of the quantitative analysis demonstrated that the incorporation of 12% PTP yielded a significant improvement in the longevity of the road, with an estimated increase of 2.81 times. Additionally, this inclusion led to a reduction in the thickness of the asphalt layer by roughly 20%.

The study conducted by Veropalumpo et al. [48] focuses on analysing the volumetric and mechanical properties of hot bituminous mastics that use plastic waste (PW) as a filler material. The production of the PW is limited to diameters not exceeding 2 mm, while its melting point spans from 120 to 260 °C. According to scanning electron microscopy (SEM), the PW exhibits a mesh-like structure composed of elongated fragments that possess a much rougher surface compared to standard limestone filler. In the first stage of the study, a total of nine distinct mastics were generated. Upon increasing the mixing duration from 10 to 60 minutes, no significant deviations were seen in terms of the softening point, penetration at 25 °C, or dynamic viscosity at 100 °C for any of the mastics. A 10-minute time interval was selected for the purpose of blending all the mastics. The two most optimal solutions resulting from this approach consist of a combination of 5% LF and 15% PW (HLP02) and 20% PW (HP02), respectively, with both solutions having an overall weight of B5070. In this particular case, it was seen that the shear modulus G* of mastics containing PW exhibited a significant increase in comparison to B5070 and typical mastics composed of LF. Furthermore, this difference becomes more evident as the temperature approaches 50 °C, which is the point at which HP02 demonstrates its greatest performance. The HP02 and HLP02 solutions displayed favourable recoverable deformation at two test temperatures and two stress levels without necessitating the completion of the last step of the unloading cycles. These observations constitute the primary conclusions of the MSCR study.

Another research realised by Veropalumpo et al. [49] focused on a novel laboratory technique for conducting measurements to evaluate the materials utilised in the building of road pavements, with a particular emphasis on their multiscale properties. In order to obtain more precise information, an investigation was conducted on the engineering performance of durable hot asphalt mixes, including plastic waste as a filler. The objective was to gain insights into the physical and mechanical characteristics of both aged and fresh mastics, since these features significantly influence the design and long-term resilience of the end result. Asphalt mastics, which are composed of bitumen-based compounds, play a crucial role in providing cohesiveness to the overall asphalt mixture. The composition of these substances consists of bitumen and filler, with varying mass percentages ranging from 70 to 100 for a sieve size of 0.063 mm. Based on an analysis of the ratio between the Storage Modulus (G') and the Loss Modulus (G''), it was found that solutions containing 15% plastic waste and solutions containing 20% plastic waste (referred to as PW20) combined with 5% limestone filler demonstrated greater durability compared to other solutions (referred to as LPW20). These solutions exhibited the highest ratio values, with mean enhancement values of 64% and 57%, respectively. Additionally, they displayed the highest degree of elasticity at 0.1 k and 3.2 kPa within the temperature range of 40 to 50 °C. Notably, these solutions maintained an elasticity similar to that of the reference material (MB) even after the loading phase, without requiring a recovery period.

The aforementioned research [48, 49] primarily examined the use of plastic waste as a substitute for conventional limestone filler in hot asphalt mastics, with a particular emphasis on their mechanical properties. The abovementioned research mostly examined mastics rather than combinations. In contrast, the aforesaid research [50] and [51] conducted an examination of the mechanical properties of non-conventional Hot Mix Asphalt (HMA) materials, namely polymer compounds derived from recycled plastics. These investigations placed specific emphasis on the methodologies employed for laboratory mixing and sample compaction. According to the findings of the study conducted by researchers [50], it is recommended to employ a combination of wet and dry techniques in order to comprehensively assess asphalt mixes that have undergone modifications using recycled polymer components. Additionally, it was recommended that modifications be made to the laboratory procedures for sample mixing and compaction. The HMAPMB exhibited a higher fatigue line value compared to a conventional asphalt solution, indicating greater resistance to fatigue failure. Additionally, the HMAPMB showed a reduced propensity for cracking. The maximum fracture stress and fracture toughness exhibited an increase of 53% and 59%, respectively. It is noteworthy to observe that the utilisation of a recycled polymer compound in the production of asphalt yields enhanced resistance to crack initiation (32% increase in ITS), improved ITSM performance (11% increase at 10 °C, 18% increase at 20 °C, and 34% increase at 40 °C), superior resistance to rutting (1.86 mm rut depth compared to 1.92 mm), and extended fatigue life when compared to alternative asphalt solutions. In addition, the research [33] investigated the mechanical performance of untraditional hot asphalt mixes made up of a polymer combination of recovered plastics. The primary advantages obtained from the implementation are: a) There is an observed enhancement in the ability to withstand moisture-induced damage at a temperature of 15 °C. b) There is an increase in resistance to cracking at a temperature of 10 °C, as well as when exposed to hot asphalt. c) The material exhibits appropriate stiffness at temperatures of 10, 20, and 40 °C. d) The material has a significant resistance to rutting, as indicated by the minimal rut depth seen at a temperature of 60 °C.

Numerous investigations have been conducted and are now ongoing on the incorporation of polyethylene (PE) into asphalt mixes. The objective of this research is to leverage the advantageous physical and chemical attributes of PE in order to construct pavements that exhibit enhanced durability, thereby reducing their susceptibility to damage and extending their service life.

Incorporating recycled waste packaging polyethylene (WPE) particles into stone matrix asphalt (SMA) mixes was the subject of a study by Moghaddam et al. [52]. The incorporation of the residue was conducted using the dry method, employing particles with a maximum size of 2.36 mm. The residue was added at varying concentrations of 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1%. Consequently, the scientists noted that the blends incorporating WPE exhibited a higher stability value in comparison to the blends without WPE. Additionally, they observed that a concentration of 0.4% WPE yielded excellent stability. In addition, the inclusion of WPE in the mixture resulted in an increase in creep values, which represent the total deformation shown by the specimen from the initial application of zero load to the subsequent application of the maximum load, expressed in tenths of a millimetre. Additionally, it is emphasised that the stiffness of the mixes dropped as a result of the incorporation of increasing amounts of WPE. However, it is observed that the fatigue life of the mixtures grew correspondingly with the increased content of WPE.

In a study conducted by Moghaddam et al. [53], the comparison between asphalt mixes containing 1% PET by weight of aggregates and a conventional SMA revealed a drop of 12.4% in the indirect tensile stiffness modulus (ITSM) of the asphalt mixtures. This decrease was seen at a temperature of 20°C and an applied stress of 250 kPa. The explanation for this conclusion was provided by highlighting that, during the process of combination, a significant proportion of PET particles undergo a transformation in their microstructure, resulting in the creation of a crystalline structure. This alteration in microstructure contributes to an enhancement in the elastic deformation of the mixture rather than the melting of the PET particles. In contrast to the traditional shape memory alloy (SMA), the modified mixes using polyethylene terephthalate (PET) exhibited a significantly extended fatigue life of 124.8%, as determined by an indirect tensile fatigue test (ITFT) conducted in accordance with the EN 12697-24 standard at a stress level of 250 kPa.

In their study, Ziari et al. [54] employed a dynamic creep test and a Hamburg wheel tracking test to investigate the effects of varying proportions of recycled polyethylene terephthalate (PET) on the total mass of aggregates. The study also examined the influence of particle sizes, namely 10.25 mm, 20.25 mm, and 30.25 mm. They observed that when the combination comprises 1% 10 mm PET instead of a usual mixture with 0% PET consisting of 5.3% bitumen.

The research conducted by Arao [55] utilised crushed material with diameters of 10 mm and 2 mm. These materials were added to the asphalt hot mix plant at concentrations of 0.5% and 1.0%. Additionally, 2.5% of the stone powder was replaced with polyethylene powder, and 0.5% of crushed polyethylene with a diameter of 10 mm was also added. Consequently, the author concluded that the optimal approach would involve including 0.5% of 10 mm polyethylene flakes and substituting 2.5% of stone powder with polyethylene powder. Significant advancements were observed in mechanical outcomes, particularly with regards to the endurance capacity. Furthermore, the author discloses that the predominant practice involved the utilisation of a specific blend, which exhibited the highest rate of reusing polyethylene bottles. This blend, when applied on a two-lane highway with a width of 6 metres on each side, has the capacity to repurpose over 400,000 polyethylene bottles with a volume of two litres per km. This noteworthy achievement holds significant implications for both the environment and socioeconomic factors.

Padhan et al. (2019) [56] suggest that cross-linking additives and some reactive polymers could be used to solve the problems that come up when waste polyethylene-modified asphalt is put into use. The scientists also reached the conclusion that modifying the binder in this manner provides significant assistance in mitigating storage stability issues. Furthermore, the elastomeric characteristics experience a substantial enhancement, while the total rheological properties exhibit improvement.

The impact of the Warm Mix Asphalt (WMA) Additive on several rheological characteristics of asphalt binder, such as viscosity (δ), complex shear modulus (G*), and viscosity, was explored by Ye et al. in their study [57]. The researchers have also conducted an investigation into the fatigue characteristics of asphalt binders, as well as the low and high temperature properties of binders containing polyethylene (PE) modifiers. Additionally, they have performed a comparative analysis of asphalt binders modified with styrene-butadiene-styrene (SBS) and crumb rubber modifiers (CRM). The researchers reached the conclusion that the characteristics of asphalt binders at elevated temperatures may be notably enhanced by the use of various quantities and types of polyethylene modifiers. The enhancement of rutting resistance factor and high temperature grade in PE-modified binders is seen to be much higher when compared to the reference binder. The overall higher frequency leads to a decrease in δ and an increase in G*. The values of δ exhibited a drop, whereas the G* showed an increase in response to an increase in the content of PE across various shear strains and frequencies. This implies that the use of PE modifiers not only enhanced the viscosity of the binders, however also enhanced their flexibility. The performance of the reference binders, SBS and CRM, was shown to be superior in comparison to the PE-modified binders. Notably, the former exhibited a greater critical low temperature. The binders exhibited a decreased resistance to thermal cracking when subjected to increasing levels of polyethylene (PE). The fatigue characteristics of PE-modified binders exhibited notable enhancements, notably within the lower shear strain range. Based on the findings, it may be inferred that the incorporation of a PE modifier in asphalt binder adversely affects its low-temperature capabilities.

Polyethylene (PE), a commonly used recycled plastic material, has the potential to serve as a substitute for both virgin aggregate and binder components. The non-water absorbent nature of PE renders it effective in enhancing stripping resistance. Nevertheless, research has indicated that the incorporation of PE with a binder has a greater impact on the mechanical qualities associated with rutting, fatigue, and resistance to thermal cracking. Bio-binders encompass a diverse array of commodities, spanning from vegetable and cooking oils to processed wood and animal by-products. The majority of bio-binders exhibit favourable performance at low temperatures.

2.1.3 Sustainable asphalt pavement

The concept of sustainable asphalt pavement entails the use of environmentally conscious and socially accountable approaches in the design, construction, and maintenance of asphalt roadways and surfaces, reducing environmental harm and maximising resource efficiency. The primary aim of this methodology is to mitigate the environmental impacts linked to asphalt production and road construction while concurrently improving their long-term functionality and resilience. Some components of sustainable asphalt pavement are essential.

Sustainable asphalt pavements include *recycled materials* in order to mitigate the use of natural resources and energy. The use of RAP, as already mentioned in this research, is prevalent due to its capacity to minimise the need for primary aggregates and binder materials.

The *Warm Mix Asphalt* (WMA) refers to a set of technologies that enable the production and placement of asphalt at lower temperatures. This innovative approach offers potential benefits such as reduced energy consumption and decreased emissions of greenhouse gases when compared to the conventional method of using hot mix asphalt.

The *Porous asphalt* is a kind of asphalt pavement that has been specifically engineered to facilitate the permeation of water through its surface, enabling the water to permeate the underlying soil. This characteristic of porous asphalt serves the purpose of mitigating stormwater runoff and contributing to the replenishment of groundwater resources.

Thin asphalt overlays are often used in pavement preservation strategies since they require a smaller quantity of material. By using this approach, the lifespan of the road may be prolonged, thereby mitigating the necessity for extensive replacement.

The *Perpetual Pavement Design* is a technique aimed at optimising the longevity of pavement construction through the use of a multi-layer system. It effectively mitigates the need for regular repair and significantly decreases both material and energy usage in the long run.

The use of *modified asphalt binders* may include increased quantities of recycled or bio-based materials, hence leading to a more pronounced reduction in the overall environmental footprint.

The possibility of extending the lifetime of a road and reducing the need for costly and resource-intensive reconstruction initiatives exists with the deployment of *maintenance and rehabilitation measures*.

A methodology known as the LCA is employed to assess the environmental consequences that are linked to different pavement design and construction alternatives. This methodology considers various factors, such as resource utilisation, emissions, energy consumption, and energy output, throughout the complete life cycle of the pavement. In addition, specific sustainable bitumen initiatives strive to obtain LEED (Leadership in Energy and Environmental Design) certification as a demonstration of their commitment to environmental responsibility.

The potential benefits of integrating intelligent traffic management systems include improved traffic flow efficiency, congestion reduction, and the maintenance of road surface quality and longevity. In addition, the use of certain sustainable asphalt technologies has the potential to mitigate road noise, hence enhancing the environmental friendliness of highways in close proximity to surrounding populations. Likewise, relying on locally sourced resources may boost economic development in the area while also reducing emissions related to transportation.

The researches have demonstrated that the implementation of sustainable asphalt pavement practises in the context of highway infrastructure yields substantial benefits in terms of environmental conservation, improved energy efficiency, and sustained cost savings.

These measures are in line with wider initiatives aimed at mitigating the carbon footprint and environmental consequences associated with infrastructure projects, making them a crucial element of contemporary road building and upkeep.

2.1.3.1 Cold mixture asphalt

The Cold mixture asphalt is a non-thermal recycling technique; it means that does not include the use of heat. It entails the pulverisation of aged asphalt pavements and their subsequent combination with new virgin aggregates and stabilising chemicals. The objective of this procedure is to generate a novel substance that adheres to the predetermined criteria and requirements for its designated use. The cost-effectiveness of cold recycling may be attributed to the elimination of material heating, leading to decreased use of energy, fuel, and materials [58]. There exist divergent viewpoints on the utilisation of this methodology, with certain proponents pushing for its use within a specialised facility, while others contend for its on-site implementation at normal temperatures, employing hydraulic binders like bituminous binders and/or cement. It is recommended that the use of cold mix recycling be limited to the building of a base course designed for regions characterised by low to moderate traffic loads. This recommendation is primarily based on the relatively lower structural strength shown by cold mixes in comparison to hot mixes. There exists a viewpoint suggesting that cold mixes possess the capacity to function as a wearing course on all road surfaces, except those that experience exceedingly significant volumes of traffic. The use of cold-recycled material demonstrates its capacity to fulfil the desired mechanical and performance attributes. Hence, it is crucial to acknowledge that the potential uses of this phenomenon should not be limited. This remark highlights the progress achieved over time and the diligent research efforts devoted to these types of mixes.

The cold recycling technique has become a more popular alternative in the redevelopment of road pavements because it reduces the financial and environmental burdens while producing materials with high performance qualities. Highway maintenance includes the removal of damaged layers and the buildup of the resulting milled material. Recycling using cold techniques, on the other hand, provides a plethora of benefits, such as energy savings, because the aggregates are not heated and, in the case of on-site recycling, the material is not transported to and from the site [59]. In addition, improved profitability and an assurance of the same longevity as using virgin materials for paving, and a decrease in the number of gases, dusts, and fumes that are released into the atmosphere as a result of burning fuel for transportation and heating.

Cold recycling allows for the use of a wide variety of aggregates (natural or recycled), including considerable amounts of bituminous mixed milled material (up to 100% of the mass of stone aggregates), any granular material from ancient road foundations, and recycled materials from the construction industry. Cold recycling can be done on-site with stabilising equipment or in a stationary or mobile plant that will be placed close to the labour work [60].

Layers of various materials and thicknesses can be used in cold in place recycling. In extensive repairs, the underlying bound layers and a portion of the unbound layers of the old surface are crushed, mixed, and stabilised after the thickness equivalent to the layer of the new hot bituminous mixture has been removed. For far shallower depths, only the layers bound to bitumen, or portions of them, can be recovered in surface interventions. It eliminates handling and storing the material retrieved from the pavements that will be renovated in comparison to that in the plant. This involves determining significant benefits of various kinds; for example, construction costs can be lower, there is a reduced risk of accidents as a result of the shorter exposure time, fewer vehicles engaged, and the elimination of numerous movements inside the road network involved and the building sites. Moreover, a shorter assistance length due to the removal of several intermediary steps of processing and the enhanced efficiency of current recyclers and users will result in less hassle.

The purpose of the research from [61] was to analyse the evolution of the mechanical characteristics of asphalt emulsion CMA mixes during the curing process and to link them with their evolving electrical resistances. The moisture loss, Marshall stability (ITS), indirect tensile stiffness modulus (ITSM), and electrical impedance of CMA mixes comprising varying percentages of Portland cement were investigated at varied curing durations up to 28 days to achieve this goal. The links between these evolutionary qualities were then investigated. Cement significantly enhanced the mechanical performance of CMA, and there were strong correlations between the Marshall stability, ITS, and ITSM, regardless of cement quantity. Furthermore, the mechanical performance of each CMA mixture with various amounts of cement was closely related to the electrical resistance, implying that it is potentially possible to predict the evolutive mechanical behaviour of CMA from the electrical resistance, which may be evaluated non-destructively. It must be observed that with higher levels of cement (4% and 6%), the modulus becomes quite high, making the combination exceedingly stiff and perhaps increasing the fragility of the mixture.

To further understand the behaviour of the cold recycled asphalt mixture (CRAM), stiffness tests (triaxial resilient modulus and dynamic modulus tests) and suction tests were undertaken. The research from [62] investigated the suction pressure phenomena and its implications on the stiffness of emulsion-stabilized cold recycled asphalt mixes with various additives. Some of the work's findings include: I CRAM stiffness may behave similarly to granular materials, with confining pressure dependence and temperature/frequency reliance (as asphaltic materials); (ii) suction phenomenon may be willing to take responsibility for part of the stiffness of CRAM; and (iii) the filler type (even in a minor percentage) affects the mechanical behaviour of CRAM.

2.1.3.1.1 Cold in-Place Recycling (CIR)

The way of performing a cold in-place recycling (CIR) of asphalt pavement is a technique that involves planning in relation to the building and upkeep, here, the term “method” refers to a typology of pavement rehabilitation and/or road restoration.

The CIR is a technique employed in the building and upkeep of asphalt pavements, serving as a means of road rehabilitation or pavement maintenance. The methodology in question is a cost-effective and ecologically sustainable method that entails the recycling of pre-existing asphalt pavement material without the requirement of heating it, as often performed in conventional hot mix asphalt (HMA) manufacture.

The use of CIR as a method for rehabilitating pavements is advised just for roadways that contain a structurally sound pavement and do not demonstrate any drainage complications. The CIR has the capability to rectify cross-slope deficiencies. The use of this methodology is not recommended in instances when the current pavement displays signs of fatigue cracking or substantial rutting.

The recycling depth utilised in practice is determined by the depth of the pre-existing pavement, with options ranging from 75 to 100 mm. To ensure best performance, it is advisable to retain a minimum thickness of 25 mm of existing asphalt over the underlying subbase or Portland Cement Concrete (PCC) pavement for both the mainline and shoulders. Milling the present underlying subbase material, such as Portland cement concrete (PCC), has the potential to create major changes in the emulsion composition, resulting in a reduction in overall pavement performance. If the asphalt shoulders fulfil the requisite pavement condition and minimum thickness standards, it is suggested that they be recycled in combination with the mainline.

Alharbi et al. conducted a research to investigate the most suitable thickness of CIR in contrast to traditional Hot Mix Asphalt (HMA) pavement, considering different traffic loading classes. Consisting in a range of 5 distinct thickness structuration for the wearing course, base and subbase in respect to 50 design situations were investigated. Each traffic class was represented by five combinations of this nature.

There were fifty potential outcomes in all, with twenty-five for CIR and twenty-five for HMA pavement. Building expenses, natural resource depletion, and the requirement for cutting-edge technology and skilled labour were only some of the factors taken into account while determining the economic, environmental, and social viability of each scenario.

The behaviour of a thicker surface layer is equivalent to that of HMA. Furthermore, it is also clear that when the relationship between the CIR and the HMA layers gradually became lower as the thickness of the sub-base and base layers increases. A discrepancy of 4 cm was seen between the very light traffic class (250,000 ESALs) and the very heavy traffic class (31,000,000 ESALs) when a 15-cm base layer was used without a sub-base. The former resulted in a 4 cm thickness, while the latter required a 12 cm thickness. The discrepancy in measurements decreased to 1 centimetre for traffic classes characterised as extremely light, while it increased to 10 centimetres for traffic classes classified as very heavy. All of these readings were obtained assuming a sub-base layer of 10 centimetres and a base layer of 20 centimetres. In circumstances of very little traffic, the thickness of the CIR and HMA were both 7 centimetres, while the thickness of the base and sub-base were both 20 centimetres. On the other hand, during periods of extreme foot activity, layers as thick as 9 centimetres appeared. With the exception of the 'very low' traffic class, the results of the sustainability study show that CIR is clearly better than HMA. This implies that CIR is a more environmentally friendly pavement overlay option for many types of roads, including feeders, collectors, main urban streets, highways, motorways, and heavily frequented highways in industrial zones. This phenomenon is especially relevant in scenarios where the Equivalent Single Axle Load (ESAL) values exhibit a range spanning from 2,000,000 to upwards of 31,000,000. In the specific instance of the traffic class categorised as 'very light', it was determined that HMA is a more sustainable alternative, taking into consideration the constrained access to sophisticated machinery and proficient workforce required for the building of farm-to-market roads [63].

The study from Ogbo et al. [64] was to replicate the in-situ curing procedure of CIR materials within a laboratory setting. They also investigated this correlation between the curing process in this study in the laboratory and on the field. The nuclear density moisture gauge (NDMG) often produces higher moisture content (MC) readings in the CIR layer compared to measurements obtained by the oven drying method of loose CIR samples collected from the windrow prior to compaction. The aforementioned highlights the importance of utilising multiple comparison corrections for non-directional mean group measurements to guarantee quality control of the common information ratio. The laboratory-based ground-penetrating radar (GPR) system frequently yields higher dielectric values for commonly employed construction and industrial materials in comparison to the field-based GPR system. A strong linear correlation can be observed between fluctuations in CIR material MC and dielectric, resulting in reliable results for monitoring MC progression in controlled laboratory environments as well as real-world field conditions. The research also reveals a noteworthy positive association between the modulus of the Load-Wheel-Deflectometer (LWD) and the depth of penetration of the Roller Compacted Concrete (RCCD) as evaluated on the CIR layer. The Michaelis-Menten model exhibits a robust association with actual observations when examining time-dependent variations in the mechanical properties of CIR materials throughout the curing procedure.

Orosa *et al.* [65] has a research that, in order of importance the, first objective was to experimentally determine the resilient moduli (Mr) of several Cold In-Place Recycling (CIR) combinations at different stages of curing. The outcomes derived from the dynamic triaxial tests performed on CIR mixtures demonstrated a significant dependence on the primary stresses 01 and 03, thereby emphasising the mixtures' nonlinear elastic properties. The research findings indicated that the variation in the resilient modulus was significantly more conspicuous under confining stress (03) as opposed to deviatoric stress (0d). The mixes containing 2.50% BC exhibited the greatest resilient moduli and had the most favourable development with respect to curing time among all the mixtures created in accordance with PG-4. A correlation analysis was conducted to determine the relationship between the water content of the mixtures and the time-dependent variation in moisture retention values caused by evaporation. The observed association exhibited a mostly linear trend for the mixtures containing BC concentrations ranging from 2.00% to 3.00%. The results indicated that the combinations featuring a constant BC of 2.50% and a variable AWC ranging from 2.00% to 2.75% demonstrated the most favourable progression. The combination containing 2.50% BC and 2.75% AWC exhibited the most favourable short-term development of Mr and achieved satisfactory values. The mixtures displayed nonlinear elastic behaviour at all curing ages, being soft at low stresses and increasing stiffness at high stresses, making them suitable for low- to medium-traffic roads and allowing adaptation to deformations without cracking.

Also, a study from Orosa *et al.* aimed to mechanically characterise three cold recycled mixtures containing 100% RAP and different proportions of bituminous emulsion and water. Binder contents of 2.00%, 2.50%, and 3.00% were selected and prepared using a gyratory compactor. Triaxial tests were performed on the specimens at different confining pressures, determining Mohr-Coulomb diagrams, failure envelopes, and shear parameters. Repeated load permanent deformation (RLPD) triaxial tests were conducted with different stress ratios (SR), obtaining cumulative permanent deformation curves and critical SRs. The main conclusions from the study are that uncured mixtures did not exhibit significant differences in failure lines and shear parameters. In cured mixtures, the effect of the binder is more decisive, with cohesion increasing by more than twice the value obtained without curing. After curing, the angle of internal friction increased slightly in the mix with less binder content, but this effect was detrimental for mixtures with a higher binder content, acting as a lubricant and reducing internal friction between aggregates. RLPD triaxial tests showed that mixtures prepared with 2.00% and 2.50% BC presented a critical SR above 30%, while those with 3.00% BC had a lower critical SR. The Model of Paute fitted the deformations well for low-load cycles and low deformations within primary and secondary stages, but when higher deformations were reached, the measured results were underestimated. The model oh Huurman model proved to be the best fit for the permanent deformation of the studied mixes, it also showed decent adjustment even in the tertiary stage due to the exponential term included in the model [66].

The utilisation of a recycled pavement mixture, in this case the CIR, has the potential to serve as a cost-effective design alternative to traditional mixes and hence warrants consideration in road design and rehabilitation endeavours. Not only an economic appeal is attributed by the aforementioned sustainable option, in spite of that also, it gives environmental conservation through the lessened utilisation of natural resources. Despite what has just been said, it should be observed that the employment of CIR might not be unanimously appropriate, specifically in circumstances where the existing pavement manifests some decay or if there should be substantial repairs done to the underlying layers. With a view to make certain of the fact of the CIR being acceptable as a viable option in a pavement or road project, their circumstances and specifications should/must be assessed.

2.2 Building Information Modelling (BIM) study

The Building Information Modelling (BIM) refers to a digitalized representation and collaborative procedure including the generation, administration, and dissemination of comprehensive data pertaining to a construction or infrastructure undertaking over its complete duration. The BIM technology is extensively utilised within the design, engineering, and construction (AEC) sectors with the aim of enhancing the effectiveness, precision, and calibre of building endeavours. There are many fundamental characteristics and ideas pertaining to BIM; the main ones are summarised in the next few paragraphs of this doctoral thesis, after a concise background on BIM.

In recent decades, several countries have taken the initiative to create laws that require the implementation of digitization in public projects. The Scandinavian countries are known for being pioneers in requiring the use of BIM technologies and methodologies in construction projects. In Denmark, it has been mandatory to have a legislative framework for BIM since 2007 for all public projects. Similarly, in Norway, it has been mandatory since 2016. In Sweden, the government is currently working on plans to mandate the use of BIM. This decision was made after the Public Transport Association started requiring the adoption of BIM in 2015. The United Kingdom is considered a leader in BIM adoption. In 2016, the government made it mandatory for public projects to implement BIM level 2, which emphasises collaborative work practices [67].

Some countries have chosen to gradually introduce BIM, taking into consideration the value of the project. One example of an introduction is happening in Italy, where the Ministerial Decree 560 of 2017 has established a timeline for the mandatory and gradual implementation of digital modelling methods and tools in the Construction Sector, based on the asset's tender value. Starting in January 2019, it is required for public works with a tender value of at least 100 million euros to utilise approaches such as BIM. By 2025, this requirement will be extended to encompass all public works [68].

The BIM facilitates the generation of a digital representation of a construction or infrastructure project. The model incorporates several essential elements, including measurements, materials, cost data, schedules, and more pertinent information. The digital representation serves as a fundamental component within the context of BIM. Likewise, collaboration is a fundamental aspect of BIM since it fosters the exchange of information and promotes cooperation among many participants involved in a building endeavour, such as architects, engineers, contractors, and owners. It aids in the dismantling of organisational barriers and promotes enhanced interpersonal communication and coordination.

The Lifecycle management refers to the entirety of project stages within BIM, which comprises the original conceptual design and building phases as well as the later operation and maintenance phases. In other words, at all phases of the construction of a building, this promotes an improved decision-making process.

The BIM is divided in dimensions, as we can see on the figure 2. The second dimension (2D) refers to a visual depiction of a work or its constituent pieces using a plan based on two-dimensional geometry. The concept of the third dimension (3D) in the context of graphical simulations refers to the representation of a structure or its constituent pieces using three-dimensional geometry in order to depict spatial relationships. The concept of the fourth dimension, 4D, refers to a simulation that incorporates the temporal dimension, in addition to the spatial dimensions to represent the dynamics of a particular work or its constituent pieces. The concept of the 5D dimension refers to a theoretical construct that involves simulating the functioning or constituents of a system, incorporating monetary considerations with spatial and temporal factors. The concept of the 6D dimension involves the creation of a simulated environment that encompasses all aspects of a project, including its utilisation, administration, upkeep, potential decommissioning, and spatial considerations. The concept of the 7D dimension involves simulating the job or its various aspects with a focus on sustainability, encompassing economic, environmental, energy-related, and other relevant factors. This dimension expands upon the traditional considerations of space, time, and production costs.

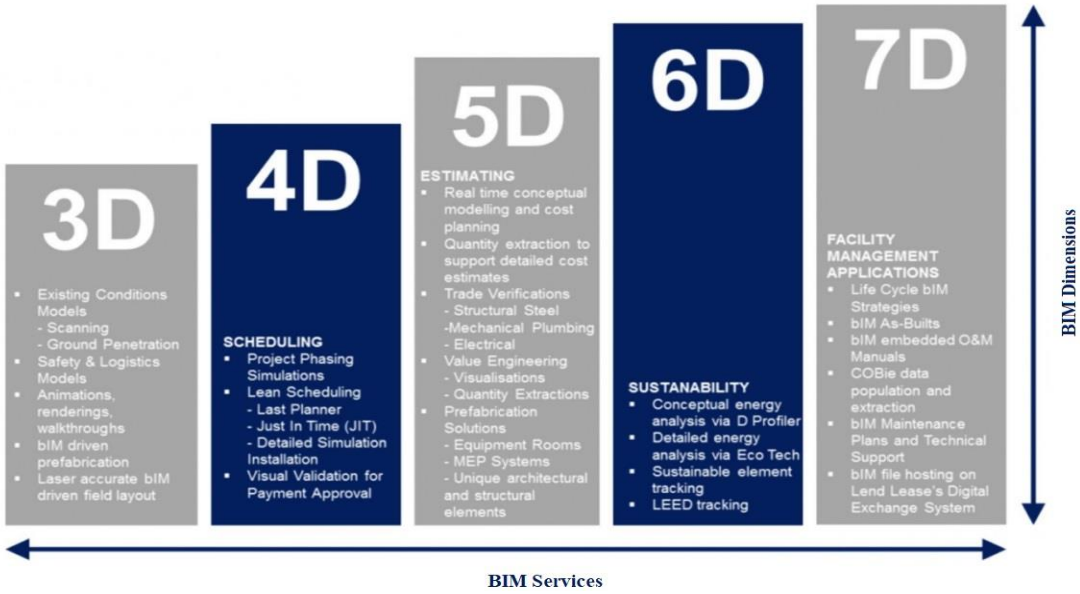


Figure 2 – BIM models dimensions.

These models have the potential to be utilised for the purposes of visualisation, collision detection, and collaboration across several design disciplines. With the objective of minimising the occurrence of mistakes as well as making the comprehension of the projects more effective, the utilisation of three-dimensional elements is the key to this improvement. Besides the three-dimensional geometry, the BIM models encompass an extensive scope of information collected properties. The abovementioned features encompass a large quantity of aspects, for example, the characteristics of the materials employed, considerations of sustainability, and the energy performance of the subject matter. The enhanced analytical and decision-making capabilities are facilitated by the data enrichment.

The capability of the BIM tools and software into interact and exchange date is related to the interoperability. This feature makes possible a smooth flow of information between multiple software platforms. This facilitates the integration of various components within a project and the utilisation of specialised software for distinct activities.

The Parametric design is a commonly utilised approach in BIM, whereby parametric modelling is employed. This technique enables changes made in a specific section of the model to be automatically applied throughout the whole project. Besides reducing the need for manual updates, this strategy guarantees uniformity. The Clash detection is a process that utilises BIM models to find clashes or conflicts within a design. It has, for example, the capacity to identify situations where the structural components prevent the operation of mechanical systems. The resolution of difficulties prior to the commencement of building activities became easier for the reason of this practice.

Several tools available for the use of BIM can facilitate cost estimation and project scheduling. As the design progresses, the tools in the BIM environment possess the capacity to be updated in real-time, constantly. The utilisation of BIM models for facility management is a common practice following the completion of building projects. It also means the monitoring of maintenance schedules, the documentation of equipment information, and the recording of other pertinent data pertaining to the operation and upkeep of the facility. Furthermore, the BIM makes a comprehensive assessment of the ecological aspects of the building footprint and energy efficiency possible.

As an indispensable component in the construction sector, all lot of benefits in respect of cost management, guarantee of quality, optimisation of project operations, and likewise promotion of sustainable practices is provided by BIM. There is a continuously progressing in respect to BIM on the field of the technology, it means that significant developments are having a profound impact on the development of smart buildings constructions and infrastructure, as well as roads.

Crespo et al. [69] stated that the coordination of the BIM model is guaranteed by a repository of standardized information inserted by the various participants throughout the entire process of construction product development. To obtain the potential advantages of the BIM model, there must be coordination between all construction processes [70].

The present study by [71] introduces a comprehensive framework that utilises BIM to optimise road alignment design. The framework focuses on two primary objectives: enhancing driving safety and improving construction economics. The article's contributions are presented as follows: This study presents a framework for road alignment design that utilises BIM and dual-objective optimisation. The suggested framework enables automatic optimisation using the NSGA-II algorithm, incorporating both construction cost and driving safety and comfort as the objective functions. The dual-objective optimisation method is employed to assess road safety and comfort in a quantitative manner, utilising vehicle dynamics simulations. Additionally, it facilitates the rapid estimation of construction costs by automatically calculating earthwork volumes within the BIM framework. Furthermore, the optimisation process is automated through data interoperability between the BIM environment and external vehicle driving simulation software. The optimisation framework will yield the ideal alignment, which will be immediately included in the BIM system. This alignment will be automatically constructed to create the BIM model for the preliminary design stage of the road. This study proposes a method for road alignment parameterization that is both reliable and efficient. The method enables the direct establishment of a mapping between a group of road alignment components and a series of spatial alignment points. This addresses a common constraint seen in many commercially available BIM tools, wherein the vertical alignment parameterization is reliant on the outcomes of the horizontal alignment parameterization. The alignment parameterization approach that has been suggested offers a practical solution for achieving data interoperability between BIM systems and the external world. The case study pertaining to the Phnom Penh-Sihanoukville highway examines the performance of alignments produced for the five segments of the JG5 project. The study compares the outcomes achieved via the use of a BIM-based framework with those resulting from the conventional design technique. The findings indicate that the alignments designed using the BIM-based framework outperform the traditional design method by 6.6% under the dual goals. The practicality of the suggested alignment optimisation methodology based on BIM is verified. Nevertheless, this study does possess several drawbacks. Potential areas for further study might encompass enhancing the precision of the driving simulation, examining the influence of road alignment on the optimisation objectives related to road maintenance benefits, and enhancing the parameterization level of road alignment as a substitute for the conventional design model.

Bosurgi et al. [72], in this study, with the objective of increasing the advantages of the use of Intelligent Building Information Modelling (I-BIM), the authors bestowed a description and analysis in relation to procedures and methodology for road upkeep management. Moreover, it investigates the feasibility of including more information about the pavement condition in these comprehensive survey data. Recognising the technological research capabilities and techniques of I-BIM, it elucidates the tangible practical benefits, with the objective of increasing the efficiency of workers on highways and improving the quality of infrastructure for end users. When considering this matter from a methodological perspective, it becomes evident that it is indeed relevant within an I-BIM context, this is due to the fact that BIM presents concepts and philosophy that are align perfectly to the purpose of road maintenance. Moreover, this proposed solution has the potential to address several practical operational and managerial challenges commonly seen in traditional PMS. For analysing and organizing data, the PMS offers enhanced capacities within a more efficient and adaptable framework. In addition, the PMS leverages, to enhance the user experience, highly collaborative and user-friendly platforms. In this framework, a preliminary experimental methodology has been employed with aim to identify and incorporate certain smart objects into the I-BIM environment. The identification and quantification of various maintenance requirements are the distinct features of these items, that make valuable. In closing, as a streamlined and effective support system, this initial experiment provided proof of how this solution has the potential to help in making decisions, aiming of improving the advantages and the quality deriving from the entirety of the accessible date.

A study of Oreto et al. [73], evaluating the environmental impact and costs of road asphalt pavements was the aim of this research, into a comprehensive framework in the IBIM environment. The understanding of the integration among IBIM-LCA-LCCA (Life Cycle Cost Analysis) was enhanced by the tool, focusing on sustainable pavement maintenance practices. A comprehensive examination and comparison of alternative road construction materials is what the IBIM- based analysis tool allows. The environmental impact category indicators become minimised when the cold in place recycling technology is employed. Replacing natural aggregates with reclaimed asphalt pavement reduced nitrogen and phosphorous compound emissions in water during the production and transportation of natural aggregates to the asphalt plant. The combination of polymer-modified asphalt (PMA) with a base layer of hot mix asphalt (HMA) demonstrated the most favourable balance between minimising environmental impacts and costs while maximising pavement solution lifespan. The findings align with local legislative frameworks for the integration of building information models. Future research will focus on uncertainty analysis, social aspects, and expanding the scope of life-cycle-based road maintenance management to the network level.

In a study from [74], a BIM solution was developed with the objective of improving road maintenance operations. To advance knowledge of these maintenance operations, laboratory testing data were used to control the mixture quality. For storing and analysing quality control data from bituminous materials after laying and compacting, the method has involved building an integrated Revit model. The model uses Dynamo, a Visual Programming Tool, to link laboratory results to the digital model. Based on the properties of the materials, a ranking algorithm is developed. This ranking algorithm was based on the positive and negative score in relation to the technical specifications of the road administration. A dynamic model was created according to this technique, that when the data spreadsheet is updated, the model changes its information package and analytical output. The use of BIM has as its main benefits the interoperable road network model, verifying the qualities of materials that satisfy technological criteria, and integrating a custom rating system for regular maintenance into the

3D road pavement model. The tool can be integrated with a model for optimum regular maintenance schedule simulation to save time on Gantt charts and track previous operations.

Oreto et al. [75] developed an effective life-cycle cost and performance estimator dynamically uses external data. Libraries, mix design, raw material, equipment, and labour unit costs, maintenance thresholds, and road asphalt pavement BIMs are examples. There were benefits achieved from this research: (I) Development of a three-dimensional informatized model to store road pavement information, such as layer geometry and alphanumeric data, which can be assigned via an external adaptable database with exploratory determinations of both mechanical and physical characteristics of materials, rational asphalt pavement arrangements, and period; (II) Integration of laboratory material analysis (mix design, mechanical characterization, and pavement design phase) into dynamic digital BIM with predictive performance equations and life-cycle management strategies; (III) Early design prediction meets pavement structural configuration and material performance threshold conditions while reducing maintenance planning and life-cycle costs. To choose pavement solutions with different LCCA indicators and DC combinations for planned maintenance tasks, the engineer can use multi-criteria weighting strategies that match intentions. (IV) Supporting waste reduction policies in construction and maintenance that reduce JGW and RAP transport and disposal to save money. The LCCA evaluates multiple scenarios in minutes. Significant input changes do this. Low-to-medium CPUs can handle 1-minute workflows. Modifying the model during design or construction allows for accurate maintenance timing and cost projections. It optimises system lifecycle costs and performance. By replacing or removing model and workflow components, model dynamism adjusts evaluation results. Flexibility, dynamism, and Civil 3D/Dynamo integration are benefits. These qualities make it ideal for BIM model creation and management. The proposed BIM-LCCA tool development addresses current issues. The AASHTO mechanistic empirical design method, global indicators, and grip indexes assess structure and function performance and aid maintenance. The use of the analysis tool to add safety, quality, and climate variables to informative pavement agencies models during construction and maintenance. The maintenance and hybrid maintenance strategies boost computational efficiency and screening algorithm expansion. The proposed Life Cycle Cost Analysis estimates user and social costs economically. The Multi-criteria analysis and environmental assessment aid in strategy selection and decision-making.

After all the research studied, they elucidate that the utilisation of BIM in the construction of road pavements has been found to result in substantial advantages. Moreover, the BIM technology is a methodology that enhances the efficiency of design and construction processes by facilitating improved accuracy, collaboration, and project efficiency, as indicated at the beginning of this subtitle (2.2). As we also saw in this part of this thesis, the decision-making capabilities are facilitated and enhanced due to the use of this technology. In other words, this use mitigates the existence of errors, and mainly a reduction of overall costs occurs. Another point to consider after reading all the studies exposed here is that BIM is important to improve the sustainability and long-term maintenance of road pavements, thereby guaranteeing their durability and safety. Considering all of these, a constructive strategy for optimising road pavement projects is the adoption of BIM.

2.3 Investigational assessment of marginal materials into asphalt mixtures

A fundamental factor in asphalt pavement design is the previous investigational assessment of marginal materials in asphalt mixtures for both the building and maintenance. The marginal materials are regularly classified as resources that may not conform to the standards specifications for asphalt mixes, but can potentially be utilised with proper testing, adjustments, or treatment.

In a study by Franesqui [76], the volcanic aggregates were characterised into three different groups and distributed into groups of different typologies, utilising a standard by which particle absorption and density were the criteria for building purposes and the classification of asphalt rubber materials comprising highly vesiculated basalt and varying binder contents. When compared to reference combinations that do not include rubber but contain the same ingredients, the air void content, and voids in semi-dense mixtures of asphalt concrete with asphalt rubber (AR) and highly-vesiculated basalt show a slight improvement. Because of the increased viscosity and elastomeric properties of the AR binder, the compaction process of asphalt-rubber (AR) mixtures is more important. The result of a maximum bulk density of 6.5-7.0% was related to the extensive absorption of the volcanic particles; in other words, it was linked to the optimal quantity of binder. The addition of AR combinations to the empirical data showed a significant improvement in moisture resistance in relation to the mixes lacking rubber components. At 15°C, the increase in the indirect tensile strength ratio of AR mixes varied from 10.4% to 24.1%. These findings suggest that the mixes fulfilled road technical criteria if the bitumen percentage was equal to or greater than 6.0%. Combinations including high-porosity marginal volcanic aggregates in asphalt-rubber (AR) outperform combinations using ordinary bitumen in terms of resistance to permanent deformations. The wheel-tracking slope of the rut depth decreased between 322.8% and 546.0%. Similarly, rut depth reduced from 197.7% to 279.6%, while proportional rut depth declined by 6.2% to 10.4%. The enhanced rutting resistance seen in this example may be ascribed to the elastic properties of the rubber material and the greater softening point of the AR binder. As a result, this discovery has important implications for the building sector, especially in locations with volcanic terrain, contributing to an improvement in asphalt pavement durability.

This study [77] performed an investigation on the homogeneity of asphalt mixtures containing RAP materials. In specific, recycled asphalt mixtures were produced in the laboratory using various combinations of mixing times and RAP binder with different ageing degrees. The distribution- and agglomeration-based homogeneity indexes were used to estimate the homogeneity of specimens. The major conclusions can be summarized as follows: (I) The order of incorporation of bitumen mastics, aggregates, and air void affected recycled asphalt mixture homogeneity, with aggregates contributing most. Air voids formed during asphalt mixture compaction contributed the least to recycled asphalt mixture homogeneity; (II) Clusters in RAP materials prevented the distribution-based index from representing recycled asphalt mixture homogeneity. The agglomeration-based homogeneity score can effectively compensate for homogeneity estimation; (III) Increasing mixing time generally reduced sample inhomogeneity. However, mixing can create new clusters, which may affect homogeneity indexes. With component flowability, new clusters appear; and (IV) The axial direction uniformity degrees and cross-section showed the indicator-dependent characteristic associated with homogeneity evaluation. Also, middle area of cylinder samples were more homogeneous than their tops or bottoms.

An interesting research from F. Russo [78] investigated four hot asphalt mixtures for the binder layer and five for the base layer, two of which were cold-recycled. The leaching and physical properties of marginal materials were investigated to determine their suitability for asphalt mixtures. The road asphalt pavement base and binder layers were designed with reclaimed asphalt pavement and construction and demolition waste as coarse aggregates and jet grouting waste (JGW) and fly ash (FA) as fillers. The mechanical properties of the $HMA_{binderJGW}$ solution were better than those of traditional asphalt mixtures. On average, S

(+144%), MS (+86%), ITS (+23%), ITSR (+10%), ITSM (+13%), Nf (+80%), and RD (−7%) all went up, which was better than all the other solutions. The cold asphalt mixtures in the base layer were less resistant to permanent deformation (RD) than HMA_{base}. $CMRA_{RAPJGW}$ had the best performance indicators, such as higher stiffness at 40 °C, MS, ITS, and ITSM (+27%, +10%, and +68%). Because of the lower OBC and the absence of the crushing phase of FA, $HMA_{binderFA}$ has the best health and environmental performance of the binder layer mixtures, reducing all impact category indicators by 2% on average compared to HMA_{binder}, $HMA_{binderCDW}$, and $HMA_{binderJGW}$. The $HMA_{binderJGW}$ reduces all impact category indicators by 1.5% on average compared to HMA_{binder} but reaches 8%. The most environmentally friendly option for the base layer is $CMR_{ARAPJGW}$, with an average impact indicator score of -35% for hot and -4% for cold asphalt mixtures. Due to lower air emissions and mineral consumption to make aggregates and cement, $CMRA_{RAPJGW}$ has 12% less effect on indicators IR, ozone formation on terrestrial ecosystems (OFT), and MR than $CMRA_{RAP}$. The multi-criteria decision analysis and sensitivity analysis helped determine which alternative was best based on road pavement construction and maintenance indicators like high- and low-temperature engineering efficiency, resistance to moisture, and environmental and human health efficiency. Considering raw material consumption, greenhouse gas emissions, and asphalt pavement service life, $HMA_{binderJGW}$ is the best option when operative conditions require the most effective mechanical performance regardless of average service temperature and humidity. Instead, decision-makers prefer the $CMRA_{RAPJGW}$ solution because it has the lowest impact on the environment and the best resistance to elevated temperatures.

The use of local recycled plastic as an environmentally sustainable modifier in C320 Australian bitumen was investigated in the study [79] using Australian standards and materials. This laboratory investigation assessment results were that the Dynamic Shear Rheometer (DSR) results indicate that PET modifier samples enhance rutting deformation and reduce bitumen susceptibility to cracking and deformation at high temperatures. Other result was that the PET additives showed reduced ageing index, increased stiffness, elasticity, and rutting factor $G^*/\sin(\delta)$ in Rolling Thin Film Oven (RTFOT) results. Thus, this indicates excellent ageing resistance during construction and better long-term durability. Also, the most PET-modified asphalt specimens have greater resistance to fatigue and extended fatigue life than unmodified C320 bitumen, according to PAV. Lower ageing indices after PAV at moderate temperatures means longer asphalt service and more durability. The PET improved medium and high-temperature characteristics over the ordinary binder.

And finally, the results indicated that employing waste plastic as a recycled polymer in asphalt modification could achieve high rutting resistance, a more elastic behaviour which enhances fatigue life, and cost-effectiveness.

A study by Gedik et al. [80] investigated recycling hazardous waste fluorescent lamps containing mercury, realising an investigational assessment to promote environmentally friendly management of waste. Nevertheless, this research had as aim to assess the potential employment of fluorescent glass waste as an alternative bituminous pavement filler. As results of this study, the micro-texture of recycled fluorescent lamb (RFL) grains improves roughness and angularity, leading to better pavement performance and increased resistance to skids. The Marshall test showed RFL mixtures have a reasonable reduction in optimal binder percentage compared to conventional mixes. When 8% RFL is added to WC and 2% is added to binder course, the stiffness modulus goes up by 10% and 3%, respectively, compared to conventional crushed stone dust mixtures. Regarding rutting, RFL should only be used on low-to-moderate traffic asphalt pavements. The RFL at 5.5% and 2% filler extends the fatigue life of WC and binder course pavement. The RFL mixtures creep similarly to control mixtures, consistent with other test results. Asphalt layers using RFL are cost-effective for most road pavement projects. The RFL reduces WC and BC material production costs by 2.7% and 2.4% per tonne, respectively.

In a nutshell, the studies realised investigational assessment of marginal materials in asphalt mixtures have proved that the incorporation of marginal materials and/or the adoption of novel technology at low-temperatures for pavement layers enhance the environmental performance when juxtaposed in order to compare with traditional ones.

3 CURRENT PRACTICE TO REEMPLOY RAP AND PW INTO ASPHALT PAVEMENT

The cost-efficiency and sustainability are the main factors influencing the current practices in relation to the reemployment of RAP and PW. These innovations of reemployment of RAP and PW into the asphalt blend to reduce the demand for virgin aggregates, saving resources, and minimise emissions, also focus on an improvement of the mechanical behaviour and compatibility by optimising the mixture designs. It is impossible to demonstrate conclusively that landfill waste is reduced due to the fact of these practices, which also conserve resources and contribute to more resilient and environmentally-friendly road infrastructure.

A substantial leap forward in terms of sustainable construction and resource conservation represents these forward-thinking practices. The three major regulatory references that serve as the fundamental methodological standard for conducting the marginal materials analysis applied for practical purposes, referred to as road works, will be analysed in detail since there are specific legislative frameworks from national and European perspectives.

3.1 Legislative framework

As an essential aspect of sustainable infrastructure development, the legislative framework governs the fundamental role of the reemployment of RAP and PW into asphalt mixtures. With the aim of promote the efficiency of the resources and reduce the environmental impact, by this commitment this reemployment practice is driven. Laws and regulations are encouraging the use of these marginal materials in road construction in many jurisdictions. As per the objective of ensuring the use of these typologies of materials in some countries, the mandates stipulate a minimum percentage of RAP and PW for the incorporation of these materials in road projects. The aim of these regulations is to effectively mitigate the management of natural resources, minimise the carbon emissions associated with traditional asphalt production, and manage plastic waste.

The legislation additionally addresses performance and quality standards to guarantee that RAP and PW-infused asphalt meet durability and safety urges. Moreover, due to the aim to promote best practices and to prevent contamination there may be guidelines for proper collection, sorting, and processing of PW. Oftentimes, the legislative frameworks are intertwined with environmental protection, emphasising the preservation of ecosystems and the management of waste materials.

As has been demonstrated in this part of the chapter, for integrating RAP and PW into asphalt pavement, the legislative framework serves as a crucial catalyst for sustainable infrastructure development. It provides, indeed, a legal foundation to address environmental concerns, resource conservation, and performance standards in road construction projects. Illustrating these legislations, there are three fundamental European standards on the requirements of criteria for qualification and use of recovery materials applied for practical purposes for use on roads.

3.1.1 Uni/TS 11688

The technical standard UNI/TS 11688 [81] lays out the requirements and employment criteria for recovering bituminous mixtures obtained from the extraction of pre-existing pavements, commonly referred to as reclaimed asphalt pavement (RAP).

The primary objective of the technical specification is to define the characteristics of the RAP with the aim of promoting its reuse within the same production chain. This is done in accordance with environmental protection laws while also ensuring that the technical performance of the resulting products is maintained. The standard mandates that the bituminous mixture resulting from the maintenance activities of flexible pavement must be recycled within the same construction process. This can be done by incorporating it into other products or by directly reusing it, potentially after undergoing typical industrial procedures aimed solely at enhancing its geometric properties. The recovery of bituminous mixtures can be derived from both the production process and the installation process as waste or scrap, albeit to a limited degree.

The bituminous mixture has the potential to be reused without significant alterations to its physical and chemical properties, or it can undergo standard mechanical operations to adapt its dimensional features as needed. Consequently, the RAP can be utilised in its current form or undergo further processing to acquire granulate. There are primarily two technologies that are relevant in this context: milling and scarifying. The Technical Specification considers the utilisation of recovery RAP in hot and cold bituminous mixtures, either as part of an *in-situ* process or as a constituent of recycled aggregates.

Irrespective of the intended application, the technical attributes of the RAP placed in a heap are established by the manufacturer, who is responsible for categorising the heaps based on their consistent qualities.

The methods for ascertaining the technical attributes are outlined in EN 13108-8, which is already cited for the accurate characterization of the RAP, as mandated by the HMA product standards. The producer assumes a significant role in delineating the responsibilities, authority, and interrelationships among the personnel involved in the management, execution, and oversight of activities, including those that are outsourced. The application for authority must be submitted: (I) Conduct inspections at different stages of the production process; (II) Implement proactive measures to mitigate non-compliance incidents; (III) Detect, document, and address any deviations from the anticipated specifications.

When outsourced activities are involved, the manufacturer implements a suitable control mechanism while retaining overall accountability for the entire process. The management of documents and data should encompass all pertinent documentation and data that are considered significant in accordance with the stipulations outlined by the standard.

The manufacturing control of the RAP encompasses the subsequent prerequisites of (I) protocols for recognising and management of incoming batches and associated piles; (II) Protocols for ensuring the identification and consolidation of materials in distinct and clearly defined locations; (III) Production procedures are implemented to ensure adherence to the specifications established by the manufacturer for processed recovery bituminous conglomerates; (IV) Protocols to safeguard the integrity of the material extracted from the heaps, thereby preserving its inherent properties without compromising its characteristics; (v) Protocols designed to ensure the proper operation of equipment and resources, encompassing the performance of maintenance tasks.

It is imperative to establish a clear definition and comprehensive documentation of proceedings. The individual responsible for overseeing production control conducts an analysis of any anomalies detected. Subsequently, the severity of the anomaly determines the appropriate corrective measures to be taken.

The manufacturer of the recovered bituminous mixture is obligated to create and maintain technical data sheets for a period of 10 years. These sheets should contain information regarding the origin and identification of each individual incoming lot, along with any supplementary documentation. The manufacturer implements comprehensive measures to ensure the preservation of material characteristics throughout all stages, encompassing the material's initial arrival at the facility, its utilisation, and subsequent delivery to external entities.

The measures are designed to mitigate the risk of contamination of the recovered bituminous conglomerate with extraneous substances or materials. The amalgamation of recovered bituminous conglomerates exhibiting non-homogeneous characteristics.

In the interest of maintain the integrity of the heaps, it is imperative that the storage areas are kept clean and free from impurities. Additionally, it is necessary to ensure that these areas are segregated using solid elements, whether fixed or mobile. Every region is characterised by sufficient signage that pertains to the specific nature of the materials being stored.

The machinery utilised at the construction site for material handling is maintained in a state of optimal efficiency and cleanliness to prevent contamination and the possibility of unintended mixing.

3.1.2 EN 13108-1

The EN 13108-1 is titled *Bituminous mixtures - Material specifications - Part 1: Asphalt concrete* [82], and your scope is about the requirements for aggregates used in bituminous mixtures and surface treatments for roads, airfields, and other trafficked areas. These aggregates are critical components in the construction of performance and quality of asphalt mixtures in road infrastructure projects throughout Europe.

As performance criteria, this standard specifies requirements of performance for asphalt concrete must meet, such as resistance to fatigue, low-temperature cracking, and rutting. About the material composition, the standard set types and properties of aggregates that can be used in asphalt concrete, including coarse and fine aggregates. The choice of aggregates is essential for achieving the desired mechanical properties and durability of the mixture.

The prescribed particle size criteria pertain to the intricate grain size thresholds of ideal composition, which necessitate the use of sieves with dimensions of 1.4 D, D, 2 mm, and 0.063 mm. The optimal composition should adhere to these overarching parameters. The selection of sieves for use in this study will consist of either the base sieve group in combination with group 1, or the base sieve group in combination with group 2. The utilisation of sieve sizes from groups 1 and 2 in combination is prohibited. The determination of the second optimal particle size necessitates the use of sieves with dimensions of 1.4 D, 2 mm, and 0.063 mm. The product application documents stipulate that the ideal particle size should be specified for up to three distinct sieves ranging from D to 2 mm, as well as for up to three distinct sieves ranging from 2 mm to 0.063 mm.

The selection of sieves for the size D and the characteristic sieve between D and 2 mm should be determined by the following options:

- Basic sieve group plus group 1: 4 mm; 5,6 mm; 8 mm; 11,2 mm; 16 mm; 22,4 mm; and 31,5mm.
- Basic sieve group plus group 2: 4 mm; 6.3 mm; 8 mm; 10 mm; 12.5 mm; 14 mm; 16 mm; 20 mm; and 31.5 mm.

The characteristic sieve between 2 mm and 0,063 mm shall be selected between the following sieves: 1 mm; 0,5 mm; 0,25 mm; and 0,125 mm.

The binder typology used in the mixture, whether it is conventional bitumen or modified bitumen, should be specified. The properties of the binder, such as penetration grade or softening point, may also be included.

The minimum binder content can be defined in the application documents and must be selected to within 0.1%, between 3.0% and 8.0% for a mixture in which the density of the aggregate is assumed to be 2,65 Mg/ma.The minimum selected binder content shall be expressed as B_{mnx}, where x is the minimum binder content in %.

The minimum binding agent content of the mixture shall be corrected by multiplying it by the coefficient.

$$\alpha = \frac{2,650}{\rho} \tag{1}$$

ρ is the weighted average of the volumetric mass of aggregate granules at the optimal particle size, in megagrams per cubic metre (Mg/ma).

When incorporating a mass of reclaimed asphalt exceeding 10% of the total mixture, derived from mixtures exclusively containing paving grade bitumen, and when the added binder is also paving grade bitumen, specific requirements may be established in relevant documentation pertaining to the product's application.

The penetration of binder and/or softening point in the resulting mixture must adhere to the penetration and/or softening point requirements of the specified grade. These values are determined by calculating the penetrations and/or softening points of both the added binder and the reclaimed binder from the asphalt. In certain instances, the binder of the reclaimed asphalt may exhibit such a high level of hardening that the selection of a considerably softer bitumen becomes necessary to meet the specified criteria.

When reclaimed asphalt comes from mixtures that contain modified bitumen and/or additives, or when the mixture itself contains modified bitumen or additives, it is best to limit the amount of reclaimed asphalt that is used in the documents that go with the product. The recommended limit is a maximum of 10% by mass of the total mixture.

In instances where the total mixture of reclaimed asphalt contains more than 20% by mass and the original mixtures exclusively utilised paving grade bitumen and the binder added to the mixture is also paving grade bitumen, certain specifications may be outlined in relevant documentation pertaining to the product's application.

The penetration of binder and/or softening point in the resulting mixture must adhere to the penetration and/or softening point specifications of the chosen grade. This is determined by calculating the penetrations and/or softening points of both the added binder and the reclaimed binder from the recycled asphalt. The calculation should be performed in accordance with Annex A, which is considered normative. In certain instances, the binder of the reclaimed asphalt may exhibit significant hardening, necessitating the selection of a highly pliable bitumen to meet the specified criteria. In instances where reclaimed asphalt is derived from mixtures that incorporate modified bitumen and/or additives, or where the mixture itself contains modified bitumen or additives, it is advisable to restrict the quantity of reclaimed asphalt utilised in regulating courses, binder courses, and base courses. This restriction is typically outlined in relevant documentation pertaining to the application of the product, specifying a maximum limit of 20% by mass of the total mixture.

3.1.3 EN 13108-8

The UNI EN 13108-8, UNI EN 13108-8, *Bituminous mixtures. Material specifications - Part 8: Reclaimed asphalt* [83], is a European standard that outlines material specifications for bituminous mixtures, particularly focusing on reclaimed asphalt.

The documentation and declaration of the binder type will occur when and if there is access to information from either current or previous investigations. This declaration will serve to specify whether the binder primarily consists of paving-grade bitumen, modified bitumen, or hard-grade bitumen. The standard in question does not provide coverage for reclaimed asphalt that is contaminated with coal tar beyond hazardous levels. Consequently, the handling and regulation of such materials will be subject to the specific regulations implemented by each Member State.

Determining the properties of the binder, it is necessary to document and declare the mean penetration, mean softening point, or mean viscosity of the binder samples based on the test frequency in order to determine the number of samples (n).

The binder shall be reclaimed in accordance with the specifications outlined in either EN 12697-3 or EN 12697-4. The determination of penetration shall be conducted in accordance with the guidelines outlined in the EN 1426 standard. The determination of the softening point shall be conducted in accordance with the guidelines outlined in the European Standard EN 1427. The determination of the viscosity of the binder shall be conducted in accordance with the PN 12S96 standard.

The declaration of binder properties can be accomplished through one or multiple methods, as outlined below:

- Reclaimed asphalt will be classified as P15 when the penetration value of the binder in each sample, as determined by parameter (n), is equal to or exceeds 10 x 0.1 mm, and the average penetration value of all samples is equal to or exceeds 15 x 0.1 mm.
- Reclaimed asphalt will be classified as S70 when the softening point of the binder in each of the samples meets the specified criteria.
- The samples, as per the variable denoted by (n), exhibit temperatures that are either equal to or below 77°C. Furthermore, the average softening point of all

the samples is equal to or below 70°C.

- Either the average penetration values or the average softening points from all samples, as determined by (n), must be designated as category P_{dec} or S_{dec}.
- For reclaimed asphalt to be utilised in soft asphalt, it is necessary to declare the mean viscosity at a temperature of 60°C as V_{dec}.

In cases where the feedstock predominantly consists of asphalt containing bitumen that is not intended for paving purposes, it is necessary to provide a formal statement specifying the specific type and characteristics of the binder. This declaration should be supported by relevant and up-to-date research and data, or alternatively, by previously conducted investigations and information. The purpose of this declaration is to facilitate the assessment of the binder's appropriateness for the intended application.

The average grade of the aggregate, as determined by the samples, will be announced based on the value of (n). The grading of the material will be determined in accordance with the EN 12697-2 standard and will be reported as the percentage of particles that pass through specific sieves, namely 1.4 D, D, 2 mm, and 0.06S mm. Additionally, the grading will also consider the percentage of particles that pass through coarse sieves ranging from D to 2 mm, as well as sieves ranging from 2 mm to 0.063 mm.

The selection of coarse sieves in accordance with EN 13043 involves choosing from the basic set, along with either set 1 or set 2. The fire sieves to be utilised will be chosen from a range of sieves with aperture sizes of 1 mm, 0.5 mm, 0.25 mm, and 0.125 mm. The value of D is calculated based on the upper sieve size of the aggregate in the reclaimed asphalt, represented in millimetres. It is determined by taking the larger value between the smallest sieve with 100% passing, divided by 1.4, and the smallest sieve with 85% passing.

The test frequency for determining the number of samples (n) for testing shall be obtained from table 1, where level Z represents the minimum test frequency in all situations.

Table 1 – Minimum frequency for testing the reclaimed asphalt.

LEVEL	TONNES /TEST
X	500
Y	1000
Z	2000

3.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a systematic approach used to assess the environmental impacts associated with a product or service throughout its entire life cycle. This encompasses the pre-production stages, such as material extraction and production, as well as the production, distribution, use (including reuse and maintenance), recycling, and final disposal phases. The growing importance of LCA can be attributed to the influence of European policies pertaining to environment, energy, resources, and waste. LCA is now considered an essential instrument for shaping public policies and enhancing the competitiveness of businesses. At the European level, LCA is currently regarded as a qualifying factor in various domains that necessitate an evaluation of sustainability. This methodology enables the assessment of the ecological benefits associated with a product by quantifying the environmental impacts linked to the company's production processes and other activities. The provision of information to consumers can be enhanced by utilising Life Cycle Assessment (LCA) to improve the accuracy of ecological claims associated with a product. The inclusion of quantitative data on environmental impacts lends credibility to the message, hence increasing customer trust. The LCA procedure is standardised internationally according to the EN ISO 14040 and 14044 standards [84, 85]. The LCA, as stipulated by the ISO 14040 standard, takes into account the ecological consequences of the specific scenario under investigation on human well-being, ecosystem integrity, and resource depletion. The primary aims of this methodology are to establish a comprehensive understanding of the interactions between a product or service and its environment. This understanding assists in discerning the direct and indirect environmental consequences caused by the product or service. Consequently, it equips decision-makers, responsible for defining regulations, with the requisite information to determine the behaviours and environmental effects associated with an activity. Moreover, it facilitates the identification of opportunities for improvement, thereby enabling the implementation of optimal solutions to mitigate the environmental impact.

This section will provide a detailed analysis of the two primary regulatory references that serve as the major methodological standard for conducting a LCA analysis in a broad context, excluding road works. It is worth noting that there is currently no explicit legislation in place at the national and European levels.

3.2.1 EN ISO 14040-14044

The growing acknowledgement of the significance of environmental preservation and the potential consequences linked to the production and consumption of products and services has sparked a heightened interest in the advancement of methodologies aimed at comprehending and mitigating these impacts. One of the methodologies currently being developed is LCA. This chapter primarily centres on the methodological framework of LCA, which is widely acknowledged internationally. The framework is based largely on the principles provided by the International Standardisation Organisation (ISO) in ISO 14040 to ISO 14044.

The LCA technique has the potential to be utilised across various industrial sectors to provide assistance in relation to the recognition of possibilities to enhance the environmental efficiency of products throughout various phases of their life cycle. Another objective is to provide information to decision-makers in industry, government, or non-governmental organisations, including strategic planning, priority choices, product or process design, or redesign, for example. In addition, the selection of appropriate environmental performance indicators and their corresponding measurement procedures, and finally, marketing, which refers to many strategies and techniques employed in promoting and selling products or services. One such strategy is the installation of an ecological label system, which involves the use of labels to communicate the environmental attributes of a product. Another approach is making environmental claims, where companies highlight the eco-friendly aspects of their offerings. Additionally, the preparation of an environmental product declaration involves creating a comprehensive document that provides detailed information about the environmental impact of a product throughout its lifecycle.

The ISO 14044 provides comprehensive guidelines for the application of LCA by specialists in the field. The LCA is concerned with examining the environmental dimensions and potential environmental consequences across the entire life cycle of a product. This life cycle encompasses a series of interrelated and sequential stages within a product system, starting with the procurement of raw materials, followed by manufacturing and utilisation, and concluding with the management of end-of-life processes such as recycling and final disposal. In essence, LCA evaluates the environmental impacts associated with a product from its inception to its ultimate disposal, encompassing the entire life span of the product.

The objective of a study serves to outline the purpose and rationale behind conducting the research, as well as identify the specific target audience for whom the analysis is intended. The scope of application, encompassing the boundaries of the system and the level of granularity of the LCA, is contingent upon the subject matter and the intended purpose of the investigation. The extent and scope of the LCA can vary significantly based on the specific goal of the LCA in question. The scope of this study encompasses various aspects, including the definitions of the product system under investigation, the functional unit, the system boundary, the allocation procedures, the chosen impact categories, the methodologies employed for evaluating the impacts and their interpretation, as well as the data quality requirements and assumptions that underlie the analysis.

The Life Cycle Inventory Analysis phase, also known as the LCI phase or Life Cycle Inventory, constitutes the second stage of the LCA process. The present document comprises a compilation of both incoming and outgoing data pertaining to the system under investigation. The LCI involves the gathering of the requisite data to accomplish the objectives outlined in the designated research.

The Life Cycle Impact Assessment (LCIA) phase, also known as the Life Cycle Impacts Assessment phase, constitutes the third stage of the LCA process. The main purpose of the LCIA is to provide extra information that helps evaluate the LCI results of a certain product system, which leads to a better understanding of how it affects the environment.

The Life Cycle Interpretation represents the ultimate phase of the LCA process. It involves the consolidation and analysis of the outcomes derived from either the LCI or the LCIA, or both. These results are then synthesised and deliberated upon in accordance with the predetermined goal and scope of the assessment. The purpose of this interpretation is to provide a foundation for drawing conclusions, formulating recommendations, and making informed decisions.

There exist instances wherein the objective of conducting a LCA can be achieved through the execution of a solitary inventory analysis and subsequent interpretation. This study is commonly referred to as the LCI study. The scope of EN ISO 14040 encompasses two distinct categories of research: life cycle assessment studies, commonly referred to as LCA studies, and life cycle inventory studies, commonly referred to as LCI studies.

Typically, the data acquired from conducting a LCA or LCI study can be integrated into a broader and more extensive framework for making informed decisions. The comparability of results from various LCA or LCI studies is contingent upon the equivalence of hypotheses and contextual factors in each study. Consequently, EN ISO 14040 encompasses a multitude of stipulations and suggestions aimed at guaranteeing transparency regarding these subject matters.

The LCA is among a range of environmental management techniques, including risk assessment, performance on the environment assessment, environmental audit, and environmental impact assessment. However, it is important to note that LCA may not always be the most appropriate technique for every situation. The LCA typically does not encompass the economic and social dimensions of a product. However, the life cycle method and techniques outlined in EN ISO 14040 can be extended to incorporate these additional aspects.

The LCA is a methodology that adopts a comparative perspective and is organised based on a defined functional unit. The functional unit establishes the scope of study. All subsequent analyses are subsequently linked to the operational unit, as all the inputs and results of the elements of the LCI and the LCIA profile are directly associated with the functional unit.

According to the EN ISO 14040 standard, the LCA methodology possesses fundamental attributes. The LCA entails a systematic evaluation of the environmental aspects and impacts associated with product systems. This evaluation encompasses the entire life cycle of a product, commencing with the acquisition of raw materials and concluding with its final disposal. The LCA methodology adheres to a defined objective and field of application. The inherent variability of the LCA can be attributed to the characteristics of the functional unit within the methodology. The level of specificity and the duration of the LCA are contingent upon the specific objective and the particular field of application. The LCA methodology is receptive to incorporating advancements in technology. There is not a singular approach to conducting LCA. Organisations possess the capacity to effectively execute LCA in alignment with the European Standard ISO 14040. The LCA methodology distinguishes itself from various other techniques, such as environmental performance assessment, environmental impact assessment, and risk assessment. Nevertheless, LCA has the capability to incorporate data gathered from these aforementioned techniques. The LCA does not facilitate the evaluation of precise or definitive environmental impacts due to several factors. Firstly, the environmental impacts are contingent upon a reference unit, which introduces a level of subjectivity. Secondly, there is inherent uncertainty in the modelling of these impacts. Lastly, in the majority of cases, the impacts being assessed are anticipated to occur in the future. The LCI and LCIA phases offer an insight into the environmental challenges and resource demands associated with one or multiple product systems. The LCIA allocates the LCI results to specific impact categories. The selection of a life cycle impact category indicator is performed for each category, and subsequently, the calculation of the indicator's result is conducted. The LCIA profile offers insights into the environmental issues linked to the inflow and outflow of elements within the product system. There is a lack of scientific foundation for the reduction of LCA results into a singular score or numerical value, as the process of weighting necessitates the selection of specific values. The interpretation of a life cycle necessitates the application of a methodical approach to identify, assess, validate, appraise, and communicate findings derived from the LCA results. This is done to fulfil the stipulations outlined in the study's objective and scope. The interpretation of the life cycle also allows for the identification of connections between the LCA and other environmental management techniques, highlighting the advantages and constraints of the LCA in relation to the determination of its purpose and the range of subjects that it covers.

The objective of the LCA is thus the product system, which is defined as a system comprising one or more functions and consisting of a sequence of individual processes. The interconnection of unit processes is facilitated through the transfer of intermediate products and/or waste that require treatment. These unit processes are further linked to other product systems through the exchange of products, while their connection to the environment is established through elementary flows.

The process of dividing the product system into individual component processes facilitates the identification of the elements that enter and exit the product system. The extent of intricacy in the modelling necessary to achieve the objective of the study establishes the limits of a unitary process. The elementary flows encompass the utilisation of resources and the discharge of substances into the atmosphere, water bodies, and soil that are linked to the system. The provided data represents the outcomes of the LCI and serves as the input component for the LCIA.

The delineation of the system boundary is responsible for identifying the specific unit processes that are required to be incorporated within the LCA. It is imperative to determine the specific unitary processes to be incorporated in the research and the extent of detail at which these unitary processes are to be examined.

The unitary processes that are required to be encompassed within the system boundary are specified in the EN ISO 14040 standard: The procurement of raw materials; The primary sequence of processes; The topics of distribution and transport are being discussed; The production and utilisation of fuels, electricity, and heat; The utilisation and upkeep of the product; The management of waste and the treatment of processed products; The process of retrieving products post-consumption, which may involve the retrieval of energy as well; The production of supplementary materials; The processes involved in the production, upkeep, and disposal of primary equipment.

The exclusion of life cycle stages, processes, and incoming or outgoing flows is permissible solely if it does not substantially alter the overall findings of the research and, in any circumstance, must be adequately rationalised. In the field of LCA, several exclusion criteria are employed, as outlined below, in accordance with the definitions provided by EN ISO 14044. In relation to accurately model the mass flow of the product system, it is necessary to include all input elements that collectively contribute to the mass in a manner exceeding a specified percentage. In respect to precisely simulate the product system, it is imperative to include all input elements that collectively contribute to the input energy flow, surpassing a predetermined threshold, in the study. The study must include all input elements that exceed a predetermined threshold of environmental relevance, as determined by the system data collected specifically for this purpose.

In an effort to compile an inventory, it is necessary to gather both qualitative and quantitative data for each individual unit process that falls within the defined system boundaries. The data that is gathered, whether through measurement, calculation, or estimation, is utilised to quantify the input and output components of a singular process. In the event that data is obtained from publicly available sources, it is imperative to acknowledge and cite the original source.

As a way to ensure a standardised and coherent comprehension of the product system that is to be modelled, various measures must be implemented during the data collection process. These measures encompass the inclusion of diverse communication sources and published references. The creation of non-specific process flow diagrams is essential to depict all the unitary processes that will be incorporated into the model, along with their interconnectedness. This response provides a comprehensive analysis of each unitary process, focusing on the factors that influence the input and output elements. The following is a compilation of flows and pertinent data pertaining to the operational circumstances linked to each individual unitary process. The establishment of a comprehensive inventory delineating the specific units of measurement employed. This section provides a comprehensive overview of the data collection and calculation techniques necessary for all data.

Data can be classified into macro categories. The aforementioned entities refer to incoming energy elements, incoming raw materials, auxiliary materials, or other incoming physical entities. The subject of discussion pertains to the various components of a production process, namely products, co-products, and waste. Emissions into the atmosphere, hydrosphere, and lithosphere, and additional environmental factors.

It is imperative to thoroughly document all calculation procedures and provide clear indications and justifications for any assumptions made. Furthermore, it is crucial to ensure consistency in the calculation procedures throughout all stages of the study. The conversion of combustible materials, such as oil, gas, or coal, into energy streams can be achieved by multiplying the quantities of incoming and outgoing elements by their respective heats of combustion. In this particular instance, it is imperative to document whether the calorific value employed is the maximum or minimum.

The allocation of inputs and outputs to various products necessitates adherence to well-defined procedures, which should be thoroughly documented and accompanied by a justification for the chosen allocation method. The total quantity of elements assigned to the input and output of a unit process should be equivalent to the quantity of elements in the input and output prior to the allocation of the unit process. The allocation process is executed in accordance with the subsequent process, which includes (I) it is advisable to minimise the need for allocation by dividing the unit process that requires allocation into multiple subprocesses. This can be achieved by establishing connections between the incoming and outgoing data associated with these subprocesses. Alternatively, expanding the product system to encompass supplementary functions associated with co-products can also help mitigate the need for allocation; (II) In cases where allocation is inevitable, it is recommended to distribute the input and output components of the system across its various products or functions in a manner that accurately represents the inherent physical connections between them; (III) when it is not possible or appropriate to determine or utilise physical relationships as a primary factor for allocation, the allocation of inputs should be conducted in a manner that takes into account the various other relationships between products and functions. This may involve allocating inputs proportionally based on the economic value attributed to each product.

The allocation procedures should be consistently applied to the comparable input and output elements of the system under consideration.

3.3 Life cycle assessment of road pavement

Currently, in order to estimate the potential repercussions on the environment and human health associated with the manufacturing and laying of bituminous mixtures, starting with the resource's consumption and emissions, a systematic, standardised, and unbiased tool is LCA. The life cycle perspective provides significant contributions to recognising and improving the environmental performances of an item with particular consideration for each stage of the life cycle; consequently, the LCA itself serves as a making-choices framework for the development of pavement solutions defined by improved sustainability in the environment.

To get universally sustainable results from road infrastructure endeavours, not only the mechanical reaction is enough; however, economic and environmental appropriateness have to be appraised [86]. The findings of the investigation conducted, for example, by [87], demonstrated that incorporating RAP up to 75% into a hot bituminous blend decreased CO2 emissions by 40% compared to HMA.

According to [88], emphasised the way that might be substantial variations in the two mixtures of bituminous substances generated by two distinct plants, as well as how these variations might not be liked if they concentrate on CO2 emissions to the atmosphere since they could present unacceptable environmental burdens.

Some researchers, including [89], say that using an aged binder made from RAP at a level of 30% by weight of dry aggregates can help lower energy use, greenhouse gas (GHG) emissions, and production costs.

The study [90] examined the emissions of hydrocarbon aerosols, vapours, and gases into the atmosphere during the heating process of a binary asphalt/waste mixture. The investigation focused on different stages of road pavement construction. The analysis has provided confirmation that temperature plays a significant role in the production of airborne substances. Specifically, the addition of wax to the mixture results in a decrease in the temperature required for mixing and laying by approximately 30°C. Moreover, this addition leads to a notable reduction in asphalt emissions, particularly at temperatures below or near the melting point of the wax, which is 110°C. [86] centred on the utilisation of LCA in the context of road construction. The objective was to assess and quantify the potential environmental impacts associated with the use of both conventional and alternative materials. The study revealed that the predominant materials identified were recycled asphalt, consisting of concrete and bitumen, fly ash, and polymer. Furthermore, the environmental impact categories that were frequently evaluated included energy consumption and Global Warming Potential (GWP). The primary benefit observed from the analysis of the materials is their ability to mitigate environmental impact through the avoidance of landfill disposal.

In their study, Turk et al. [91] examined two distinct road pavement rehabilitation techniques using LCA. The first technique was a hypothetical traditional approach that was designed to be comparable to the second technique, which was the cold-inplace recycling approach actually implemented in practice. Both techniques were found to provide a similar extension of road service life, estimated to be approximately 20 years. The scenarios exhibit variations in the processes employed for earthworks performance, while the placement of asphalt, encompassing the installation of both the base and wearing courses, follows a uniform procedure. Consequently, it can be inferred that the equipment and construction techniques employed for these tasks are identical. The practice of recycling has been found to yield a reduction in environmental impacts of approximately 15–18% in relation to acidification potential (AP), abiotic depletion of fossil fuels, and energy consumption. Nevertheless, in terms of GWP, recycling does not demonstrate any discernible advantage. The most unfavourable scenario for cold-in-place recycling would arise when Portland cement is employed, particularly with a high clinker percentage.

The study conducted by Farina et al. (92) centred on the life cycle assessment (LCA) of various road paving technologies that utilise bituminous mixtures incorporating recycled materials, including crumb rubber sourced from end-of-life tyres and reclaimed asphalt pavement (RAP). The analyses were conducted by taking into account various scenarios that arise from the integration of production, construction, and maintenance operations. These scenarios were then compared to a reference case that involved the use of conventional paving materials. The findings indicate that the utilisation of wearing courses incorporating asphalt rubber, produced through the wet technology process, can yield substantial advantages in terms of energy conservation, environmental sustainability, human well-being, ecosystem preservation, and resource conservation. The aforementioned advantages are only marginally enhanced through the utilisation of RAP as a partial replacement for primary aggregates. These benefits are assured solely when mixtures are appropriately formulated and applied, thereby potentially reducing the thickness of surface courses and the frequency of maintenance. [93] conducted an analysis to evaluate the individual contributions of various processes within the transportation project life cycle. This analysis was conducted using an environmental impact assessment (EIA) model. The findings from the empirical analysis indicate that within the life cycle of a fast-track transport project, the construction phase exhibits the most significant environmental impact, accounting for 62.7% of the total. Subsequently, the demolition phase follows with a contribution of 35.8%, while the maintenance phase has a relatively minor impact of 1.7%.

In summary, the research conducted using LCA has shown that the incorporation of alternative materials and the utilisation of new technology at lower temperatures in pavement layers yield enhanced environmental outcomes in comparison to conventional methods.

3.4 Minimum Environmental Criteria (MEC)

The Minimum Environmental Criteria (MEC) refer to the set of environmental requirements that enable the assessment and selection of design solutions, products, or services with the highest environmental performance across their entire life cycle. These criteria are established as part of the Strategies for sustainable development of consumption in the public administration industry and are officially adopted through the Minister of the Environment for the Protection of the Territory and the Sea's Decree (Interministerial Decree of 11 April 2008, subsequently confirmed by the Decree of 10 April 2013). The objective of the plan is to enhance the diffusion of "Green Public Procurement," also known as Green Purchases, as defined by the European Union. This refers to the procurement process employed by public administrations to acquire goods and services that have a reduced environmental impact throughout their life cycle. The promotion and utilisation of Green Public Procurement (GPP) enables public authorities to exert influence on the market by incentivizing the industry to advance the development of environmentally friendly technologies that encompass the entire life cycle of products. This includes various stages such as production, supply, transportation, utilisation, and disposal.

The enactment of the obligation of GPP was first established by Article 68 bis in

Legislative Decree number 163/2006, as subsequently amended. In order to ensure sustainable and environmentally friendly procurement practises, the Public Administration (PA) is required to adhere to the guidelines provided by the Ministry of the Environment (MEC) on an annual basis. These guidelines are presented in special lists that outline the categories of goods and services, their environmental impacts, and the corresponding expenditure volumes.

The effectiveness of the MEC and its governance is regulated by national legislation, specifically Article 18 of Law 221/2015e and Article 34 of Legislative Decree 50/2016, also known as the "Procurement Code" (amended by Legislative Decree 56/2017). These legislative provisions make it obligatory for all contracting stations to adhere to energy and environmental sustainability criteria.

The obligation ensures that the national policy on green public procurement is comprehensive, encompassing not only the objective of reducing environmental impacts, but also the objective of promoting more sustainable, "circular" production and consumption models. Additionally, it aims to facilitate the dissemination of "Green" employment opportunities, while simultaneously rationalising consumption and conducting spending reviews.

The MECs encompass seventeen distinct categories that pertain to supplies and assignments. These criteria, in conjunction with the minimum environmental criteria for the allocation of design services and construction projects for public buildings, dictate the selection process for candidates. They also establish the technical specifications for buildings or groups of buildings, ranging from the specifications for the construction site to those for the building components. The MEC documents, individually tailored, exhibit a comparable fundamental framework.

The introduction section discusses the relevant environmental and social legislation, provides recommendations for the analysis of needs for contracting authorities, offers additional guidance on completing the related tender, and outlines the approach taken to define the Minimum Environmental Criteria (MEC), including the use of a technical support document.

The primary focus of the contract pertains to environmental sustainability, with potential consideration for social sustainability, thereby indicating the inclusion of environmental and potentially social criteria within the tender process. It is imperative for the contracting authorities to consistently specify the ministerial decree that sanctions the environmental criteria employed in the subject of the contract.

The MEC are specifically established for one or more stages of the tender procedure's definition phase. Candidate selection: these are subjective qualification criteria intended to demonstrate the candidate's technical capability to execute the contract with minimal environmental impact.

The technical specifications, as delineated in Legislative Decree 50/2016, pertain to the attributes intended for products, services, or materials. Furthermore, aside from not comprising the substantial content, these attributes may pertain to the method or process by which the requested works, supplies, or services are produced or performed, or to a particular phase of their life cycle. It is sufficient that such details are connected to the subject of the contract and commensurate with its value and objectives.

The reward criteria: these are prerequisites designed to identify products and services that exhibit superior environmental performance beyond what is specified in the technical specifications. A technical score is assigned to these products and services, and they are awarded based on the offer that provides the greatest value for money.

Lastly, the contractual clauses: furnish pertinent details necessary for the efficient execution of the assignment or provision in an environmentally sustainable manner.

In the Verifications section, each environmental criterion also specifies the supporting documentation required to establish compliance.

The identification of environmental criteria commences with a market analysis of the relevant sector and incorporates a diverse set of prerequisites, such as those outlined in the European GPP toolkit ("toolbox") by the European Commission or in the regulations imposing specific environmental standards.

A distinct set of EU GPP criteria was formulated regarding the construction and maintenance of road pavements, specifically for the "Road Design, Construction, and Maintenance" product group [94]. As in other areas of public bidding, the practical implementation of these principles is bolstered by a preliminary guidance document and a technical report. These resources offer valuable perspectives on the integration of GPP criteria into the public procurement process and provide additional justifications for the selection of sustainability criteria.

With the intention of reducing the degree of methodological and technical intricacy, procurers are presented with the subsequent award criteria in the public bidding process:

- Promoting reduced emissions during transport phases: This incentivizes the transportation of aggregates, binders, finished products, and waste utilised in the construction of primary road elements to produce low CO_{2eq} emissions.

- Specific useful life thresholds are mandatory. Bidders are obligated to submit solutions that meet a minimum performance requirement with respect to the anticipated number of years until specific structural distresses manifest on the road pavement.

- LCA: The process by which a Life Cycle Assessment is conducted. Bidders are obligated to compile lists of input and output flows originating from the system being evaluated, as well as assess the life cycle consequences of the primary road components.

- Mandatory incorporation of recycled and reused materials: bidders are obligated to furnish materials that meet a minimum specification concerning the quantity of recycled and reused material to be included in the main road elements.

- Carbon footprint (CF): The process by which carbon is produced. Bidders are obligated to assess the global warming potential (GWP) of the primary road elements throughout their life cycle.

3.5 Road BIM (legislative)

The establishment of standardised protocols for BIM in the context of road and infrastructure projects is crucial in order to guarantee uniformity, compatibility, and the seamless exchange of data across the diverse parties engaged in the process of road and transportation infrastructure planning, design, building, and maintenance. These standards facilitate the enhancement of collaboration, the reduction of errors, and the improvement of project efficiency. Although there may be variations in specific standards across different regions and countries, there are some internationally recognised standards and recommendations pertaining to road BIM.

The ISO 19650, developed by the International Organisation for Standardisation (ISO), encompasses a comprehensive set of standards designed to establish a systematic approach for effectively managing information over the complete life cycle of a constructed asset, encompassing various elements such as roads and infrastructure. The subject matter encompasses a range of facets pertaining to BIM, encompassing information management and the interchange of data.

The Industry Foundation Classes (IFC) are a data format that promotes interoperability among various BIM software systems. It is designed to be open and neutral, allowing for seamless communication and the exchange of information between different software platforms. The utilisation of data communication between different software tools is prevalent in road and infrastructure projects.

The IFC 4 - ISO 16738:2013 [95] expands its capabilities to include parametric geometries, materials, and structural entity management, along with several other modifications. Additionally, it facilitates the eventual shift to XML as the digital format. The addendum of IFC 4 – ISO 16739-1:2018 enhances the structure of linear infrastructure, specifically roads and railways, by introducing updated guidelines for the identification of alignments.

The IFC 4 refers to the set of rules governing civil infrastructures, encompassing various elements such as roads and buildingSMART is actively engaged in the development of multiple concurrent sub-projects aimed at enhancing the file format to increase its applicability in various domains such as bridges, trains, ports, waterways, and tunnels. For example, the inclusion of a 3D solid and appropriate pipe and lining materials is recommended for the drainage pipe model. The creation of drainage pipe models that adhere to specified standards can be accomplished using Bentley OpenRoads and Autodesk Civil3D software. These tools can be utilised to explore the importation of IFC data, with a particular focus on determining the most suitable IFC version for various projects. The Figure 3 illustrates it.

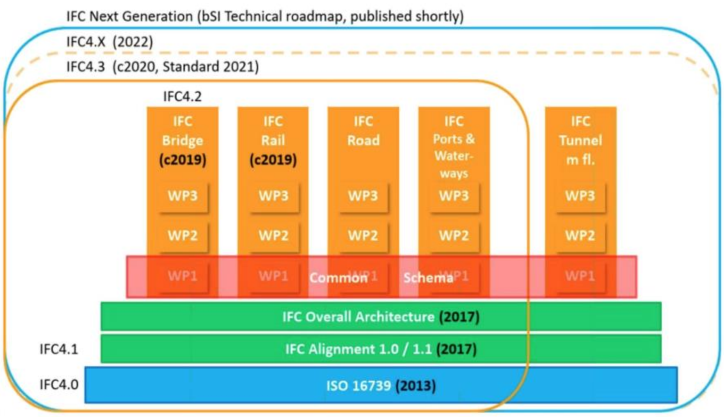


Figure 3 – IFC infrastructure extensions (BuildingSMART, 2020)

The Construction-Operations Building Information Exchange (COBie) was first developed for building projects but has now been modified to include infrastructure endeavours, such as road construction. The Construction COBie offers a standardised framework for the exchange of facility and asset data.

Numerous countries and regions have formulated distinct BIM standards tailored to road and infrastructure projects. An illustration of this can be seen in the United Kingdom, where the implementation of BIM Level 2 standards has been observed in numerous road infrastructure projects.

The industry-specific standards have been established by certain organisations, such as the American Association of State Highway and Transportation Officials (AASHTO) in the United States, to provide rules and standards specifically tailored to road and transportation projects within the context of BIM. The Bentley Systems provides the OpenRoads platform, which is utilised for road design and building endeavours adhering to established standards. Although road BIM does not have universal adoption, it has established its own specific principles and criteria. The notion of "smart infrastructure" encompasses the integration of many technology and data sources throughout transportation and infrastructure initiatives. Emerging standards pertaining to data for smart infrastructure, encompassing sensor data, are becoming increasingly relevant within the context of road BIM.

Furthermore, the UNI 11337 standard is of paramount importance. The development of this standard is attributed to the Italian organisation UNI (*Ente Nazionale Italiano di Unificazione*), which has the responsibility for the creation and dissemination of technical standards within Italy. The standards established by universities encompass a diverse array of subjects, such as engineering, technology, and various sectors within industries. These subjects are divided into 7 parts:

- Part 1: Models, documents, and informative objects for products and processes.
- Part 2: Naming and classification criteria for models, products, and processes.
- Part 3: Models for collecting, organising, and storing technical information for construction products (digital information sheets for products and processes).
- Part 4: Evolution and development of information within models, documents, and objects.
- Part 5: Informative flows in digital processes.
- Part 6: Guidance to redaction the informative specific information.
- Part 7: Integrated Information and Decision Management Processes.

The UNI 11337- Part 1 [97] standard encompasses the fundamental elements of managing digital information processes within the construction industry. These elements include: (I) the structure of the information carrier; (II) the structure of the process information; and (III) the structure of the product information.

This standard is relevant for all types of products derived from the Architecture, Engineering, and Construction (AEC) sector, including buildings and infrastructure. It also applies to various processes, such as conceptualization, production, and operation. These processes can be directed towards new construction, environmental preservation, or the restoration of existing structures and cultural heritage. In addition, this part 1 is applicable to any type of intervention and/or work, affects the general aspects of digital management in the information process of construction, such as:

- Digital maturity in the building process.
- Information structure of the building industry product.
- Structure of the construction information process.
- Informative breakdown of the product and process.

Understanding the level of *digital maturity in the building process* is important because it shows the logical shift from traditional management of the process and the steps that need to be taken to get from traditional management to the best level of digital management of the information processes of construction. In traditional management, the fact that the project is the sum of graphic elaborations, often inconsistent between them, while in the management type manifested in the norm, the informative model is the unique source of the data and the information of the process, and the documents and tables are directly extrapolated from it. The digital information maturity levels are defined by UNI 11337-1, which considers the different levels of data content transfer:

- Level 0, non-digital.
- Level 1, base.
- Level 2, elementary.
- Level 3, advanced.
- Level 4, optimal.

Table 2 – Levels of data content transfer

Maturity level	Level 0	Level 1	Level 2	Level 3	Level 4
The needs that have been identified according to the standard.	The transmission of informational content using non-digital mediums	The transmission of information material via both digital and non-digital methods of information processing.	The primary means of information transmission is predominantly facilitated by graphical information models, potentially supplemented by digital graphical information processing.	Graphic and elaborate information models use digital product and process information sheets to communicate	The transmission of information content via information models, which can be observed in graphical, documentary, and cognitive forms.

The *Information structure of the building industry product* refers to the alteration of the natural environment resulting from the construction of a building or infrastructure. A complex of works refers to a collection of interconnected works that possess distinct intrinsic functions yet share a unifying aggregating function. An instance of a motorway can be understood as a comprehensive system comprising various elements, such as the roadway itself, service areas, and other related components. The artistic creations, or collections of artistic creations, are inherently connected to the physical and digital landscape in which they are situated or installed. The information structure of the works encompasses both tangible elements, such as their parts and components, as well as intangible aspects related to procedures or spatial organisation. The term "process" refers to the information content that is associated with the activities and resources utilised as production factors. Space refers to the informational content that pertains to specific areas or volumes, which are categorised or combined based on their function or intended use. The website provides information pertaining to the environment and the anthropogenic alterations that have been made to it. The subject matter pertains to the building and infrastructure sectors, encompassing data and knowledge pertaining to various projects, their constituent elements, and components. These projects are either commissioned or distributed across a given geographical area.

The *structure of the construction information process* is the structured sequence of stages and phases that concern the production and management of information content related to the entire life cycle of a work, from the expression of the client's needs to their satisfaction, through the sequence of strategic programming, design, production, and commissioning of the work itself.

The *informative breakdown of the product and process* concerns both the intangible aspects of a procedural or spatial nature, as well as the tangible aspects relating to the resulting product (building or infrastructure) and the context in which it is installed.

The models, their constituent objects, and the information they contain undergo changes in quality and quantity over time as the various stages and phases of the process are refined. These changes are characterised by varying degrees of depth, stability, and reliability. Making sure that collaboration spaces for digitization processes work well and efficiently means that everyone involved needs to know and understand the qualitative and quantitative requirements for the information content. Additionally, stakeholders should be aware of the progress and approval status of the process as it unfolds.

Another important part of the standard UNI 11337-4 [98] is the part 4: Evolution and development of information within models, documents, and objects. This standard is relevant for all types of products that arise from the field of Architecture, Engineering, and Construction (AEC), including buildings and infrastructures. It is also applicable to various processes such as conception, production, and operation. These processes can be directed towards new construction, preservation, and/or restoration of the environment or the built heritage.

This part 4 refers to the delineation of the level of information detail. This refers to the categorization of the informational components of an asset, which are produced during the construction information process. The purpose of this categorization is to enable the quantification of the information model's content, as well as the graphic parametric model and the documental relational model. Drawing primarily from international documentation such as ISO, PAS 1192-2 [99], AIA Document G202-2013, and the Italian text of UNI 11337, there is a proposed implementation of a classification system for information contents. This system aims to enhance the measurability and effectiveness of information content management within a collaborative workplace. By doing so, it seeks to address the potential challenges of interpretation and subjectivity that often arise in such environments.

It specifically defines four classification systems that are based on various levels of detail pertaining to the information content of the model under consideration.

- Level of Detail (LOD),
- Level of Information (LOI),
- Level of Document (LD),
- Level of Study of the Information Model (LOM).

The concepts of LOD and LOI enable the quantification of the geometric and non-geometric aspects of the information graphic content inside a parametric graphic model. The use of the LD enables the measurement of both the geometric and non-geometric aspects of the informational content of the documental relational model. Ultimately, the use of LOM enables the assessment of the development of the information model throughout the construction information process. The first two categorization systems, as well as the last one, correspond to the Italian adaptation of the Level of Detail, Level of Information, and Level of Definition found in English documentation. In the international arena, there is a predominant emphasis on the classification of graphic elements and their association with modelling. Within this context, a level of documentation with Italian origins has been introduced. This level has been developed to address the need for seamless coordination of informational content within documents, a practice that is currently lacking despite its significance, which is on par with the importance of graphic content. The Italian information detail levels pertain to the notion of data uniqueness. In other words, the data and information that constitute the information content of the information model must be consistent, regardless of whether they are expressed through a graphic parametric model or a relational document.

From this perspective, the UNI 11337 standard is considered to be at the forefront of consolidating thoughts and experiences in the area of managing information material related to graphics. It adopts an innovative approach that focuses on the informational aspects of documents.

In conclusion of this segment of this chapter, it is essential to acknowledge that the particular standards and principles to be adhered to may differ contingent upon the geographical context of the project and the entities engaged in it. In addition, it is crucial to stay current with the latest criteria relevant to the project, as these standards are subject to potential updates and revisions. Active involvement with BIM legislation aids in proficiently navigating the specific requisites that pertain to road and infrastructure projects.

4 MATERIALS STUDY

In this chapter, we will detail the materials used in the research project, including RAP, into cold mix asphalt recycling, plastic waste, and the binder. The selection of these materials is crucial for understanding the objectives and outcomes of the study.

4.1 Plastic waste (PW)

By incorporating shredded plastic waste into the asphalt mix, it not only reduces the demand for virgin materials but also it can increase the durability of roads. These polymers are often known as "hydrogenated polymers" or "hydrogenated styrene-butadiene-styrene (SBS) polymers". Therefore, this become evident that the integration of plastic waste into asphalt is a small yet significant step toward a more sustainable and resilient road network.

4.3.1 Polyethylene (HDPE)

Polyethylene (HDPE), or high-density polyethylene, is a type of plastic that is commonly used in various applications due to its versatility and durability. According to [100], the HDPE $(C_2H_4)_n$ is a thermoplastic polymer made from ethylene monomers, and it is known for its high strength-to-density ratio, which makes it a preferred choice for many industrial and commercial uses, and it is also known for its excellent chemical resistance. HDPE's chemical resistance is attributed to its molecular structure, which consists of long chains of hydrocarbon polymers with relatively few polar groups. Despite possessing satisfactory properties such as chemical resistance, thermal stability, ease of manufacturing, and commendable mechanical strength, it is important to note that HDPE has a significant susceptibility to combustion. The thermal breakdown and combustion processes of polyethylene (PE) include free radical chain reactions, which result in the generation of a significant quantity of highly reactive free radicals upon heating or ignition. The mitigation of materials flammability may lead to a reduction of fire disasters and economic losses.

Its resistance to various chemicals and solvents makes it a popular choice for a wide range of applications, including pipes, containers, tanks, and more.

4.3.2 Polypropylene (PP)

Polypropylene (PP) is classified as a polyolefin with a higher degree of hardness compared to polyethylene. The material in question is a kind of plastic that is often used as a commodity due to its low density and notable tolerance to high temperatures. The chemical formula of the compound is shown as $(C_3H_6)n$. This technology is used in several industries, such as packaging, automotive, consumer goods, medical, and cast films, among others. The potential attributes of PP might vary depending on the methods and composition used in its production and formulation. When considering material properties, one must evaluate if a substance is hard or soft, opaque or transparent, light or heavy, insulating or conductive, and whether it is plain or reinforced with inexpensive mineral fillers, short or long glass fibres, natural fibres, or self-reinforced.

The following are the many fundamental characteristics and advantages associated with polypropylene: The melting point of PP exhibits a variation. The melting temperature range of a homopolymer is between 160ºC and 165ºC and the copolymer has a melting point range of 135ºC to 159ºC [101]. PP has a relatively low density compared to other commonly used polymers in the field of commodity plastics. This characteristic makes it a viable choice for applications that prioritise lightweight and weight-saving attributes. The density of the homopolymer ranges from 0.904 to 0.908 g/cm3 and the density range of the random copolymer is 0.904–0.908 g/cm3. The density range of the impact copolymer is 0.898–0.900 g/cm3 [102].

The resistance of the material under consideration is constrained when exposed to aromatic and halogenated hydrocarbons, as well as oxidising chemicals. In relation to flammability, the PP exhibits a high degree of flammability, and it has the ability to maintain its mechanical and electrical characteristics even when exposed to high temperatures. This phenomenon takes place in circumstances of high humidity and when the object is fully immersed in water. The material PP has hydrophobic properties and has notable resistance to environmental stress cracking.

4.3.3 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET), also known as poly (ethylene terephthalate), is a very prevalent semicrystalline thermoplastic resin. Notably, PET stands out as the only saturated polymer that has significant economic value in terms of its use as both a fibre and film-forming material [103]. Furthermore, PET has favourable mechanical characteristics, including notable tensile and tear strength. Additionally, it possesses the capacity to be heat sealed and demonstrates exceptional barrier properties against various substances such as oxygen, carbon dioxide, anhydride, and fragrance compounds. The use of this particular polymeric resin extends to the manufacturing of thermoformed structures, as well as its incorporation into composite materials in conjunction with glass fibres [104].

According to the same research [105], the density of crystalline PET is 1.455 g/cm3, whereas the density of amorphous PET is 1.333 g/cm3. Nevertheless, the crystallisation of PET occurs at a rather sluggish rate when nucleating chemicals and plasticizers are absent, hence posing challenges during the injection moulding process. The induction of crystallinity in films, such as biaxial oriented PET films, is facilitated by mechanical actions. Furthermore, annealing is an additional procedure that involves subjecting the polymer film to temperatures ranging from 180 to 220°C for a brief duration, enabling the amorphous chains within the film to relax.

4.3.4 Plastic waste into asphalt mixtures

This present study utilises plastic waste PW material as a substitute filler in bituminous mixtures. The PW consists of the three types of plastics aforementioned and elucidated: PP, PET, and HDPE. The compound obtained from the PW successfully passes the 2 mm sieve size with a 100% passing rate. The post-consumer PW obtained through the mechanical shredding process of plastic bottles was subsequently subjected to thorough washing in appropriate facilities to eliminate any non-plastic residues. The washed PW was then dried using centrifugation and air stream ventilation. Finally, the dried PW was fed into an extruder that was equipped with a perforated plate measuring 2 mm in diameter. The Figure 4 shows the PW employed on the asphalt mixtures.

Figure 4 – Plastic Waste filler

The Table 3 presents a comprehensive overview of the principal physical characteristics of PW and limestone (LF) fillers, including specific gravity, Rigden voids (RV)s – the presence of fractional voids within the dry compacted mineral filler is observed –, and specific surface area.

The information displayed in Table 3. reveals that the average specific gravity of PW is 1.363 g cm^{-3}, which is comparatively lower than that of LF. This discrepancy can be attributed to the varying plastic types present within the overall plastic matrix. Specifically, the specific gravity ranges from 0.9 g cm^{-3} for PP to 1.4 g cm^{-3} for PET.

According to Table 3, the mean PW Rigden void value is 56% higher compared to LF. This disparity in void values is expected to have a significant impact on the ultimate stiffness of the mastics that incorporate the aforementioned fillers. This is due to the fact that the void value regulates the quantity of bitumen that is retained within the interparticle voids, consequently influencing the amount of bitumen that remains unbound. This suggests that mastics composed of PW may exhibit more stiffness compared to those composed of LF. According to Table 3, the specific surface area of PW is 45% bigger than that of LF. This higher surface area suggests that the filler particles in PW have the capacity to absorb a larger amount of bitumen. This is owing to the increased interface surface between the granular particles and the binder. This idea aligns perfectly with the principles and significance of the RVs.

Table 3 – The prime volumetric characteristics of the fillers employed.

	Specific gravity [g/cm^3] EN 1097-6	Rigden voids [%] EN 1097-7	Specific surface area [cm^2/g] ISO 927
PW	1.363	64.368	7930
LF	2.737	41.440	5480

4.2 Reclaimed Asphalt Pavement (RAP)

The RAP utilised in this study was acquired through the process of milling and stockpiling aged asphalt pavements. The RAP incorporated, illustrated on the Figure 5, is a combination of basalt and limestone aggregates, with their respective properties outlined in Table 4. The utilisation of RAP aggregate, also known as black rock [71], involves the incorporation of aggregates that are coated with an aged bitumen film, which does not contribute to the internal cohesion of the mixture. The information in Table 5. shows all the different features of bitumen made from RAP that are required by the EN 12697-1 standard.

Figure 5 – The RAP employed into the asphalt mixtures.

Table 4 – The RAP prime properties

Parameter	Unit	Value	Standard
Specific gravity	g/cm3	2.52	EN 1097-6
Water absorption	%	1.6	EN 1097-6
Sand equivalent	%	71	EN 933-8
Flakiness Index	%	10	EN 933-3

Table 5 – The RAP properties binder recovery

			Amount of recovery binder equals 4.41% (EN 12697-1)
Properties	Unit	Standard	Value
Penetration at 25°C	dmm	EN 1426	54
Softening point	°C	EN 1427	50.71
Dynamic viscosity at 160°C	Pa s	EN 13702	0.39
Frass	°C	EN 12593	-6

4.2.1 Cold Mix Asphalt Recycling

With the objective of enhancing the environmental characteristics of bituminous road mixtures, an investigation was conducted to examine the impact of Cold Mix Asphalt Recycling on the design of binder layer mixes.

4.3 Aggregates

The aggregates adopted as part of the research are of calcareous origin (Figure 6), divided into 4 different sizes: 10/16 limestone; limestone 6/12; limestone sand, fillers, reclaimed asphalt pavement and plastic waste. Analyses were carried out on each piece of material to test the crushing resistance (Los Angeles coefficient), the shape index, the flattening index, the content of organic substances and the specific weight. The results of the analyses carried out are shown in Table 6.

Figure 6 – Limestone aggregates used in the research.

Table 6 – Aggregates Physical-mechanical characteristics.

Analysis	Sample	Unity	Value	Standard
Coefficient Los Angeles	Limestone 10/18	%	20.6	UNI EN 1097-2
	Limestone 6/12	%	20.1	UNI EN 1097-2
Shape index	Limestone 10/18	%	4	UNI EN 933-4
	Limestone 6/12	%	8	UNI EN 933-4
Flattening index	Limestone 10/18	%	8	UNI EN 933-3
	Limestone 6/12	%	11	UNI EN 933-3
Equivalent in sand	Calcareous sand	%	95.3	UNI EN 933-8
Specific weight	Limestone 10/18		2.694	UNI EN 1097-6
	Limestone 6/12		2.713	UNI EN 1097-6
	Calcareous sand		2.718	UNI EN 1097-6
	Filler		2.737	UNI EN 1097-6

4.4 Cement

In this study used 2 typologies of cement to improve the mechanical properties of the cold mix asphalt recycling. These will be described below.

4.4.1 Portland cement

Portland cement, the most widely used type of cement in construction, possesses distinctive characteristics that are crucial to the field of civil engineering. Composed primarily of finely ground clinker, a product of heated limestone and clay, Portland cement exhibits remarkable binding properties when mixed with water.

One of its defining features is its rapid setting time, which allows for expedited construction processes. This attribute is particularly advantageous in projects where quick strength development is essential. Additionally, Portland cement demonstrates commendable compressive strength, providing durability and stability to structures over time.

Versatility is another hallmark of Portland cement. Its adaptability to various construction applications, including concrete, mortar, and grout, makes it an indispensable material in the industry. The ability of cement to form a strong bond with aggregates contributes to the overall robustness of structures.

The characteristics of Portland cement, including rapid setting, impressive strength, and versatility, make it a cornerstone in construction. Balancing its advantages with environmental considerations remains a key aspect of sustainable and responsible engineering practices.

4.4.2 Pozzolanic cement

Pozzolanic cement is a type of hydraulic cement that incorporates pozzolans, which are siliceous or siliceous and aluminous materials, in addition to the traditional ingredients found in ordinary Portland cement. The addition of pozzolans enhances the performance and characteristics of the cement, resulting in several key features.

One notable characteristic of pozzolanic cement is its ability to improve the long-term durability and strength of structures. Pozzolans react with calcium hydroxide produced during the cement hydration process to form additional cementitious compounds, such as calcium silicate hydrate (CSH), which contributes to the densification of the concrete matrix.

Moreover, pozzolanic cement exhibits a reduced heat of hydration compared to ordinary Portland cement. This is advantageous in large concrete pours, as it helps mitigate the risk of thermal cracking and ensures a more controlled setting process. Pozzolanic cement also enhances the resistance of concrete to chemical attacks and aggressive environments. The pozzolanic reactions create a more impermeable structure, reducing the penetration of harmful substances and enhancing the overall durability of the material. Additionally, the use of pozzolanic materials in cement production promotes sustainable practices by utilising industrial by-products or natural materials, thereby reducing the demand for traditional raw materials and minimising environmental impact.

In summary, pozzolanic cement offers improved durability, reduced heat of hydration, enhanced chemical resistance, and a more sustainable approach to cement production, making it a valuable option for various construction applications.

4.5 Binder

Neat Bitumen, standard bitumen, with a penetration class of 50/70 was adopted as a binder of the same type. This type of bituminous binder was selected, among the various ones available on the market, as it is considered the most used in Italy for the packaging of bituminous mixes and produced by an oil refinery in southern Italy. Also a modified bitumen was used in the composition of an asphalt mixture, with the objective to do a comparison with these mixtures. The assessments were carried out on a sample of bitumen, taken from the totality of binder supplied, to certify the performance of the binder. The results of the analyses carried out are shown in Table 7.

Table 7 – Proprieties of Neat Bitumen 50/70 and Modified Bitumen.

Analysis	Unit	Value		Standard
		NB	**MB**	
Penetration @ 25 ºC	dmm	61	68	UNI EN 1426
Sifting point (Ball and Ring)	ºC	48.8	46	UNI EN 1427
Dynamic Viscosity @ 60 ºC	Pa s	186	185	UNI EN 13702
Dynamic Viscosity @ 100 ºC	Pa s	3.220	4.10	UNI EN 13702
Dynamic Viscosity @ 135ºC	Pa s	0.413	0.25	UNI EN 13702
Dynamic Viscosity @ 150 ºC	Pa s	0.250	-	UNI EN 13702

4.6 Binder Rheology

The asphalt binder is a linear viscoelastic material (LVE), which is responsible for providing this property to asphalt mixtures [106]. Asphalt binder is a viscous fluid that, when requested at high temperatures and/or during slow loading, it behaves like a viscoelastic and thermoplastic liquid that acts as an elastic solid at low temperatures and/or over short loading times. At the macroscopic level, it is considered a continuous, homogeneous, and isotropic material, and its behaviour is dependent on three factors: temperature, amplitude of deformation, and number of loading cycles [107]. Therefore, understanding its characteristics is fundamental to predicting, modelling, and improving the mechanical properties of asphalt mixtures.

In general, the materials have a behaviour that varies according to the type of request and may be dynamic, static, short- or long-term, in addition to conditions of confinement and environmental conditions, humidity, and temperature. Also, considering the loading application time, in relation to the study of the stress-strain behaviour of a material, this is within the field of rheology.

The origin of rheology will be given by an essential interdisciplinary science, referring to research on the intrinsic reaction of real materials to stresses. The etymology of the word rheology comes from the Greeks Rheo = flow and logos = study, to describe the deformation, in solid materials and, the flow, in liquid materials, being this explanation was first presented by Bingham and Crawford [108]. Hunter et al. [109] present that rheology is derived from Greek and translates literally as *rheos* (flow) and l*ogy* (science); that is, for the author, rheology means nothing more than "the science of flow". In the same way, rheology - broadly specified in relation to asphalt binders - is defined as an essential measure associated with the deformation and flow properties of the binder.

The physical properties of the binder are commonly associated with its temperature from the point of view of the characteristics of the material. In addition to being a material that has its properties changed according to temperature, asphalt binders are viscous; thus, the combination of these properties makes it a thermos-viscoplastic material in the field of small deformations.

Bernucci et al. [110]. describe the structure of binder as the dispersion of polar molecules in a non-polar environment, it helping to understand the effect of temperature on asphalt binders. At very low temperatures, the molecules are unable to move relative to each other, and the viscosity becomes very high. In this situation, the binder behaves like a solid. As the temperature rises, some molecules begin to move, creating a flow between them. Increased movement decreases viscosity, and at high temperatures, the binder behaves like a liquid. This transition can be reversible when there is a domain of linear viscoelasticity. According to Hunter et al. [109], the main physical properties of Petroleum Asphalt Cement (PAC) are durability, adhesiveness, thermal susceptibility, and hardening.

The effects of time and temperature are related to the properties of asphalt binder. For example, the behaviour of the binder when maintained at high temperatures for a short period of time is similar to that when it is maintained for long periods at mild temperatures.

When required for stationary loading (vehicles that travel at low speeds or parked loads) at high temperatures, the PAC resembles a viscous liquid. Viscous liquids are often called plastics because of the amount of deformation that the material cannot recover after the load is removed. When subjected to intermediate temperatures, they exhibit viscous and elastic behaviour. When subjected to low temperatures, the binder exhibits elastic behaviour, and it can become brittle when overcharged, which may cause breakage. Thus, the susceptibility to temperature and loading time of PAC, rheology (or viscoelasticity) is an important variable in the performance of asphalt pavements.

Usually, viscoelastic creep data are presented in two ways. The total voltage related to the time of a given temperature or temperatures. The linear viscoelasticity of a material can be below the critical value of applied stress. Another way to graphically represent the viscoelastic creep of a material is according to creep as a function of time. Below the critical deformation, the viscoelastic creep modulus does not depend on the applied deformation. A group of curves describing the stress versus time response to various applied stresses can be represented by a single modulus of viscoelastic creep versus time curve if the applied stresses are below the critical stress value of the material [111].

The stress-strain ratio (Equation 1), in elastic materials, can be obtained from the use of Hooke's law, that is, the stress and strain are linearly equivalent, and the material is affected only by the stress or strain applied at the current moment.

$$\varepsilon = \frac{\sigma}{E} \qquad \text{Equation 1}$$

Hence, E is the modulus of elasticity; the ε and σ are, in due to the order, the deformations (stress) and uniaxial tensions (strain).

In the condition of removing the applied stress, it can be said that the retained "deformation memory" will cause the material to recover (deformation returns to zero), and creep tests can be used to define the elasticity of the material by regulating the recovered stress [109]. In addition, according to [112], the viscous deformation of the material during the loading application results in an unrecoverable deformation when the loading is removed.

This, being a time-dependent deformation, is manifested through creep and relaxation.

As also defined by [113] binders are materials that have the ability to store and dissipate mechanical energy in reaction to a deformation triggered by mechanical tension. This ability to store is linked to elastic performance; already dispersive losses the viscous properties, that is, they have viscous properties, deform or tend to deform after the load application ceases and does not recover its deformation suffered; also elastic, deform if or tend to deform when applied a load, but when removing it, its deformity is fully recovered.

Figure 7 shows the typical viscoelastic response of a binder under loading, highlighting the elastic, delayed elastic, and viscous properties.

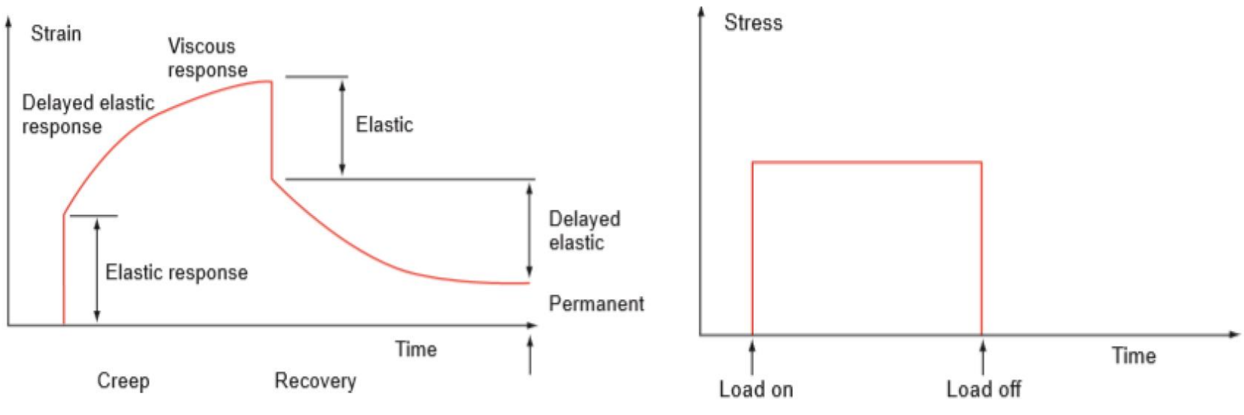


Figure 7 – Strain-stress response during a creep and recovery test.

Due to the amplitudes of loading time and temperature, for the characterization of the stiffness of an asphalt binder, the logarithmic scale representation is indicated. The curves of creep tests and strain measurement under constant load conditions, as shown in Figure 8, allowing the determination of stiffness variability, are presented in Figure 9. These tests were performed at different temperatures (T1; T2; Tr; T4; T5). With the possibility of combining the results, the "master curve" is created by overlapping the creep curves along the abscisse axis. A conversion factor has been established for each creep curve at a given temperature, a (T).

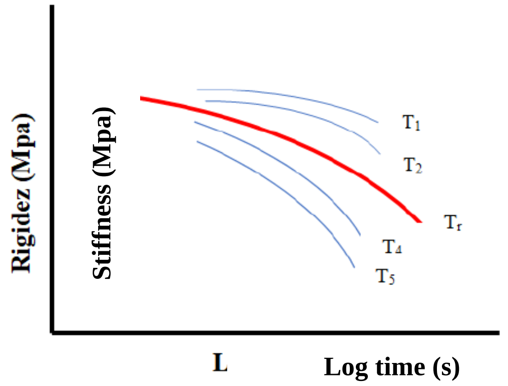


Figure 8 – Creep curves performed at different temperatures used to determine the master curve.

In the same way described aforesaid, data from recovery tests can be treated and represented, and unlike stiffness over time in recovery, this is known as recovery compliance (Jr). A relaxation test reverses the creep test. In the relaxation tests conformity of recovery, the deformation is suddenly imposed and then maintained at a constant level. The total viscoelastic resistance to deformation at a constant stress level can be evaluated by measuring the total accumulated stress after the material has had enough time to relax [109].

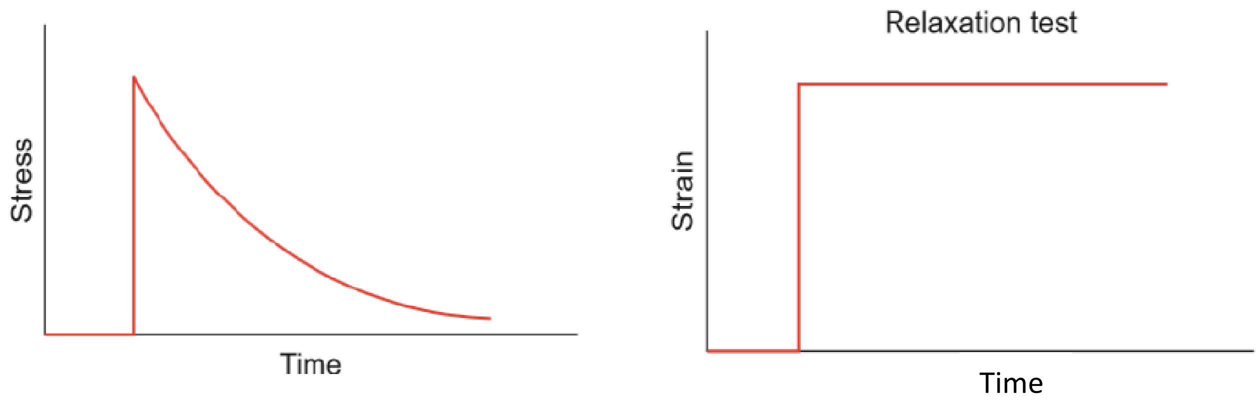


Figure 9 – Stress-strain response during a relaxation test.

Hunter et al. [109] further elucidate that in the order of reaction to the material being viscous and elastic, it will be given in relation to temperature and loading period, commonly designated loading time. At long loading times and high temperatures, the asphalt binder behaves as liquid viscous. However, in short loading times and temperatures with low intensities, the binder behaves as brittle elastic solids. In service conditions, it is more characteristic to obtain an intermediate range between temperature and loading time, resulting in viscoelastic behaviour.

The behaviour of the asphalt binder fits in the order in which it behaves in three different ways: an elastic region of low temperature; a high temperature viscous region; and a viscoelastic region of intermediate temperature.

The linear behaviour is done at low temperatures with short loading times at high frequencies, where the behaviour of the asphalt binder is solid-elastic. In the case of unmodified asphalt binders, linearity is also maintained at long loading times, at low frequencies, and at elevated temperatures, where the behaviour of the material acts almost absolutely as a fluid.

The Bending Beam Rheometer (BBR), a creep rheometer in a beam, obtains the first behaviour of the asphalt binder, in the low-temperature linear elastic region. It is a test device more commonly used to define the stiffness of the asphalt binder at low temperatures. Theoretically, the BBR is a constant stress extensional rheometer that aims to produce a module of Young [109]. However, in the asphalt binder industry, stiffness is usually mentioned as flexural stiffness (S(t)). The test method was adopted as a standard test in the Standard specification for asphalt binder with Standard Specification performance graded Asphalt Binder [114]. There is still a specification for the American Society for Testing and Materials Specification (ASTM D6648) (ASTM, 2008).

To perform this test, on a 100 g load piston, an asphalt binder beam is sent to a constant tension on a three-point bending machine. Then, this beam is suspended in an equi-dense cooled fluid, so the displacement of the piston is measured by the time function. The relationship between the relative parameters is given by Equation (2):

$$\mathrm{S(t)} = \frac{pL^3}{4\delta(t)bh^3} \qquad \text{Equation 2}$$

Where:

L = beam length;

h = beam height;

p = constant load applied;

b = beam width;

δ(t) = displacement without time t

According to [109], with the purpose of specification, S(t) and the slope of the curve, normally designated as value *m, are* both determined at a load time of 60s. Alternatively, stiffness curves can be acquired at different temperatures and structured as the main bending stiffness curves. For the purpose of calculating compliance data, information can be addressed in precisely the same way as fluency test information. In order to transform the results of the extensional mode into shear mode, it becomes imperative to take into account the Poisson coefficient (v).

The Poisson coefficient points to the fact that an object will compress in the perpendicular direction and expand in the axial direction, in which this object is being pulled. In the high-temperature viscous region, practically all asphalt binders have newtonic behaviour (this means that when the resulting stresses are linearly proportional to the local deformation rate) at very low shear rates or very low stress levels. As the stress level increases and/or the shear rate increases, the non-Newtonized behaviour gradually appears. In relation to the behaviour of asphalt binders, they present Newtonian behaviour at temperatures around 60°C. But polymer modified asphalt binders are likely to be susceptible to shear at temperatures above 60°C.

The third way of behaviour, according to [115], the intermediate temperatures and the viscoelastic region, the asphalt binder has properties that are in the viscoelastic region at pavement temperatures in service. The binder, in addition to displaying a time-dependent relationship between the stress or strain applied and the permanent strain or strain, displays a viscoelastic behaviour. The viscoelastic properties necessary to relate the essential properties of the physical binder to performance cannot be completely described by conventional methods of characterization of the rheological properties of the asphalt binder [109]. Also, according to the same author, to characterise the viscoelastic behaviour of the asphalt binder, softening and penetration point tests, even conducted around the temperatures in question, are most often completely empirical, so these are not relevant for that. Typically, through time-dependent tests characterising the viscoelasticity of the binder. Oscillatory dynamics, alternating strain and strain of constant amplitude and frequencies, creep and recovery, and transient load are the two most common methods of determining the viscoelastic properties of asphalt binder.

In short, the viscoelasticity of the asphalt binder is based on the mechanical behaviour it performs on the pavement structure. In relation to this characteristic, the asphalt binder wakes up to two distinct behaviours: the viscous, under overlapping slow and heavy loads, and the elastic, under overlapping fast and light loads. As a typical viscoelastic material, both the low temperature performance and the high temperature performance of asphalts are related to the viscoelastic properties of binders. Also, the response of the asphalt binder stresses is therefore dependent on temperature and loading time, and consequently, the rheology of the binder is defined by its response to stress/strain/time/temperature, however, traditionally, the binder has been predominantly characterised and specified using empirical tests [111].

5 METHODOLOGY

This chapter presents the research planning, methodology, and process, along with the materials utilized in this Ph.D. thesis.

This section focuses on a remarkable study that examines the performance evaluation of a pavement structure using an alternative binder layer solution. The road pavement in question has a width of 7.2m and consists of layers: the wearing course, the binder layer, the base layer, and subbase (unbound granular). The study proposes a single alternative pavement project solution for the binder layer, incorporating alternative mixtures in its design.

The primary objective of this section is to show the way for stress and strain calculations for the road pavement structure, which consists of a wearing course and base layer made of traditional hot mix asphalt (HMA), an unbound granular material serving as the subbase layer, and a binder layer composed of eight different asphalt mixtures. These calculations will be conducted for the distinct mixture solutions that have been derived from the optimisation phase, which will be further elucidated in Section 6 and, at a subsequent time, in Section 7, the creation of pavement information models in the BIM environment.

The Figure 10 illustrates how the workflow works.

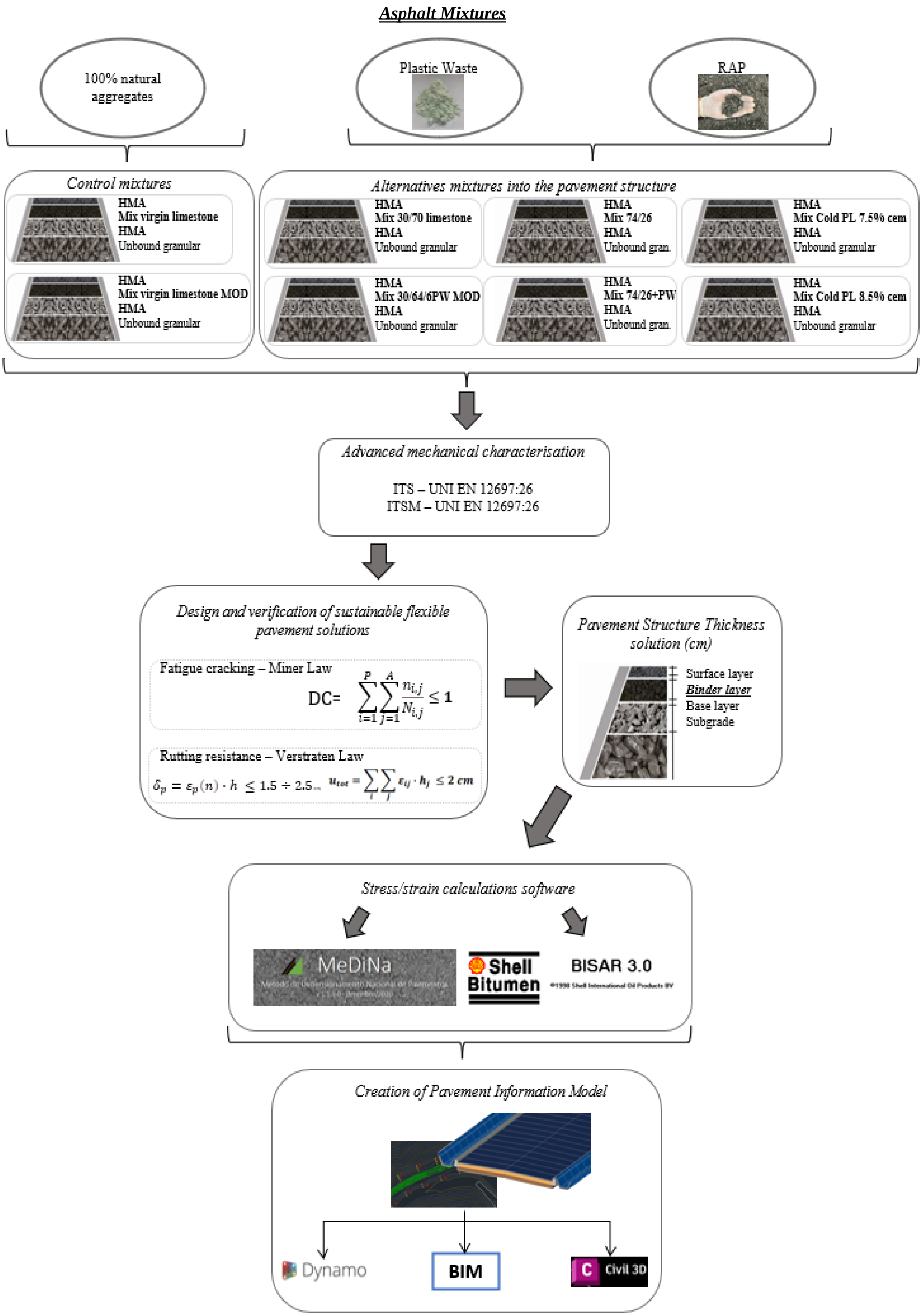


Figure 10 – Performance assessment of pavement structure with alternative solutions pertaining to the binder layer.

5.1 Asphalt mixtures

The asphalt mixtures are composite materials that are formed through the combination of aggregates, bituminous binder, filler, and various additives. The predominant application of asphalt mixtures is in the construction of flexible or semi-rigid pavements. These mixtures exhibit distinct characteristics depending on the specific layer of pavement they are designed for, namely the base, binder, and wearing course. These characteristics encompass composition, volumetric properties, and mechanical behaviour.

5.1.1 Composition

The primary factors pertaining to the composition pertain to the granulometric distribution of aggregates and the dosage of binder. In order to conform to a particle fused grain, which is characterized by an optimal distribution curve and predetermined tolerances, it is necessary for the aggregates mixture to adhere to specific dimensional limits.
In conventional literature, Fuller's formulation is commonly cited, wherein the maximum density curve of the aggregates is derived from Equation (3) as follows:

$$P = 100\left(\frac{d}{D}\right)^{n} \quad \text{Equation 3}$$

Where:

- *P* represents the passing percentage associated with a specific dimension;
- *D* represents the maximum aggregate size;
- *n* is a constant.

The Federal Highway Administration (FHWA) recommends a value of n = 0.45 in the formulation of bituminous mixtures. Additionally, the maximum aggregate size is suggested to increase for the base layers, indicating a coarser assortment, while for the higher layers, characterized by a finer assortment, the values are gradually decreased. The control points and the sand restriction zone in the SUPERPAVE system serve as indicators of the granulometric limits. The control points were determined through experimental methods in relation to the maximum density line and were subsequently established as a function of both the maximum and minimum nominal size.

The filler is classified as a distinct type of aggregate because it impacts both the particle size distribution of a mixture and has a direct influence on the other components, such as the binder, due to its dimensional properties. The particulate matter that is able to pass through the sieve with a mesh size of 0.063mm is commonly referred to as filler in the context of mineral materials. The composition of aggregates for construction purposes can vary, with the highest quality materials typically being sourced. Alternatively, rock dust, particularly limestone, cement, hydrated lime, hydraulic lime, asphalt dust, and fly ash, may be utilized in the production of aggregates. The purpose of adding filler to the aggregate mixture is to fill the intergranular voids left by the larger elements and/or adjust the granulometric curve in its lower section. In the context of bituminous mixtures, the bitumen combines with other components to create a substance known as bituminous mastic. The rheological characteristics of this mastic significantly influence the properties of the overall mixtures.

In addition, the particle size additionally impacts the second parameter, namely the bitumen content, which is typically quantified as a percentage relative to the weight of the aggregates. However, it is worth noting that the latest European regulations, specifically EN 13108-1, refer to the total mass of the mixture when discussing bitumen content. The ideal quantity should be sufficient to completely coat the entire surface of all particles with a binding film of suitable thickness. Each type of aggregate has its own unique surface area, which generally increases as the average size of the aggregate decreases. The determination of the optimal dosage is achieved through the mix design procedure.

5.1.2 Volumetric characteristics

The internal structure of asphalt mixtures plays a significant role in determining their performance characteristics. This structure can be described by considering the volumetric and weight ratios between the various components: solid aggregates, semi-solid binder (bitumen), and gaseous air. The structure of the mixture, as depicted in Figure 11, is characterized by the arrangement of spheroidal particles. In this arrangement, the smaller particles gradually fill the voids created by the larger particles. The bond between each stone element is characterized by two components: partial penetration of the bond into the porous surface, allowing water and absorbed binder to enter, and the formation of a thin film on the surface, known as effective binder. The voids present in the mixture are determined by the volume of air occupying the spaces between the grains.

When examining a representative portion of a compacted mixture with a volume (V) and mass (M), it is possible to decompose it based on the diagram presented in Figure 12. This diagram allows for the association of volume and mass values with each component phase. It is important to acknowledge that the precise volume of the aggregate. The variable VG partially intersects with the quantity VBA, which denotes the portion of bitumen that has been absorbed.

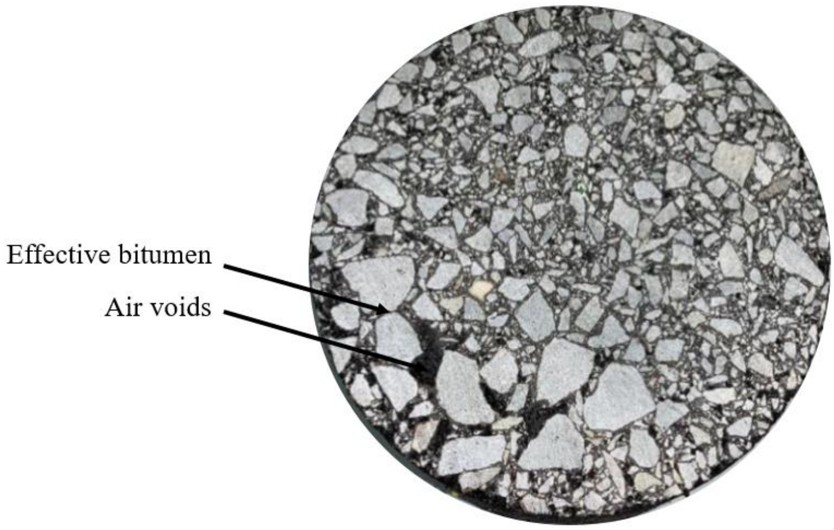


Figure 11 – Composition of the interior of an asphalt mixture.

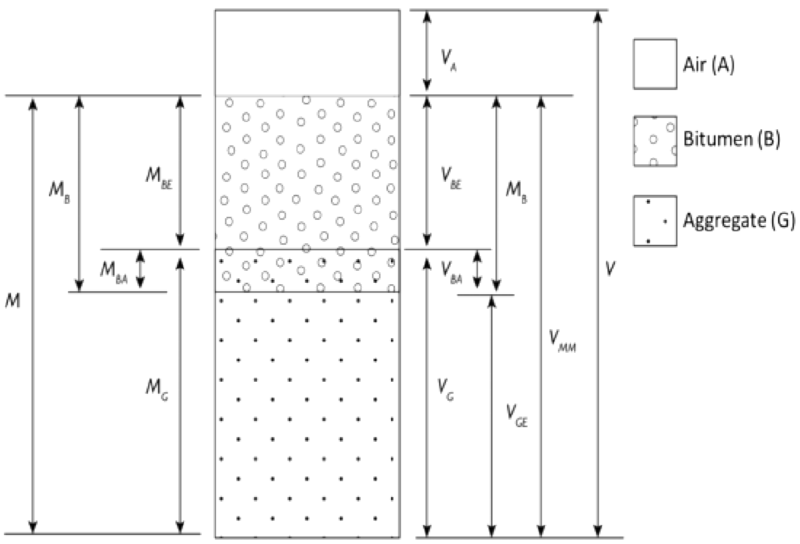


Figure 12 – The correlation between the volume and weight of the asphalt mixture.

5.1.3 Density

For the most prevalent method of determining density (MV), a sample (which may be packaged in a laboratory or extracted from the pavement via coring) is subjected to three distinct determinations: mass in air after drying (MD), mass in water (MW) under saturation conditions, and mass in air under saturated dry surface conditions (MSSD). There are:

$$MV = \frac{M_D}{M_{SSD} - M_W} \cdot \rho_{w,T} \qquad \text{Equation 4}$$

where [59] represents the density of water at the test temperature T, as denoted by Equation (5):

$$\boldsymbol{\rho}_{w,T} = 1.00016584 - 0.000793 \cdot T - 0.00000529 \cdot T2 \qquad \text{Equation 5}$$

5.1.4 Maximum theoretical density

Maximum theoretical density (MMVT) corresponds to the density limit value under the condition of zero voids; it is defined as follows:

$$\mathrm{MMVT} = \frac{\mathrm{M}}{\mathrm{V_{MM}}} = \frac{\mathrm{M}}{\mathrm{V_G} + \mathrm{V_{BE}}} \qquad \text{Equation 6}$$

which represents an intrinsic quantity of the mixture and is independent of the compaction level to which it is applied; the calculation formula is as follows: which is determined using the pycnometer method on a sample in the dissolved state:

$$\mathrm{MMVT} = \frac{\mathrm{M_D}}{(\mathrm{M_D} + \mathrm{M_{Pw}}) - \mathrm{M_{PGW}}} \cdot \rho_{\mathrm{w,T}} \qquad \text{Equation 7}$$

The mass of the sample in air is denoted as MD, the mass of the pycnometer filled with water (MPw) is the mass of the pycnometer containing the sample and filled with water (as determined by the calibration curve), and the density of water at the temperature being measured is denoted as MPGW.

5.1.5 Percentage of voids

Usually, it is feasible to identify an ideal void range for a conventional generic mixture in which it exhibits a mechanical response that harmonizes two contrasting behaviors: a significant rise in porosity, for instance, renders the mixture less durable due to the accelerated fatigue breaking process induced by water; conversely, an overbearing increase in porosity decreases the resistance to ruthless deformations.

The proportion of voids (a) is calculated using Equation (8), which begins with the preceding quantities:

$$v = 100 \cdot \left(1 - \frac{MV}{MMVT}\right) \quad \text{Equation 8}$$

5.1.6 Binder content

The binder content (P_B) is denoted by weight percentages and, as stated earlier, can pertain to both the aggregates' mass and the mixture's total mass, as illustrated by Equation (9).

$$P_B = 100 \frac{M_B}{M_G} \quad \text{Equation 9}$$

5.1.7 Mix design

The mix design of the blends encompasses several parts. These include (I) determining the granulometric composition of the aggregate mixture, (II) establishing the water content, (III) selecting the appropriate binder based on the predominant intended use, and (IV) determining the dosage of the binder.

The granulometric composition of the aggregate mixtures, in the field of mixture analysis, it is necessary to collect on-site samples of the aggregates, namely the milled bituminous mixture and any portion of the underlying foundation. These samples should be obtained immediately after the passing of the stabilising machine, known as a pulvimixer, and before the application of binders. Our operational approach considers the influence of the mixing rotor, which has a tendency to break up the larger lumps of the milled product. Samples of the different particle size fractions derived from the crushing of the RAP are collected at the facility, and the proportions of their utilisation are determined, similar to the practice followed for hot bituminous mixtures. The wet method is necessary for doing the particle size analysis. Single granules, whether they be small or huge lumps, are generally regarded as having no impact on the workability and performance of the final mixture. Due to this rationale, there is minimal interest, other than determining the identity of the lumps, in doing a particle size study on the aggregates derived from the milled bituminous mixture. Frequently, particularly in the context of on-site mixing, there arises a need to incorporate recycled aggregates alongside virgin material. The adjustment of the granulometric curve often pertains to the larger portion of the material when it is obtained from the removal of upper layers (such as binder and wearing course) during demolition. In contrast, the finer fraction and filler, which are abundant in the original bituminous mixture, tend to be scarce in the milled material due to their retention within the bitumen. The absence of large aggregates does not have a substantial impact on the properties of the final mixture, unlike the absence of fine aggregates, which greatly compromises all mechanical parameters.

The water content is an essential constituent of the mixture and must be accurately measured in order to permit compaction. The substance is typically inherent in the moist grout and may be incorporated into it prior to the process of blending. The comprehensive estimate should consider the content present in the bituminous emulsion. To ascertain the most suitable water content, the specimens are initially prepared by eliminating the larger particles from the aggregates, which are contained within a 20 mm screen. This is achieved by introducing a consistent amount of cement (2% of the aggregate weight) and varying water levels, typically ranging from 3% to 8%.

The typology of binder. The available binders for use in this context consist of over-stabilized emulsion of conventional bitumen, an over-stabilised emulsion of modified bitumen, foamed bitumen, and Portland cement. The selection of binders and their dosage is contingent upon several factors, including the desired composition of the mixture, the accessibility and customary applications of available options, and the specific intended application within the three distinct materials commonly employed for road pavement maintenance and construction: (I) Cold mixes are typically designed for use in the base layer; (II) the utilisation of a stabilised mixture comprising cement and bitumen for the construction of foundation layers; (II) Portland cement was mixed.

The utilisation of cement and bitumen, either in the form of foam or emulsion, for stabilisation purposes enables the creation of a layer that is less rigid yet more long-lasting.

This layer serves as an intermediary between the cement mixture and the hot bituminous mixture, effectively combining the desirable characteristics of both binders (cement and bitumen). The aim is to achieve the strength and lift properties typically associated with cemented mixes, while also ensuring that the fatigue performance remains uncompromised. The manipulation of bitumen and cement dosages allows for the regulation of the stiffness of the mixture and its sensitivity to temperature. This enables the adjustment of its rheological properties to align with either a cemented or bituminous mixture. The binding behaviour of emulsion and bitumen foam to the lithic skeleton varies due to the characteristics of the binder, which influence its distribution within the mixture.

The incorporation of the fine fraction by the foamed bitumen results in the formation of a bituminous mortar, which subsequently forms localised bonds with the coarse fraction. When the aggregate mixture is deficient in fine particles, the dispersion of foamed bitumen is insufficient, resulting in the formation of *veins* which are agglomerations of fine material with a high bitumen content. The absence of fines significantly contributes to the formation of numerous prominent veins, which function as lubricated sliding interfaces within the mixture, consequently diminishing its overall strength and stability.

The bituminous emulsion exhibits enhanced dispersion properties, resulting in a more extensive and uniform coating on both the fine and coarse fractions. By utilising foamed bitumen or emulsion, it becomes feasible to achieve mixtures that exhibit comparable mechanical and performance attributes over an extended period of time. Nevertheless, it has been noted that the use of bituminous emulsion necessitates extended curing durations, resulting in diminished short-term properties. When the bitumen content, whether in foam or emulsion form, is insufficient, the larger grains are not fully coated, resulting in the cement adhering to exposed surfaces. This leads to the formation of inflexible and fragile bonds. In the given circumstances, it can be observed that there is a positive correlation between the increase in cement content and the growth of the module. When an optimal quantity of bitumen is present and a suitable equilibrium is achieved between the two constituents, significant fluctuations in stiffness are not observed with the progressive augmentation of cement content. In circumstances where there is an ample supply of bitumen, the structure exhibits greater deformability and flexibility, resulting in a decrease in stiffness. Under these circumstances, the primary role of cement is to act as a filler. Its addition enhances the viscosity of the bitumen, resulting in a stiffer recovery, assuming all other factors remain constant. When considering the technical aspects and on-site safety, the utilisation of emulsion presents several advantages in comparison to foamed bitumen. In fact, the process does not necessitate the application of heat to the binder, thereby mitigating potential hazards for workers and offering increased flexibility in the scheduling of waiting periods prior to mixing. Additionally, the utilisation of foamed bitumen entails that any instance of bitumen reaching a significantly low temperature (below 160°C), regardless of the underlying cause, results in the rejection of the binder and necessitates the return of the tanker (even if only partially utilised) to the loading site. The emulsion that has been excessively stabilised, due to its extended breaking times, offers the advantage of providing a wider time frame for managing the levelling and compacting stages without jeopardising the effectiveness of the treatment.

In the manufacturing of cold mixtures for base layers, a modified bituminous emulsion is employed instead of cement, as the latter does not serve as a binding agent in this particular context. This applies to both on-site and plant-based production processes. The stone aggregates primarily comprise a recycled bituminous mixture, with a minor inclusion of virgin material (up to a maximum of 15-20%) to potentially adjust the granulometric curve. The utilisation of modified bituminous emulsion, along with the typically elevated dosage in comparison to the aforementioned stabilisations, enables the attainment of performance attributes that are akin to those exhibited by conventionally packaged bituminous mixtures. In the cement mixture, it is imperative to incorporate the milled bituminous mixture with either virgin or recycled aggregates that are not coated with bitumen. This is necessary to achieve granulometric correction and ensure the desired mechanical properties. The inclusion of milled material leads to a reduction in mechanical properties at a consistent cement dosage.

The dosage of the binder: In the process of cold recycling, the bitumen found in the reclaimed aggregate does not appear to significantly impact the properties of the resulting binder. As a result, there is no need to conduct rheological characterization of the binder. In this context, the recovery mixture is solely regarded as stone aggregate. In order to establish the appropriate dosage of binders, it is necessary to prepare samples containing varying dosages of cement and either foamed bitumen or bituminous emulsion (specifically, normal over-stabilised, or modified bitumen). These samples should be prepared using the same compaction procedure and the optimal water content. Following a maturation period of 72 hours at a temperature of 60°C, the indirect tensile strength and strength degradation are assessed subsequent to a 1-hour immersion period (both mechanical tests and water immersion are conducted at a temperature of 25°C). The specified criteria encompass a minimum strength threshold of 0.35 MPa and a maximum allowable strength reduction of 70%. The determination of the indirect tensile stiffness modulus (ITSM) at a temperature of 20°C is typically conducted.

5.2 Mechanical Properties

For the purpose of accurately forecasting the performance of a pavement design, it is of paramount importance to possess a comprehensive understanding of pavement distress. Two forms of asphalt pavement distress include fatigue cracking and permanent deformation. Fatigue cracking occurs as a result of tensile strain experienced at the lower portion of the asphalt layer. Rutting is a phenomenon that arises as a result of the gradual accumulation of permanent deformations on the surface of a road. Both permanent deformation and tensile strain arise from the repetitive loading conditions imposed on the material properties within each layer, as well as the intricate interplay between all layers within the pavement structure. The following subjects will explain these referred mechanical properties.

5.2.1 Indirect Tensile Strength (ITS) test

The tensile strength (TS) is a fundamental property of rocks that holds significant importance in the strategic considerations, conceptualization, and evaluation of subterranean structures, including mining roofs, galleries, fracturing, crushing, tunnel boring, drilling, and blasting. The thermal conductivity of rock materials is influenced by various factors, such as the presence of discontinuities, foliation, lamination, mineral composition, cementing material, hardness, and porosity. According to Liu et al. [116], rocks exhibit a lower resistance to tension compared to compression or shear. Tension cracks frequently emerge prior to the occurrence of compression or shear failure.

The indirect tensile configuration is commonly employed in classical failure tests to determine the ITS, which is a mechanical parameter associated with the test, also known as the Brazilian Tensile Strength rest. The indirect tensile strength test serves as a reliable measure of a material's strength and its ability to withstand fatigue, temperature-induced cracking, and rutting. Directly measuring the tensile strength of a material poses challenges due to the presence of secondary stresses that are induced when gripping a specimen in order to subject it to a pulling force for separation. Hence, the measurement of tensile stresses is commonly conducted through the utilization of an indirect method known as the splitting tensile test.

This particular testing method entails the utilization of cylindrical specimens that are subjected to a vertical force across their entire thickness. As a result, these specimens experience normal compression stresses in the horizontal diametrical plane and normal tensile stresses in the vertical plane.

The specimens are placed between two strips, and a piston is used to apply a compressive load along a vertical diameter plane that is coaxial with the specimens. By utilizing a polar coordinate system, one can effectively determine the energy at any given point. However, our specific focus lies on identifying either the maximum energy point or the centre of the specimen. The fracture transpires via a fissure that traverses the specimen in a diametrical manner, aligning with the direction in which the load is applied. This outcome arises from the tensile stresses that surpass the material's characteristic limit value (as specified in EN 12697-23).

Given the value of *P*, representing the maximum load, and the known dimensions of the sample, specifically the diameter (*d*) and height (*t*), the resistance of the material, denoted as ITS, can be determined using the Equation (10). It is important to note that this equation assumes the material to be homogeneous and isotropic.

The utilization of this test can vary depending on the specific conditions under which it is administered. At lower temperatures, it becomes possible to assess the properties of bituminous mixtures in relation to thermally-induced cracking and determine the relevant tensile strength parameters that should be incorporated into analysis models for thermal cracking analysis. At elevated temperatures, specifically at 25°C, it is employed for the purpose of evaluating the vulnerability of bituminous mixtures to water or for quality control purposes, both during the mixture design process and during the execution phase.

$$ITS = \sigma_t = \frac{2 \cdot P}{\pi \cdot d \cdot t} \quad \text{Equation 10}$$

Where:

σ_t is the tensile strength,

P is the maximum load,

d is the diameter of the specimen,

h h is the height of the specimen.

The utilization of this test can vary depending on the specific conditions under which it is administered. At lower temperatures, it becomes possible to assess the properties of bituminous mixtures in relation to thermally-induced cracking and determine the relevant tensile strength parameters that should be incorporated into analysis models for thermal cracking analysis. At elevated temperatures, specifically at 25°C, it is employed for the purpose of evaluating the vulnerability of bituminous mixtures to water or for quality control purposes, both during the mixture design process and during the execution phase.

5.2.2 Complex modulus (E)*

The complex modulus is the most important property to be characterised in asphalt mixtures. The complex modulus represents the stiffness characteristics of the material within the dependence of the frequency and temperature variation to which it is exposed.

The complex modulus test can be used to determine both the elastic characteristics and the linear viscoelastic properties of the material. In addition, the importance of considering the influence of temperature and different loading frequencies makes the complex module the main test for a better understanding of the stiffness of asphalt mixtures. The complex module is usually understood as an assay that presents results closer to the real properties of the material. For linear viscoelastic materials such as asphalt mixtures, the stress/strain ratio over continuous sine loading can be defined as a complex modulus (*E*).*

The test is performed under different frequency and temperature conditions, seeking to understand the viscoelastic behaviour of the material. In addition to the module values, we can also infer about another property, known as phase angle (ϕ), as shown in Figure 13. This parameter is directly linked to the requested viscoelastic plots and can be checked by the lag between the stress peak and the deformation peak. For a purely elastic material, ϕ = 00, and the sample does not develop a delay between stress and strain waves. For purely viscous materials, ϕ = 900. Viscoelastic materials have a phase angle range between $0^0 < \phi < 900$.

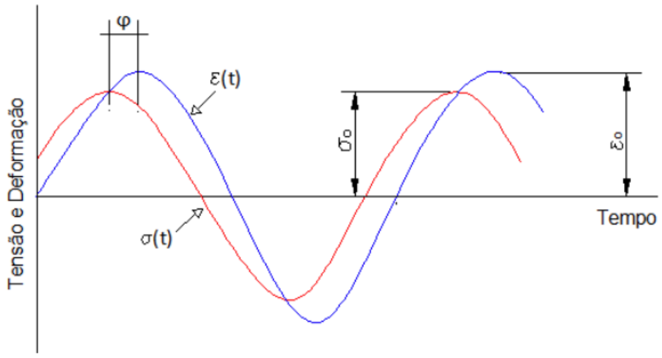


Figure 13 – Representation of strain and stress behaviour, and phase angle obtained in a mechanical loading (complex modulus) test on a visco-elastic material.

The relation of stress and strain in a linear visco-elastic material subjected to a sinusoidal load wave at time t. The strain, ε × sin (ω × t − Φ), has a phase angle, Φ, with regard to the stress when a stress, σ × sin (ω × t), is applied (UNI EN 12697:24; [117]).

The test temperature (*Θ*) and frequency (*f*) determine the phase angle and strain amplitude.

The complex modulus *E** is defined by the stress strain ratio as follows:

$$E^* = |E^*| \cdot (\cos(\Phi) + i \cdot \sin(\Phi))$$ Equation 11

The magnitude of the complex modulus is contingent upon both the frequency, denoted as f, and the temperature, represented by θ. The complex modulus can be characterised in two distinct manners:

(I) . Through the utilization of the actual component E1 and the imagined component E2:

$$E_1 = |E^*| \cdot \cos(\Phi)$$ Equation 12

$$E_2 = |E^*| \cdot \sin(\Phi)$$ Equation 13

(II). Through the utilization of the absolute value of the complex modulus, denoted as |E*|, in conjunction with the phase angle, represented as Φ,

$$|E^*| = \sqrt{E_1{}^2 + E_2{}^2}$$ Equation 14

$$\Phi = \arctan\left(\frac{E_2}{E_1}\right)$$ Equation 15

The utilization of this second characteristic is more commonly observed in practical applications. In the context of linear elastic multi-layer computations, it is common practice to utilize the E* modulus as the input parameter for Young's modulus.

To the entry, in the case of materials exhibiting entirely elastic behaviour, the phase angle is equal to zero, resulting in the complex modulus being equivalent to the Young's modulus. This phenomenon occurs when bituminous materials are subjected to extremely low temperatures. At this juncture, the complex modulus attains its utmost attainable magnitude, denoted as $E\infty$.

5.2.3 Indirect Tensile Stiffness Modulus (ITSM) test

The Indirect Tensile Stiffness Modulus test was used to investigate the stiffness modulus in this Ph.D. thesis. This test was conducted according to the Standard UNI EN 12697-26 [117], it already explained on the aforementioned subtopic (5.2.1). A servo-pneumatic universal testing machine (Asphalt Qube, 79-PV72Q02/I2, IPC Global, Control-Group) for asphalt material was used in the test. In order to investigate the temperature sensitivity of modulus, this test was conducted at 5 °C, 10 °C, and 25 °C, respectively. Three specimens were used for the test of each content. And the size of the specimen is φ101.6 mm × 63.5 mm, also. They were placed in the chamber at the test temperature for 6 hours before the test. The schematic diagram of the load is shown in Figure 14. The rise time of one impulse is 124 ms. The load duration period from the start of the load application until the start of the next is 3.0 s. The target deformation in the horizontal direction is 5 μm. The peak load was adjusted according to the test value of target deformation during the test. Data of five waveforms were recorded after adjustment. The test procedure is shown in Figure 15.

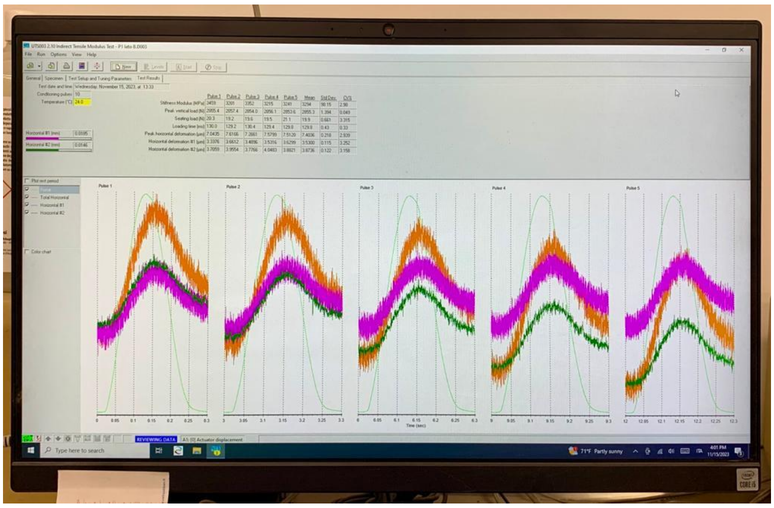


Figure 14 – Schematic diagram of the load in ITSM.

Figure 15 – Indirect tensile stiffness modulus test.

The stiffness modulus can be determined using the following equation (16):

$$S_m = \frac{F \times (\mu + 0.27)}{h \times Z} \qquad \text{Equation 16}$$

In this context, *Sm* represents the ITSM, measured in MPa. F denotes the peak load, measured in N. The Poisson ratio, denoted by μ, varies depending on the temperature, with values of 0.25, 0.30, and 0.40 at 5 °C, 15 °C, and 25 °C, respectively. The Z represents the deformation in the horizontal direction, measured in mm, while *h* represents the height of the specimen, also measured in mm.

5.3 Asphalt pavement Design

Currently, there are three methods of dimensioning: (I) the empirical method, which is derived from the statistical modelling of predetermined parameters obtained through test pavements. (II) The semi-empirical method, obtained through empirical data with a consistent analytical theory, and (III) the empirical-mechanistic method, in which the theoretical models are calibrated with specific experimental data for each material characteristic, can be obtained in the field or in the laboratory.

Regarding the design of floors containing layers of rigid materials, one should take into account two points: the fatigue limits of the material and the rutting criterion. Fatigue limits should be observed because it is the most common defect in this type of pavement. The rutting of the material should be taken into account to avoid defects such as pumping fines, possible cracks, and steps on the pavement.

The increasing use of empirical-mechanistic dimensioning was due to the problems of dimensioning presented by empirical methods, such as the realisation of subjective evaluations of the pavement, low attention to fatigue and sinking failures by wheel track, and a lack of coverage of various field conditions. Moreover, this design method allows the evaluation of layers in the presence of recycled materials.

The empirical-mechanistic design occurs through the process presented in Figure 16, where the following input data are considered: the environmental factors of the project, traffic volume data, the physical and chemical characteristics of the materials and the construction techniques applied. A thickness is adopted, and the stress and deformation states for this structure are calculated, then compared with the limits established for each design until a satisfactory structure is obtained.

The prediction models used for the empirical-mechanistic design method are: fatigue of the materials used in the pavement layers; permissible deflection on the surface; limit stress at the top of the subgrade; permanent deformation in the asphalt mixtures; granular materials; soils; and fine soils. Regarding the design limits, the author adds that it depends on the type of road for which the pavement is designed and that the values can be determined by the designer.

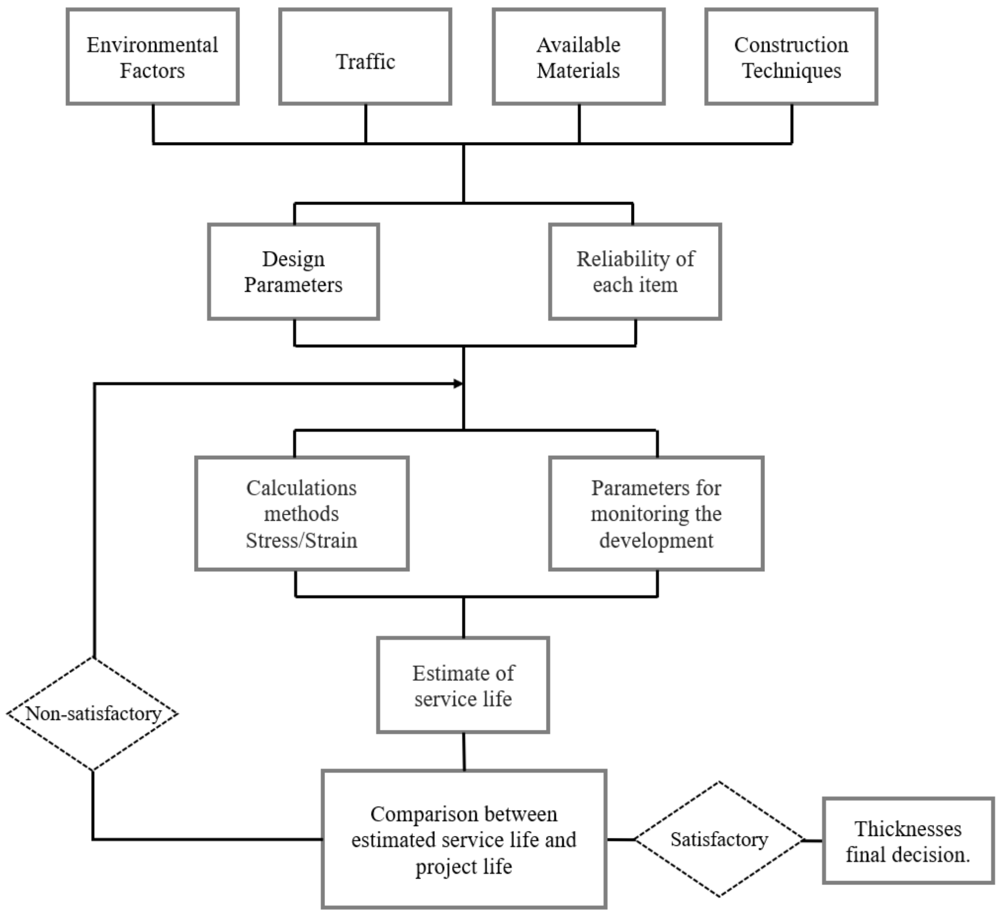


Figure 16 – Scheme of empirical-mechanistic design

5.3.1 Stress/strain calculations

The calculation for stress and strain will be done in two different software programmes to make a comparison between these results and make a decision about which one works better in relation to the alternative materials employed in this research. Furthermore, the calculations were done at four different temperatures: 10°C, 20°C, 40°C, and 60°C; winter, autumn, spring, and summer, respectively, representing the four seasons of the year. It is of paramount importance to assess the mechanical behaviour of asphalt mixtures from this point of view, due to the fact that the pavement structure performance is dissimilar to each season.

5.3.1.1 BISAR (Bitumen Structures Analysis in Roads) Software

The Bitumen Structures Analysis in Roads software is an intellectual property owned by Shell International Oil Products. Its development took place in the early 1970s, primarily for the purpose of creating design charts for the Shell Pavement Design Manual. Currently, the BISAR programme has been created as a mainframe computer software application. The subsequent iterations devised by Shell facilitated the utilisation of BISAR on various personal computing systems, enabling its application by pavement designers, researchers, and other relevant stakeholders.

The BISAR 3.0 software version enables the computation of stresses, strains, and deflections in response to diverse loading configurations and patterns. This version enables the user to consider the influence of horizontal forces and the potential slippage between the layers of the pavement. It is of utmost significance to acknowledge that BISAR 3.0 employs an elastic theory to compute stress, strains, and deflections in multi-layered systems.

As stated in BISAR 3.0, the software enables the consideration of horizontal forces and slippage, both of which are closely associated with the bonding condition within the interlayers of the analysed pavement. This software facilitates the analysis of these considerations by utilising the principle of shear spring compliance. Before delving into the intricacies of this concept, it is essential to illustrate the manner in which these values are entered into the software. Figure 17 depicts the interface whereby the adjustment of the slippage degree between layers can be executed.

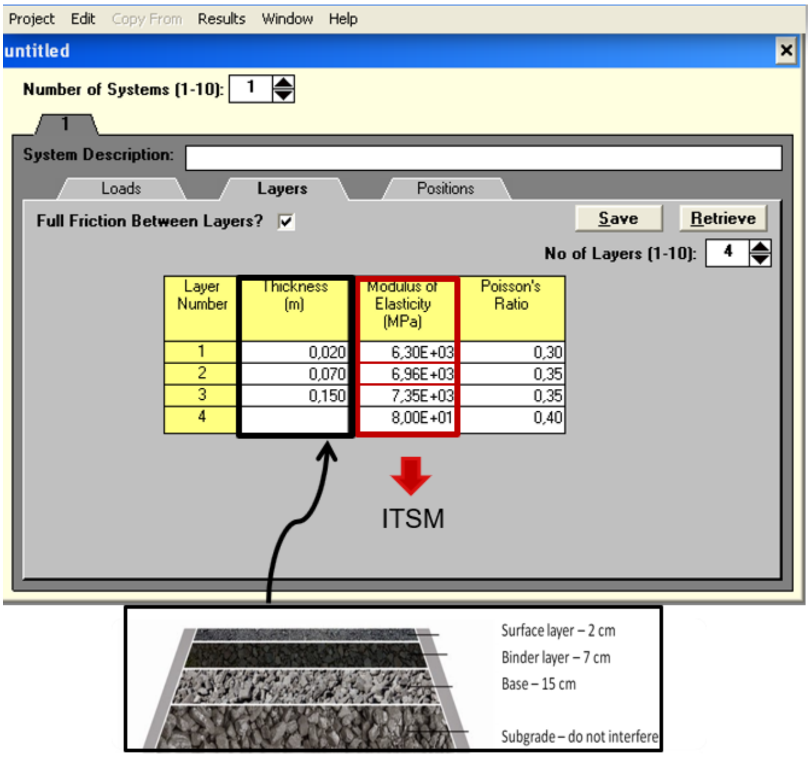


Figure 17 – Input screen to define slippage between layers.

The preceding image provides a visual representation of how the degree of slippage between two layers might be defined. The values are the real numbers of the pavement structure analysed in this research. Firstly, located directly beneath the "Layers" tab, there is a checkbox that allows for the specification of whether there exists complete friction between the levels. In the present scenario, complete friction between layers denotes complete adhesion, indicating that the two layers being examined are entirely linked.

In the case where a few layers are deemed to lack complete friction, it is imperative that the checkbox remain unchecked. Instead, the user should choose between inputting either the Standard Spring Compliance or the Reduced Spring Compliance.

The theoretical foundation for the study of slippage, which, as previously stated, relies on the notion of shear spring compliance. One crucial consideration is that the interlayers are depicted as infinitely thin membranes, whose strength is determined by the spring compliance. The parameter referred to as AK is formally specified in Equation (17):

$$AK = \frac{\Delta\varepsilon}{\tau} \qquad \text{Equation 17}$$

The shear spring compliance can be described as the quotient of the relative displacement between the layers and the applied shear stress, as seen from observation. The parameter in question is evidently the reciprocal of the interlayer's stiffness, denoted as K. Based on this, it can be inferred that BISAR operates under the assumption that the displacement is directly proportional to the applied stress at the interlayers, as previously stated in Equation (18) on multiple occasions.

$$\tau = K.\Delta\varepsilon$$ Equation 18

It can be observed, based on this equation, that the interlayer stiffness K can be readily determined by dividing the applied shear stress by the relative displacement between layers. The spring shear compliance, as previously mentioned, is the reciprocal of this quantity and is expressed in units of cubic metres per Newton (m3/N) in the BISAR system.

However, the spring compliance AK does not offer any meaningful understanding of the occurrence of slippage between layers, whether it is partial or complete. The determination of slippage magnitude in BISAR is facilitated by the incorporation of the friction parameter, denoted as α, which is mathematically specified in Equation (19).

$$\alpha = \frac{AK}{AK + \frac{1+v}{E}.a}$$ Equation 19

Where:

a is Radius of the load [m].

E is Modulus of the layer right above the interlayer [Pa].

v is Poisson's ratio of the layer above the interlayer.

The friction parameter α is bounded between zero and one. When the value of α is 0, it indicates the presence of maximum friction, and when α equals 1, it signifies the occurrence of complete slippage. Based on the aforementioned equation, it is evident that the friction parameter differs significantly from classical friction coefficients and is not solely determined by material characteristics. Instead, it is influenced by the radius of the applied load.

The reduced shear spring compliance, ALK (m), is defined in the BISAR 3.0 User

Manual. It is determined by the equation (20), which establishes a relationship between the shear spring compliance, AK, and the reduced shear spring compliance. This relationship is based on the modulus and Poisson's ratio of the layers present in the structure.

$$AK = ALK \,.\, \frac{1+v}{E}$$ Equation 20

Furthermore, it is feasible to get the diminished shear compliance of the spring, denoted as ALK, using an alternative equation including the friction parameter α and the load radius a (measured in meters), as expressed in Equation (21).

$$ALK = \frac{\alpha}{1-\alpha} \,.\, a$$ Equation 21

The BISAR software has the capability to determine the friction parameter by utilising Equations (17), (19), (20), and (21). This determination is based on the input values of the layers' characteristics, the loading characteristics, and the shear spring compliance (or reduced spring shear compliance). These parameters collectively define the mechanical response at the interlayers. Moreover, in the event that the user manually inputs the value of spring shear compliance and subsequently changes the input value checkbox from spring shear compliance to the reduced shear compliance option, the software will perform automatic calculations to determine the ALK associated with the previously input AK value (and vice versa).

It is noteworthy to acknowledge that the BISAR 3.0 [118] articulates the challenge of assigning a specific value, necessitating the adoption of a recommended approach to choose a value for either AK or ALK. This approach involves conducting a sensitivity analysis by exploring many values for each parameter. When considering ALK, it is advisable to do calculations by systematically altering this parameter within a range of 0 to 100 times the load's radius. This approach ensures that the analysis encompasses the entire spectrum of slippage, ranging from $\alpha = 0$ to $\alpha = 0.99$.

The BISAR model comprises a dual-layered system, designed to closely approximate the test conditions. This may be viewed in Figure 18, which displays the geometric and layer characteristics employed in BISAR.

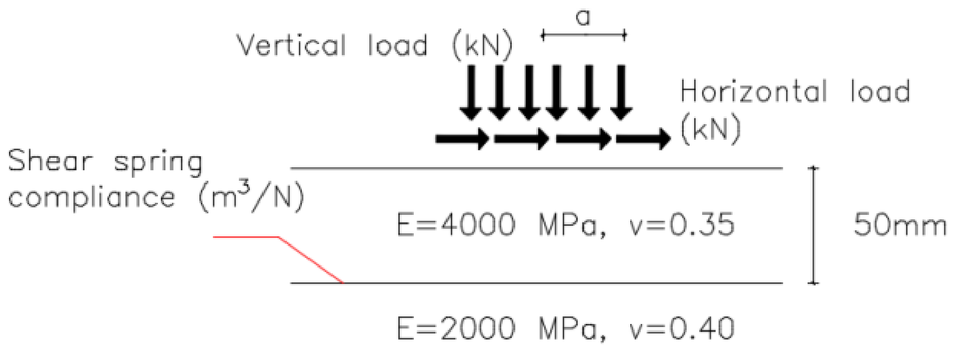


Figure 18 – Scheme of the modelled pavement section.

To realise the calculation of the Z coordinate (depth), the tab Positions is needed. Figure 19 shows the values from this study already inputted, illustrating how it works.

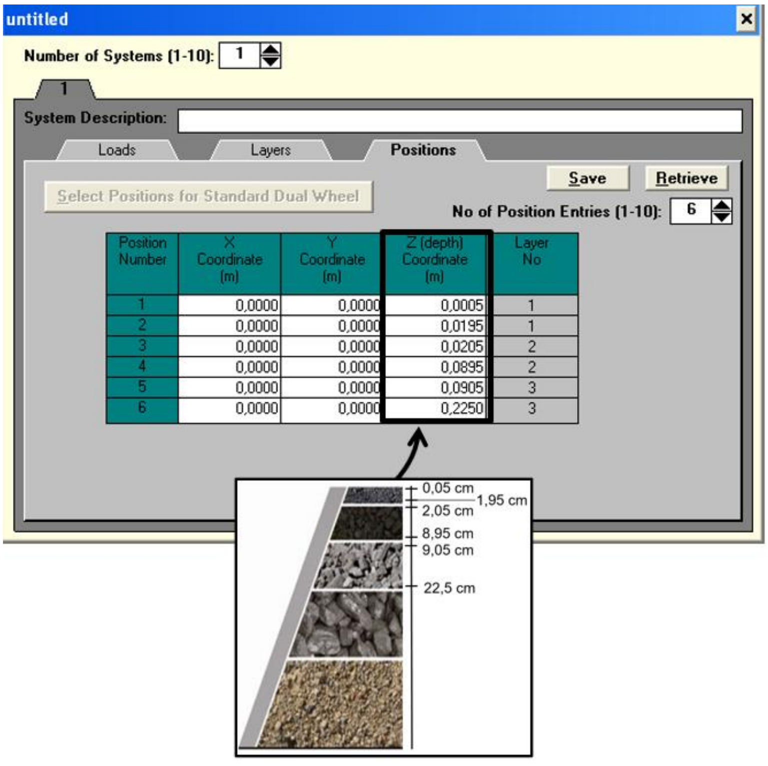


Figure 19 – Values to calculation of the Z coordinate.

Nevertheless, conducting this type of sensitivity analysis can be somewhat time-consuming, as it entails completing multiple calculations solely to calibrate a single value (or a group of values if analysing more than two layers).

5.3.1.2 MeDiNa (Método de Dimensionamento Nacional) Software

Medina *Método de Dimensionamento Nacional* is a Brazilian software that performs the verification and mechanistic-empirical design of pavement structures through the AEMC routine "Elastic Analysis of Multiple Layers". This routine calculates stresses and deformations in pavement structures under road axle-type wheel loading and applies fatigue and permanent deformation models to adjust layer thicknesses.

The analysis of a pavement structure or even its dimensioning requires a broad set of information so that the results obtained are reliable. The information passes through the knowledge of the subgrade as its module and permanent deformation curve. Another key piece of information for the correct operation of the Medina software is the definition of the equivalent number of axes, the number N. The models used in the MeDiNa programme are sensitive to small variations of the N number (USACE and AASHTO methods), and therefore, an accurate estimate is of great importance for the success of the project.

The MeDiNa software has its interface divided into tabs, which are denoted as structure, modelling, and results. When starting the software, it always appears in the structure tab, where the project identification information is inserted; pavement structure; traffic; and panel, where the software records the summary of the results of the analysis or the dimensioning. Before filling in the project data, it is defined in which mode the programme will process the data.

Figure 20 illustrates the initial tap of the programme, presenting a pavement structure with three layers to assist in understanding the software. To add new materials, you must select the type of field, choose an existing material in the database, or input new materials. For the addition of materials to its own database, the following characteristics must be known: the Poisson coefficient, tensile strength, resilience modulus (MR) in MPa, compressive strength, and material density.

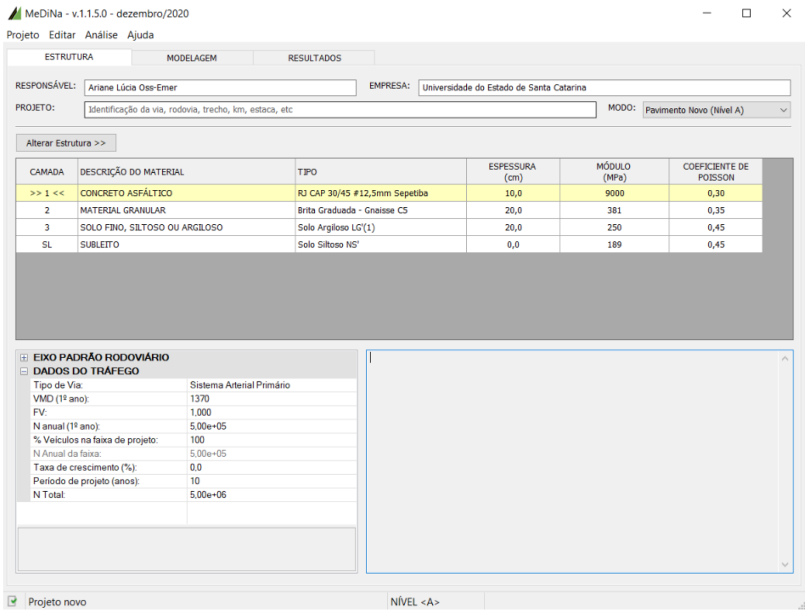


Figure 20 ─ Home screen of Medina.

The AEMC is an elastic layer analysis computer software developed for use as a component in the Medina software. The general structure of calculus uses Gauss-Laguerre integration in the calculations of the integral equations.

A frame structure consists of two elements. A button, Command Structure>>, and a table represent the pavement profile. Each row of the Table is equivalent to one layer of the pavement structure. The last line represents the subgrade that, by convention, has a thickness equal 0 cm.
The initial structure presented in the AEMC software has four layers, including the subgrade.

This structure can be totally changed, with at least two and at most eight layers allowed.
In the table that shows the "Structure of the pavement," information about the properties of each of the layers of the pavement structure is presented, such as: thickness, elastic behaviour (whether linear or non-linear), module, specific mass, modulus parameters (K1, K2, K3, and K4) coefficient, and the condition of adhesion.

About the MR, the layer materials can be considered linear or non-linear elastic, and the resilient behaviour constituent models are represented by the definition of the constants of the general model presented in the expression below:

$$MR = k_1 \cdot \sigma_3^{k2} \cdot \sigma_d^{k3} \cdot \theta^{k4}$$ Equation 22

In the model presented in the above expression, K1, K2, K3, and K4 are laboratory constants; θ is the octahedral voltage (equal to the sum of the principal stresses σ1 + σ2 + σ3), σd is the stress deviation, σ3 is the confinement stress, and MR is the resilience modulus in MPa.

However, it is observed that if the designer chooses the linear elastic model, the software will take into account only the value defined in the Module column, independent of the module coefficients (K1, K2, K3, and K4) that were inserted.

The software for the calculation of stress, strain, and displacements, AEMC, makes a physical model similar to the theory of springs in order to allow relative horizontal movement at the interface between two layers. The spring acts in the radial direction, resisting the relative displacement along the interface between two layers, as follows:

$$\tau_i = k_i \cdot (u_i - u_{i+1})$$ Equation 23

Where:

Ti is the radial shear stress between layers *i* and *i*+1;

Ui-Ui+1 is the relative radial displacement along the interface of layers *i* and *i*+1;

Ki is the "spring" stiffness module that resists relative radial displacement along the interface.

The wheel load is assumed in the programme to be evenly distributed in a circular contact area between the tyre and the pavement surface. The contact pressure between the tyre and the pavement is assumed to be equal to the inflation pressure of the tyres, for lack of more specific data on the configurations of wheels and tyres used in the country. The size of the contact area therefore depends on the wheel load and the inflation pressure of the tires.

The loading table, shown in the following figure (21), shows a list of axes that allows you to choose the type of loading that you want to analyse. In the list of properties, the values of tyre pressure, axle load, or wheel load, in addition to the wheelbase and wheelbase distances (Tx and Ty) and axle gauge (Lx) of the selected configuration, can be changed. The values of the contact area and the loading radius are calculated automatically by the AEMC.

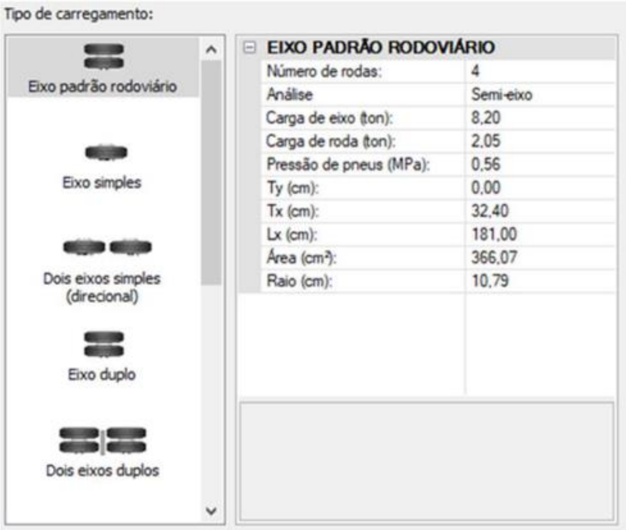


Figure 211 – Type of load.

In this table, the units used are centimetres for distances; cm² for contact area; tonnes for axle and wheel loads; and MPa for tyre pressure.

After that, in another tab (Figure 22), all the information from the pavement design needed to be inserted to calculate the stress/strain in relation to these characteristics. Figure 22 illustrates how the calculations were made for the pavement structure for each asphalt mixture for the binder layer in relation to every season of the year, that is, different temperatures.

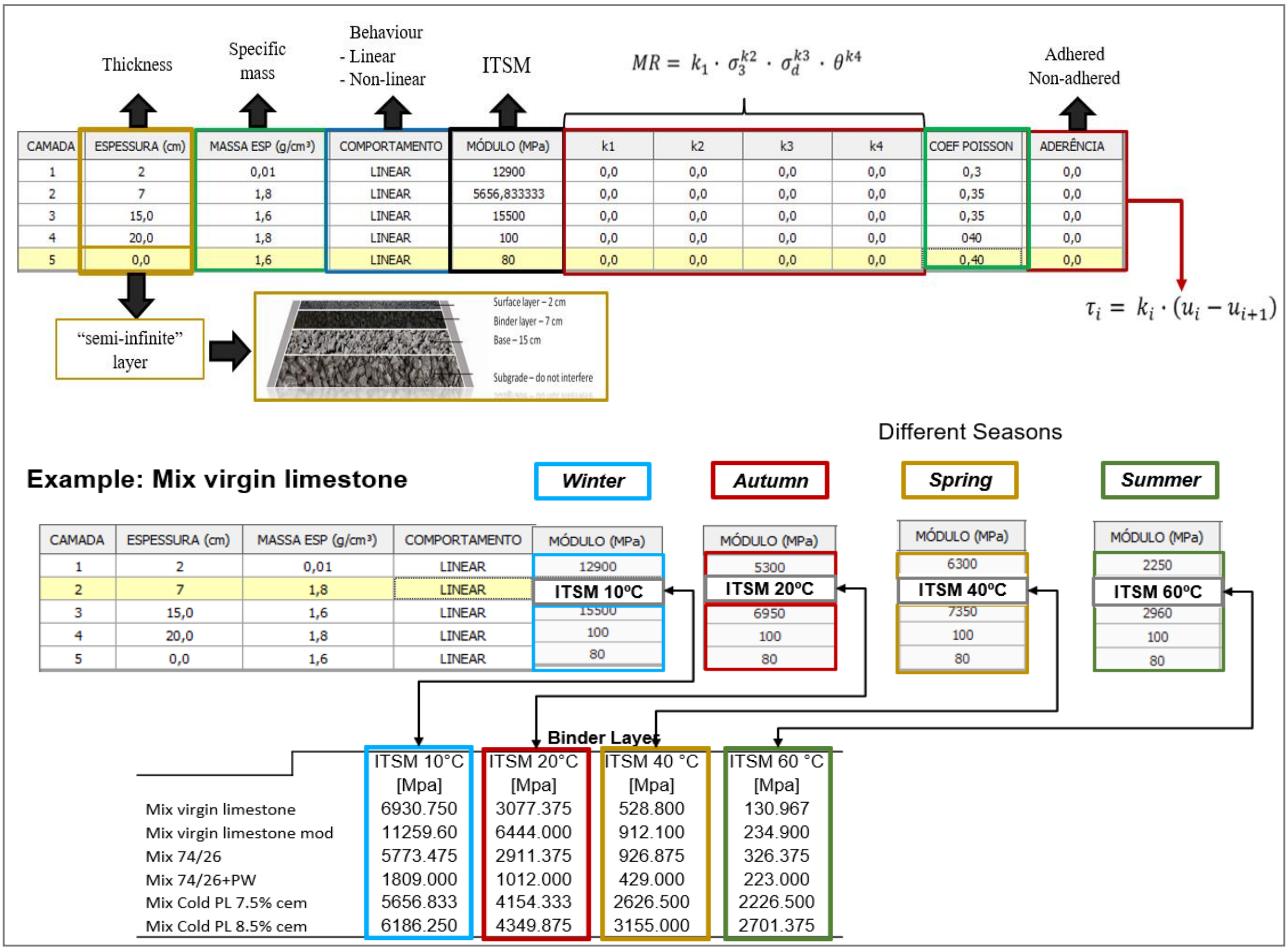
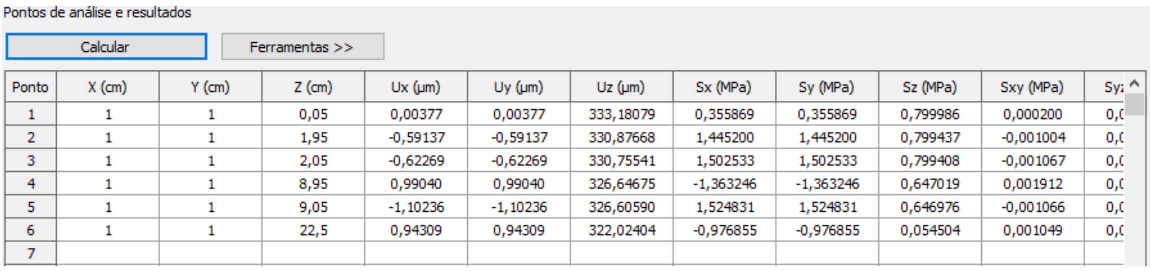


Figure 22 – Structure Settings.

The results table is where stress, strain, and displacement calculations occur at all user-defined points. The points can be typed one by one in the table, in columns X, Y, and Z, respecting the convention of the coordinate system, or filled automatically by pressing the Tools button in the option Generate Points Automatically. The Figure 23 illustrates it.



Pontos de análise e resultados

Calcular | Ferramentas >>

Ponto	X (cm)	Y (cm)	Z (cm)	Ux (µm)	Uy (µm)	Uz (µm)	Sx (MPa)	Sy (MPa)	Sz (MPa)	Sxy (MPa)	Sy:
1	1	1	0,05	0,00377	0,00377	333,18079	0,355869	0,355869	0,799986	0,000200	0,(
2	1	1	1,95	-0,59137	-0,59137	330,87668	1,445200	1,445200	0,799437	-0,001004	0,(
3	1	1	2,05	-0,62269	-0,62269	330,75541	1,502533	1,502533	0,799408	-0,001067	0,(
4	1	1	8,95	0,99040	0,99040	326,64675	-1,363246	-1,363246	0,647019	0,001912	0,(
5	1	1	9,05	-1,10236	-1,10236	326,60590	1,524831	1,524831	0,646976	-0,001066	0,(
6	1	1	22,5	0,94309	0,94309	322,02404	-0,976855	-0,976855	0,054504	0,001049	0,(
7											

Figure 23 – Coordinate line calculations in X, Y, and Z.

The software makes two checks to evaluate the use of cemented material in the pavement structure in relation to fatigue damage. The first check is when the module of the cemented material decals more than 25% of the initial value to the end. If the evaluation of the structure is being carried out, the program issues an alert that the module has rapidly decayed. In the event that it is performing dimensioning, the program increases the thickness of this layer until it meets the criterion; if this is not possible, the same alert is issued in the evaluation process.

The second check is in relation to the layer supported on the cemented layer; if the upper layer has theoretical deflections greater than 70 x 10^{-2}mm, the software will warn that the structure needs to be revised.

For calculation purposes, Medina disregards permanent deformations in layers stabilized with cement. According to the program's own user manual, when properly executed and maintained, the layers stabilized with cement do not effectively contribute to the value of the pavement structure's wheel track.

There is a necessity to inform the type of route to be analysed or dimensioned. Each type has a design stop criterion as well as the degree of reliability of the analysis performed by MeDiNa. The different types of pathways have been defined in accordance with the hierarchy of functional systems published by the DNIT. Table 8 summarises the criteria and reliability of each type of track.

Table 8 – Criteria for stopping and reliability of the analyses performed by MeDiNa.

TYPE OF ROAD	RELIABILITY	FATIGUE CRACKED	PERMANENT DEFORMATION
Main Arterial System	95%	30%	10mm
Primary Arterial System	85%	30%	13mm
Secondary Arterial System	75%	30%	20mm
Primary Collector System	85%	30%	13mm
Secondary Collector System	75%	30%	20mm
Local System	65%	30%	20mm

5.3.2 Permanent Deformation

The permanent deformation (rutting) in the asphalt coating can be defined as longitudinal depressions in the wheel tracks due to the accumulation of small, non-recoverable deformations resulting from the application of repeated loads (vehicle traffic), especially at high temperatures. Simultaneously, viscous deformation of the binder and plastic deformation of the mineral structure occur. Currently, given the increase in traffic volume and axle loads, this type of damage becomes frequent, reducing the service life of the pavement, the rolling comfort and safety of users, and operating costs.

Several factors influence this type of damage. Briefly, they can be related to mineral aggregates (surface texture, grain size, shape, and size), asphalt binder (type), and asphalt mixture (binder content, volume of voids, and voids in the mineral aggregate). The type of ligand is the most influential in permanent deformation, as presented in the present research. This is because asphalt mixtures inherit the viscoelastic and thermosusceptible characteristics of asphalt binders, which, depending on the type and content, are more or less susceptible to the variation of temperature, frequency, and time of load application [119] and, consequently, present permanent deformation at high temperatures.

Permanent deformation can occur in the subgrade depending on the allusive strength of the pavement layers and the magnitude of the loads on the asphalt layers applied to the coating or the base layers. The different times of the year end up governing vulnerability to these layers. Permanent deformation in the asphalt coating, for example, occurs more in periods of hot months of the first summer compared to winter, in the same proportion that granular base layers are more susceptible to sinking in periods of rain. Another significant element is the active stresses of an individual layer of the pavement, which are due to the materials applied and the thickness of the layers, in addition to the loads from heavy vehicles [120].

The main causes of sinking are related to densification and consolidation of materials, when poor compaction of layers occurs. On the other hand, due to adequate compaction, research carried out in the experimental runways of the AASHO in 1962 and in experimental segments pointed out how shear deformation is, in this case, the main determinant mechanism of the rutting, as opposed to densification.

However, a frequent cause of rutting is permanent deformation related to the asphalt coating layer, especially on high-traffic highways, accompanied by high tyre pressure and high axle loads. Improper dosing of asphalt mixtures leads to many of these sinks. One of the major causes of rutting is the excessive application of asphalt binder. This happens because a greater volume of asphalt ends up acting as a lubricant, minimising the interlocking of the stone skeleton and the internal friction of the mixture. Thus, the deformation in asphalt concrete is lower in depth and increases gradually close to the requested surface, according to [121]. At the time, this decrease was linked to the elevation of the confining stress with depth, which caused a greater resistance to plastic flow in addition to the decrease of shear stresses.

The thickness of the asphalt coating is directly related to the occurrence of rutting. From a defined threshold (around 13mm), increasing the thickness of this layer does not increase the deformation in it. That is, asphalt coatings with thicknesses less than 13 cm will experience more deformations the greater their thickness. Despite this, coatings with thicknesses greater than the limit of 13 cm do not influence the sinking. Thicknesses with about 25 cm of asphalt mass indicate that rutting manifests a maximum value, according to measurements performed on the AASHO runways. However, layers with greater thickness do not exhibit additional sinking. The elevation of thickness, as suggested in these results, in thin coatings contributes to the continuation of wheel tracks originating from this layer.

These understandings about rutting behaviour were proven in research. The flow of deformation without or with a change in volume in two stages is what causes this process in the asphalt layer:

- The first stage refers to the first demands of vehicle traffic, which may cause an increase in irreversible deformations under the tyres, which are higher than the deformations observed in the close areas to the loads (lateral elevation), signalling that they are occurring in such a way as to have greater relevance in relation to volumetric variations, that is, by densification that occurs the reduction of the volume of voids (Vv) of the material;
- After this primary stage, the volume increase below is similar to the volume increase in nearby areas. This event is an indication that the largest portion of overcompaction caused by vehicle traffic has been completed and that the rutting will be caused mainly by constant volume shear. Faced with permanent deformation, this second stage is considered the most expressive, as its manifestation happens on a larger scale in the pavement design life.

In the second stage, the rutting can be considered shear sinking, through the displacement of mixtures on the loads of vehicle traffic, revealing itself after the time of consolidation of the asphalt layer.

To effectively implement a sizing method in practice, it is essential to have laboratory performance models that allow for the determination of the materials and stipulate the ordered arrangement of each in the rutting in order to determine the appropriate thicknesses under this condition.

For mechanistic design, the deformation calculation is performed taking into account the sum of the inputs of each layer in accordance with the following equation (Equation 24):

$$\delta^{\rho}_{total} = \sum_{i=1}^{n} \varepsilon^{i}_{p\ hi}$$ Equation 24

Where:

δ^{p}_{total} = total permanent deformation;
ε^{i}_{p} = specific deformation of each layer of the pavement;
h_i = thickness of each floor layer
n = total number of layers.

5.3.2.1 Behaviour of asphalt mixtures in relation to permanent deformation

When studying the mechanical behaviour of asphalt mixtures, it is known that their extreme complexity is influenced by a range of external factors in addition to their intrinsic properties. When portrayed at a macroscopic level, asphalt concrete can be considered a continuous, isotropic, and homogeneous material, and its behaviour is influenced by three factors: the number of load cycles, the amplitude of deformations, and temperature.

Due to the influence of numerous variables, the laboratory reproduction of the behaviour of asphalt mixtures and their reactions to the actions of climate and traffic have become complex. The behaviour of asphalt materials and their responses to traffic and climate actions are difficult to reproduce in the laboratory due to the influence of numerous variables. Nevertheless, through mechanical tests, it is sought to evaluate the mechanical behaviour of these mixtures, establishing their relationship with field performance. In relation to design pavements and specify materials appropriate to the climate and traffic, it is imperative to know the behaviour and properties of the pavement layers, especially asphalt concrete.

Different domains of the mechanical behaviour of the mixture can be defined from the values assumed for the aforementioned factors. From this, the domains of mechanical behaviour are presented in Figure 24, depending on the amplitude of deformations (ε) and temperature (T), and, for a given temperature, the different behavioural domains are presented in Figure 25, amplitude of deformation (ε) and number of cycles (N) [122].

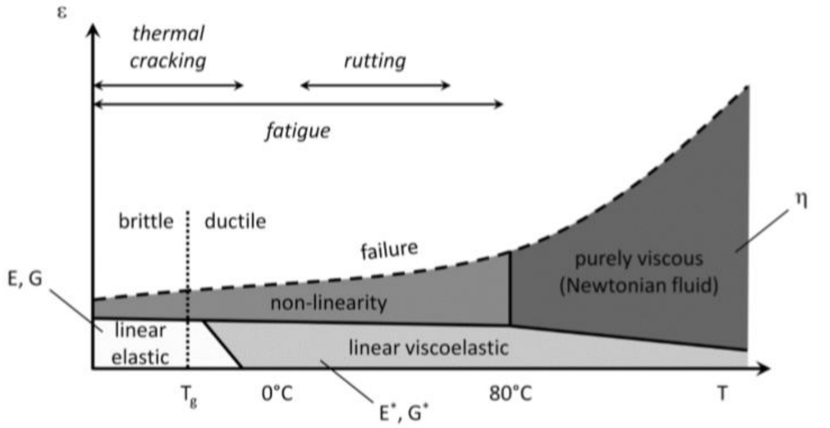


Figure 24 – Mechanical behaviour of asphalt materials: typical domains as a function of deformations and temperature.

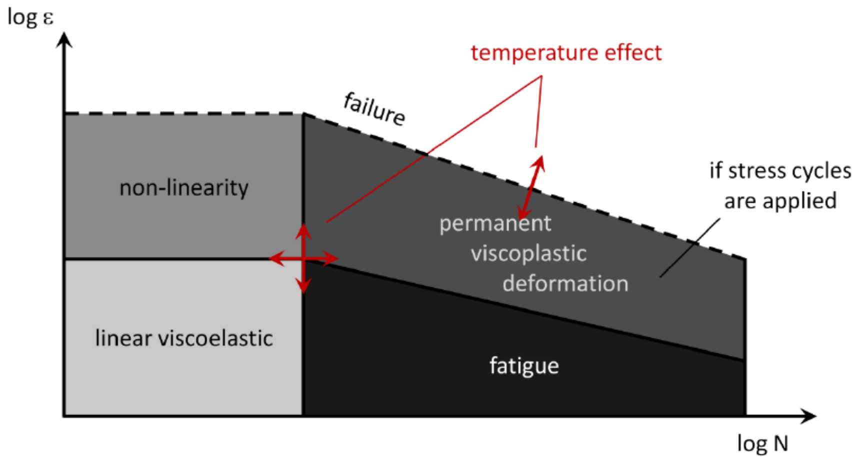


Figure 25 – Mechanical behaviour of asphalt materials: typical domains as a function of deformations and number of cycles.

According to the number of load cycles and the amplitude of deformation applied, Figure 26 shows the types of diversified behaviours analysed for bituminous mixture. Bituminous materials have linear viscoelastic behaviour, which refers to a limited number of cycles and a small deformation domain (ε <100µm/m).

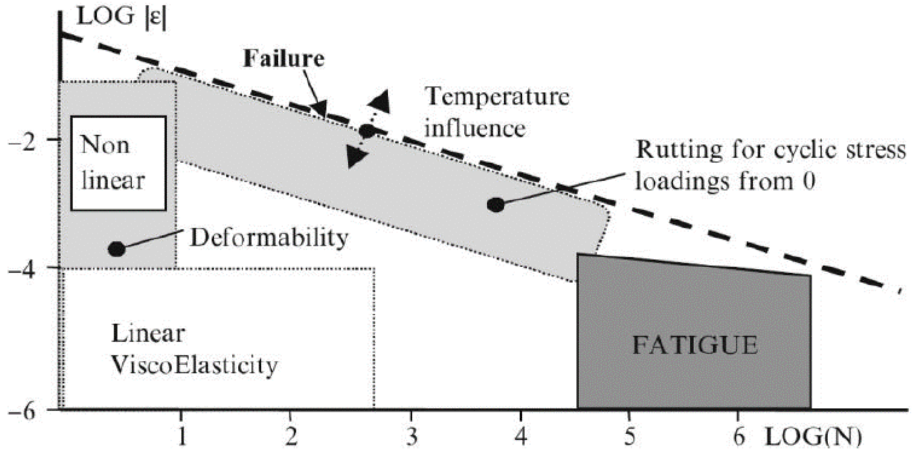


Figure 26 – Behaviour of conventional asphalt concretes: typical domains.

In order to better understand the behaviour of asphalt concrete and its responses, it is essential to understand its stiffness characteristics. The term stiffness, mainly used in the study of asphalt mixtures, indicates the ability of the material to resist deformation.

The behaviour of the asphalt material is affected by temperature in two fundamental ways: the first refers to the modification of the stiffness of the material; the second concerns the temperature changes triggered during the action of thermal displacements.

The predisposition of resistance to deformation is indicated by the stiffness of the asphalt mixtures, which also depends on the temperature [123]. Thus, the condition of air temperature variability and/or meteorological conditions in a global way is what grants the fact of less or greater deformability of the pavement. This property is achieved by several elements, as examples: deformation rate; stress state; the type of binder; temperature; the particles of the aggregates; the fines of the polymer; the water in the mixture, whether liquid or steam; its location in the mixture; and the age of the mixture, among others. Still, according to the author, stiffness in asphalt concrete is a material parameter, nothing but the slope of the stress curve, which is a unique property (independent of the test, the size, or the geometry of the sample).

In current cases in engineering, the theory of elasticity, governed by Hooke's law, provides the mechanical analysis with an equation independent of time and simple, determined material parameters. Hooke's law, however, is not able to accurately interpret phenomena present in a variety of materials, such as asphalt materials, at certain temperatures, lending itself only to an introductory assessment. In this context, viscoelasticity is presented as a more complete theory capable of representing phenomena beyond those modelled by elasticity, introducing to the subject of the study of deformable bodies a relationship in time between the history of stress and deformation fields present in the body, a characteristic that gives these materials the title of materials with memory [124].

The resilience modulus (RM) test determines the stiffness of asphalt mixtures, which in turn considers their linear elastic performance when displacements considered are resilient (recoverable), given Hooke's law. However, it should be noted that the RM does not display a uniquely elastic parameter for asphalt mixtures because, in the calculation related to a given loading pulse, it causes an increase in viscoelastic deformations, which are relatively linked to elastic deformations.

The use of a single charge frequency and a single temperature in the MR assay neglects the temperature susceptibility inherited from the asphalt binder and its viscoelastic essence, frequency, or time dependence.

Another important factor in the behaviour of asphalt mixtures is linked to influence, which is not simply linked to their mineralogical origin. The strength of the stony skeleton also relates to the texture of the aggregates, the angularity, and the shape. The surface texture of the aggregate plays a significant role in strength, especially in the thicker asphalt layers and in warmer climates.

The permanent deformation is the consequence of the plastic behaviour; that is, when exercising a load action by the vehicle traffic in the pavement layer, there is a fraction of the total deformation that does not return to its original disposition, triggering the accumulation of low amounts of non-recoverable deformation over the lifetime of the pavement. This deformation in the structure, when occurring in the extension of a longitudinal segment of the traffic range in the wheel tracks, is called sinking of a wheel triple (rutting), which, when passing a certain depth, is considered a severe structural deformation. A loss of lateral drainage capacity of the pavement occurs due to an accumulation of water in the sinking of the wheel tread. In addition, this accumulation of water makes the safety situation more vulnerable for road users. The implication of the accumulation of permanent deformations, which can happen in the coating and the subgrade, or as a collaboration of all the layers that structure the pavement.

The way of operation of permanent deformations that happen in asphalt concrete is distinct in comparison to how they happen in geotechnical layers, and the design procedure is conceptualised as a mixture dosing dysfunction, not a matter of layer thickness.

5.3.2.2 Influence of asphalt mixture characteristics on permanent deformation resistance

Usually, the displacement of the asphalt mixture happens in the first 10 centimetres of the pavement's depth, eventually happening in larger thicknesses when using materials of low quality. As already commented in this research, at elevated temperatures, the viscosity of the binder tends to decrease, producing less resistance to deformation of the pavement. Thus, in asphalt mixtures, permanent deformation happens, especially at high temperatures, around 60ºC, when the stiffness of the asphalt binder in the structured coating is observed.

Besides the influence of materials and their proportions, other factors must be investigated. Some factors are discussed in detail, and among them, we can mention two groups [125]:

- Aggregates: aggregate particle size: Mixtures with larger aggregates and continuous particle sizes exhibit better resistance to permanent deformation due to better interlocking of aggregate particles, offering greater strength; Aggregate form: cubic aggregate mixtures are more resistant to permanent deformation than rolled aggregate compounds because cubic aggregates provide better friction resistance.
- Asphalt binder: Too binder tends to function as a lubricant, facilitating relative movement between particles; Asphalt binder viscosity: The use of harder or modified binders increases the resistance to permanent deformation of asphalt mixtures.

In addition, binder acting like aggregate plays a key role in the mechanical behaviour of the asphalt mixture. The asphalt content in the mixture, the viscosity, and mainly the modification are important factors that depend directly on the asphalt binder. In general, less viscous binders make mixtures less rigid and more susceptible to permanent deformation accumulation.

The factor that most altered the stiffness and resistance to permanent deformation of the mixtures was the type of asphalt binder, in which the polymer-modified binder increased stiffness and resistance to damage. The Bailey method of particle size selection also improved the behaviour of mixtures on a smaller scale when compared to the influence of the binder and the design of the mixture. The author proved that the design method of the mixture (Marshall or Superpave) changed the results of the mixtures, making the mixtures dosed by the Superpave method more resistant to permanent deformation due to their lower binder content.

On the field, the most important elements that impair the resistance to permanent deformation are load repetitions, temperature, water action, and stress state.

The typology of binder is what triggers the working temperature of the asphalt mixtures, as these acquire the viscous properties of binders that are moderately susceptible to temperature, according to the class. The same author notes an intense relationship with the rise in temperature and permanent deformation in the wheel tracks of these mixtures.

The deformation rate can increase due to changes in traffic distribution, especially the proportions of heavy trucks, and even the pavement being, in its origin, well designed and structured. The increased rate of pavement deformation is caused by the large tyre inflation pressures and larger wheel loads.

On this logic, the main factors that interfere with permanent deformation in asphalt concrete are summarised in Figure 27.

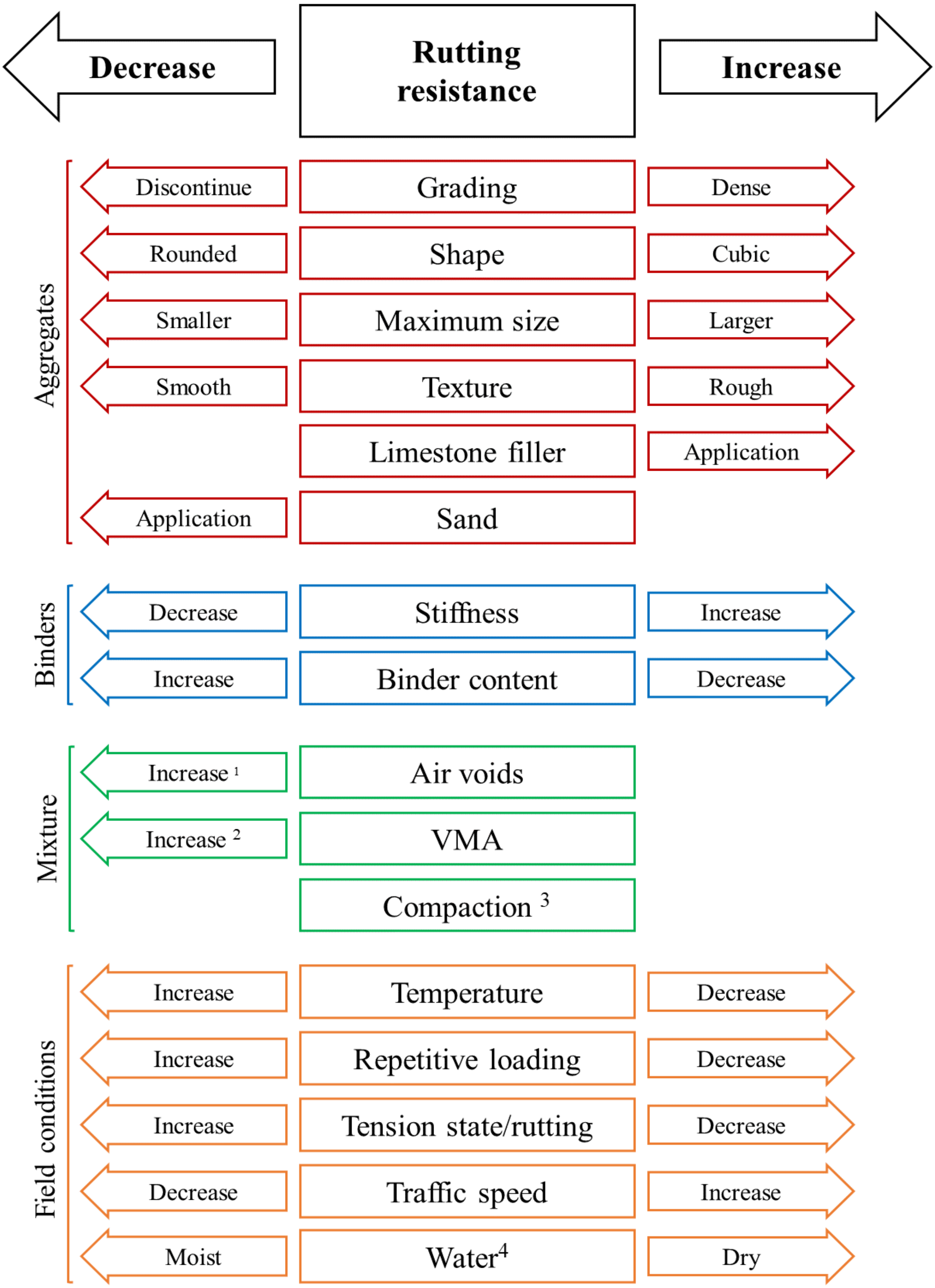


Figure 27 – Elements that interfere with the permanent deformation resistance of asphalt concrete layers.

[1] When Vv is less than 3%, the propensity for permanent deformation increases.
[2] Very low VMA's (less than 10%) should be avoided.
[3] The compaction method can influence the propensity for plastic sinks.
[4] Exerts influence if the mixture is sensitive to water.

5.3.2.3 Multiple Stress Creep and Recovery (MSCR*)*

As already elucidated, permanent deformation is a more common type of damage in asphalt pavements, which relates mainly to the high temperature properties of the binder. For this, the selection of an asphalt binder suitable for traffic and weather conditions enhances the durability of the pavement.

For a few years, the analysis of resistance to permanent deformation was performed using |G*|/sen φ from the viscoelastic characterization of the material; however, a large number of studies describe a low correlation between the parameter and the actual field performance. From this, research from the U.S. Federal Highway Administration proposed the essay Multiple Stress Creep and Recovery. The ligands in their collection conditions for this research were evaluated through this test, performed in the rheometer (Dynamic Shear Rheometer, DSR) Figure 28.

Figure 28 – Dynamic Shear Rheometer Labotatorio di Strade Luigi Tocchetti - University of Naples.

The Multiple Stress Creep Recovery (MSCR) test is an important tool for verifying the susceptibility of the asphalt binder to permanent deformation. This structured test has a total of 30 cycles of load application, that is, two levels of voltage; the first 20 cycles are performed with a voltage of 0.1 kPa, and the last 10 cycles result in an increase of the applied voltage to 3.2 kPa. The test is triggered by applying the load at constant stress for 1 s (shear deformation), followed by the application of a zero load for 9 s (rest) for each cycle of 10 seconds duration. The graphical representation of deformation and rest is presented in Figure 29, (a) with 20 cycles in the stress of 0.1 kPa (within the linear viscoelastic domain) and (b) with 10 cycles in the stress of 3.2 kPa (damage domain) The Figure 29 illustrates it [126].

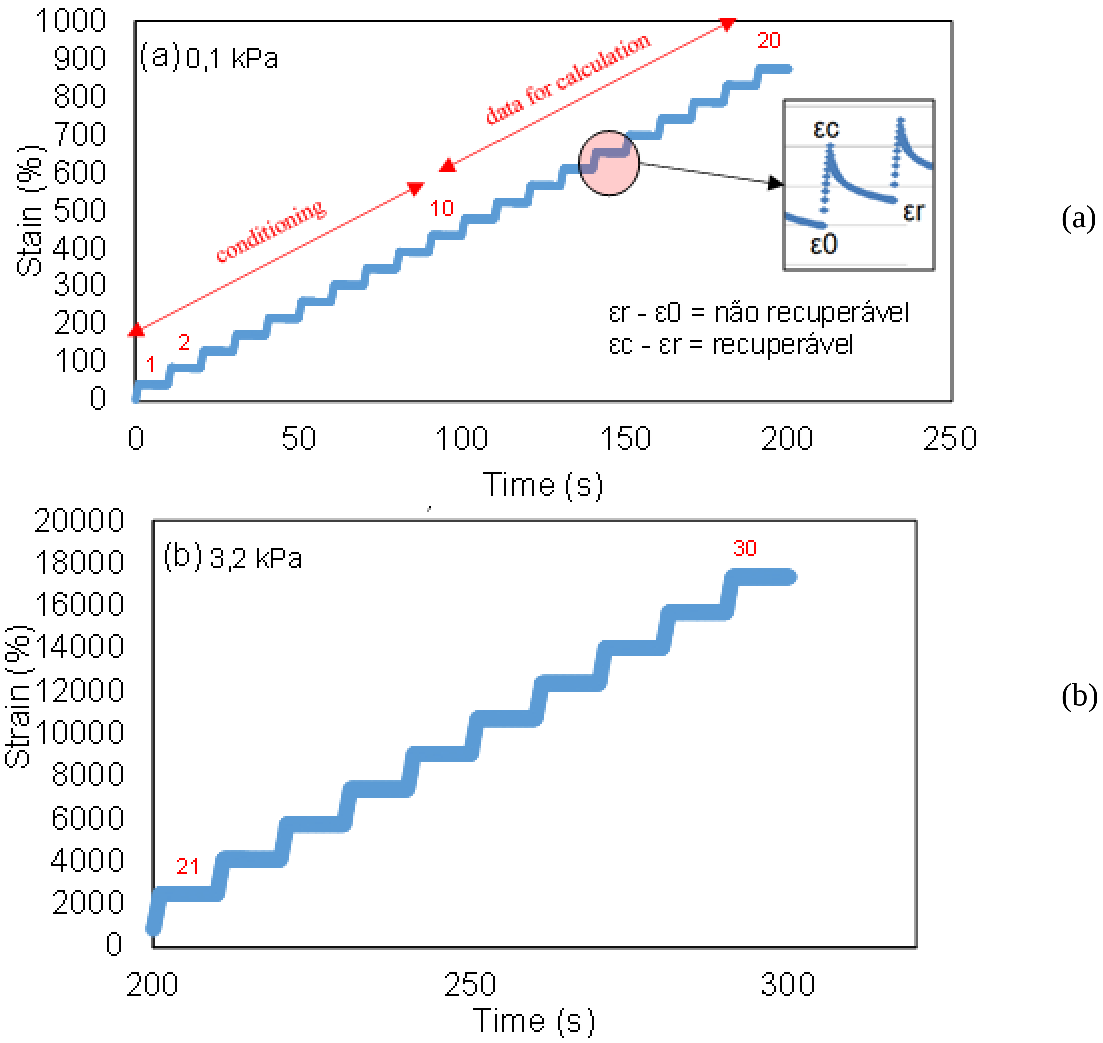


Figure 29 – Deformation and loading scheme with 20 cycles at 0.1 kPa (a) and 10 cycles at 3.2 kPa (b).

Obtaining the values of the initial and final deformation of the cycles, load-rest, it becomes possible to calculate the non-recoverable complexity (J_{nR}), and recovery percentage (R%), parameters that make it possible to evaluate the performance of binders at high temperatures. The first 10 cycles at 0.1 kPa voltage are for sample conditioning, while the last 10 cycles at 0.1 kPa voltage and the 10 cycles at 3.2 kPa voltage are used for the determination of the following parameters: $J_{nR\ 0,1}$; $J_{nR\ 3,2}$; $R_{0,1}$; $R_{3,2}$; $J_{nR\ diff}$ e R_{diff}.

The Equations (25) and (26) calculate $J_{nR\ 0,1}$ and $J_{nR\ 3,2}$, respectively. J_{nR} (0.1, N) and J_{nR} (3.2, N) are the non-recoverable creep compliances at 0.1 kPa and 3.2 kPa in cycle N, respectively. The J_{nR} in cycle N is calculated by the relationship between the non-recoverable strain (εr - ε0) and the stress in kPa.

$$Jnr_{0,1} = \frac{\sum_{n=11}^{20}[Jnr(0.1,N)]}{10}$$ Equation 25

$$Jnr_{3,2} = \frac{\sum_{n=1}^{10}[Jnr(3,2,N)]}{10}$$ Equation 26

The Equations (27) and (28) calculate $R_{0,1}$ and $R_{3,2}$, respectively. The $\in_r$ (0.1, N) and $\in_r$ (3.2.N) are the percentages of recovery at 0.1 kPa and 3.2 kPa in cycle N, respectively. The $\in_r$ in each cycle is given by the relationship between recoverable deformation (εc - εr) and the stress in kPa.

$$R_{0,1} = \frac{\sum_{n=11}^{20}[\hat{I}r(0.1,N)]}{10}$$ Equation 27

$$R_{3,2} = \frac{\sum_{n=1}^{10}[\hat{I}r(3,2,N)]}{10}$$ Equation 28

The two other parameters can be obtained from the percentage difference of non-recoverable compliance between 0.1 kPa and 3.2 kPa (Equation 29) and the percentage difference (R%) in recovery between 0.1 kPa and 3.2 kPa (Equation 30).

$$Jnr_{\text{diff}} = \frac{[Jnr_{3.2} - Jnr_{0.1}].100}{Jnr_{0.1}}$$ Equation 29

$$R_{\text{diff}} = \frac{[R_{3.2} - R_{0.1}].100}{R_{0.1}}$$ Equation 30

The 0.1 J_{nR} is used to classify binders according to traffic level as standard (2.0< J_{nR} <4.5), heavy (1.0< J_{nR} <2.5), very heavy (0.5< J_{nR} <1.0), or extremely heavy (J_{nR} <0.5), according to the AASHTO M 332 [127], Superpave characterisation. According to Table 9, based on speed and traffic level, it is possible to select a binder based on its resistance to permanent deformation.

Table 9 – Choice of binder based on speed and traffic level MSCR test (after AASHTO M 332).

ESALs[a] Project (million)	Speed		
	Constant[b]	Slow[c]	Standard[d]
<0,3	V	H	S
0,3 a < 3	V	H	S
3 a < 10	V	H	S
10 a < 30	V	H	H
≥ 30	E	V	V

[a] Expected traffic level over a period of 20 years (*Equivalent Single Axle Load)*.
[b] Where the average traffic speed is less than 20km/h.
[c] Where the average traffic speed ranges from 20 to 70 is less than 20 km/h.
[d] Where the average traffic speed is greater than 70 km/h.
S, H, V and E are designated as: standard; high; very high and extremely high.

5.3.3 Fatigue

Fatigue cracking represents the most common form of damage observed in asphalt pavement. The term "fatigue resistance" or "fatigue life" refers to the capacity of an asphalt mixture to withstand repetitive traffic loading in various environmental conditions without experiencing fracture. The fatigue properties of asphalt pavement have a significant impact on the performance of the mixture, which subsequently influences the overall performance of the pavement. There are two primary classifications of fatigue cracking, namely bottom-up cracking and top-down cracking. Bottom-up cracks are commonly observed fatigue cracks that initiate at the lower portion of the asphalt layer and propagate towards the upper surface

[113]. The process of bottom-up cracking is significantly impacted by environmental variables, including moisture and temperature variations, as well as the tensile strain resulting from repeated vehicular loading at the lower portion of the surface layer. The potential for bottom-up cracks in the surface layers is heightened by the presence of moisture within the weaker base and subgrade layers. The Figure 30 illustrates the bottom-up cracking propagation.

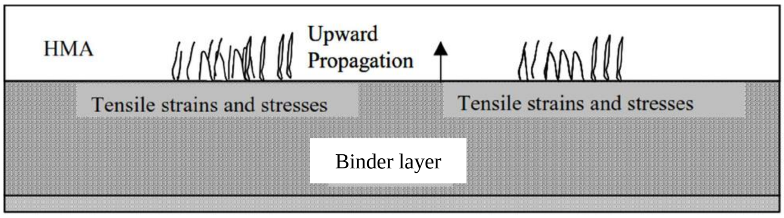


Figure 30 – Bottom-up propagation.

Top-down cracks typically propagate from the uppermost layer of a surface to the underlying layers, as implied by their name. There are two primary mechanisms that give rise to top-down cracks. One of the primary factors to consider is the formation of surface tension that occurs at a distance from the tyre in pavements with thin to medium thickness, typically ranging from 1.5 to 5 inches. The second factor to consider is the shear stress that is generated at the edges of the tyre, specifically in relation to the near-tyre mechanism, when thicker layers of asphalt are present. The process of fatigue crack propagation on an asphalt-aggregate mixture pavement predominantly takes place within the bitumen film rather than within the aggregate. The Figure 31 demonstrates the top-down transmission.

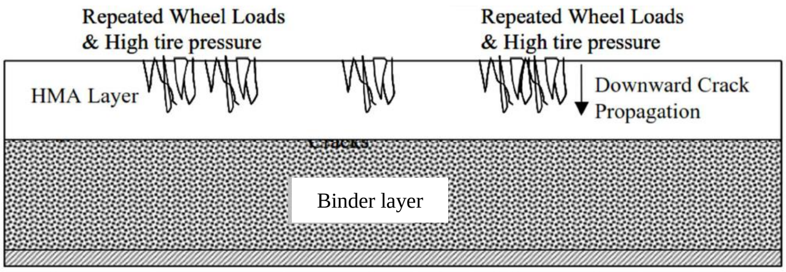


Figure 31 – Top-down propagation.

From a mechanical standpoint, the fatigue phenomenon occurs through the systematic generation of ruptures of the bonds and successive nucleation of microcracks. Often, these ruptures are characterised by a simple loss of cohesion between the different phases of the material. As such microscopic discontinuities occur in the most tensioned regions of the material, either in brittle fracture or ductile fracture, the voids that characterize them eventually meet, giving rise to one or more cracks. The individual growth of these fissures, or the occurrence of a new process of iocoalescence of them, generates the macro fissure, which is the one that can be detected visually. In the beginning, the process of damage is stable and characterised by the stable spread of the microcracks. However, this process is evolutionary and leads the structure to collapse for the reasons previously exposed.

Repeated vehicular loading and temperature variations are the main causes of fatigue cracking in asphalt pavement. Figure 32 illustrates the critical points that indicate the underlying factors contributing to the occurrence of rutting and fatigue cracking. The accumulation of damage in the layer of the asphalt concrete in vulnerable regions, resulting in the generation of microcracks, is facilitated by cyclic tensile stress (see Figure 32). It is important to note that this stress level remains significantly lower than the tensile strength of the asphalt mix.

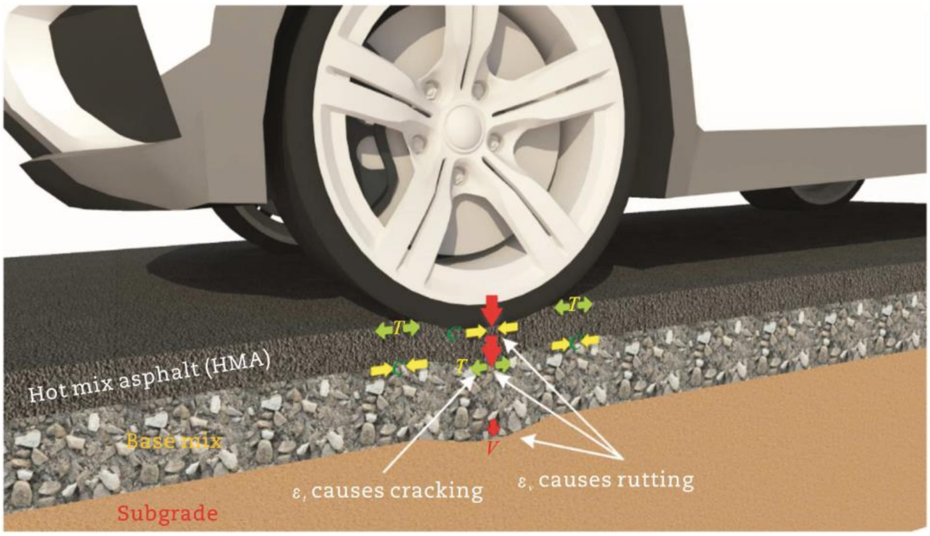


Figure 32 – Stress formation in the asphalt layer resulting from tyre loading.

The microcracks amalgamate to form macrocracks and propagate through the asphalt pavement layer in a direction perpendicular to the maximum tensile stress, resulting in the development of fatigue cracks. Figure 33(a) and (b) illustrate the accumulation of fatigue cracking in viscoelastic asphalt concrete (AC) material subjected to repeated cyclic loading.

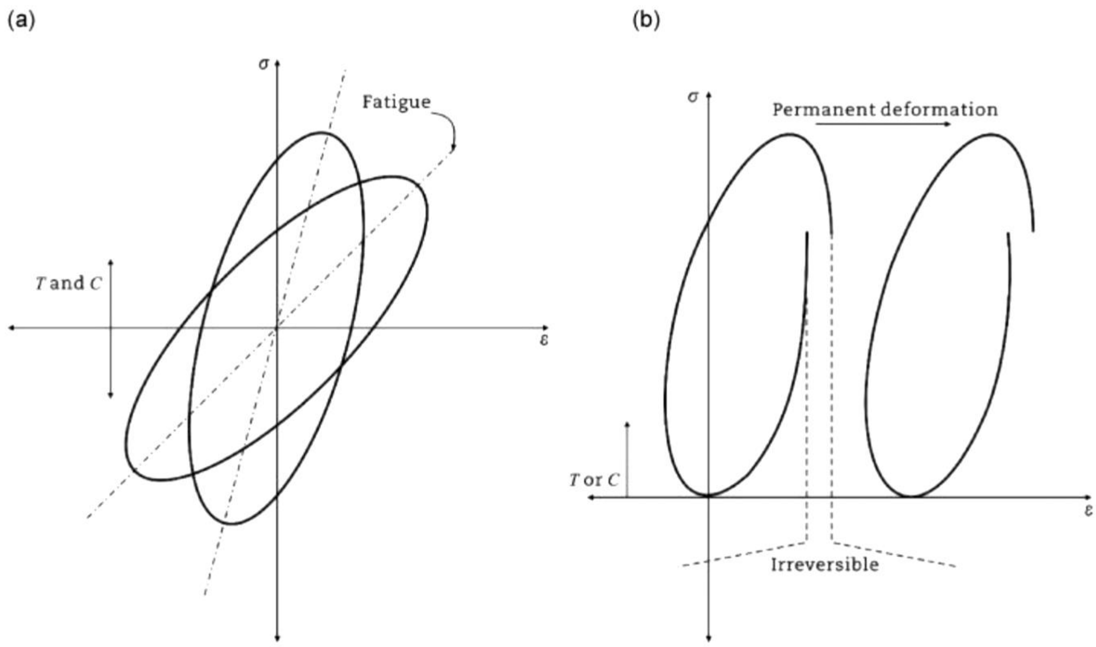


Figure 33 – Differences under (a) Fatigue cracking and (b) Permanent deformation (rutting) (tensile (T) or compressive (C) loading).

When exclusively subjected to compressive excitation (or tensile excitation, respectively), the irreversible cumulative strain has the potential to reach significant levels, hence potentially obscuring the fatigue-related effect. In addition, the characterization of fatigue behaviour is subject to the influence of current boundary and loading conditions.

The aforementioned concise depiction (Figure 31) illustrates the intricate nature of fatigue characterization in bituminous blends and thus demonstrates the absence of a standardised fatigue methodology. When examining test findings, it is essential to address two primary inquiries. Firstly, it is crucial to determine the specific sort of deterioration that is taking place, whether it is initiation or propagation. Secondly, it is important to assess whether the presence of biased effects, which are distinct from fatigue, has any impact on the test results [124].

In conclusion, knowing the fatigue cracking of asphalt mixtures becomes relevant for the formulation of mixtures, for the dimensioning of a structure, or for the choice of an appropriate solution in the pavement recovery work of a highway.

5.3.4 Design of the eight layout solutions

The stress-strain behaviour of the layouts was investigated by considering data obtained from the laboratory phase for the binder layer, along with data from previous studies on the wearing course and base layer of the HMA. These findings will be presented in Section 8 - Results. The layouts were modelled as an elastic, homogeneous, and isotropic multilayer. The findings of the stress-strain analysis will also be reported in Section 8. The aforementioned findings are crucial for the validation of fatigue cracking and rutting, which will be clarified hereinafter.

Rutting and fatigue cracking were verified for the hypothesised layouts based on the calculations presented in Equations 31 and 32. The equation 31 is known by *Miner law*, and it is the verification of fatigue. On the other hand, equation 32, the *Verstraeten law*, is the verification of the rutting.

$$DC = \sum_{i=1}^{P} \sum_{j=1}^{A} \frac{n_{i,j}}{N_{i,j}} < 1 \qquad \text{Equation 31}$$

The variable $n_{i,j}$ represents the number of the actual passage of *j*-th axle loads during the *i*-th period of analysis. The variable $N_{i,j}$ represents the frequency of occurrence of the *j*-th axle load in the *i*-th analysis period, which results in the failure of the layout.

$$\delta p = \sum_i \sum_j \varepsilon_{ij} \cdot h_j < 2\text{cm} \qquad \text{Equation 32}$$

The value of the variable ε_{ij} represents the amount of permanent deformation that occurs after a specific number of load cycles in the *i*-th layer during the *j*-th period of analysis. On the other hand, h_j denotes the thickness of the *j*-th layer.

6 EXPERIMENTAL STUDY

This chapter will outline the laboratory experiment conducted to evaluate the feasibility of incorporating RAP and plastic waste into asphalt mixtures. The study will be divided into three parts. The first part will focus on the identification of the optimal mixtures containing plastic waste and RAP, through the application of a colt technology, with the aim of reusing as much recycled material as possible; everything will be validated by comparison with the traditional hot asphalt mixtures, which are highly performing, even with the introduction of a modified bitumen. The second portion will focus on the advanced mechanical characterization of identified optimum asphalt mixtures. The last objective is the design and verification of the most optimal and environmentally friendly methods for constructing flexible pavements.

The asphalt mixtures investigated in this study are:

- Mix virgin limestone,
- Mix virgin limestone MOD,
- Mix 30/70 limestone,
- Mix 30/64/6 PW limestone MOD,
- Mix 74/26,
- Mix 74/26+PW,
- Mix Cold PW 7.5% cem.
- Mix Cold PW 8.5% cem.

The two mixtures namely Mix virgin limestone and Mix virgin limestone MOD were used as control for the purpose of the study.

In the following section, the mixtures will be detailed, including optimum aggregate size, water and cement content, and bituminous emulsion.

6.1 Design of asphalt blends

The experimental analysis also concerned the cold reuse of the RAP to create mixtures suitable for binder layers of road pavements. RAP is the asphalt mixture coming from the milling operations carried out on the surface layers of the pavements during routine maintenance. This material, together with the plastic waste, was used as a base for making mixtures.

First of all, the next step was the determination of optimum aggregate size. The RAP was used as inert on the blends, it means waste that does not undergo major biological, physical, or chemical changes and which cannot trigger a negative impact on the other materials with which it comes into contact. Consequently, it was chosen how and how much to use of RAP and PW in the eight mixtures set up for comparison, with a percentage equal to:

- *Mix virgin limestone:*
  - 100% limestone aggregates and neat bitumen,
- *Mix virgin limestone MOD:*
  - 100% limestone aggregates and modified bitumen (Polymer Modified Bitumen - PMB),
- *Mix 30/70 limestone:*
  - 30% RAP of the total plus 64% limestone aggregates plus 6% filler,
- *Mix 30/64/6 PW limestone MOD*:
  - 30% RAP of the total plus 64% limestone aggregates plus 6% plastic waste (PW),
- *Mix 74/26:*
  - 74% RAP of the total aggregates plus an integration of 26% with limestone aggregates,
- *Mix 74/26+PW:*
  - 74% RAP of the total aggregates plus an integration of 20% (2% of this is filler) with limestone aggregates and 6% PW,
- *Mix Cold PW 7.5% cem.*
  - 74% RAP of the total aggregates plus an integration of 20% (2% of

this is filler) with limestone aggregates and 6% PW – 7,5 % cement as binder,

- *Mix Cold PW 8.5% cem.*

  - 74% RAP of the total aggregates plus an integration of 20% (2% of this is filler) with limestone aggregates and 6% PW – 8,5% cement as binder.

6.1.1 Optimum aggregate size

The selection of the optimum aggregate size in asphalt mixtures is a crucial issue that has a substantial impact on the performance and longevity of asphalt pavements. The precise selection of aggregate size is essential for achieving the desired mechanical qualities, stability, and resistance to damage of the asphalt mixture. The optimisation procedure entails identifying the optimal combination of aggregate sizes to improve the overall performance of the asphalt mixture. The aggregate in asphalt mixtures fulfils multiple roles, such as offering structural reinforcement, enhancing skid resistance, and bolstering the overall longevity of the pavement.

Various elements, such as traffic loads, environmental conditions, binder qualities, and the intended usage of the pavement, affect the determination of the ideal aggregate size. The procedure commonly entails employing gradation analysis and performance testing to assess the interaction between various aggregate sizes and the asphalt binder. The objective of engineers and asphalt mix designers is to attain an equilibrium between coarse and fine aggregates to maximise the density of packing and interlocking features, hence improving the overall mechanical qualities of the asphalt mixture.

Optimising the size of aggregates enhances the performance of asphalt mixtures by increasing their resistance to rutting, fatigue cracking, and other forms of damage. This leads to the creation of longer lasting and more economically efficient pavements.

The Figure 34 shows the graphic from the Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD asphalt blends, and the table 10 the grading curve from these blends.

Table 10 – Values of aggregates grading curve Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD

SIEVES	*Mix 30/70 limestone and Mix 30//64/6 PW limestone MOD*
[MM]	
0.063	4.722098594
0.075	5.328593972
0.125	7.31677646
0.25	9.619270242
0.5	12.72412431
1	18.25760692
2	27.94448549
4	41.52168947
6.3	53.58190971
8	63.02456819
10	72.95426661
12.5	82.65062211
14	86.55564173
16	92.42000989
20	99.68027942
31.5	100
40	100
63	100

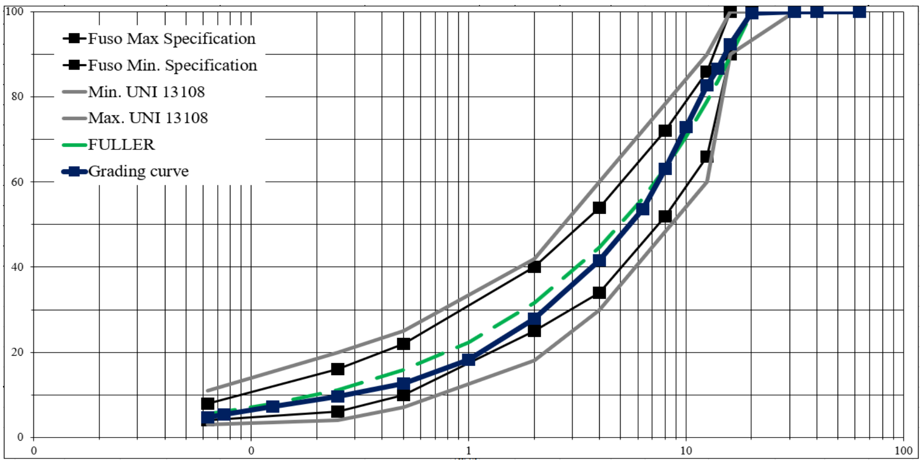


Figure 34 – Grading curve of Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD.

The Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD asphalt mixtures have the same aggregates curve, as we just saw. The difference is that the Mix 30/70 limestone is composed just with limestone (100% natural aggregates), and a neat bitumen 50/70. In the other hand, the Mix 30/64/6 PW limestone MOD is composed with a modified binder (PMB), which does not change the grading curve in the skeleton of the aggregates in the mixture.

The Table 11 illustrate the gradulometry by sieves from the aggregates from the mixtures Mix 74/26; Mix 74/26+PW; Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem.

Figure 35 shows the grading curve.

Table 11 – Values of aggregates grading curve Mix 74/26; Mix 74/26+PW; Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem.

SIEVES	***Mix 74/26; Mix 74/26+PW; Mix Cold PW 7.5% cem; Mix Cold PW 8.5% cem***
[MM]	
0.063	4.953162276
0.075	5.475105331
0.125	7.311564313
0.25	9.58248911
0.5	12.63003605
1	18.01433536
2	27.31291188
4	39.81800573
6.3	50.46148098
8	58.86200472
10	67.55847429
12.5	76.68838921
14	81.29681149
16	88.92482121
20	99.36055884
31.5	100
40	100
63	100

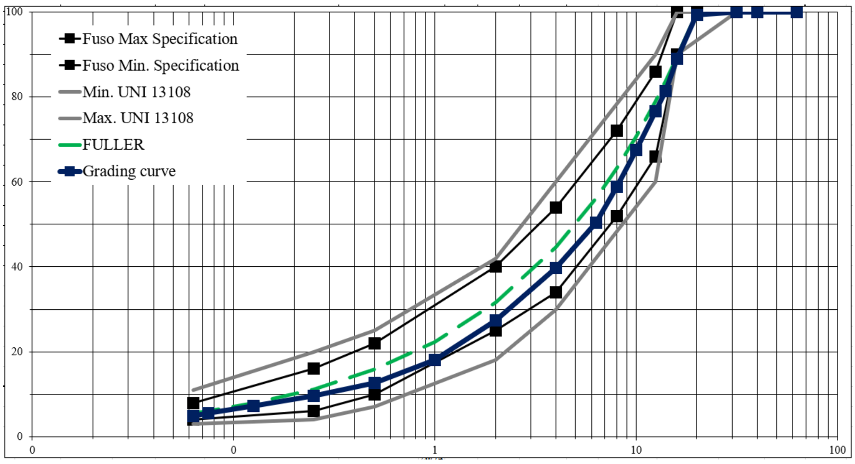


Figure 35 – Grading curve of Mix 74/26; Mix 74/26+PW; Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem.

The compositions of aggregates in these mixtures are almost the same. The difference is that the mixtures Mix 74/26, Mix Cold PW 7.5% cem. and Mix Cold PW 8.5% cem. have the same aggregate composition. Also, an important information is that the cold mixtures were made at a temperature of 60°C, which means that GHG emissions were lower in their production. In the Mix 74/26+PW, 20% of the composition is limestone (filler is present in 2%). Plastic waste is 6% of the skeleton of the mixture. Almost the entire composition of filler is substituted in this mixture. It also means that when the grading curves are overlapping, they are the same. Here it is also of paramount importance to comprehend that when the same granulometric skeleton is applied, the assessment of the different compositions of the mixture will be more effective.

6.1.2 Optimal water and cement content

Determining the optimal water and cement content for mixtures involves finding a balance between workability, strength, and durability based on specific project requirements. The water-cement ratio (w/c ratio) is a crucial factor, with lower ratios generally contributing to higher strength and durability. However, excessively low ratios can lead to challenges in workability. In other words, it is a critical parameter that influences the performance of the mixture.

The next step consisted of determining this optimal water plus cement content, was consisted of the combinations of water and cement contents. The percentages of water were 4 – 5 – 6 – 7 – 8 – 10 – 15 – 18%; and the percentages of cement were 0,5 – 1 – 1,5 – 3 – 4 – 5 %. The optimal content was identified on the basis of preliminary evaluation of the parameters Degree of densification (Gmm thickening) and Indirect Tensile Strength.

Illustrating how some the results were obtained, the following figures show them.

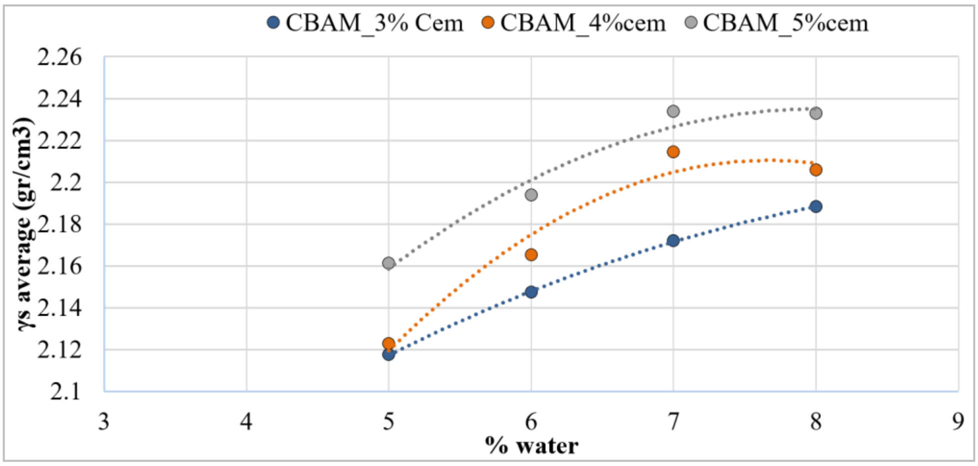


Figure 36 – Specific weight average (γs) *versus* Water% Mix 30/70 limestone.

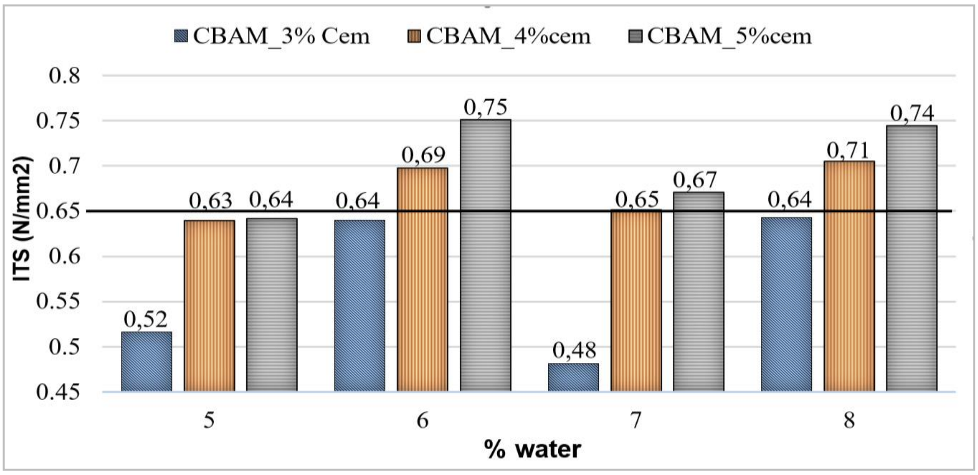


Figure 37 – Indirect Tensile Strength (ITS) *versus* Water% Mix 30/70 limestone.

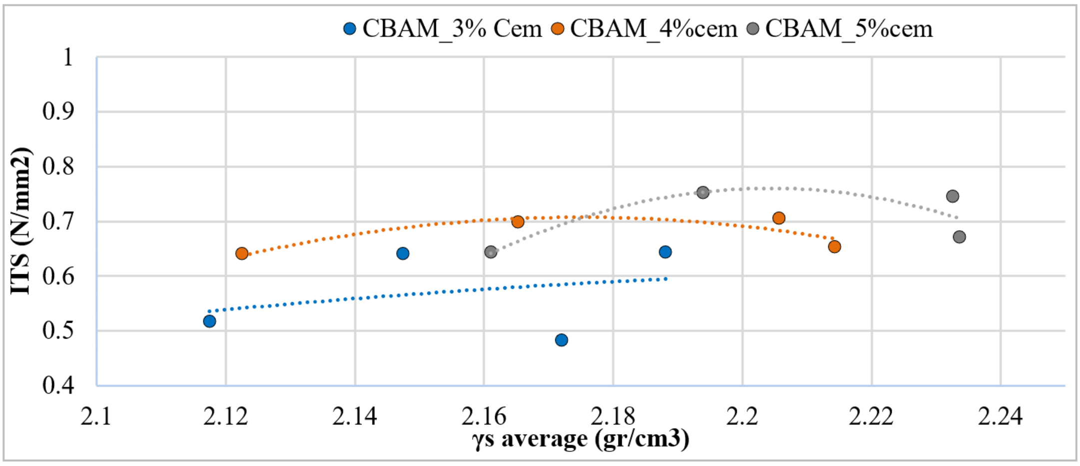


Figure 38 – Indirect Tensile Strength (ITS) *versus* Specific weight average Mix 30/70 limestone.

The graphs in figures 36, 37, and 38 showed the results of tests that looked at the effects of water and the type of cement used. The tests also investigated at the average specific weight and ITS of the Mix 30/70 limestone.

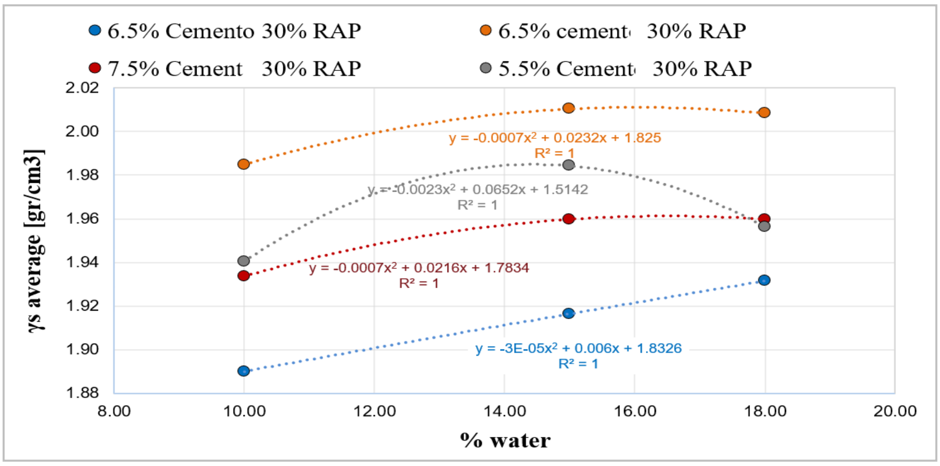


Figure 39 – Specific weight average (γs) *versus* Water% Mix 30/64/6PW.

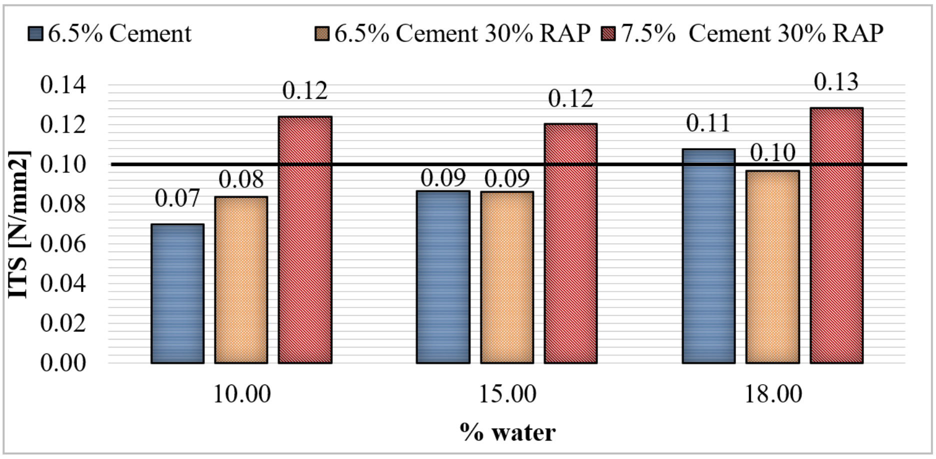


Figure 40 – Indirect Tensile Strength (ITS) *versus* Water% Mix 30/64/6PW.

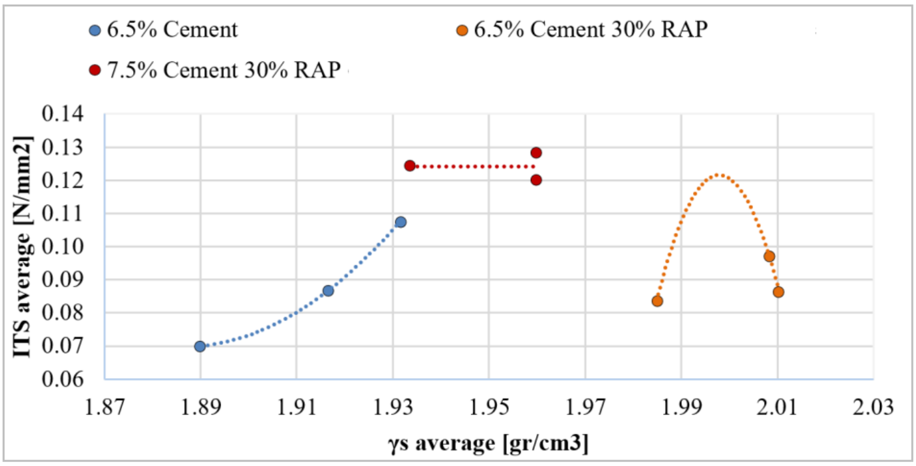


Figure 41 – Indirect Tensile Strength (ITS) *versus* Specific weight average Mix 30/64/6PW.

The Figures 39, 40, and 41 were representations of the results after the same tests about the blend with 30% RAP plus 6% plastic waste (Mix 30/64/6PW). This asphalt blend was optimised with 15% water and 7.5% cement. To add plastic waste to the blend, it was needed to increase the percentage of cement. To add the plastic waste, it was known that the maximum quantity of plastic that it could add to the blend was 6%, in relation to the grading curve. To combine the plastic waste with all the other elements of the blend, I needed to modify the cement quantitative. Thus, I used 2 percentages of cement, and to improve the mechanical properties, I also used another typology of cement, the Pozzolanic.

The next graphs (Figure 42, Figure 43, and Figure 44) will exemplify results of the asphalt blend Mix 74/26.

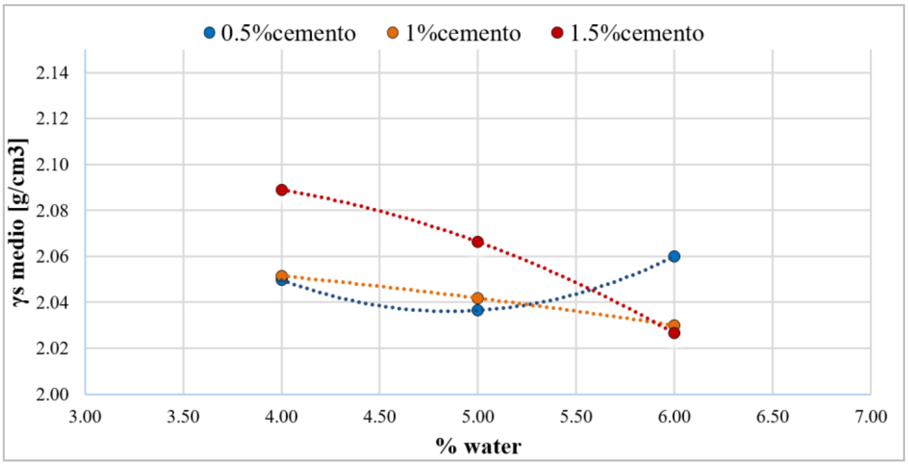


Figure 42 – Specific weight average (γs) *versus* Water% Mix 74/26.

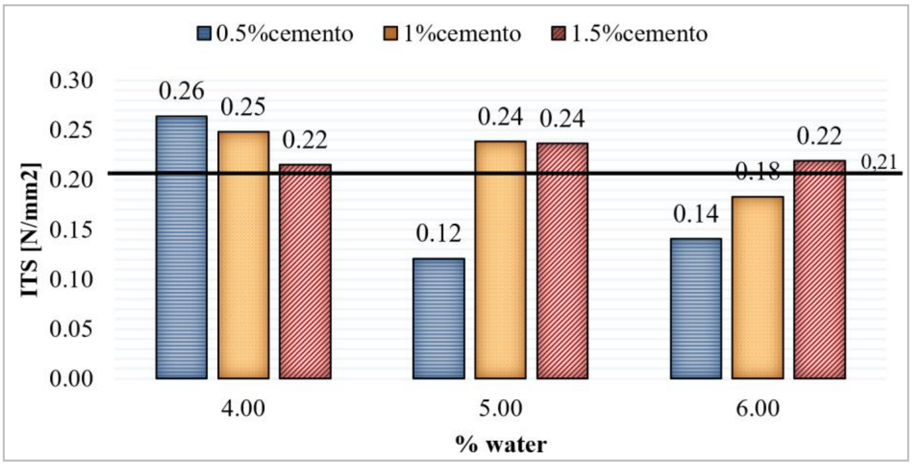


Figure 43 – Indirect Tensile Strength (ITS) *versus* Water% Mix 74/26.

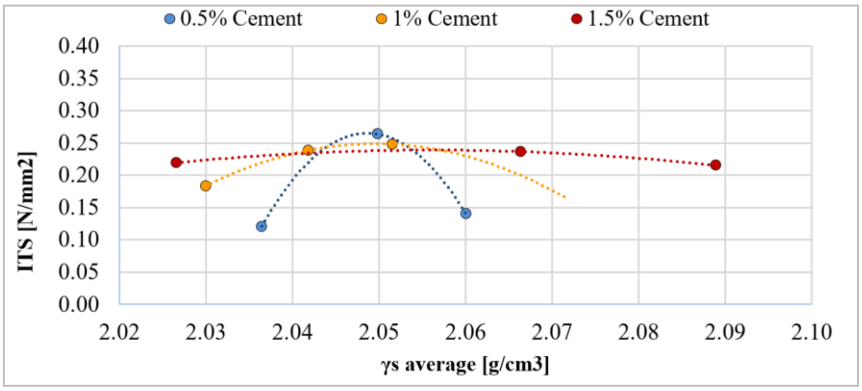


Figure 44 – Indirect Tensile Strength (ITS) *versus* Specific weight average Mix 74/26.

The representation of the results after the same tests for the blend Mix 74/26. This asphalt blend was beginning to be optimized with 0,5% of cement and 4% of water.

The other mixtures that compose this study followed the same procedure to obtain the results. Table 12 elucidates, in a way that is clear and easy to understand, all results from all mixtures about the optimum water and cement content.

Table 12 – Mixtures results of optimal water and cement content.

	Water (%)	Cement (%)
Mix 30/70 limestone	6	5
Mix 30/64/6PW	15	7.5
Mix 74/26	0.5	4
Mix 74/26+PW	6	2.5
Mix Cold PW 7.5% cem	15	7.5
Mix Cold PW 8.5% cem	15	8.5

6.1.3 Bituminous emulsion content

The study also focused on composite materials comprising bituminous emulsions in mixtures. The investigations involved varying percentages, specifically exploring combinations of 3%, 4%, and 5% for the bituminous emulsion, along with different optimal proportions of water and cement, already investigated and presented.

Assessing the composition of the material, a preliminary analysis was conducted based on two key parameters: Gmm (thickening) and ITS. These parameters were crucial in identifying the overall characteristics and performance of the specimens.

A total of 54 specimens were analysed in this specific portion of the investigation. Every three specimens represented a unique combination of bituminous emulsion percentage and the corresponding mix of water and cement. The goal was to understand how these variations influenced the material's thickening properties (Gmm) and its resistance to indirect tensile forces (ITS) (Figures 45, 46 and 47).

The results of the optimum emulsion content in the blends are presented below. Tabele 13 show the results from all asphalt blends.

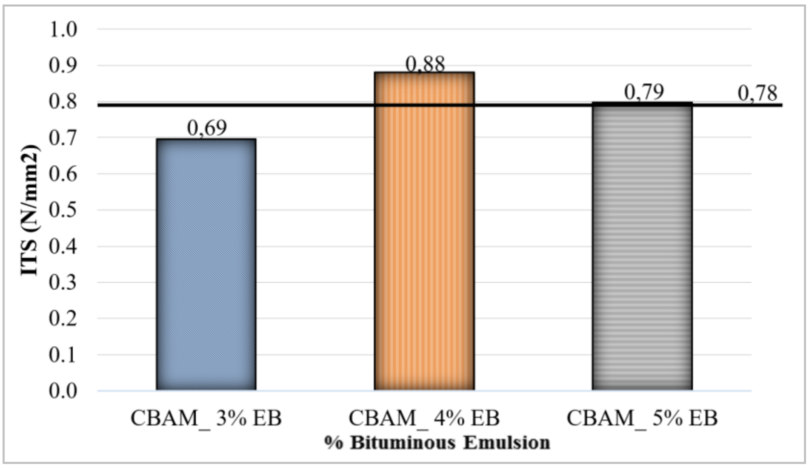


Figure 45 – ITS (N/mm2) *versus* % Bituminous Emulsion Mix 30/70 limestone.

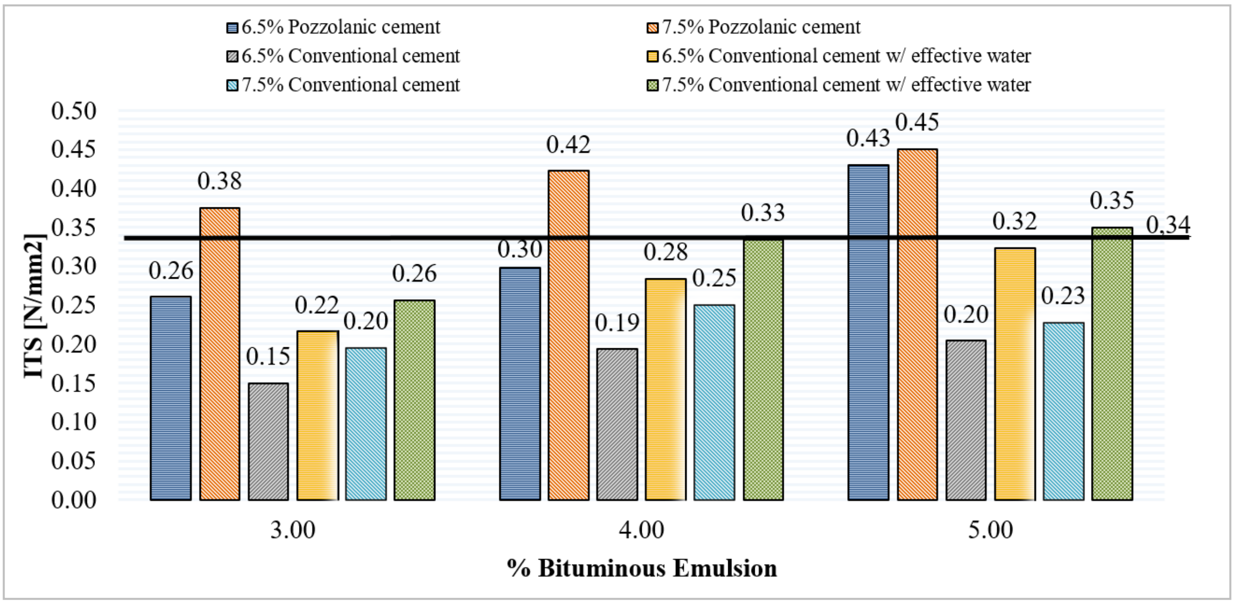


Figure 46 – ITS (N/mm2) *versus* % Bituminous Emulsion Mix 30/64/6PW.

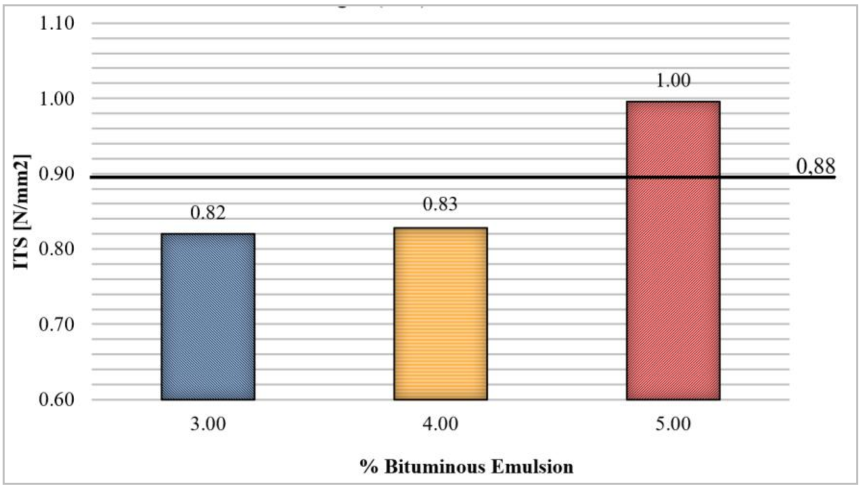


Figure 47 – ITS (N/mm2) *versus* % Bituminous Emulsion Mix 74/26.

Table 13 further shows the results of the percentage of the bituminous emulsion the structures the blends.

Table 13 – Mixtures results of optimal Bituminous emulsion plus water and cement content.

	Water (%)	Cement (%)	Bituminous emulsion (%)
Mix 30/70 limestone	6	5	4
Mix 30/64/6PW	15	7.5	5
Mix 74/26	0.5	4	5
Mix 74/26+PW	6	2.5	5
Mix Cold PW 7.5% cem	15	7.5	5
Mix Cold PW 8.5% cem	15	8.5	5

6.1.4 Blend optimisation with: RAP + water + cement + bituminous emulsion

This blend optimisation was curry out in 4 steps: Sieving of the dry RAP, Blending, Superpave Gyratory compaction, and curing time.

6.1.2.1 Sieving of the dry RAP

In the realm of materials testing and particle analysis, the EN 2332 standard plays a pivotal role, particularly in the context of sieving. The methodology employed involves a stack of sieves meticulously arranged with a gradation of mesh dimensions from the top to the bottom (Figure 48) and the dimensions of this sieves are already elucidated at Table 10. This gradation is crucial as it facilitates the differentiation and classification of particles based on their sizes.

Figure 48 – EN 2332 sieves arranged with decreasing dimensions from top to bottom of the mesh opening.

The initial step in this intricate process is the selection of the first sieve. This selection is made with precision to ensure that the entire sample (aggregates) passes through it. This serves as a benchmark for the subsequent sieves and aids in establishing a baseline for particle distribution. The chosen sieve sets the stage for a comprehensive analysis of the material under analysis.

The sieving process itself is carried out with the aid of a vibrating screen (Figure 49). This dynamic element introduces an additional layer of efficiency to the process by imparting vibrational energy, which aids in the separation of particles based on their sizes. The vibrating screen becomes an instrumental tool in achieving accurate and reliable results, as it imparts a dynamic force to the sieving process.

Figure 49 – Vibrating Screen in the *Laboratorio di Strade Luigi Tocchetti* – University of Naples Federico II

As the sample traverses through each sieve, meticulous records are maintained. At each sieve, the corresponding material's restraint is diligently noted. This comprehensive documentation ensures that the entire range of particle sizes is accounted for, contributing to the accuracy and reliability of the analysis.

In essence, the EN 2332 standard, with its elaborate arrangement of sieves, vibrating screen technology, and meticulous data collection, provides a robust framework for particle size analysis. This methodology is foundational, where understanding particle distribution is imperative for quality control and product performance. The Figure 50 shows the aggregates after passing through the sieves.

Figure 50 – Aggregates in the specific dimensions after the sieves.

6.1.2.2 Blending

In the process of creating specimens for various mixtures, a systematic approach was employed. The initial step involved the mechanical mixing of aggregates combined with additives, encompassing water, cement, and bituminous emulsion. The sequence of mixing was meticulously followed, emphasising specific durations for each phase to ensure optimal amalgamation.

The first stage entailed the amalgamation of aggregates with water, a swift but crucial process lasting 30 seconds. Subsequently, the mixture underwent a more elaborate blending phase, encompassing aggregates, water, cement, and filler. This phase spanned 180 seconds, allowing for thorough integration and homogeneity.

The final stage of the mixing process involved the addition of bituminous emulsion to the pre-existing combination of aggregates, water, cement, and filler. This phase also endured for 180 seconds, completing the comprehensive mixing protocol. The specific order and durations were imperative to achieve a uniform composition and enhance the properties of the specimens.

Figure 51 – Heavy Duty Lab Mixer in the *Laboratorio di Strade Luigi Tocchetti* – University of Naples Federico II.

This methodical approach aimed not only to create consistent specimens but also to understand and manipulate the interplay between the diverse components. Each step in the mixing process played a crucial role in determining the final characteristics of the specimens, contributing to the overall success of the experimental endeavours.

6.5.1.3 Superpave Gyratory Compaction

The compaction process utilised the Superpave Gyratory Compaction (Figure 52) method, a technique designed to accurately replicate on-site compaction achieved by compacting rollers. The procedure involved maintaining a constant pressure of 600 kPa, a rotation speed of 30 turns per minute, and an angle of inclination set at 1.25°.

To conform to the specifications for typical operating conditions on a local suburban road, the compaction was concluded after 180 turns, as recommended. Throughout the compaction, the machine systematically recorded the reduction in specimen height with increasing revolutions. Concurrently, it monitored the percentage of air voids or its complement, denoting the degree of thickening (Gmm).

Figure 52 – Superpave Gyratory in the *Laboratorio di Strade Luigi Tocchetti* – University of Naples Federico II.

This meticulous recording process allowed for a comprehensive analysis of the compaction dynamics, offering insights into the material's behaviour under the specified conditions. The data collected, including specimen height reduction and air void percentages, serves as valuable information for assessing the effectiveness of the compaction process and ensuring that the material meets the desired engineering standards for road construction.

6.5.1.4 Curing time

After compaction, the specimens were placed in an oven set at 60°C for three days to undergo an essential curing phase (Figure 53). The controlled atmosphere has two main functions: to accelerate the cement curing process and to completely remove any remaining traces of water. The high temperature within the oven significantly improves the strength and durability of the specimens, guaranteeing their optimal structural integrity. This rigorous method follows established standards, ensuring the dependability and effectiveness of the materials.

Figure 53 – Specimens took off the oven at 60°C after three days of curing time.

By employing this method, a total of 144 specimens were successfully generated (Figure 54). The technique required rigorous adherence to a series of precise processes, with careful attention to detail, with the goal to guarantee the quality and integrity of every specimen. This achievement demonstrates the effectiveness and dependability of the selected approach in generating a significant quantity of samples for subsequent examination and assessment.

Figure 54 – Specimens.

According to the National Autonomous Road Agency (*Azienda Nazionale Autonoma delle Strade* - ANAS), the characteristics of resistance pertaining to of ITS (dry at 25°C) results need to be within the range of 0.20MPa to 0.45MPa. This information underscores the critical role of ITS in ensuring the structural integrity and durability of road infrastructure. The ITS was performed as already described on section 5.2.1.

ANAS, plays a pivotal role in establishing and maintaining standards for road quality and safety in Italy. The specified range of 0.20MPa to 0.45MPa corresponds to a metric used to measure the ITS of materials after this curing period. This metric is crucial for evaluating the ability of road materials to withstand stress and pressure, ultimately contributing to the resilience of road networks. The road transportation sector relies on such precise guidelines (standards) to ensure that roadways meet the required standards for safety and longevity.

Since one of the main objectives of this study is to find a mix design for cold recycling mixtures, in particular when PW is added, such as to allow the same or higher mechanical performance as a traditional HMA, the mixtures curing process was evaluated by monitoring the ITS value over a period of 28 days.

The ITS (EN 12697-24) was carried out after 1, 5, 10, 14, 20, 25, and 28 days, starting from the compaction phase of each specimen that was prepared according to the procedures shown in the previous sections and then stored at ambient temperature for all the time before the test (three specimens were tested at each curing day).

In respect to the mixtures Mix virgin limestone and Mix virgin limestone MOD, the values of ITS dry 25°C are 0.78 MPa and 1.23 MPa, respectively. In comparison to the standard values (0.20 MPa and 0.45 MPa), both mixtures had ITS values above the maximum stabilised by the standard. The asphalt blend Mix 30/70 limestone has a value of 73% higher than the maximum value of ITS. Furthermore, the valuer of the mixture Mix virgin limestone MOD has values of 1.23 MPa, which is 173.33% higher than the maximum value of ITS in dry conditions at 25°C.

The mixtures of Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD also got great results from the ITS test. The mix Mix 30/70 limestone had a value of ITS dry 25°C at 0.32 MPa, and the mix Mix 30/64/6 PW limestone MOD got a value of 0.38 MPa. We can see that the value of the Mix 30/64/6 PW limestone MOD is greater than the other Mix 30/70 limestone. Even if the composition of the mix has PW (material that affects the mechanical behaviour of the mixtures), there is a high probability that the modified binder worked on this effect.

The ITS result for the mixture Mix 74/26 is 0.42 MPa; it is between the values specified by ANAS for ITS, and Mix 74/26+PW has a result of 0.24 MPa. We can see that both asphalt blends are in the range of values for ITS according to ANAS for the three-day curing time. We can also realise that the quantity of PW changed remarkably the mechanical behaviour of the mixture structured with it. Even with a decrease of 57% in the mechanical behaviour of the mixture Mix 74/26+PW, the mixture still remains within the values stipulated for mechanical behaviour for ITS values according to the ANAS.

About the results from the mixtures Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem, both asphalt blends have values of ITS higher in relation to the ANAS' range. The mixture of Cold PW 7.5% cem has a value 40% higher in relation to the maximum value of ITS, according to ANAS. On the other hand, the mixture Mix Cold PW 8.5% cem has a lower value of ITS in comparison with the other mixture, however a higher value of 20% of ITS, corresponding to ANAS standard values of optimal ITS values.

Moreover, it means that the employment of plastic waste in the asphalt mixture is meaningful due to the fact that there is less use of natural aggregates and more use of marginal materials, and it is still in the mechanical behaviour range, in accordance with the ANAS. Chard 1 illustrate these values.

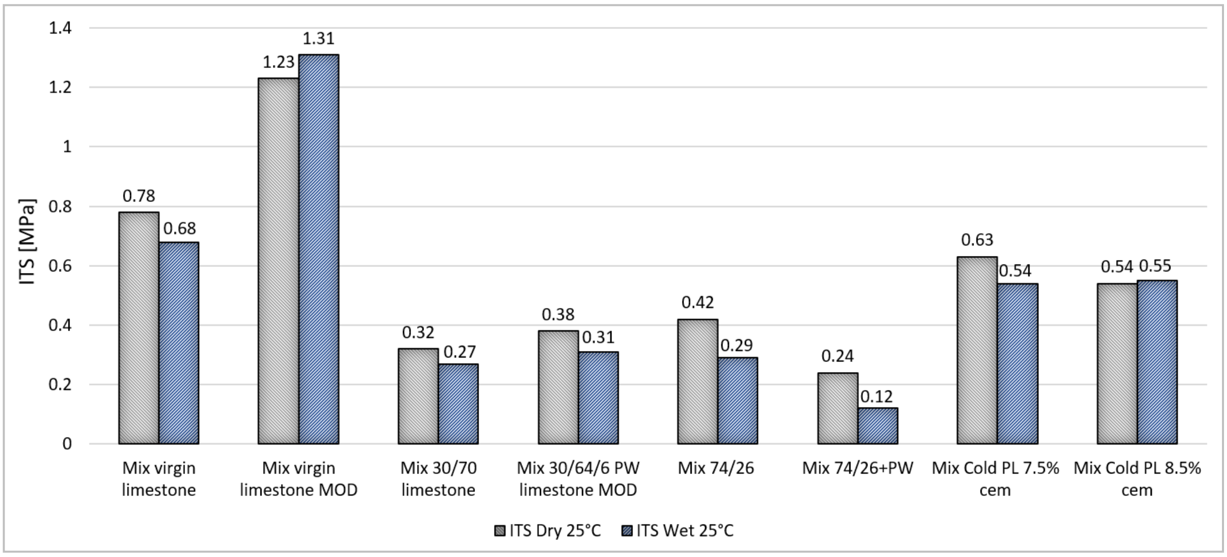


Chart 1 – Dry - blue bars / Wet - grey bars ITS

In accordance with the results in Chart 1, adequate utilization of PW is achieved when it is added to the mix process since it helps to achieve the range of the ITS values, and above all, it affects the stability of mechanical performance after imbibition.

The following session will focus on the design of asphalt mixtures that incorporate recycled aggregates in quantities greater than 70%, with the aim of maximising the application of alternative materials. Therefore, after it has been carefully thought out, the mixtures Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD will no longer be investigated in this study. It is of paramount importance for this study since it has as one of its main objectives the evaluation of recycled asphalt mixes for binder layers of road pavements.

6.2 Advanced mechanical characterisation

The advanced mechanical characterisation of asphalt mixtures involves the precise measurement and study of fundamental features, such as stiffness and resistance to primary failure and degradation mechanisms. While conventional calculation methods often assume linear elasticity, bituminous mixes have a significantly more intricate behaviour resulting from the combination of elastic, viscous, and plastic components. The assessment of the mechanical response parameters, therefore necessary for determining the ideal thickness of pavement layers in mix design or for quality control purposes, should be conducted by subjecting the pavement to load and temperature conditions that accurately reflect real-world usage and performance.

The dynamic characterisation of the optimised mixtures was carried out on all asphalt blend solutions since the aim of the research was to obtain a cold mixture with PW that achieved the same performance as traditional hot bituminous mixtures. The MSRC and the stiffness results are described below. The ITSM was performed (EN 12697-26 Annex C) as already described on section 5.2.3.

6.2.1 Multiple Stress Creep Recovery (MSCR) test results

The stress generated on the pavement by the passing loads of vehicles causes accumulated strain in the mixture. The rutting resistance of traditional HMA, like those cold asphalt mixtures, is due to the correlation between aggregates, their shape, and the impact of the mastic. In this part of this current study, the dosing projects used to produce the mixtures with binder, which composed part of the structuring of some of the asphalt concrete in this research, were benchmarks to perform a comparison of weighty instabilities in relation to the asphaltic mixtures structured with mineral materials. It means that the binder response to permanent deformation was estimated using the MSCR test.

Table 14 demonstrates individually the values of the binders in relation to the J_{nr} at temperatures of 40°C, 50°C, 60°C and 70°C and 0.1kPa and 3.2kPa stress levels. As anticipated, the J_{nr} values are on increase as the temperatures have risen with regard to binders neat binder 50/70 and binder PMB. This is due to lower viscoelasticity during the bituminous phase at higher temperatures, which results in higher permanent strain in the material under stress.

Table 14 – Values of the binders in relation to the J_{nr} at different temperatures.

ID specimens	Test temperatures							
	40°C		50°C		60°C		70°C	
	Jnr_0.1 kPa	Jnr_3.2 kPa	Jnr_0.1 kPa	Jnr_3.2 kPa	Jnr_0.1 kPa	Jnr_3.2 kPa	Jnr_0.1 kPa	Jnr_3.2 kPa
1 Neat binder 50/70	0.154	0.158	0.81	0.878	3.006	3.747	12.979	14.181
2 Modified binder PMB	0.0196	0.022	0.0593	0.0564	-	-	-	-

For a better understanding of what happens with the binder in the MSCR test, the strain and rest scheme is presented in Figure 55, elucidating the process that happens with the binders when tested (it was also already illustrated in Figure 29 and explained in Section 5.3.2.3).

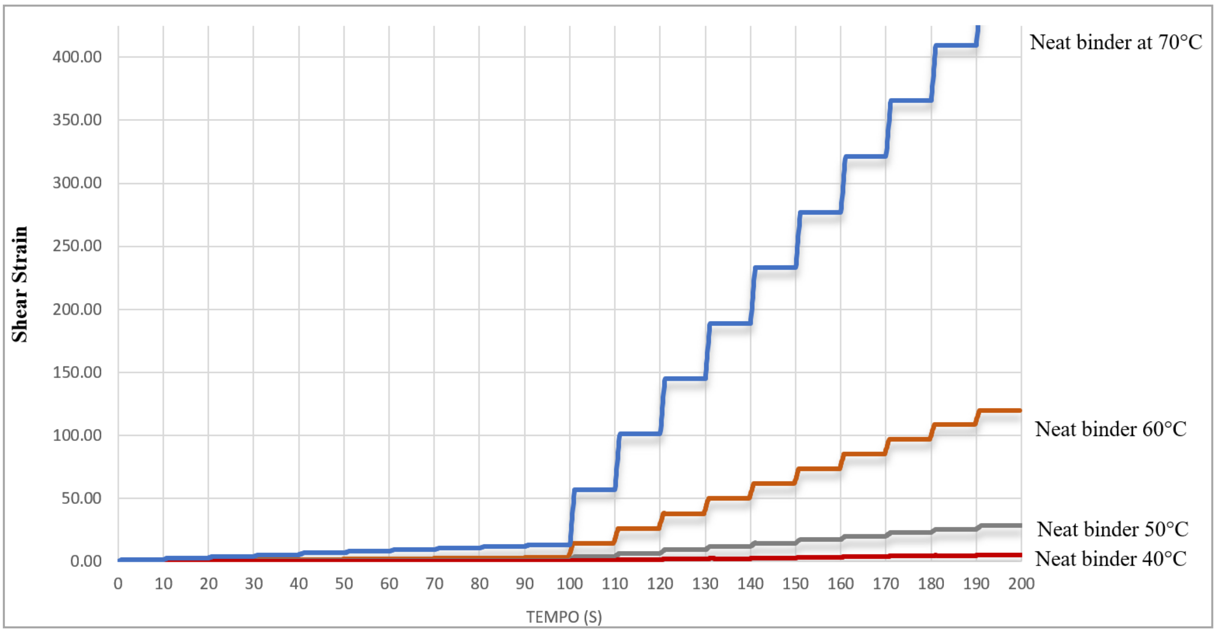


Figure 55 – Strain and loading results with 20 cycles at 0.1 kPa and 10 cycles at 3.2 kPa neat binder 50/70.

On Figure 56, we can see that the results of the neat binder 50/70 presented high values at the different temperatures tested. The recovery of the binder was reduced as the temperature increased. Furthermore, it is difficult to see a small bend in the response when the load is ceased.

The polymeric binders deform to the loading, and after it ceases, they recover, causing a small curvature in the response. About the modified binder, the PMB, it is easily to see the recovery curve when the load is stopped. Making a comparison with the binder in the different temperatures, we see that the recovery curve at the temperature 40°C is more smoothly curve in respect to when compared to the temperature 50°C. The Figure 56 illustrates these curves according to the results of the test MSCR.

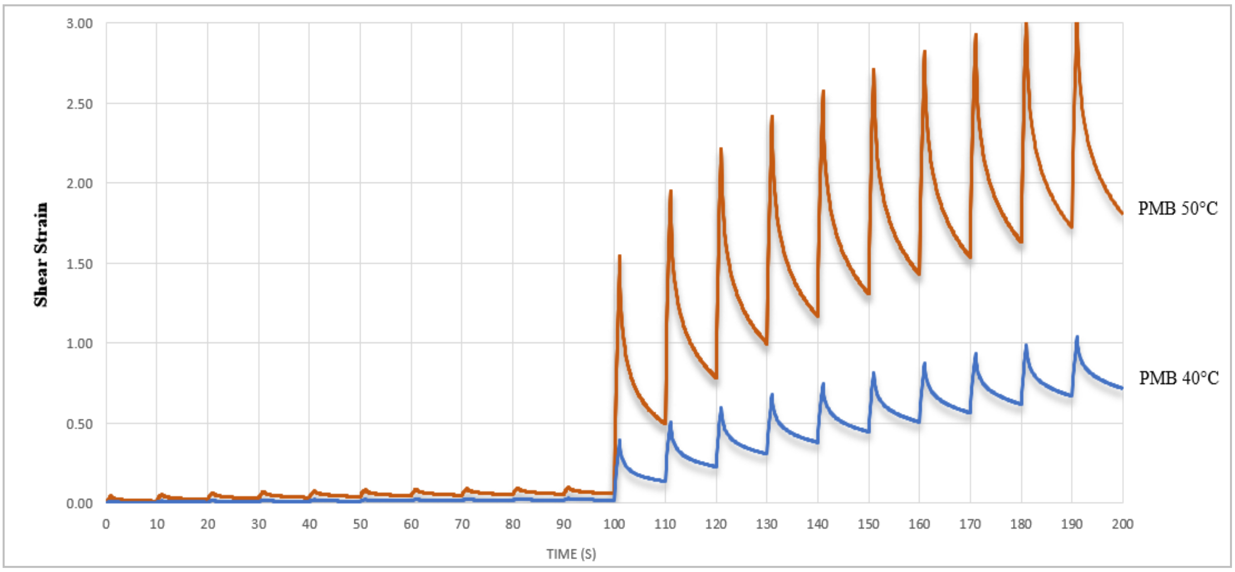


Figure 56 – Strain and loading results with 20 cycles at 0.1 kPa and 10 cycles at 3.2 kPa neat binder PMB

The capacity of each binder to recover its original shape after deformation during the creep phase was assessed in terms of J_{nr}/J_{TOT}. Furthermore, the J_{TOT}, which represents the overall creep compliance at the conclusion of the creep phase just before to the removal of the load, was examined to facilitate a comprehensive comparison of the materials. The average total creep compliance is utilised for doing comparative analysis.

If the material is incapable of returning to its original shape after deformation, and the strain recorded at the end of the creep phase is unchanged at the conclusion of the recovery phase, the J_{nr}/J_{TOT} ratio will be 1. Conversely, if the material is completely elastic and capable of fully recovering from all the accumulated deformation, the J_{nr}/J_{TOT} value will be 0.

The results, in terms of J_{nr}/J_{TOT} are reported in Tabel 15.

Table 15 – Values of the binders in relation to the J_{nr}/J_{TOT} at different temperatures.

ID specimens	Test temperatures							
	40°C		50°C		60°C		70°C	
	J_{nr}/J_{TOT} _0.1 kPa	J_{nr}/J_{TOT} _3.2 kPa	J_{nr}/J_{TOT} _0.1 kPa	J_{nr}/J_{TOT} _3.2 kPa	J_{nr}/J_{TOT} _0.1 kPa	J_{nr}/J_{TOT} _3.2 kPa	J_{nr}/J_{TOT} _0.1 kPa	J_{nr}/J_{TOT} _3.2 kPa
1 Neat binder 50/70	0.987	0.989	0.995	0.998	0.997	1.001	1.003	1.004
2 Modified binder PMB	0.665	0.691	0.598	0.581	-	-	-	-

The results from the J_{nr}/J_{TOT} show clearly when higher the temperature, higher the J_{nr}/J_{TOT} ratio. It means that the higher the temperature, the recovery from the accumulate deformation is lower, in respect to the neat bitumen 50/70. On the other hand, the situation from the modified PMB, in respect to the 40°C and 50°C, the binder work more elastic, it means that the capably of recovering from the accumulated deformation is higher.

The frequency sweep (FS) test (EN 14770) was conducted using frequency values ranging from 0.1 to 10 Hz. A total of 20 observations were made, with a frequency gap of 0.1 for frequencies between 0.1 and 1 Hz and a gap of 1 Hz for frequencies between 1 and 10 Hz, including 1.59 Hz. The test was performed at six different temperatures: 0, 10, 20, 30, 40, and 50°C.

Prior to conducting the FS test, adherence to EN 14770 required the identification of a viscoelastic linear area (LVE) based on three specific conditions: a) The strain sweep was conducted using a "25 mm plate-plate geometry" setup at a temperature of 50°C and a frequency of 0.1 Hz. b) The strain sweep was conducted using an "8-mm plate-plate geometry" setup at a temperature of 0°C and a frequency of 10 Hz. c) To ensure that the measurements were within the linear viscoelastic (LVE) region, it was verified that the difference between the storage modulus (G') and the loss modulus (G") did not deviate by more than 5% from its initial value. The initial value was determined by the point where a regression line intersected the observed data. The master curves show the results obtained. These results are not for comparison since the results are only for the binder-modified PMB, so a better comprehension of the behaviour of this binder.

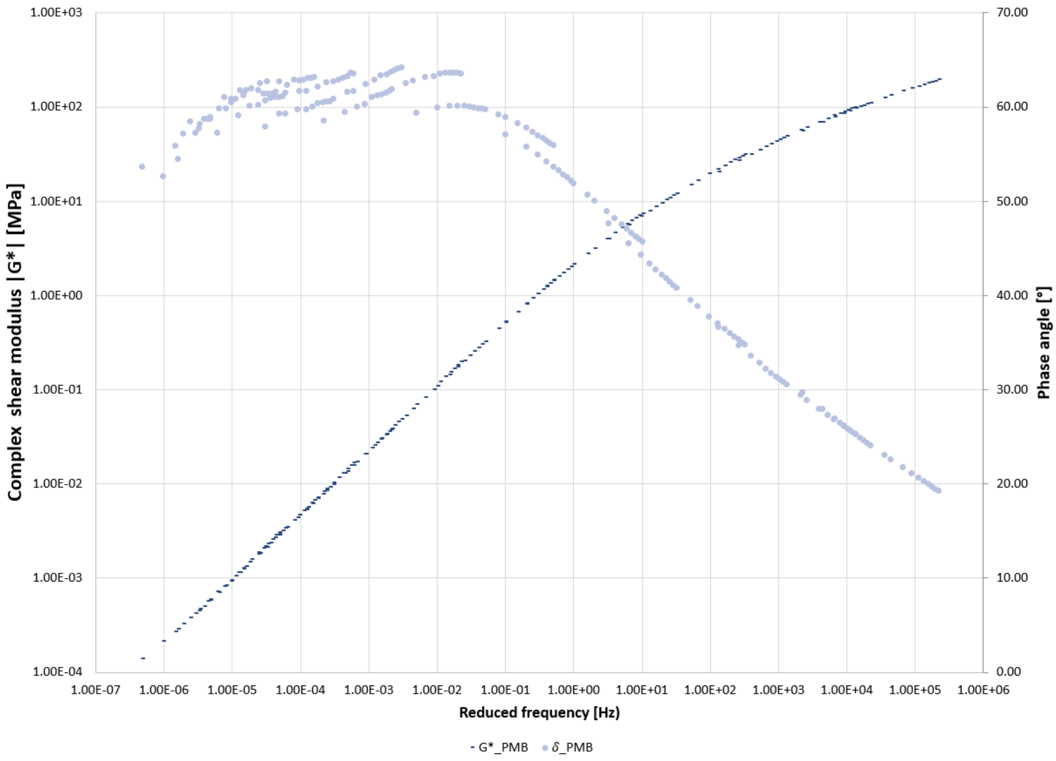


Figure 57 – PMB as master curve, showing phase angels.

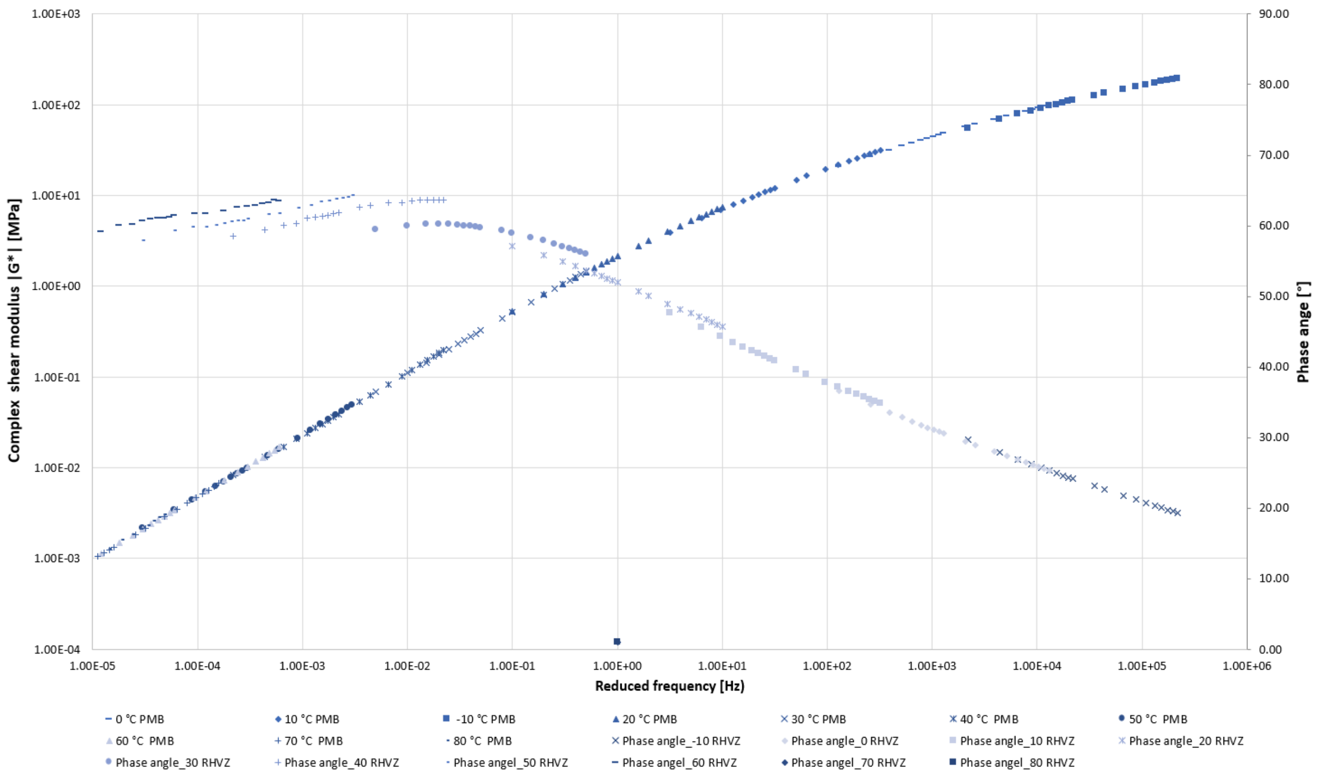


Figure 58 – Different temperatures of PMB as master curve and phase angels.

6.2.2 Indirect Tensile Stiffness Modulus (ITSM) test results

Four specimens for mixtures solutions were prepared and then tested at four temperatures (10°C; 20°C; 40°C and 60°C, representing the different seasons of the year) after conditioning for 4 hours at test temperatures. The mean values of ITSM for the asphalt blends are shown in Chart 2, where a linear increase in stiffness from 60°C to 10°C is almost equal for the mixes.

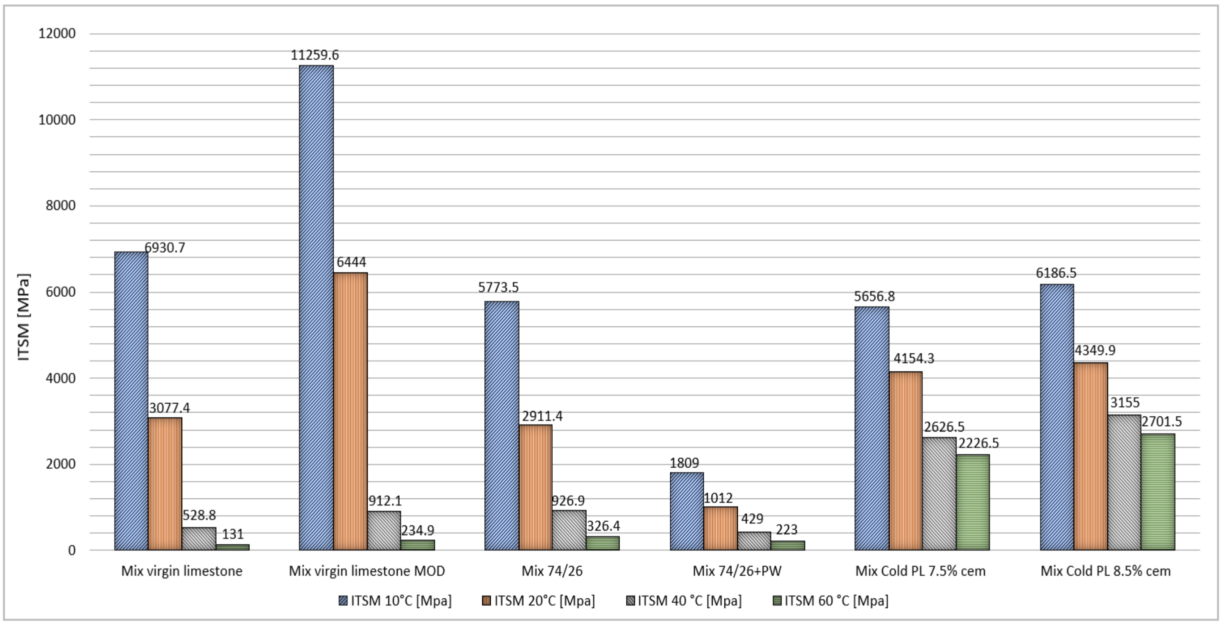


Chart 2 – Main values of ITSM of the mixtures solutions at four test temperatures

As just said, it is possible to see in Chard 2 that the mixtures have a linear increase. However, the mixtures containing PW (Mix 74/26+PW, Mix Cold PW 7.5% cem, and Mix Cold PW 8.5%) also have a linear increase, with the main values also more similar from temperature of 10°C to 60°C in these increases. In respect to the mixtures Mix virgin limestone and Mix virgin limestone MOD, the values of ITSM from the mixture Mix virgin limestone MOD at 10°C, 20°C, 40°C, and 60°C are 38.5%, 52.2%, 42.1%, and 44.2%, respectively, higher in respect to Mix virgin limestone, where just the binder is different in these mixtures. It also means that the mean value of ITSM from the Mix virgin limestone MOD is 55.75% higher with respect to the Mix virgin limestone. About the mixtures with PW, another comparison is between Mix 74/26 and Mix 74/26+PW. All ITSM main values from the mixture without PW are higher, so we can comprehend that PW plays an important role in the mechanical behaviour of the blends. The values of ITSM from the mixture Mix

74/26 at 10°C, 20°C, 40°C, and 60°C are 31.33%, 34.76%, 46.28%, and 68.3%, with a main value of 45.27% higher than Mix 74/26+PW. The mixtures Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem have very similar results, however also a linear increase, and the mixture with a higher percentage of PW had higher results. The values of ITSM from the mixture Mix Cold PW 8.5% at 10°C, 20°C, 40°C, and 60°C are 8.55%, 4.5%, 16.76%, and 17.58%, respectively, and it means 11.85% higher value in respect to the Mix Cold PW 7.5%.

Furthermore, when we compare the results of ITSM at 10°C [MPa] and 20°C [MPa] of the mixtures Mix virgin limestone, Mix 74/26, Mix Cold PW 7.5% cem, and Mix Cold PW 8.5% cem; all values are similar. It also means that the mixtures structured with percentages of RAP and/or RAP+PW had almost the same mechanical behaviour in comparison to one of the control mixtures. It further indicates that the use of these marginal materials in the structure of the different asphalt mixtures had a great performance in juxtaposition with the virgin aggregates.

6.3 Design and verification of the best sustainable flexible pavement solutions

The design and verification of sustainable road pavement solutions stand at the forefront of innovation in this study. This pivotal study seeks to harmonise infrastructure development with environmental consciousness, addressing the dual imperatives of durability and ecological responsibility. By integrating cutting-edge technologies and eco-friendly materials, these solutions aim to revolutionise traditional pavement systems. This pioneering endeavour focuses on integrating recycled plastic waste into pavement construction, presenting a dual solution for waste management and sustainable infrastructure development. Through meticulous design and rigorous verification processes, this Ph.D. research strived to create six resilient and adaptable binder layer (already elucidated) surfaces that minimise environmental impact and maintain the mechanical behaviour of the pavements already stipulated by road standards.

In this section, the results of stress and strain from both software, Medina and Bisar, will be shown. The verification of rutting and fatigue cracking laws will also be illustrated. And finally, the optimum thickness of pavement layers will be identified.

6.3.3 Medina vs Bisar results

In pavement design, the calculation of stress and strain holds paramount importance for several critical reasons, as previously highlighted in this study. Load distribution plays a pivotal role, as the stresses and strains within the pavement structure emanate from the dynamic wheel loads. A material's stiffness determines how effectively it disperses the load over the underlying layers, thereby mitigating the impact on the pavement's lower strata. Furthermore, the time-dependent response of road materials to dynamic wheel loads is a crucial parameter.

As formerly elucidated in Sections 5.3.1.1 and 5.3.1.2, Medina and Bisar conducted a comprehensive study on the thickness of pavement, presenting insightful results that contribute significantly to our understanding of this critical aspect of infrastructure. Their research delves into various factors influencing pavement thickness, addressing key considerations in design and construction. By analysing their findings, engineers and urban planners can make informed decisions to enhance the durability and performance of roadways. The software Medina and Bisar stand as valuable resources in the ongoing efforts to optimise pavement design and maintenance strategies for sustainable and resilient transportation infrastructure.

The results from the software are shown in tables. The results are organised by the different mixtures, the different temperatures for calculations of stress and strain. The calculation points are illustrated in the Figure 59.

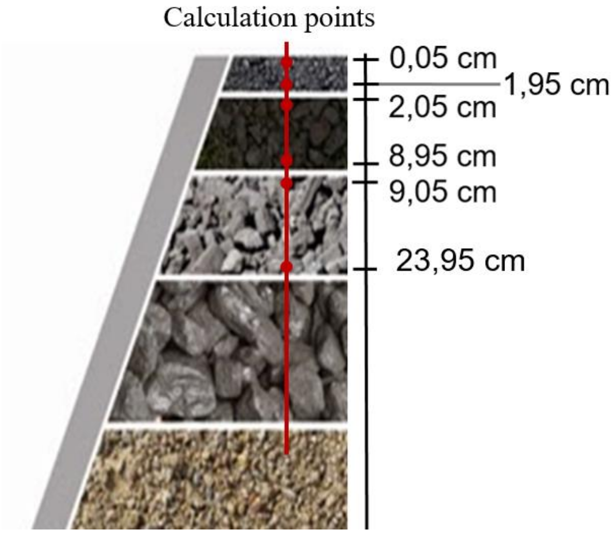


Figure 59 – Bisar and Medina calculation points.

Table 16 – Results Stress *Mix virgin limestone.*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,802080	0,80200	0,801896	0,80200	0,812923	0,80210	0,813577	0,80210
1,95	0,808111	0,80580	0,807394	0,80580	0,850399	0,85340	0,852949	0,86060
2,05	0,808527	0,80550	0,807773	0,80550	0,852984	0,85400	0,855664	0,86110
8,95	0,792628	0,59880	0,794212	0,60440	0,851567	0,69620	0,846991	0,71120
9,05	0,792597	0,59350	0,794182	0,59920	0,851531	0,69150	0,846955	0,70660
22,5	0,044754	0,02516	0,060179	0,03624	0,060980	0,04548	0,090481	0,07497

Table 17 – Results Strain *Mix virgin limestone.*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000041	9,71500	0,000105	40,68000	0,000272	0,80370	0,001046	9,445
1,95	0,000042	24,57000	0,000106	72,22000	0,001013	124,90000	0,004228	487,000
2,05	0,000042	45,90000	0,000107	113,70000	0,001064	1044,00000	0,004448	4383,000
8,95	0,000159	49,42000	0,000348	116,40000	0,001625	785,70000	0,006337	3318,000
9,05	-0,00004	19,48000	-6,7E-05	47,85000	-6,5E-05	19,51000	-0,0001	63,620
22,5	0,000062	35,26000	0,000123	69,77000	0,000122	80,28000	0,000261	174,700

Table 18 – Results Stress *Mix virgin limestone MOD.*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,800780	0,80200	0,800329	0,80200	0,809817	0,80210	0,812047	0,80210
1,95	0,803043	0,79870	0,801283	0,79650	0,838288	0,83840	0,846985	0,84950
2,05	0,803199	0,79810	0,801349	0,79580	0,840252	0,83900	0,849394	0,85030
8,95	0,750594	0,56530	0,725064	0,55340	0,848633	0,67640	0,854794	0,70050
9,05	0,750559	0,55990	0,725028	0,54810	0,848599	0,67150	0,854759	0,69580
22,5	0,043049	0,02292	0,056668	0,03153	0,061023	0,04258	0,091034	0,07095

Table 19 – Results Strain *Mix virgin limestone MOD*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000035	12,28000	0,000086	47,57000	0,000181	17,71000	0,000668	81,720
1,95	0,000013	24,06000	0,000017	69,84000	0,000551	90,43000	0,002291	345,700
2,05	0,000011	17,19000	0,000012	25,91000	0,000577	567,20000	0,002403	2353,000
8,95	0,000112	31,31000	0,000204	60,78000	0,000982	435,30000	0,003664	1802,000
9,05	-3,9E-05	22,82000	-6,6E-05	56,76000	-6,5E-05	27,82000	-0,0001	80,520
22,5	0,00006	33,39000	0,000117	64,34000	0,000121	76,06000	0,000262	167,300

Table 20 – Results Stress *Mix Cold PW 7.5% cem*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,802879	0,80200	0,801078	0,80200	0,803085	0,80200	0,803897	0,80200
1,95	0,811227	0,80950	0,804206	0,80140	0,812032	0,81040	0,815198	0,79900
2,05	0,811803	0,80940	0,804421	0,80100	0,812649	0,81030	0,815978	0,79840
8,95	0,806187	0,61210	0,770408	0,58450	0,808043	0,61580	0,817342	0,57420
9,05	0,806155	0,60690	0,770375	0,57920	0,808012	0,61060	0,817311	0,56900
22,5	0,045279	0,02609	0,058995	0,03432	0,059445	0,03623	0,059861	0,05076

Table 21 – Results Strain *Mix Cold PW 7.5% cem.*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000045	8,86000	0,000095	43,03000	0,000096	26,74000	0,000104	131,3000
1,95	0,00006	25,39000	0,000061	70,21000	0,000139	60,43000	0,000178	184,7000
2,05	0,000061	63,44000	0,000058	69,03000	0,000142	149,90000	0,000183	127,0000
8,95	0,000186	61,01000	0,000277	87,42000	0,000391	137,20000	0,000447	178,2000
9,05	-0,00004	17,98000	-6,7E-05	51,80000	-6,5E-05	42,85000	-6,5E-05	138,1000
22,5	0,000063	36,07000	0,000121	67,50000	0,000118	67,68000	0,000119	132,9000

Table 22 – Results Stress *Mix Cold PW 8.5% cem*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,802506	0,80200	0,800978	0,80200	0,802320	0,80200	0,800360	0,80200
1,95	0,809775	0,80780	0,803816	0,80080	0,809048	0,80680	0,801404	0,79700
2,05	0,810276	0,80760	0,804012	0,80030	0,809512	0,80660	0,801476	0,79630
8,95	0,800474	0,60630	0,766379	0,58130	0,796196	0,60380	0,729575	0,56040
9,05	0,800444	0,60100	0,766346	0,57600	0,796166	0,59850	0,729540	0,55530
22,5	0,04506	0,02568	0,060447	0,03401	0,058895	0,03509	0,083221	0,04901

Table 23 – Results Strain *Mix Cold PW 8.5% cem*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000043	9,22700	0,000094	43,45000	0,000089	27,79000	0,000213	134,4000
1,95	0,000052	24,97000	0,000057	70,03000	0,000104	58,25000	0,000064	183,4000
2,05	0,000053	55,19000	0,000054	63,27000	0,000105	114,60000	0,000054	86,6600
8,95	0,000174	55,52000	0,000266	83,77000	0,000337	113,60000	0,000459	153,1000
9,05	-0,00004	18,65000	-6,3E-05	52,38000	-6,5E-05	45,24000	-0,0001	141,4000
22,5	0,000062	35,71000	0,000118	67,15000	0,000117	66,31000	0,00024	130,2000

Table 24 – Results Stress *Mix 74/26.*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,802791	0,80200	0,802081	0,80200	0,809704	0,80210	0,809938	0,80210
1,95	0,810884	0,80910	0,808117	0,80670	0,837847	0,83790	0,838759	0,84010
2,05	0,811442	0,80900	0,808534	0,80650	0,839788	0,83850	0,840747	0,84080
8,95	0,804917	0,61090	0,798055	0,60820	0,848350	0,67560	0,852153	0,68860
9,05	0,804887	0,60560	0,798026	0,60300	0,848316	0,67070	0,852120	0,68380
22,5	0,045231	0,02600	0,060366	0,03660	0,061016	0,04249	0,091013	0,06835

Table 25 – Results Strain *Mix 74/26*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000044	8,93700	0,000107	40,30000	0,000179	18,00000	0,00053	104,6000
1,95	0,000058	25,29000	0,000117	72,80000	0,000541	89,66000	0,001596	294,9000
2,05	0,000059	61,59000	0,000117	124,10000	0,000566	556,60000	0,00167	1641,0000
8,95	0,000183	59,77000	0,000363	123,30000	0,000968	427,60000	0,002692	1269,0000
9,05	-0,00004	18,12000	-6,7E-05	47,06000	-6,5E-05	28,06000	-0,0001	89,7100
22,5	0,000063	35,99000	0,000123	70,21000	0,000121	75,93000	0,000262	162,5000

Table 26 – Results Stress *Mix 74/26+PW*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,810063	0,80210	0,807947	0,80200	0,813435	0,80210	0,812325	0,80210
1,95	0,839245	0,83930	0,830994	0,83140	0,852395	0,85740	0,848067	0,85090
2,05	0,841258	0,83990	0,832584	0,83200	0,855082	0,85790	0,850532	0,85160
8,95	0,849706	0,67680	0,846075	0,67070	0,848837	0,70070	0,854787	0,70200
9,05	0,849671	0,67180	0,845775	0,66580	0,848800	0,69600	0,854753	0,69730
22,5	0,046660	0,03106	0,062405	0,04321	0,060823	0,04649	0,091015	0,07135

Table 27 – Results Strain *Mix 74/26+PW*

	ITSM 10°C (MPa)		ITSM 20°C (MPa)		ITSM 40°C (MPa)		ITSM 60°C (MPa)	
THK (cm)	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar	MeDiNa	Bisar
0,05	0,000089	12,28000	0,000183	33,16000	0,000321	10,91000	0,000694	76,560
1,95	0,000277	24,06000	0,000485	98,79000	0,001265	143,90000	0,002423	355,400
2,05	0,00029	17,19000	0,000506	495,10000	0,00133	1310,00000	0,002543	2491,000
8,95	0,000497	31,31000	0,000897	387,40000	0,001973	980,90000	0,003848	1905,000
9,05	-0,00004	22,82000	-6,7E-05	31,49000	-6,5E-05	16,20000	-0,0001	79,040
22,5	0,000064	33,39000	0,000127	78,83000	0,000122	81,80000	0,000262	168,100

Making sure about the results from both software, regarding a comparison among the values obtained on them, before calculating the stress and strain values in the pavement structure, the software were calibrated with the same vertical loads and types of axes. Also, the tyre area in contact with the surface layer (wearing course) had set in the same contact area. Analysing the results of stress from both software, we can see that the values are really similar. On the other hand, the results of strain were not able to be compared among the different temperatures by both programmes. From here, it was decided to use the Bisar outcomes because this software is more widely known worldwide, and because the software realises that in the composition of the mixture there are marginal materials, it implies that it can better evaluate the mechanical behaviour of the mixtures.

6.3.2 Verification of rutting and fatigue cracking law

The composition and mechanical properties of asphalt mixtures play a crucial role in assessing their resistance to rutting and fatigue cracking. Rutting, characterized by permanent deformation under traffic loads, and fatigue cracking, resulting from repeated loading cycles, are key distress mechanisms affecting pavement performance, as previously described on prior sections. The aggregate gradation of the mixtures, asphalt binder content, and stiffness significantly influence these properties. The composition and mechanical properties of the mixtures, to realise the verification of rutting and fatigue cracking, are presented at the Table 28. These data were essential to assess the pavement layers. The date for the wearing course and base layer were collected from a study [128].

Table 28 – Composition and Mechanical properties of the mixtures

Layer	Bituminous mixture type	Bitumen [%]	Water [%]	Cement [%]	Bituminous emulsion [%]	ITS [MPa] EN 12697-23	Stiffness [MPa] EN 12697-26			
							10°C	20°C	40°C	60°C
Wearing course	HMA	6				1.3	14600	8120	773	523
Binder	**Mix virgin limestone**	4.5	-	-	-	0.78	6930	3077	529	131
	Mix virgin limestone MOD	5	-	-	-	1.23	11259	6444	912.1	235
	Mix Cold PW 7.5% cem	-	15	7.5	5	0.63	5656	4154	2626	2226
	Mix Cold PW 8.5% cem	-	15	8.5	5	0.54	6186	4349	3155	2701
	Mix 74/26	-	4	-	5	0.42	5773	2911	926	326
	Mix 74/26+PW	-	6	-	5	0.24	1809	1012	429	223
Base	HMA	4.85	-	-	-	0.77	14700	8950	960	635

Using the results in the table 28, obtained on the laboratory investigation, it was possible to calculate the fatigue (|DC|) and rutting [$\boldsymbol{\delta p}$] (cm), and consequently, calculate the thickness of the pavements structured and investigated with the different asphalt blends in this study.

Table 29 – Verification of the rutting and fatigue cracking law results.

Mixture Type	Fatigue |DC|	Rutting [$\boldsymbol{\delta p}$] (cm)
Mix virgin limestone	0,89	0,67
Mix virgin limestone MOD	0,86	0,61
Mix Cold PW 7.5% cem	0,90	1,81
Mix Cold PW 8.5% cem	0,92	1,84
Mix 74/26	0,84	1,66
Mix 74/26+PW	0,81	1,59

The mathematical calculation of the verification of the rutting and fatigue cracking law was already included in Sections 5.3.2 and 5.3.3 of this investigation.

6.3.1 Identification of the optimum thickness Pavement layers

The identification of the optimum thickness for a pavement layer is a critical aspect of ensuring the longevity and structural integrity of road infrastructure. Several factors come into play, including average daily traffic, the percentage of vehicles on the road, the annual percentage increase, and the desired service life.

With an average daily traffic of 6,000 vehicles per day, as one of the parameters to structure the layers of the pavement, it is essential to consider the impact of this load on the pavement. The percentage of vehicles on the road, estimated at 1%, represents a baseline for current usage. However, the annual percentage increase of 2% must be factored into account for potential growth in traffic over the pavement's service life.

To determine the optimum thickness, it is necessary to employ sophisticated analysis and modelling techniques. This involves considering the load-bearing capacity of the pavement materials, subgrade strength, and environmental conditions. The goal is to design a pavement that can withstand the anticipated traffic and environmental stresses over its intended service life of 20 years.

Table 30 shows the date of the pavement designed to create and evaluate the thickness of the pavement layers that would be analysed.

Table 30 – Pavement details

Pavement data	
Average daily traffic:	*6000 vehicles per day*
Percentage of vehicles on the road:	*1%*
Annual percentage increase:	*2%*
Service life:	*20 years*

The road pavement in question has a width of 7.2 m and consists of layers: the wearing course, the binder layer, the base layer, and subbase (unbound granular) with respective thicknesses of 2cm, 7cm, and 15cm. The Subbase layer thickness does not interfere on these calculations.

In regions experiencing rapid urbanisation or economic development, the annual percentage increase becomes a crucial parameter. It influences the rate at which the pavement will be subjected to additional stress, requiring a thicker layer to accommodate the growing traffic volume.

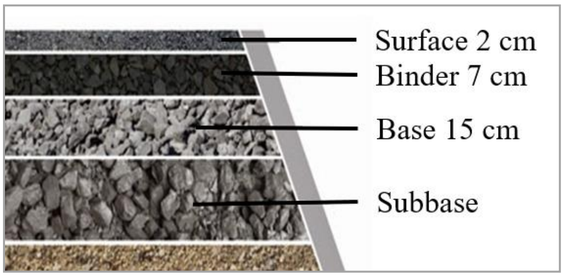


Figure 60 – Pavement thickness layers illustration.

The stress-strain behaviour of six layouts, modelled as an elastic, homogeneous, and isotropic multilayer, was investigated. This investigation considered the data obtained from the laboratory phase for the binder layer as well as the data collected from the previous study [128] for the wearing course and base layer of the HMA. These data are reported in Table 30.

Furthermore, to get these values of thickness for the pavement structure (Figure 58), several times the thickness calculation needed to be done. It means that to calculate the fatigue (|DC|) and rutting $[\boldsymbol{\delta p}]$ (cm) values, the same layer thicknesses for the layers Wearing course, Binder layer, Base layer and subbase were used to calculate the pavement structure. However, how the asphalt mixtures for the Binder Layer were always different, once they are objective of this study, and they were already elucidated in this text, the values of the fatigue (|DC|) must reach the maximum value of 1, according to the Miner Law, and the rutting $[\boldsymbol{\delta p}]$ values must reach the maximum value of 2 cm, according to the Verstraten law (verification of the rutting). These calculations were already elucidated in Section 5.3.4. of this research. It means that when one of these values was not satisfactory, a new pavement structure in relation to its entire thickness must be overthought and recalculated. When the pavement thickness layers were decided, regarding also the pavement details (Table 30), several calculations about the values of fatigue (|DC|) and rutting $[\boldsymbol{\delta p}]$ (cm) must be done. When one of these values was not satisfactory, other pavement thickness layers for every layer must be decided and recalculated until it reaches a satisfactory pavement thickness, in other words, the same pavement thickness that reaches all satisfactory values for fatigue (|DC|) and rutting $[\boldsymbol{\delta p}]$, for all different 6 asphalt blends.

Table 31 – Results of fatigue cracking and rutting resistance evaluation

Layer type	Material	Stiffness [MPa]				Layer thickness [cm]	Fatigue [DC]	Rutting [δp] [cm]
				Pavement structure 1				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix virgin limestone**	**6930**	**3077**	**529**	**131**	**7**	**0,89**	**0,67**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		
				Pavement structure 2				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix virgin limestone MOD**	**11259**	**6444**	**912.1**	**235**	**7**	**0,86**	**0,61**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		
				Pavement structure 3				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix Cold PW 7.5% cem**	**5656**	**4154**	**2626**	**2226**	**7**	**0,90**	**1,81**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		
				Pavement structure 4				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix Cold PW 8.5% cem**	**6186**	**4349**	**3155**	**2701**	**7**	**0,92**	**1,84**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		
				Pavement structure 5				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix 74/26**	**5773**	**2911**	**926**	**326**	**7**	**0,84**	**1,66**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		
				Pavement structure 6				
		10°C	20°C	40°C	60°C			
Wearing course	HMA	14600	8120	773	523	2		
Binder	**Mix 74/26+PW**	**1809**	**1012**	**429**	**223**	**7**	**0,81**	**1,59**
Base	HMA	14700	8950	960	635	15		
Subbase	Unbound Granular		183.95			20		

7 BIM STUDY – DESIGN OF PAVEMENT INFORMATION MODEL

In the first part of the present study, several asphalt mixtures were designed using waste in partial substitution of natural ones, aiming firstly to lower the consumption of exhaustible natural resources and secondly to reduce and save pollutant emissions and the consequent effects on the cause-damage path that affect several environmental problems. In this second part, the aim is to set up an automated, complete, and reversible decision support algorithm based on discriminating variables appropriately integrated with a sufficient level of detail in the specific BIM semantics of the roads, such as the performance of the mixtures, such as those made in the first part of this study.

7.1 Making of the Pavement Information Model

In consideration of the engineered reversible decision support algorithm, a visual programming tool (namely Dynamo, an open source add-in for Autodesk and Revit applications) was leveraged to implement, based on discriminating variables appropriately integrated, a sufficient level of detail in the specific BIM semantics of the roads, such as the performance of the mixtures, by analysing a BIM project.

"Visual Programming Language" represents a concept empowering designers to forge distinctive relationships between digital objects through an intuitive graphical user interface. Departing from the traditional method of coding from the ground up, this paradigm allows users to seamlessly construct unique relationships by connecting pre-packaged nodes. These nodes serve as building blocks, enabling the creation of custom algorithms without the need for extensive coding expertise. The fundamental impact of the Visual Programming Language lies in its ability to democratise computational creativity. Designers can implement sophisticated computational concepts and infuse their projects with targeted calculations. By providing a visual and accessible platform for algorithmic design, it fosters a more inclusive and collaborative environment in digital creation.

Dynamo, a tool in the realm of design and BIM, empowers designers to create workflows, automate intricate processes, and unlock new possibilities beyond the constraints of traditional modelling interfaces. This versatile platform is used for data manipulation, enabling designers to harness a level of control that goes beyond the conventional boundaries of design. One of the remarkable features of Dynamo is its capability to implement relational structures within the design process. Designers can establish connections and dependencies between different elements, fostering a more cohesive and integrated approach to their projects. This relational functionality elevates the precision and efficiency of the design process, allowing for a more sophisticated and interconnected representation of the envisioned structures. Furthermore, Dynamo extends its capabilities to include analytic features, providing designers with tools to assess and evaluate different aspects of their designs. This analytical prowess enables informed decision-making, as designers can gather insights into the performance, feasibility, and other critical aspects of their projects.

An exceptional facet of Dynamo is its ability to seamlessly control Vasari Families and Parameters. This control extends beyond what is typically achievable through standard modelling interfaces. Designers can fine-tune and customise their designs with a level of precision that enhances the overall quality and uniqueness of their creations. Perhaps most notably, Dynamo operates within the framework of a BIM environment, adding an extra layer of significance to its capabilities. This integration ensures that automated processes, data manipulations, relational structures, analytics, and control over Vasari Families and Parameters all take place within the broader context of building information modelling. This not only enhances the synergy between different design elements but also aligns the entire design process with the principles of BIM, promoting consistency, collaboration, and a holistic understanding of the project. From automation to analytics and nuanced control over design elements, Dynamo empowers designers to craft more sophisticated and informed solutions, all within the encompassing embrace of a BIM environment.

At this juncture, the BIM of the road pavement, facilitated through Civil 3D [129], has undergone complete informatization. This process involved a seamless integration of visual scripting and Python scripting, meticulously employed to extract essential information at each stage of the Pavement Management System (PMS). In order to enhance the digital representation of the road pavement, additional alphanumeric data was meticulously assigned to the digital 3D solids. These augmentations encompassed not only the property sets obtained in the laboratory of the parametric pavement section extruded along the road alignment but also supplementary information.

The integration of these data was accomplished through the creation of property sets. These sets are essentially customised collections of parameters linked to a specific object within the BIM, providing a comprehensive repository of relevant details. This dataset includes both characteristics of the materials that structure every asphalt mixture and alphanumeric specifics, seamlessly organised within the property sets. The accessibility of this data has been streamlined for user convenience through the extended data tab, facilitating effortless retrieval and manipulation during various stages of the project lifecycle. This careful combination of visual and Python scripting, along with smart use of property sets, creates a strong and well-documented BIM for the road pavement, which helps the PMS work better and more efficiently. A schematic representation of the Pavement Information Model is illustrated in Figure 60.

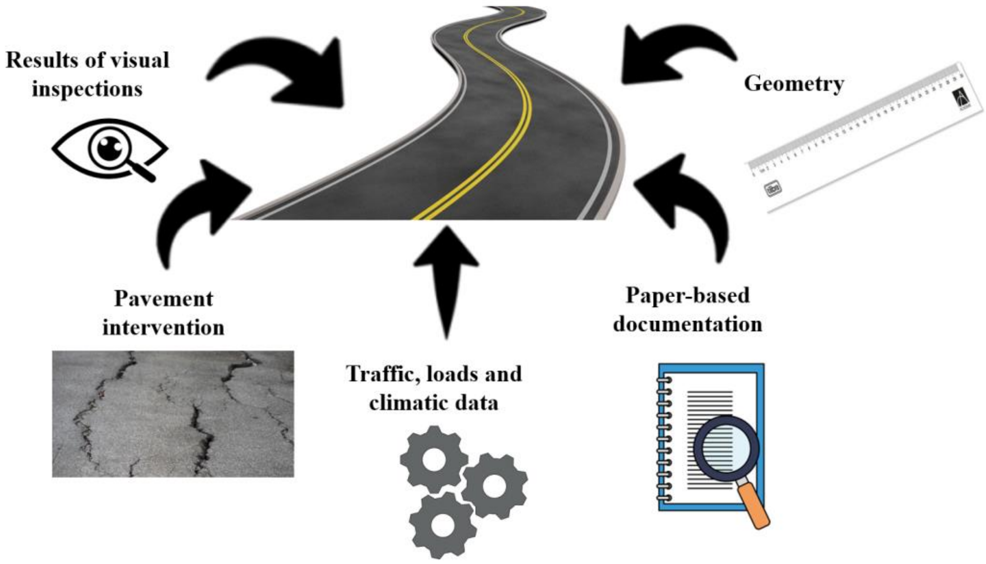


Figure 61 – Scheme of Pavement Information Model

To begin with, a design of the pavement structure chosen to analyse the mixtures was created in Civil3D.

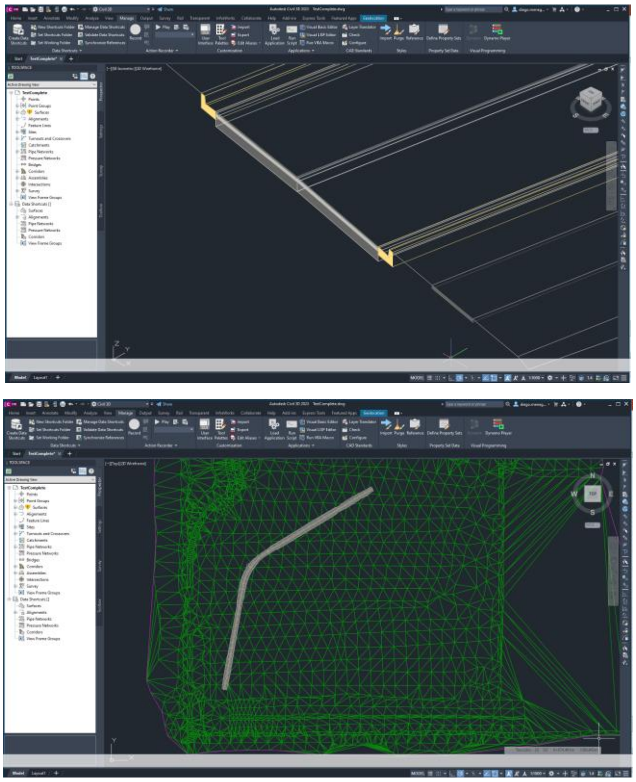


Figure 62 – Pavement Structure in Civil3D.

The properties of the asphalt mixtures obtained in the laboratory must be allocated to the Civil 3D (Figure 62) road project as property sets. Table 32 shows all these properties for every asphalt blend to be assigned.

Table 32 – Asphalt blend properties

Mixture Type	Aggregate size limits	% Bitume	% Bitumen emulsion by weight of aggregates	% Cement by weight of aggregates	% Total Water by weight of aggregates	Fatigue
(1) Mix virgin limestone	Fuso Binder ANAS	4.50%	n.a.	n.a.	n.a.	0,89
(2) Mix vir. limestone MOD	Fuso Binder ANAS	5%	n.a.	n.a.	n.a.	0,86
(3) Mix Cold PW 7.5% cem	Fuso Binder ANAS	n.a.	5%	7.50%	15%	0,90
(4) Mix Cold PW 8.5% cem	Fuso Binder ANAS	n.a.	5%	8.50%	15%	0,92
(5) Mix 74/26+PW	Fuso Binder ANAS	n.a.	5%	2.50%	6%	0,81
(6) Mix 74/26	Fuso Binder ANAS	n.a.	5%	0.50%	4%	0,84

Mixture Type	Rutting	Gmb	Gmm	Air voids@Ndes Values [%]	Air voids@Ndes Distance from HMANB [%]	ITS @10°C @Nmax Values [MPa]
1	0,67	2.703	2.523	3.9	-	2.53
2	0,61	2.703	2.506	3.62	**-7%**	2.74
3	1,81	2.563	-	-	**-100%**	0.45
4	1,84	2.56	-	-	**-100%**	0.86
5	1,59	2.48	-	-	**-**	0.44
6	1,66	2.559	-	-	**-**	1

Mixture Type	ITS @10°C @Nmax Distance from HMANB [%]	ITSdry @25°C Values [MPa]	ITSdry @25°C Distance from HMANB [%]	ITSwet @25°C Values [MPa]	ITSwet @25°C Distance from HMANB [%]	ITSR @25°C Values [MPa]
1	-	0.78	-	0.68	-	87%
2	**8%**	1.23	**57%**	1.31	**91%**	107%
3	**-82%**	0.63	**-20%**	0.54	**-21%**	85%
4	**-66%**	0.54	**-31%**	0.55	**-20%**	101%
5	**-**	0.24	**-**	0.12	**-**	86%
6	**-**	0.42	**-**	0.29	**-**	68%

Mixture Type	ITSR @25°C Distance from HMANB [%]	Stress Value Top Surface(10°C)	Stress Value Bottom Surface (10°C)	Strain Value Top Surface (10°C)	Strain Value Bottom Surface (10°C)	Stress Value Top Surface (20°C)
1	-	0.8055	0.5988	45.9	49.42	0.8055
2	**22%**	0.7981	0.5653	**17.19**	31.31	***0.7958***
3	**-2%**	0.8094	0.6121	63.44	61.01	0.801
4	**16%**	0.8076	0.601	55.19	55.52	0.8003
5	**-**	0.8399	0.6768	17.19	**31.31**	0.832
6	**-**	0.8598	0.6865	61.59	59.77	0.843

Mixture Type	Stress Value Bottom Surface (20°C)	Strain Value Top Surface (20°C)	Strain Value Bottom Surface (20°C)	Stress Value Top Surface (40°C)	Stress Value Bottom Surface (40°C)	Strain Value Top Surface (40°C)
1	0.6044	113.7	116.4	0.854	0.696	1044
2	***0.5534***	25.91	60.78	0.839	0.6764	567.2
3	0.5845	69.03	87.42	0.8103	0.6158	149.9
4	0.5813	63.27	83.77	0.8066	0.6038	114.6
5	0.6707	495.1	387.4	0.8579	0.7007	1310
6	0.6534	124.1	123.1	0.8621	0.7007	556.6

Mixture Type	Strain Value Bottom Surface (40°C)	Stress Value Top Surface (60°C)	Stress Value Bottom Surface (60°C)	Strain Value Top Surface (60°C)	Strain Value Bottom Surface (60°C)
1	785.7	**0.8611**	**0.7112**	**4383**	**3318**
2	435.3	0.8503	0.7005	2353	1802
3	137.2	**0.7984**	0.5742	127	178.2
4	113.6	0.7963	0.5604	86.66	153.1
5	980.9	0.8516	0.702	2491	1905
6	427.6	0.8357	0.754	1641	1269

Mixture Type	Media TOP STRESS	Media BOTTOM STRESS	Media TOP STRAIN	Media BOTTOM STRAIN
1	0.831525	0.6526	1396.65	1067.38
2	0.8208	0.6239	740.825	582.3475
3	0.804775	0.59665	102.3425	115.9575
4	0.8027	0.586625	79.93	101.4975
5	0.84535	0.68755	1078.3225	826.1525
6	0.85015	0.69865	595.8225	469.8675

Each property can be classified as either an input property or an output property, delineating their roles in the BIM process.

An *input property* is one whose value is directly assigned from the data template imported by the user. In this context, users input specific data values that serve as foundational information for the pavement BIM. These properties do not necessitate additional calculations since their values are provided explicitly, forming the basis for subsequent analyses and simulations.

On the other hand, an *output property* takes on a different role within the pavement BIM landscape. Unlike input properties, the value of an output property is not directly specified by the user. Instead, it is derived as a result of the intricate calculations performed by analytic tools integrated into the BIM system. These tools are designed to process and analyse the input properties, applying algorithms and methodologies to generate meaningful output values. Output properties encapsulate the insights, predictions, or assessments produced by the analytical tools, offering a comprehensive view of the pavement's performance and characteristics.

Into the BIM environment were implemented the following property sets (Figure 63).

- PropSet_BinderLayer: The property set includes the current features of the asphalt pavement layer, such as the asphalt mixture identifiers, and all the necessary information that should be uploaded in the BIM environment.
- PropSet_Stress_Strain_BinderLayer(Mix): Values of stress and stain calculated in the Bisar software in the different temperatures representing the different seasons to evaluate the LCA.
- PropSet_Maintenance_List: a list of maintenance (interventions) into the Binder layer according to the value of stress and strain. This list is composed of 23 distinct pavement distresses.

Due to the time-consuming nature and potential for errors in manually creating property sets, the command block inside the Dynamo programming interface was utilised to automate the process of creating and uploading parameters into the BIM environment.

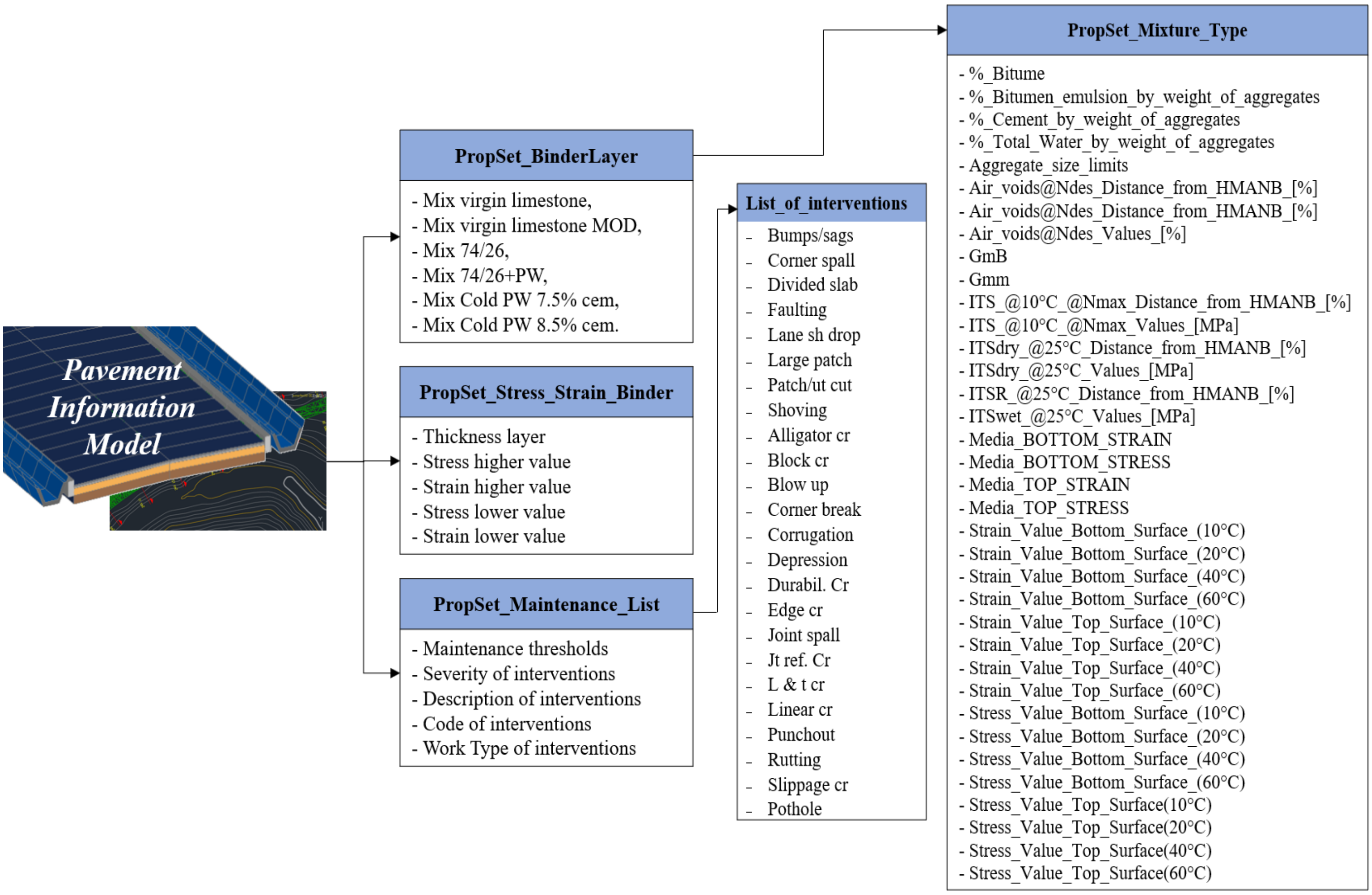


Figure 63 – Arrangement of the pavement information model and principal properties add in each property set.

7.2 Making of the analytic BIM-based tools

In terms of integrating BIM, PMS, and life cycle analyses, I utilised Dynamo, an extension of Civil3D that establishes a dynamic connection between the BIM environment and an open-source visual programming environment. This allowed me to enhance the pavement BIM by incorporating additional analytic tools that perform calculations and automatically update the object properties with the calculated results.

Figure 64 presents a schematic representation of the analytic tools that have been designed.

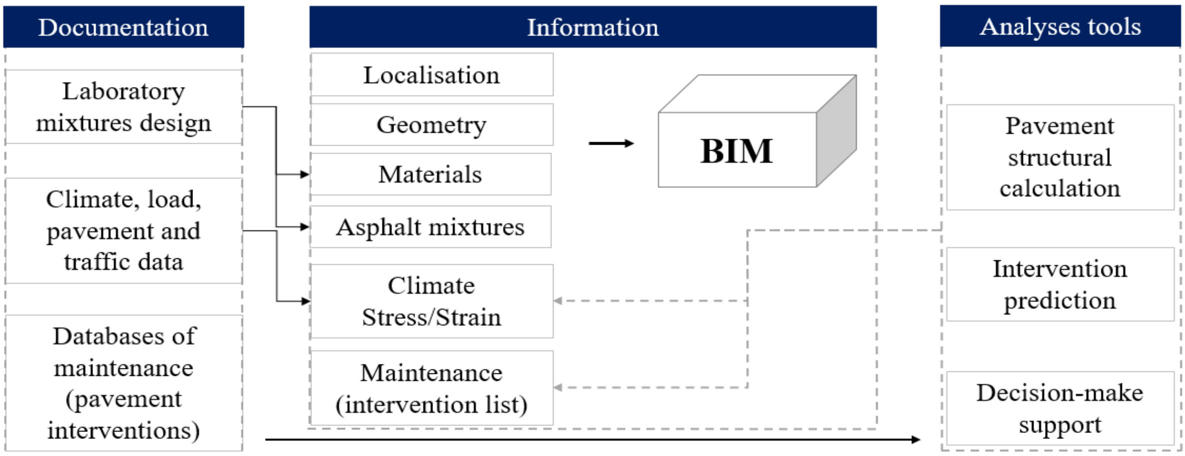


Figure 64 – General diagram of BIM analytic tool components and data exchange pathway.

The analytic tools (which are Dynamo files with .dyn extension) must be executed in series to produce the desired decision-making result and are presented on the section 8.5.

8 RESULTS

In considering the application of this study, it was sectioned into two major areas. The first significant part of this study was that the described methodology was implemented to design six asphalt blends made with marginal materials, with the goal of getting the most out of these waste materials in the mix composition. The second important part was to design a fully informatized BIM of road pavement for which a series of previously collected data about the mechanical behaviour of the asphalt mixtures was available. To begin with, the basic model was implemented with all the geometric information about the thicknesses of the asphalt layers, enabling the automation of materials' volumes and surface area calculations. In the present work, the pavement geometry was reconstructed based on the project documentation, i.e., the coordinates of the road axis, the width of the transverse sections, the thickness of the pavement layers, etc.

Subsequent to the traditional modelling phase, the pavement BIM was enhanced with various analysis tools using Dynamo, a visual programming tool integrated with Autodesk calculation codes. These tools were developed using a combination of visual programming language and Python scripting.

The next sections essentially demonstrate the outcomes reached. Due to the fact that these results of the first part of this study (at the laboratory) have already been discussed in the preceding sections in detail, I will now just emphasise the most important of them. In the second part of this section, it demonstrates the results achieved in the laboratory by importing the information them into the BIM environment and running the BIM analysis tools.

8.1 Design of asphalt blends

One of the objectives of this study was to evaluate the possibility of using more sustainable asphalt pavements for roads that maximise the recycling and re-use of potential waste by incorporating the maximum amount of it into the design of a bituminous mixture. In this part of the study, in particular, the innovation is represented by the incorporation of plastic waste, RAP, and cold technology with low workability temperatures (<60°C).

8.1.1 Water and cement content

In the section 6.1.2 was reported the results of the optimum content in respect to the water and cement into the asphalt mixtures. We can see at the Table 12 the results obtained in the laboratory. Making a comparison with the results between the asphalt mixtures Mix 74/26 and Mix 74/26+PW, it is the easily comprehension that both mixtures, besides the almost the same percentage ant materials composed, the different of the percent of water was lower in the mixture Mix 74/26, 0.5%; and in the mixture Mix 74/26+PW it was 6%. On the other hand, the percentage of cement in the Mix 74/26 was 4%, however in the Mix 74/26+PW it was 2.5%. So, it means that the mixture without PW needed more cement to have a great mechanical behaviour in respect to the mix with PW.

8.1.2 Bituminous emulsion content

In this section, as we saw in Table 13 that all mixtures that were studied until the end of this research contained 5% bituminous emulsion. Due to the fact that these mixtures had almost the same aggregate grading curve, the percentage of the bituminous emulsion was also the same. The bituminous emulsion ensures enhanced dispersion and wider coverage on both the fine and coarse fractions. Emulsion allows for the creation of mixes that exhibit highly comparable mechanical and performance properties over extended periods of time.

8.1 Indirect Tensile Strength (ITS) Test

Mix virgin limestone and Mix virgin limestone MOD have ITS dry 25°C values of 0.78 MPa and 1.23 MPa, respectively. ITS values for both mixtures exceeded the standard values (0.20 MPa and 0.45 MPa). The asphalt blend Mix 30/70 limestone has 73% more ITS than the maximum. Additionally, the value of Mix virgin limestone MOD is 1.23 MPa, 173.33% higher than the maximum ITS value in dry conditions at 25°C.

Mix 30/70 limestone and Mix 30/64/6 PW limestone MOD also performed well in the ITS test. Mix 30/70 limestone had ITS dry 25°C at 0.32 MPa, and Mix 30/64/6 PW limestone MOD had 0.38 MPa. Mix 30/64/6 PW limestone MOD has a higher value than Mix 30/70 limestone. Even if the mix contains PW (material that affects mechanical behaviour), the modified binder likely mitigated this effect.

Mix 74/26+PW has an ITS result of 0.24 MPa, while Mix 74/26 is 0.42 MPa, which is between ANAS's ITS values. Both asphalt blends meet the ITS values according to ANAS. We can also see that the amount of PW changed the mechanical behaviour of the mixture. Mix 74/26+PW's mechanical behaviour decreases by 57%, but it still meets ANAS ITS mechanical behaviour standards.

In comparison to the ANAS range, Mix Cold PW 7.5% cem and 8.5% cem asphalt blends have higher ITS values. ANAS says the Cold PW 7.5% cem mixture has a 40% higher ITS value than the maximum. However, Mix Cold PW 8.5% cem has a lower ITS value than the other mixture but a higher 20% ITS value, which matches ANAS optimal ITS values.

8.3 Indirect Tensile Stiffness Modulus (ITSM) test results

Chard 2 shows linear mixture growth. However, mixtures containing PW (Mix 74/26+PW, Mix Cold PW 7.5% cem, and Mix Cold PW 8.5%) also increase linearly, with main values more similar from 10°C to 60°C. The ITSM values of Mix virgin limestone MOD at 10°C, 20°C, 40°C, and 60°C are 38.5%, 52.2%, 42.1%, and 44.2% higher than Mix virgin limestone, where only the binder is different. The ITSM value of the Mix virgin limestone MOD is 55.75% higher than the Mix virgin limestone. Another PW mixture comparison is Mix 74/26 and Mix 74/26+PW. All ITSM main values from the mixture without PW are higher, indicating that PW affects blend mechanical behaviour. ITSM values for Mix 74/26 at 10°C, 20°C, 40°C, and 60°C are 31.33%, 34.76%, 46.28%, and 68.3%, with a main value of 45.27% higher than Mix 74/26+PW. Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem have similar results, but a linear increase, and the higher PW mixture has better results. ITSM values for Mix Cold PW 8.5% at 10°C, 20°C, 40°C, and 60°C are 8.55%, 4.5%, 16.76%, and 17.58%, respectively, 11.85% higher than Mix Cold PW 7.5%.

All ITSM results at 10°C [MPa] and 20°C [MPa] for Mix virgin limestone, Mix 74/26, Mix Cold PW 7.5% cem, and Mix Cold PW 8.5% cem are similar. It also means that mixtures with percentages of RAP and/or RAP+PW behaved similarly to control mixtures. It also shows that marginal materials in asphalt mixtures performed well compared to virgin aggregates.

8.4 Designs and verification of the best sustainable flexible pavement solutions Bisar results

The analysis of stress results obtained from both software tools revealed striking similarities in the values generated. On the other hand, the same did not happen with the strain values. After careful consideration, it was determined that the Bisar software's outcomes would be utilized for further discussions and conclusions. This decision was primarily based on the widespread recognition of the Bisar software on a global scale.

The similarity in stress values between the two software platforms suggests a level of consistency and reliability in their predictive capabilities. However, the preference for Bisar stems not only from the congruence in results but also from its established reputation within the international engineering community. This widespread recognition and acceptance of Bisar in various regions contributes to its perceived reliability in evaluating complex material compositions, such as those found in our mixture.

One key advantage of opting for Bisar is its capacity to discern and account for any typology of materials within the composition of the mixture; in this study, the marginal materials. This capability is crucial, as it implies heightened sensitivity and accuracy in assessing the mechanical behaviour of the mixtures. The inclusion of marginal materials poses a significant challenge in predicting the stress distribution accurately, and the preference for Bisar in this context underscores its capability to address such intricacies.

8.4.1 Fatigue cracking and rutting law

The present study investigated, as well, the mechanical performance of different asphalt mixes incorporating RAP and plastic waste. It means that performance indicators under consideration include, as well, fatigue cracking and rutting [$\boldsymbol{\delta p}$], crucial factors in assessing the durability and structural integrity of asphalt pavements.

About the fatigue |DC| and the rutting [$\boldsymbol{\delta p}$] results from the asphalt mixture Mix virgin limestone, it showed a fatigue cracking |DC| of 0.89 and a rutting [$\boldsymbol{\delta p}$] of 0.67. It is important to mention that the addition of RAP along with limestone seems to marginally reduce fatigue cracking |DC| when compared to traditional asphalt mixtures. Nevertheless, the rutting [$\boldsymbol{\delta p}$] of this combination remains within acceptable parameters, indicating a well-balanced performance. On the other hand, the Mix virgin limestone MOD demonstrated enhanced mechanical properties. With a fatigue cracking |DC| of 0.86 and a rutting [$\boldsymbol{\delta p}$] of 0.61, the incorporation of the modified binder had to positively impact the performance of the asphalt mix. This result suggests that the addition of modified binder contributes to improving the fatigue |DC| and rutting [$\boldsymbol{\delta p}$] resistance of asphalt pavements, possibly due to the fact that of the properties of this modified binder.

Analysing the results from the asphalt blends Mix Cold PW 7.5% cem and Mix Cold PW 8.5% cem, these were designed to investigate the influence of plastic waste and cement content on asphalt performance at lower temperatures. Both mixes exhibited comparable fatigue cracking |DC| values of 0.90 and 0.92, respectively. However, the rutting [$\boldsymbol{\delta p}$] resistance increased from 1.81 to 1.84 as the cement content increased from 7.5% to 8.5%. This suggests that higher cement content influences rutting [$\boldsymbol{\delta p}$] resistance, potentially due to binder-aggregate adhesion at lower temperatures.

The Mix 74/26, structured with a higher percentage of RAP, displayed a fatigue cracking |DC| of 0.84 and a rutting [$\boldsymbol{\delta p}$] of 1.66. This mix, while showing a reduction in fatigue cracking |DC| compared to mixes with lower RAP content, exhibited higher rutting [$\boldsymbol{\delta p}$] resistance. The trade-off between fatigue |DC| and rutting [$\boldsymbol{\delta p}$] resistance should be carefully considered when selecting the appropriate mix for specific applications. Furthermore, the Mix 74/26+PW presented a fatigue cracking |DC| of 0.81 and a rutting [$\boldsymbol{\delta p}$] of 1.59. The addition of plastic waste modifiers in this mix appears to contribute to improved rutting [$\boldsymbol{\delta p}$] resistance while slightly compromising fatigue cracking |DC|.

8.5 BIM - pavement information models

In the attempts I made before reaching the final solution, the attempt presented below was of paramount importance in relation to reaching the final solution. The Design of the pavement model (geometry) to draft a PMS was designed on Dynamo. This was divided in: (I) Path – parameter for pavement design, (II) Points or corners, (III) Links or Edges, and (IV) Pavement structure model.

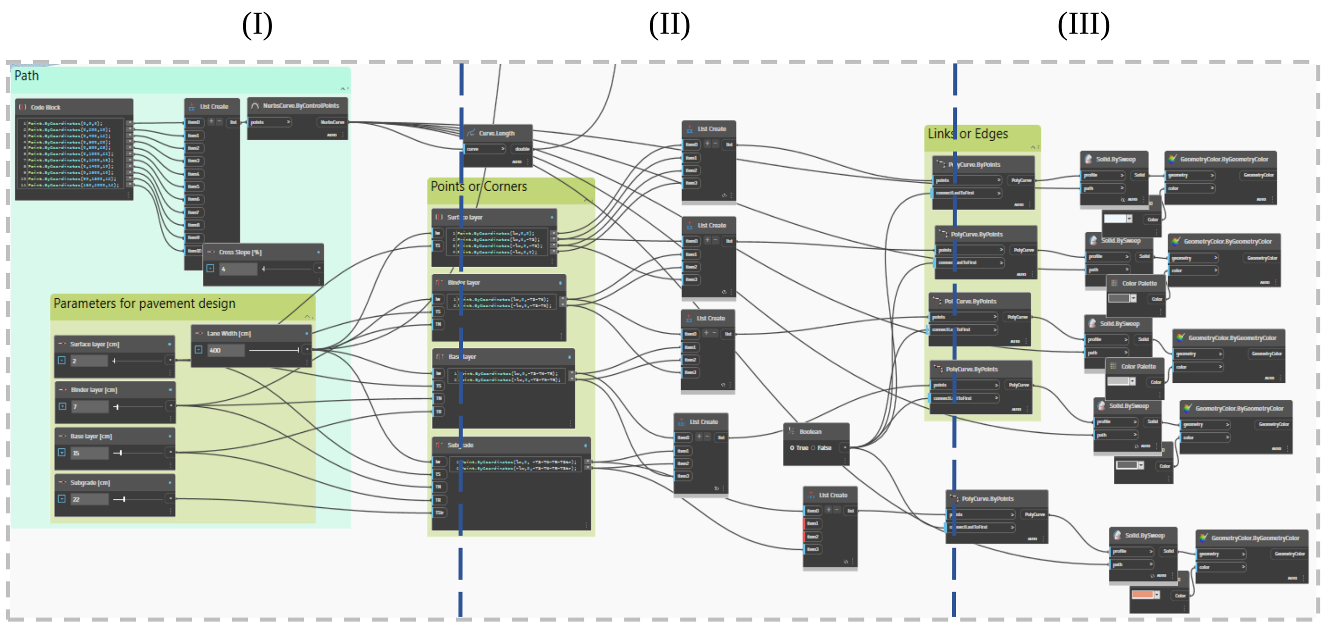


Figure 65 – Schematic overview of the pavement model.

(I) Path – parameter for pavement design:

These nodes are used to produce the geometry in Dynamo of the road layout through a NurbsCurve, a mathematically defined curve that interpolates several points defined from their coordinates (x,y,z) (easting, northing, elevation). In this part, there are grouped nodes that allow the user to enter as input the geometric data of the road, i.e., the thickness in cm of the individual layers, from wear to the foundation, and the width of the lane.

(II) Points or corners:

This group of nodes is used to recreate the geometry of road layers from user data inputs. In fact, they create points that represent the vertices of the rectangular shapes that represent the sectional views.

(III) Links or Edges:

Next, these nodes join together the points created, the vertices of which were created before, to create the links, or edges, according to closed polylines. These polylines are then extruded along the previously defined curve (the Nurbs) with the "Sweep" method. This creates the solid geometries with which material information and tests can be associated.

(IV) Pavement structure model:

Figures 66 and 67 show the result of the pavement structure model solid on

Dynamo.

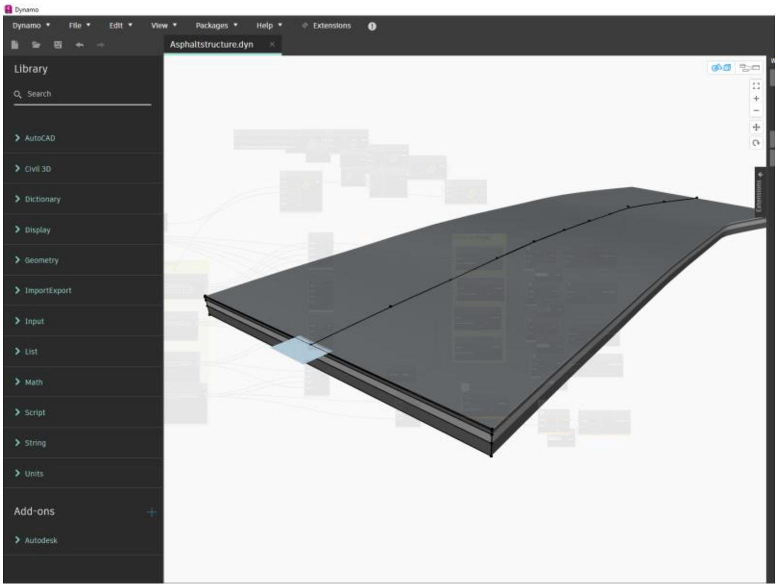


Figure 66 – View (a) of pavement structure model solid on Dynamo.

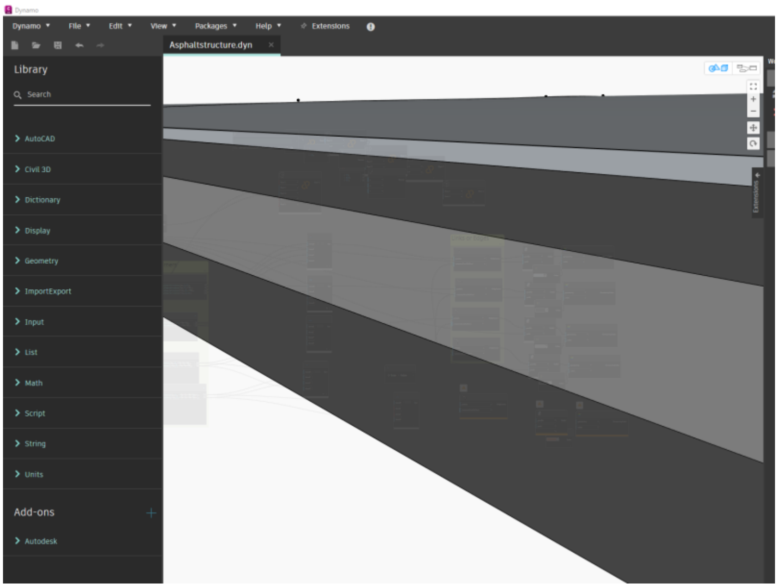


Figure 67 – View (B) of pavement structure model solid on Dynamo

8.5.1 Decision support algorithm

Viewing property sets from the user interface in Civil 3D allows users to effortlessly access and analyse detailed information associated with design elements, providing a comprehensive overview of key attributes, and facilitating efficient decision-making in the design process. Figure 68 shows the result of the viewing property sets (the properties from Table 32) from the user interface in Civil 3D.

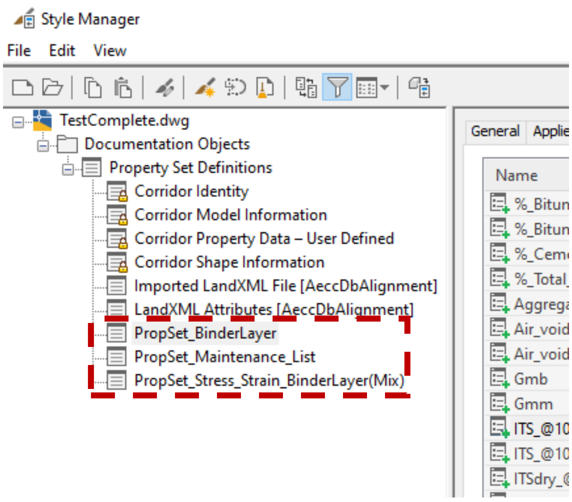
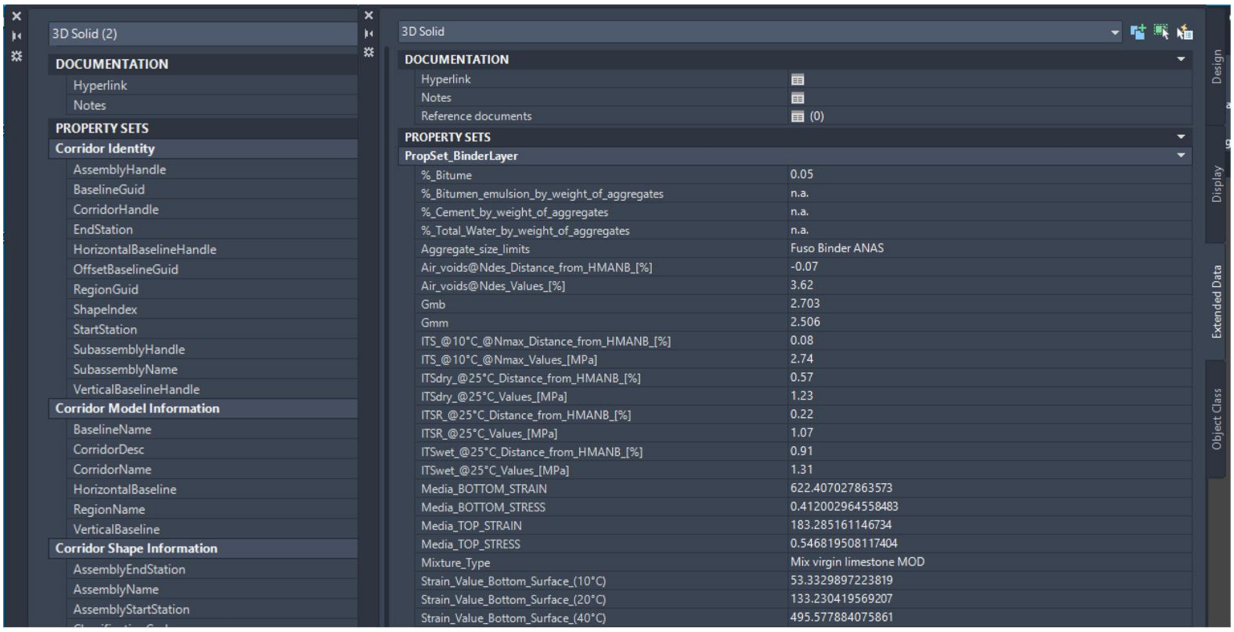


Figure 68 – Viewing property sets in Civil3D

After running the analysis tool, the user can view the updated property sets with the results of the algorithm in the property panel of the item of interest. Figures 69 and 70 illustrate it.



(a) (b)

Figure 69 – Before running the script (a); after running the script for the Binder layer properties (b).

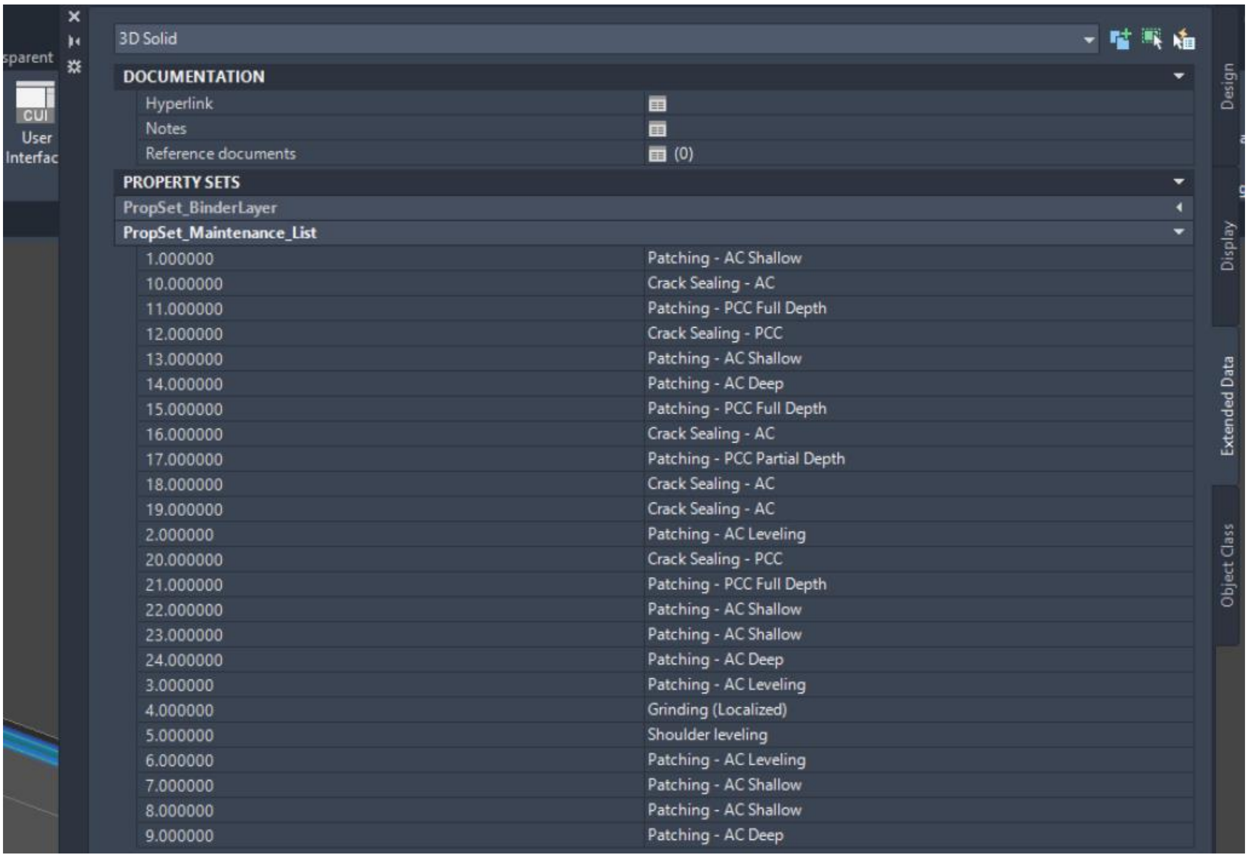


Figure 70 – After running the script for Maintenance list.

The analytic tools, which are Dynamo files with a .dyn extension, need to be executed sequentially (in series) in order to get the appropriate decision-making outcome. The tools are listed below:

- In the User Input, for analysing the pavement structure, the user is required to input specific details. Before anything else, the user must provide the Civil3D layer name for the solids embodying the binder layer. Next, specify the binder mixture type for accurate characterization. Additionally, an upload of three essential Excel files must be done: one containing parameter thresholds, another with parameter values, and the last with material properties. These files collectively enable comprehensive evaluation and modelling. The Civil3D layer name ensures precise identification, while the binder mixture type establishes material composition. The Excel files, housing thresholds, values, and properties, facilitate a thorough analysis of the pavement structure's wearing course for optimal performance and longevity. The Solids Import nodes facilitate the incorporation of solids from the present document, categorized by Civil3D layer. Simultaneously, the data extraction from Excel file nodes handles the extraction of data related to property sets from an Excel file. Upon selection, the data is imported as a set of lists. To enhance readability, operations such as transpose, clean, deconstruct, and chop have been employed on these lists. The Data node displays Property Sets Names, Properties Names, and Properties Values, offering a comprehensive overview of the organised data structure.

- The PMS tool gathers information on the Threshold Selection, in the context of binder layer analysis, which is the primary focus of this algorithmic module, utilising an Excel file. Once a binder mixture type is specified, the algorithm automatically identifies and sets the optimal thresholds for both strain and stress parameters. Leveraging the provided Excel data, the module facilitates precise data selection aligned with the chosen mixture type. The outcome is a streamlined process for determining the critical stress and strain values crucial for comprehensive material assessment.
- The maintenance status (LCA) of the binder layer is indicated by stress and strain values in its top and bottom regions. A green layer signals no maintenance is required, while high values turn it red. In red status, a maintenance list displays necessary pavement tasks. This colour-coded system streamlines the understanding of which maintenance must be done, ensuring timely interventions based on real-time stress and strain assessments in the binder layer.

Figures 71, 72 and 73 illustrate, accordingly, the visual programming scripts for analysing the pavement structure, PMS, and LCA tools within the Dynamo programming environment.

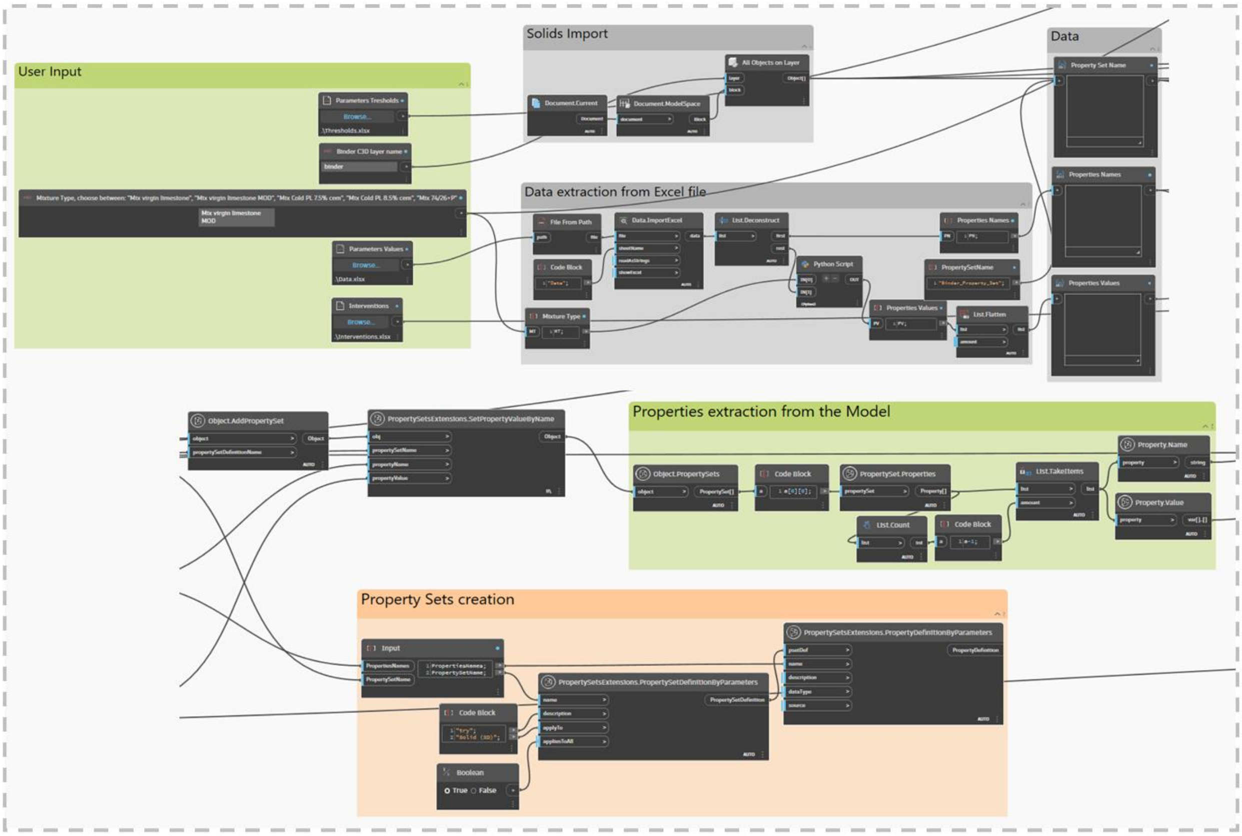


Figure 71 – Illustration of the visual programming code for analysing the pavement structure calculation as it shows up in the Dynamo programming setting.

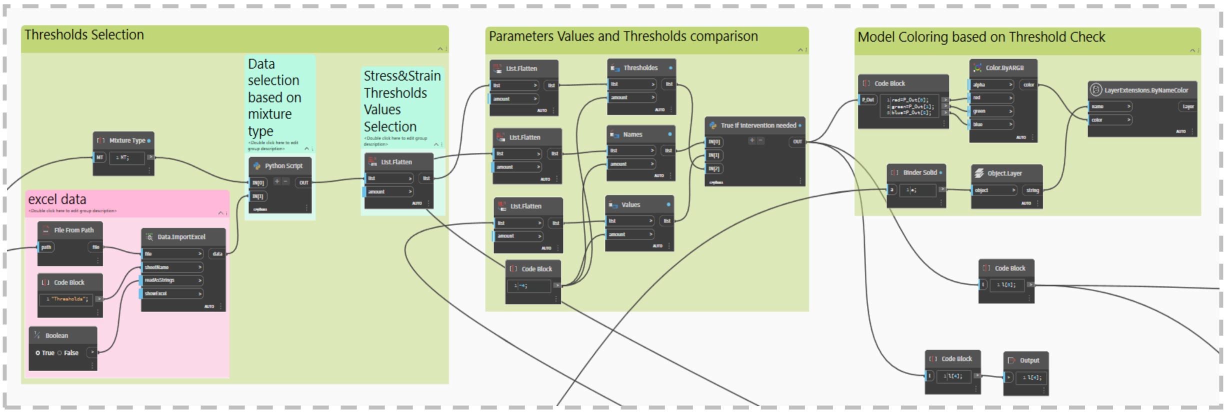


Figure 72 – Illustration of the visual programming code for PMS calculation as it shows up in the Dynamo programming setting.

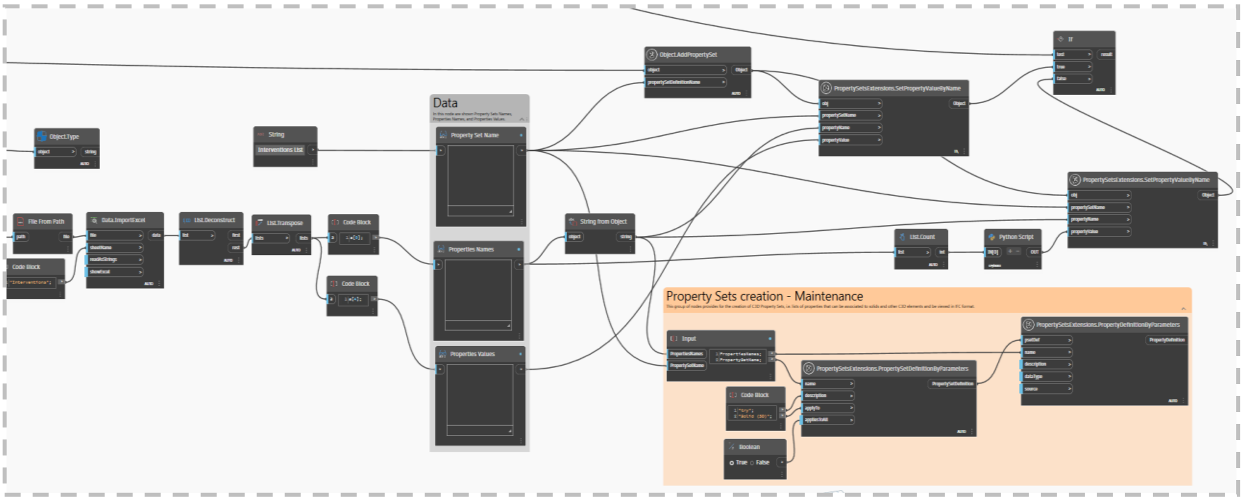


Figure 73 – Illustration of the visual programming code for LCA (maintenance) calculation as it shows up in the Dynamo programming setting.

Table 33 shows the list of interventions, indicating the severity of each pathology on the pavement. Using the Python script and the results of stress and strain, having as parameters the values of maximum and low of them (Table 32), two solutions are able to realise whether or not maintenance in the Binde Layer is required:

(I): A message on the Dynamo display appears with the list of interventions. In this list, when there is no necessity for maintenance, the message next to the specific pathology is "no need for intervention." (Figure 74),

(II): Together on the situation (I), when some maintenance must be done, the Binder Layer represented on the pavement structure on Civil3D becomes red, or when no maintenance must be done, the layer becomes green. Figures 75 and 76 one of these situations, when it is green.

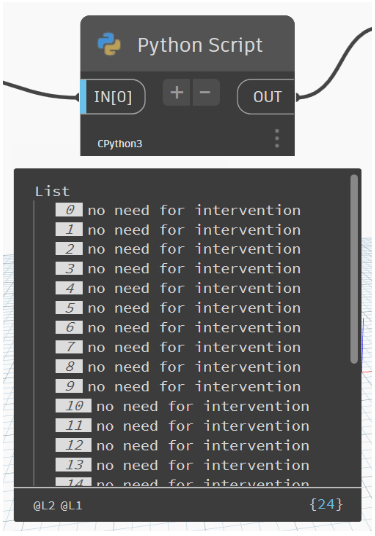


Figure 74 – Dynamo display when there is "no need for intervention".

Table 33 – List of interventions on the Dynamo programming setting

Severity	Description	Code	Work Type
High	*BUMPS/SAGS*	*PA-AS*	Patching - AC Shallow
High	*CORNER SPALL*	*PA-AL*	Patching - AC Leveling
High	*DIVIDED SLAB*	*PA-AL*	Patching - AC Leveling
High	*FAULTING*	*GR-PP*	Grinding (Localized)
High	*LANE SH DROP*	*SH-LE*	Shoulder leveling
High	*LARGE PATCH*	*PA-AL*	Patching - AC Leveling
High	*PATCH/UT CUT*	*PA-AS*	Patching - AC Shallow
High	*SHOVING*	*PA-AS*	Patching - AC Shallow
Medium	*ALLIGATOR CR*	*PA-AD*	Patching - AC Deep
Medium	*BLOCK CR*	*CS-AC*	Crack Sealing - AC
Medium	*BLOW UP*	*PA-PF*	Patching - PCC Full Depth
Medium	*CORNER BREAK*	*CS-PC*	Crack Sealing - PCC
Medium	*CORRUGATION*	*PA-AS*	Patching - AC Shallow
Medium	*DEPRESSION*	*PA-AD*	Patching - AC Deep
Medium	*DURABIL. CR*	*PA-PF*	Patching - PCC Full Depth
Medium	*EDGE CR*	*CS-AC*	Crack Sealing - AC
Medium	*JOINT SPALL*	*PA-PP*	Patching - PCC Partial Depth
Medium	*JT REF. CR*	*CS-AC*	Crack Sealing - AC
Medium	*L & T CR*	*CS-AC*	Crack Sealing - AC
Medium	*LINEAR CR*	*CS-PC*	Crack Sealing - PCC
Medium	*PUNCHOUT*	*PA-PF*	Patching - PCC Full Depth
Medium	*RUTTING*	*PA-AS*	Patching - AC Shallow
Medium	*SLIPPAGE CR*	*PA-AS*	Patching - AC Shallow
Low	*POTHOLE*	*PA-AD*	Patching - AC Deep

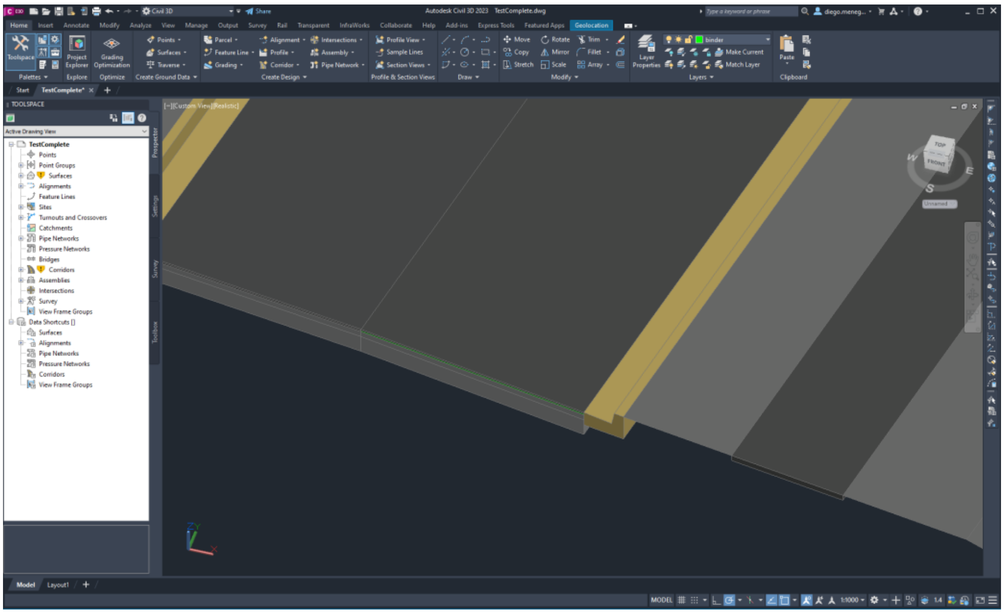


Figure 75 – Entire pavement structure at Civil3D, and in green the Binder Layer when there is "no need for intervention".

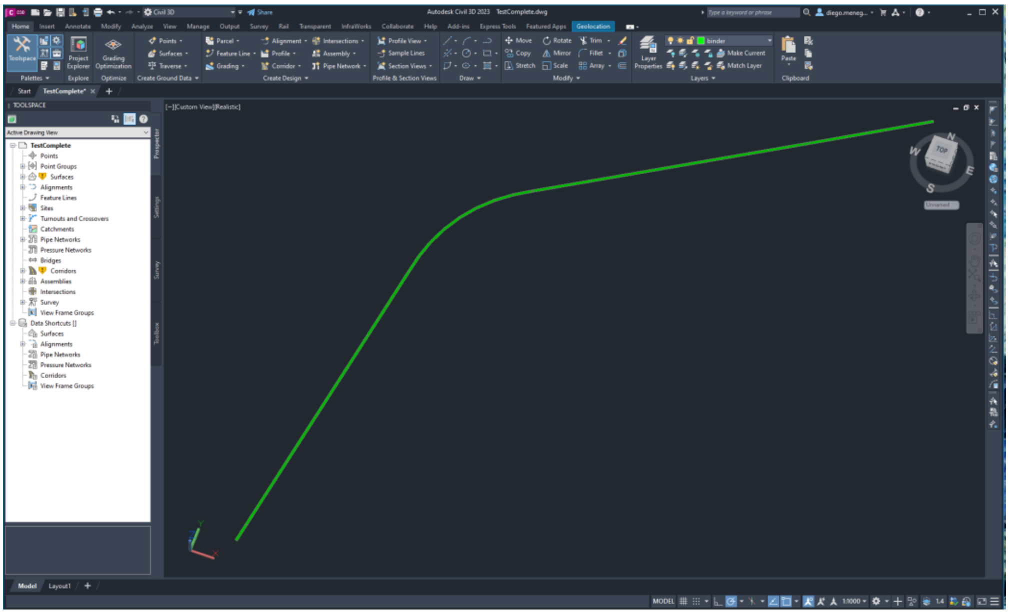


Figure 76 – Only the entire Binder Layer when there is "no need for intervention".

9 CONCLUSIONS

The multifaceted nature of the present economic and social system benefits from a linear economy model even nowadays since companies, which are not highly responsive to financial incentives, operate on their own, rendering it challenging for them to establish a moral and economically sustainable system of recovery and recycling waste. It is possible to promise these requirements with the introduction of the Minimum Environmental Criteria (MEC) required by the implementation of Art. 18. This article is about the 'Application of minimum environmental criteria in public procurement of supplies and the provision of services' structured on Legislative Decree No. 6/2016. on 'Environmental provisions to promote green economy measures and contain the excessive use of natural resources', along with Article 34 of the 'Energy and environmental sustainability criteria' of Legislative Decree No. 50/2016 of the 'Procurement Code'.

Regarding the principles of life cycle thought and sustainability getting increasingly essential in the sector of asphalt pavements, engineers are recognising a rising necessity for providing environmentally friendly roads, as examined via LCA. Concomitantly, BIM tools can automate and simplify the handling of intricate data in infrastructure construction and converge towards sustainable decision-making strategies. Nevertheless, assessing sustainability is a challenging process and currently lacks an effective strategy for integrating sustainable aspects into the asphalt pavement engineering decision-making method.

Thus, one of the major objectives was to investigate an optimal solution for making cold mixtures with RAP and PW, with the goal of saving natural resources without negatively affecting performance. The research was designed to investigate — and indeed evaluate — responses that might achieve the same mechanical performance as conventional limestone mixtures. By using RAP for substituting a significant percentage of the limestone aggregates and PW as the filler type, keeping the weight ratios constant, and different percentages of cement, it was found that:

- Regarding the results of the ITS test results, the asphalt blend Mix Cold PW 7.5% cem had the best results in relation to the mixtures structured with RAP and PW. This mixture reached an ITS value 40% higher than the maximum specified by ANAS, indicating its superior mechanical performance. The incorporation of RAP and PW in this mixture is significant due to the fact that it allows for less use of natural aggregates and more use of marginal materials while still meeting the mechanical behaviour range specified by ANAS. Therefore, based on the ITS test results and conformity with ANAS standards, the most promising asphalt blend with marginal materials by the ITS test is the Mix Cold PW 7.5% cem.
- The optimal asphalt mixture, according to the ITSM results, is Mix Cold PW 8.5% cem, which exhibits superior performance across various temperatures. When considering the best mixture with plastic waste, Mix Cold PW 8.5% cem also emerges as the most promising option, showcasing improved mechanical behaviour compared to Mix Cold PW 7.5% cem. Furthermore, the use of RAP and PW in the mixtures demonstrates comparable mechanical behaviour to the traditional mixtures (control mixtures), indicating their potential for sustainable asphalt solutions.
- The results about the optimal performance in relation to fatigue |DC| and rutting [$\boldsymbol{\delta p}$] were that the asphalt mixture is Mix virgin limestone MOD, which demonstrated enhanced mechanical properties with a fatigue cracking |DC| of 0.86 and a rutting [$\boldsymbol{\delta p}$] of 0.61. The incorporation of the modified binder positively impacted the performance of the asphalt mix, improving fatigue |DC| and rutting [$\boldsymbol{\delta p}$] resistance. When considering the best mixture with RAP and PW, Mix Cold PW 8.5% cem emerges as the most promising option, exhibiting comparable fatigue cracking |DC| values and increased rutting [$\boldsymbol{\delta p}$] resistance with higher cement content. The incorporation of the has made the difference of the mechanical behaviour on this asphalt blend.

The asphalt blend Mix Cold PW 7.5% cem stands out as the most promising option, excelling in the ITS test with superior mechanical performance and conforming to ANAS standards. About optimum performance across temperatures and sustainable use of plastic waste, Mix Cold PW 8.5% cem emerges as the top choice. Additionally, the Mix virgin limestone MOD demonstrates enhanced fatigue and rutting resistance. The trade-off among all the results obtained should be carefully considered when selecting the appropriate asphalt blend for specific applications. On a final note, all of these research results demonstrate the potential of blending RAP and PW into sustainable asphalt solutions while maintaining the integrity of their mechanical performance. In other words, the use RAP and PW in asphalt mixtures make them have a mechanical behaviour comparable to traditional mixtures. It reduces reliance on natural aggregates, promoting sustainability by utilizing more marginal materials effectively.

With relation to algorithm designed is of paramount importance in terms of enriching the informative content of the model for use in the BIM environment, using this algorithm as an analysis tool. For the creation of the same, a combination was run between the visual programming language and the Python programming language.

The use of this methodology and the applications developed in this work can benefit decision-makers and road managers in their projects, since this work can impact the road industry. The findings of the study indicate a needed innovation to meet the future requirements of both the local legislative systems with regard to the mandatory implementation of BIM in public solicitation processes and the use of MEC to promote sustainability throughout the conception, design, and operation phases of the life cycle of an infrastructure.

The second the objective of the study aimed at the elaboration of this BIM-based methodology related to the evaluation of the asphalt mixtures developed in the first part of this research, the regarding the management of the pavement data and the drafting of the pavement maintenance the interventions the involving a library of the solutions. The main objective was to create a methodological the structure implemented in a BIM the environment for the automated analysis of the values of the stress and the strain of the road pavement in the Binder Layer through the specific condition the indicators, namely the ITS, the ITSM, the cumulated fatigue cracking damage, the rutting depth, and other important results obtained in laboratory. The BIM analysis of tool allowed for the drawing of the following the conclusions:

- All typologies of asphaltic mixtures (hot, cold, and warm) can be used in this algorithm, from the uploading of the database of these mixtures, thus performing the calculations.

- A database of pavement structures, such as the mechanical behaviour of asphaltic mixtures (laboratory results), average daily traffic, percentage of vehicles on the road, annual percentage increase, and service life, can be loaded into Dynamo, in excel format by the designer. Thus, it can evaluate which intervention is calculated by the algorithm, thus assisting the designer in decision-making.
- The results of stress and strain were used as the main basis for the calculations of the possible interventions required. From a Python script in the algorithm, the values were placed (these can be changed by the designer within the algorithm) in relation to the values obtained preliminary to the construction of the pavement structure (thicknesses).
- Exploration of the potential of Infrastructure BIM software for the creation of an informative model of a road pavement supported by analysis tools for predictive maintenance.
- Considering potential impacts, decision-makers and road managing bodies can gain from utilizing the developed methodology to meet future requirements for Building Information Modelling and Minimum Environmental Criteria.

As a road engineer, it is known to be good practice, and it is necessary, before any decision, to carry out a field visit on site to better comprehend the condition of the pavement. According to the results, about the mechanical behaviour, from the asphalt mixtures developed in this research, and the severity of the interventions needed, when higher the severity, the mixture with the better mechanical performance would be used for the necessity of the intervention. For Example, how much greater the severity in relation to maintenance, the mixture Mix virgin limestone MOD should be used, and how lower severity of the intervention, the Mix 74/26+PW could be applied. The hierarchy of the results of the mixtures would result in this solution, which would solve the required maintenance on the pavement structure.

As future developments, the principal constraints of the study, which do not aim to provide an exhaustive framework for the integration of PMS-life cycle management, can be succinctly outlined in the following areas necessitating further exploration: Absence of an uncertainty analysis to scrutinize the variability of factors utilized in decision-making contexts where both observations and models constitute the knowledge foundation. Incorporating uncertainty analysis in intricate decision-making scenarios could enrich technical insights into decision-making processes by quantifying uncertainties associated with pertinent variables. Integration of social dimensions through Social-LCA to evaluate the societal and sociological dimensions of products, encompassing their actual and potential positive and negative impacts throughout their life cycles. Social-LCA encompasses the examination of raw material extraction and processing, manufacturing, distribution, use, reuse, maintenance, recycling, and final disposal. Leveraging both generic and site-specific data, Social-LCA complements LCA and LCCA. Expansion of the scope of road maintenance management issues by incorporating life cycle indicators at the network level. BIM solutions for road infrastructure management should facilitate the aggregation, upkeep, and analysis of road assets, providing a central platform for users to strategize, operate, and maintain an increasingly intelligent transportation network. This entails considerations such as the geospatial positioning of assets, graphical representation of networks, and their spatial context in map formats. Subsequent advancements ought to delve into the examination of the physical and mechanical properties of additional layers of pavement, as well as the refinement of BIM tools for enhanced precision.

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