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"Valutazione del comportamento meccanico e ambientale di miscele di conglomerato bituminoso a caldo modificate con rifiuti plastici non riciclabili"

"*Mechanical and environmental assessment of Hot Mix Asphalt mixtures modified with non-recyclable plastic wastes*"

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BS EN	British Standard European Norm
HMA	Hot Mix Asphalt
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PP	Polypropylene
PET	Polyethylene Terephthalate
XLPE	Cross-linked polyethylene
PVC	Polyvinyl Chloride
ITSM	Indirect Tensile Stiffness Modulus
ITS	Indirect Tensile Strength
LA	Los Angeles Coefficient
SE	Sand Equivalent
L/S	Liquid-to-Solid Ratio
OBC	Optimum Binder Content
Ba	Barium
Be	Beryllium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Ni	Nickel
Pb	Lead
V	Vanadium
Zn	Zinc

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ABSTRACT

Because of fewer opportunities for recycling and more difficulties with disposal, the growing amount of non-recoverable plastic waste has become a significant environmental concern. Incorporating recycled plastic debris into Hot Mix Asphalt (HMA) has become a viable strategy for enhancing pavement performance and promoting environmentally friendly waste management techniques in recent years. The viability of utilizing non-recoverable plastic waste as a modifier in asphalt mixtures for transportation infrastructure applications is examined in this study. The engineering and environmental performance of plastic-modified HMA at the binder and mixture levels is the main objective of the study. Particular attention is given to the influence of plastic incorporation methods on the mechanical and durability properties of asphalt mixtures, including stability, stiffness, and cracking behaviour. Additionally, the study uses leaching studies to evaluate possible environmental effects related to the use of plastic waste. By advancing knowledge of the behavior of non-recoverable plastic waste and its possible use in long-lasting and ecologically sustainable pavement systems, this work advances the development of sustainable asphalt technologies.

1. INTRODUCTION

1.1 Background and Motivation

The rapid growth of industrialization, urbanization, and population has led to a substantial increase in the production and consumption of plastic materials worldwide. Plastics have become indispensable in modern society due to their versatility, durability, lightweight nature, and low production cost. They are extensively used in packaging, construction, transportation, electronics, healthcare, and numerous consumer products. As a result, global plastic production has increased significantly over the past decades, generating large quantities of plastic waste that require effective management and disposal strategies [1].

Despite the benefits associated with plastic materials, the accumulation of plastic waste has emerged as a major environmental challenge. Conventional waste management practices, including landfilling and incineration, present significant limitations. Landfilled plastics can persist in the environment for hundreds of years due to their resistance to biological degradation, while incineration may contribute to greenhouse gas emissions and the release of potentially harmful substances. Furthermore, a considerable proportion of plastic waste consists of mixed, contaminated, or degraded materials that cannot be efficiently recycled through conventional recycling processes. These non-recoverable plastic wastes represent a growing concern for both environmental protection and sustainable resource management [2].

In recent years, increasing attention has been directed towards the development of circular economy strategies aimed at reducing waste generation and promoting the reuse of discarded materials. Within this framework, researchers and industries have explored innovative approaches to transform waste materials into valuable resources for engineering applications. The construction sector, due to its large demand for raw materials, offers significant opportunities for the utilization of recycled and waste-derived products. Incorporating waste materials into construction applications not only reduces the consumption of natural resources but also contributes to the diversion of waste from landfills [1].

Among various construction materials, asphalt pavements are particularly suitable for the incorporation of recycled materials because they are produced in large quantities and can accommodate a wide range of additives and modifiers. The asphalt industry has successfully

incorporated several recycled materials, including reclaimed asphalt pavement (RAP), recycled aggregates, industrial by-products, and waste-derived additives, demonstrating the potential for more sustainable pavement technologies [3].

The reuse of non-recoverable plastic waste in Hot Mix Asphalt (HMA) represents a promising solution that simultaneously addresses waste management and infrastructure sustainability challenges. By incorporating plastic waste into asphalt materials, it may be possible to improve pavement performance while reducing the environmental burden associated with plastic disposal. Consequently, the investigation of plastic-modified asphalt mixtures has become an important area of research within pavement engineering, supporting the transition towards more sustainable and resource-efficient transport infrastructure systems [2].

1.2 Plastic Waste Management Challenges

The widespread use of plastic materials has resulted in a significant increase in plastic waste generation across the world. Owing to their durability, low cost, and versatility, plastics have become essential in numerous industrial and domestic applications. However, the rapid growth in plastic consumption has created considerable challenges for waste management systems, particularly due to the large quantities of plastic waste generated each year and the limited capacity of existing recycling infrastructures [1].

Plastic waste can generally be classified into recyclable and non-recyclable fractions. Recyclable plastics, such as certain types of polyethylene terephthalate (PET) and polyethylene (PE), can be collected, sorted, and reprocessed into new products through established recycling processes. Nevertheless, a substantial proportion of plastic waste consists of mixed, contaminated, multi-layered, or degraded materials that are difficult or economically unfeasible to recycle. These materials are commonly referred to as non-recyclable or non-recoverable plastic wastes and represent a major challenge for sustainable waste management [2].

Traditional disposal methods for non-recoverable plastics primarily include landfilling and incineration. Although landfilling remains one of the most common waste disposal practices worldwide, it is increasingly recognized as an unsustainable solution due to land consumption, long degradation periods, and the potential release of pollutants into surrounding environments. Plastics disposed of in landfills can remain intact for hundreds of years, contributing to the long-term accumulation of waste. Incineration, while reducing waste volume and potentially generating

energy, may lead to greenhouse gas emissions and the release of hazardous compounds if not properly controlled [1].

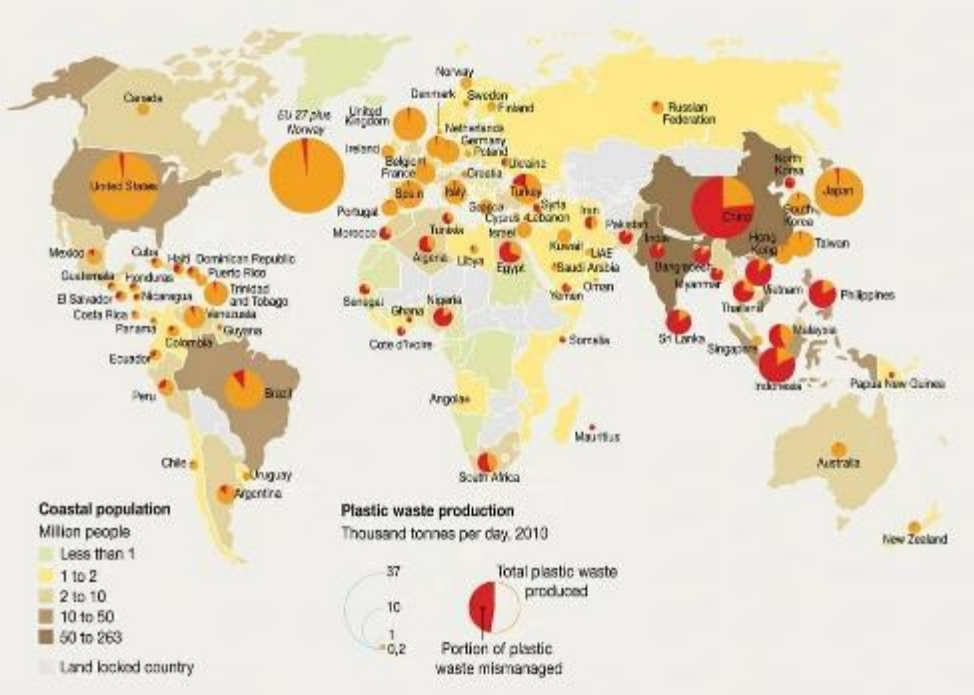

Figure 1.1: Plastic waste generation and mismanagement [4].

Another growing concern is the formation of microplastics resulting from the fragmentation and weathering of larger plastic products. These particles can accumulate in soil, freshwater, and marine environments, where they may be ingested by living organisms and enter food chains. Recent studies have highlighted the widespread presence of microplastics in environmental systems, raising concerns regarding ecological impacts and potential risks to human health [5]. Consequently, reducing the quantity of plastic waste entering the environment has become a priority for governments, researchers, and environmental agencies.

The limitations associated with conventional disposal and recycling methods have stimulated interest in alternative approaches for managing non-recoverable plastic waste. Rather than considering these materials solely as waste, current research increasingly explores opportunities for their reuse in engineering applications. Such approaches support the principles of the circular economy by extending the useful life of materials and reducing the demand for virgin resources [1].

Within the construction sector, the incorporation of waste materials into infrastructure projects has gained considerable attention as a sustainable waste management strategy. Due to the large volumes of materials required for road construction and maintenance, asphalt pavements provide a potential outlet for the utilization of significant quantities of plastic waste. The incorporation of non-recoverable plastics into asphalt mixtures may contribute to reducing landfill disposal while simultaneously improving the performance characteristics of pavement materials [3].

Despite the promising potential of this approach, several challenges remain regarding the effective use of plastic waste in asphalt applications. These challenges include variability in plastic composition, compatibility with asphalt binders, processing requirements, long-term durability, and potential environmental impacts. Addressing these issues requires comprehensive research to evaluate both the engineering performance and environmental behaviour of plastic-modified asphalt systems. Such investigations are essential to support the safe and sustainable implementation of non-recoverable plastic waste in transport infrastructure [2].

1.3 Use of Recycled Plastics in Asphalt Pavements

The increasing demand for sustainable construction materials has encouraged researchers and practitioners to explore innovative methods for incorporating waste products into civil engineering applications. Among these approaches, the utilization of recycled plastic waste in asphalt pavements has gained considerable attention due to its potential environmental and engineering benefits. Asphalt pavements require large quantities of materials, making them a suitable destination for the reuse of waste products that would otherwise be disposed of in landfills or through incineration [3].

The asphalt industry has a long history of incorporating recycled and secondary materials into pavement construction. Materials such as reclaimed asphalt pavement (RAP), recycled aggregates, industrial by-products, slags, ashes, and waste-derived modifiers have been successfully used to improve sustainability while maintaining satisfactory pavement performance [6]. Building upon these practices, researchers have investigated the possibility of incorporating recycled plastic waste into asphalt binders and asphalt mixtures as a means of reducing plastic waste accumulation and enhancing pavement properties.

The use of recycled plastics in asphalt pavements dates back to the early 1990s, when preliminary studies explored their feasibility as modifiers for asphalt binders and mixtures. Since then, research

activities have increased significantly due to growing environmental concerns and the need for alternative waste management solutions. Over the past two decades, thousands of kilometres of roads containing recycled plastic materials have been constructed, demonstrating the practical applicability of this technology under field conditions [6].

Various types of recycled plastics have been investigated for asphalt applications, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and mixed plastic waste streams. Among these materials, polyethylene-based plastics, particularly high-density polyethylene (HDPE) and low-density polyethylene (LDPE), are the most frequently studied due to their availability in municipal waste streams and their compatibility with asphalt production temperatures. Polypropylene and polyethylene terephthalate have also been widely evaluated and have demonstrated promising performance under specific conditions [3].

The incorporation of plastic waste into asphalt materials can generally be achieved through two principal approaches: the wet process and the dry process. In the wet process, plastic materials are blended directly with the asphalt binder before mixing with aggregates. This approach aims to modify the rheological properties of the binder and improve its resistance to deformation and ageing. In contrast, the dry process involves adding plastic particles directly to the aggregates during the mixing stage, allowing the plastic to function as a mixture modifier or partial aggregate substitute. Both methods have demonstrated potential advantages, although their effectiveness depends on factors such as plastic type, particle size, dosage, and processing conditions [7].

Numerous studies have reported improvements in the engineering performance of asphalt mixtures containing recycled plastics. The incorporation of plastic waste has been associated with increased Marshall stability, improved stiffness, enhanced rutting resistance, and greater durability compared with conventional asphalt mixtures. In addition, some studies have reported improved resistance to moisture damage and cracking, indicating that plastic-modified asphalt may provide longer service life under traffic and environmental loading conditions [8].

Despite these promising findings, the use of recycled plastics in asphalt pavements is not without challenges. Variations in plastic composition, compatibility between plastics and asphalt binders, processing requirements, and long-term performance remain important areas of investigation. Furthermore, environmental concerns related to emissions during production, microplastic

generation, and potential contaminant leaching require further assessment before widespread implementation can be fully supported [5].

Nevertheless, the incorporation of recycled plastic waste into asphalt pavements represents a promising strategy for addressing both waste management and infrastructure sustainability objectives. By transforming non-recoverable plastic waste into valuable construction material, this approach contributes to resource conservation, landfill diversion, and the development of more sustainable transport infrastructure systems. Consequently, continued research is required to better understand the engineering and environmental implications of plastic-modified asphalt and to establish reliable guidelines for its practical application [2].

1.4 Research Problem

The incorporation of recycled plastic waste into asphalt materials has attracted significant research interest over the past three decades. Numerous studies have investigated the use of various plastic types, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), as modifiers for asphalt binders and mixtures. Reported findings generally indicate improvements in mechanical properties such as stability, stiffness, rutting resistance, and durability, suggesting that plastic-modified asphalt may offer both engineering and environmental advantages [3].

Despite the promising results reported in the literature, several important challenges and knowledge gaps remain. A substantial proportion of existing research has focused on well-characterized and recyclable plastic materials, whereas limited attention has been given to non-recoverable plastic waste streams. These materials often consist of mixed, contaminated, or degraded plastics that cannot be efficiently processed through conventional recycling methods. As a result, their behaviour when incorporated into asphalt materials is not yet fully understood [2].

In addition, previous studies have employed different plastic types, incorporation methods, material dosages, and testing procedures, leading to variations in reported results. This diversity makes it difficult to establish consistent conclusions regarding the most effective approaches for incorporating plastic waste into asphalt mixtures. Questions remain concerning the influence of plastic waste on mixture performance, durability, and environmental behaviour [6].

Environmental considerations represent another important area requiring further investigation. While the reuse of plastic waste in asphalt mixtures has the potential to reduce landfill disposal and support circular economy objectives, concerns have been raised regarding possible environmental impacts including microplastics generation, emissions during production, and the potential release of contaminants through leaching processes.

Therefore, there is a need for a comprehensive evaluation of asphalt mixtures incorporating non-recoverable plastic waste, considering both engineering performance and environmental behaviour. Such an assessment is essential to determine whether these materials can be safely and effectively used in transport infrastructure applications while contributing to sustainable waste management practices. This research seeks to address these challenges by investigating the mechanical and environmental performance of Hot Mix Asphalt mixtures modified with non-recyclable plastic wastes [2].

1.5 Aim of the Study

The primary aim of this research is to evaluate the feasibility of using non-recyclable plastic waste as a modifier in Hot Mix Asphalt (HMA) mixtures for transport infrastructure applications. The study seeks to investigate the potential of these waste materials to improve pavement performance while simultaneously contributing to more sustainable waste management practices.

Particular emphasis is placed on assessing the influence of non-recyclable plastic waste on the mechanical performance of asphalt mixtures, including stiffness, tensile strength, and volumetric characteristics. In addition to engineering performance, the study aims to evaluate the environmental implications associated with the incorporation of plastic waste in asphalt mixtures through leaching assessment.

Ultimately, this research aims to contribute to the development of sustainable pavement technologies by providing a comprehensive mechanical and environmental assessment of Hot Mix Asphalt mixtures modified with non-recyclable plastic waste.

1.6 Research Objectives

To achieve the aim of this study, the following objectives have been established:

1. Characterize the conventional Hot Mix Asphalt (HMA) mixture used as the reference material.

2. Investigate the incorporation of non-recyclable plastic waste into HMA mixtures using the dry process.
3. Assess the influence of non-recyclable plastic waste on the volumetric properties of asphalt mixtures, including bulk density and air void content.
4. Evaluate the mechanical performance of plastic-modified asphalt mixtures using the Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS) tests.
5. Compare the volumetric and mechanical performance of conventional and plastic-modified Hot Mix Asphalt mixtures.
6. Investigate the environmental behaviour of plastic-modified asphalt mixtures through leaching tests.
7. Determine the feasibility of utilizing non-recyclable plastic waste in Hot Mix Asphalt as a sustainable solution for transport infrastructure applications.

1.7 Scope of the Study

This research focuses on the mechanical and environmental assessment of Hot Mix Asphalt (HMA) mixtures modified with non-recyclable plastic wastes for potential application in transport infrastructure. The study investigates the feasibility of incorporating plastic waste into asphalt materials and evaluates its influence on both engineering performance and environmental behaviour.

The experimental work includes the characterization of conventional and plastic-modified Hot Mix Asphalt mixtures produced using the dry incorporation method. Mechanical performance is assessed through laboratory testing, including bulk density, air void content, Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS). Particular attention is given to understanding how the incorporation of non-recyclable plastic waste affects the overall performance of asphalt mixtures compared with conventional HMA.

In addition to the engineering assessment, the study examines the environmental implications associated with the use of plastic waste in asphalt mixtures. Environmental evaluation is conducted through leaching tests to investigate the potential release of contaminants from plastic-modified asphalt materials.

The scope of this research is limited to laboratory-scale investigations and does not include large-scale field implementation, pavement construction, or long-term in-service monitoring of asphalt pavements. Furthermore, the study focuses specifically on the plastic waste materials selected for the experimental program and does not attempt to evaluate all categories of plastic waste available in municipal or industrial waste streams.

Finally, while the environmental assessment considers leaching behaviour, it does not include a complete life cycle assessment (LCA), economic analysis, or comprehensive environmental impact assessment. These aspects are recognized as important areas for future research and development.

1.8 Research Methodology Overview

The methodology adopted in this study was designed to evaluate the mechanical and environmental performance of Hot Mix Asphalt (HMA) mixtures modified with non-recyclable plastic wastes. The research combines material characterization, laboratory testing, and environmental assessment to provide a comprehensive understanding of the feasibility of incorporating plastic waste into asphalt materials for transport infrastructure applications.

The study began with an extensive review of scientific literature related to plastic waste management, asphalt modification technologies, and the use of recycled plastics in pavement engineering. Particular attention was given to the types of plastics used in asphalt applications, incorporation methods, mechanical performance, durability characteristics, and environmental considerations.

Following the literature review, the materials used in the experimental program were selected and characterized. These materials included the conventional asphalt binder, aggregates, and the non-recyclable plastic waste used as a modifier. Hot Mix Asphalt mixtures containing non-recyclable plastic waste were then prepared using the selected dry incorporation procedure.

The experimental investigation focused on Hot Mix Asphalt mixtures produced using the dry incorporation method. Conventional and plastic-modified mixtures were prepared and subjected to laboratory testing to evaluate their engineering performance. The experimental program included bulk density, air void content, Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Strength (ITS), and leaching tests.

In addition to the mechanical assessment, an environmental evaluation was conducted through leaching tests to investigate the potential release of contaminants from plastic-modified asphalt mixtures. The results obtained from the experimental program were analyzed and compared with those of conventional asphalt materials as well as findings reported in the literature. Based on the experimental outcomes, conclusions were drawn regarding the suitability of non-recyclable plastic waste as a modifier for Hot Mix Asphalt mixtures from both engineering and environmental perspectives.

1.9 Thesis Structure

Chapter 1: introduces the research background, problem statement, objectives, scope, and methodology overview.

Chapter 2: presents a review of the literature related to plastic waste management, asphalt materials, plastic-modified asphalt mixtures, and associated environmental considerations.

Chapter 3: describes the materials used and the experimental program adopted in the study, including specimen preparation and laboratory testing procedures.

Chapter 4: presents and discusses the volumetric and mechanical performance of conventional and plastic-modified Hot Mix Asphalt mixtures.

Chapter 5: focuses on environmental assessment through leaching tests and the evaluation of potential environmental impacts.

Chapter 6: summarizes the main conclusions of the study and presents recommendations for future research.

2. LITERATURE REVIEW

2.1 Plastic Waste and Environmental Concerns

The widespread use of plastic materials has transformed modern society due to their versatility, durability, low cost, and ease of manufacturing. Plastics are extensively employed in packaging, transportation, construction, agriculture, electronics, healthcare, and numerous consumer products. As global demand for plastic products continues to increase, plastic production has reached unprecedented levels, resulting in a corresponding growth in plastic waste generation. While plastics provide significant economic and functional benefits, their management at the end of their service life remains one of the most pressing environmental challenges of the twenty-first century [1].

Plastic materials can generally be classified into two main categories: thermoplastics and thermosetting plastics. Thermoplastics, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS), soften when heated and can be remolded multiple times. Consequently, these materials are theoretically recyclable through mechanical or chemical recycling processes. In contrast, thermosetting plastics undergo irreversible chemical reactions during manufacturing and cannot be remelted after curing. Examples include epoxy resins, polyurethane-based products, and fibre-reinforced composites used in construction and transportation applications [3].

Although recycling is widely recognized as a preferred waste management strategy, only a relatively small fraction of plastic waste is effectively recycled worldwide. Many plastic products consist of mixed polymers, multilayer packaging materials, or contaminated waste streams that are difficult and economically unfeasible to process using conventional recycling technologies. As a result, significant quantities of plastic waste are classified as non-recyclable or non-recoverable materials and are commonly disposed of through landfilling or incineration [2].

Landfilling remains one of the most widely used disposal methods for plastic waste. However, plastics are highly resistant to biological degradation and can persist in landfill environments for hundreds of years. The accumulation of plastic waste in landfills contributes to increasing land consumption and represents a long-term environmental burden. Furthermore, weathering processes may gradually degrade plastic materials into smaller particles that can migrate into surrounding ecosystems [1].

Incineration offers an alternative disposal route by reducing waste volume and recovering energy. Nevertheless, this process may generate greenhouse gas emissions and release potentially hazardous substances if combustion conditions are not adequately controlled. Although modern waste-to-energy facilities have improved emission control systems, concerns regarding environmental impacts and public acceptance continue to influence the adoption of incineration as a large-scale waste management solution [2].

One of the most significant environmental concerns associated with plastic waste is the formation of microplastics. Larger plastic products exposed to environmental conditions such as ultraviolet radiation, temperature fluctuations, mechanical abrasion, and chemical degradation gradually fragment into smaller particles. These particles, commonly referred to as microplastics, have been detected in terrestrial, freshwater, and marine environments worldwide. Their persistence and widespread distribution have raised concerns regarding ecosystem health, biodiversity, and potential impacts on human health through food chain contamination [5].

In response to these challenges, increasing attention has been directed towards the implementation of circular economy principles. The circular economy seeks to minimize waste generation by extending the useful life of materials, promoting recycling and reuse, and reducing dependence on virgin resources. Within this framework, alternative applications for plastic waste are being actively investigated to divert materials from landfills and create value from waste streams that would otherwise be discarded [1].

The construction industry has emerged as one of the most promising sectors for the utilization of recycled materials due to its high consumption of raw materials and large-scale infrastructure requirements. Various waste products, including recycled aggregates, industrial by-products, slags, ashes, and reclaimed asphalt pavement, have already been successfully incorporated into construction materials. More recently, researchers have explored the incorporation of plastic waste into asphalt pavements as a potential solution that addresses both waste management and infrastructure sustainability objectives [3].

The reuse of plastic waste in asphalt mixtures offers several potential advantages. First, it provides an alternative destination for non-recoverable plastic materials that cannot be efficiently recycled through conventional methods. Second, it may reduce the demand for virgin construction materials and contribute to resource conservation. Third, numerous studies have reported improvements in

the engineering performance of asphalt materials modified with recycled plastics, including increased stability, stiffness, rutting resistance, and durability. These benefits have stimulated substantial research interest in plastic-modified asphalt technologies over the last three decades [6].

Despite these potential advantages, concerns remain regarding the environmental behaviour of plastic-modified asphalt materials. Issues such as emissions during production, microplastic generation during pavement service life, and the potential release of contaminants through leaching processes require careful investigation. Recent studies have also highlighted concerns regarding emerging contaminants that may be associated with recycled waste materials. Understanding the environmental implications associated with the incorporation of plastic waste into asphalt mixtures is therefore essential for ensuring the safe and sustainable implementation of these technologies [5].

Overall, the increasing accumulation of non-recoverable plastic waste, combined with growing environmental concerns and the need for sustainable resource management, has encouraged the development of innovative reuse strategies. Among these strategies, the incorporation of plastic waste into asphalt pavements has emerged as a promising approach capable of simultaneously addressing waste management challenges and supporting the transition towards more sustainable transport infrastructure systems [2].

2.2 Hot Mix Asphalt (HMA): Materials and Characteristics

Hot Mix Asphalt (HMA) is one of the most widely used pavement materials for road construction and rehabilitation due to its excellent mechanical performance, durability, and cost-effectiveness. HMA consists of a carefully designed combination of asphalt binder, aggregates, and mineral filler mixed at elevated temperatures to produce a homogeneous material capable of withstanding traffic loads and environmental conditions. The performance of an asphalt pavement depends largely on the properties of its constituent materials and the interaction between them [7].

2.2.1 Asphalt Binder

Asphalt binder, commonly referred to as bitumen, is a viscoelastic petroleum-derived material that acts as the binding agent in asphalt mixtures. Its primary function is to coat and bind aggregate

particles together, providing cohesion within the mixture and ensuring adequate resistance to traffic loading and environmental stresses.

The behaviour of asphalt binder is highly dependent on temperature. At high temperatures, the binder becomes softer and more susceptible to permanent deformation, whereas at low temperatures it becomes stiffer and more prone to cracking. Consequently, the rheological properties of asphalt binders play a critical role in determining pavement performance throughout its service life.

To improve pavement performance, various modification techniques have been developed over the years. Conventional modifiers include polymers such as styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), and ethylene-vinyl acetate (EVA). These modifiers are used to enhance resistance to rutting, fatigue cracking, thermal cracking, and ageing. More recently, recycled plastic waste has been investigated as an alternative modifier capable of improving binder performance while simultaneously contributing to sustainable waste management practices [3].

2.2.2 Aggregates

Aggregates constitute the largest proportion of Hot Mix Asphalt, typically accounting for approximately 90–95% of the total mixture by weight. They provide the structural framework of the pavement and significantly influence its mechanical performance, durability, and resistance to deformation.

Aggregates used in asphalt mixtures are generally classified according to particle size into coarse aggregates, fine aggregates, and mineral fillers. Coarse aggregates contribute to load distribution and rutting resistance, while fine aggregates fill voids between larger particles and improve mixture stability. Mineral fillers occupy the smallest voids within the aggregate skeleton and contribute to mixture cohesion and stiffness.

The quality of aggregates is a key factor in pavement performance. Important aggregate properties include particle shape, surface texture, strength, abrasion resistance, durability, and affinity with asphalt binder. Well-graded aggregate structures promote adequate load transfer and help achieve the desired balance between stability, durability, and workability [7].

2.2.3 Mineral Fillers

Mineral fillers are fine particles that pass through the 0.075 mm sieve and are incorporated into asphalt mixtures to improve particle packing and binder interaction. Common fillers include limestone dust, cement, fly ash, and other finely divided mineral materials.

Although fillers represent a relatively small proportion of the total mixture, they significantly influence asphalt mixture performance. Fillers contribute to increased stiffness, reduced permeability, and improved resistance to moisture damage. Furthermore, the interaction between fillers and asphalt binder affects the rheological behaviour of the mastic phase, which plays an important role in pavement durability [7].

2.2.4 Performance Requirements of Hot Mix Asphalt

Hot Mix Asphalt pavements are subjected to repeated traffic loading and varying environmental conditions throughout their service life. Consequently, asphalt mixtures must satisfy several performance requirements to ensure long-term functionality and durability.

One of the primary requirements is resistance to permanent deformation, commonly known as rutting, which occurs when repeated traffic loads cause irreversible deformation within the pavement structure. Adequate resistance to fatigue cracking is also essential, as repeated loading can initiate and propagate cracks that compromise pavement integrity.

Thermal cracking resistance is particularly important in regions experiencing low temperatures, while moisture resistance is necessary to prevent stripping and deterioration caused by water infiltration. In addition, asphalt mixtures should possess sufficient flexibility to accommodate traffic-induced stresses without excessive cracking while maintaining adequate stiffness to resist deformation.

The balance between these performance requirements is influenced by the characteristics of the asphalt binder, aggregate structure, mixture design, and any modifiers incorporated into the system. As a result, researchers continue to explore innovative modification techniques aimed at enhancing pavement performance while addressing environmental and sustainability challenges [6].

2.2.5 Sustainable Development of Asphalt Materials

Growing environmental concerns and increasing pressure to reduce resource consumption have encouraged the development of more sustainable asphalt technologies. The asphalt industry has progressively incorporated recycled materials such as reclaimed asphalt pavement (RAP), recycled aggregates, industrial by-products, and waste-derived modifiers into pavement construction.

Among these alternatives, the use of recycled plastic waste has attracted considerable interest because it simultaneously addresses waste management challenges and offers potential performance benefits. Plastic-modified asphalt has emerged as a promising approach for improving pavement characteristics while supporting circular economy principles through the valorization of waste materials.

Consequently, understanding the behaviour of conventional Hot Mix Asphalt materials provides the necessary foundation for evaluating the effects of incorporating non-recyclable plastic waste into Hot Mix Asphalt mixtures. This understanding is essential for assessing the feasibility of plastic-modified asphalt as a sustainable solution for transport infrastructure applications [2].

2.3 Plastic Waste in Asphalt Mixtures

The increasing generation of plastic waste and the limitations of conventional recycling methods have encouraged researchers to explore alternative applications capable of utilizing large quantities of discarded plastics. Among these alternatives, the incorporation of plastic waste into asphalt mixtures has emerged as a promising solution due to the large volume of materials used in pavement construction and maintenance [2].

Research on plastic-modified asphalt began in the early 1990s and has gained significant attention over the past three decades. Growing environmental concerns, circular economy objectives, and the need to reduce reliance on virgin materials have driven the development of this field. Numerous studies have demonstrated that recycled plastic waste can be successfully incorporated into asphalt materials while maintaining or improving pavement performance [3].

The use of plastic waste in asphalt mixtures offers both engineering and environmental benefits. Reported improvements include increased stability, enhanced rutting resistance, improved moisture resistance, and greater pavement durability. At the same time, the reuse of plastic waste helps reduce landfill disposal and supports sustainable resource management [6].

Despite these advantages, several challenges remain. Variability in plastic waste composition, compatibility with asphalt materials, and the selection of appropriate incorporation methods may influence mixture performance. In addition, environmental aspects such as emissions, microplastic generation, and contaminant leaching require careful evaluation [5].

Overall, the incorporation of plastic waste into asphalt mixtures represents a sustainable approach for managing plastic waste while improving pavement performance. The following sections review the principal plastic types used in asphalt modification, their incorporation methods, and their effects on engineering and environmental performance [2].

2.4 Types of Plastics Used in Asphalt Modification

Various plastic wastes have been investigated as modifiers for asphalt binders and mixtures due to their availability, engineering properties, and potential environmental benefits. Among the most studied plastics are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), cross-linked polyethylene (XLPE), and mixed non-recyclable plastic wastes. The selection of plastic types significantly influences the mechanical performance, durability, and processing characteristics of plastic-modified asphalt materials [3].

2.4.1 Polyethylene (PE)

Polyethylene is the most widely used plastic in asphalt modification and is commonly available in waste streams such as plastic bags, packaging films, bottles, and containers. It is generally classified as high-density polyethylene (HDPE) and low-density polyethylene (LDPE).

HDPE is characterized by higher stiffness and strength, which can improve Marshall stability, rutting resistance, and overall structural performance of asphalt mixtures. LDPE possesses greater flexibility and a lower melting temperature, allowing easier incorporation through both wet and dry processes. Studies have shown that both HDPE and LDPE can enhance pavement performance, although HDPE generally provides greater stiffness while LDPE offers improved flexibility and workability [9].

2.4.2 Polypropylene (PP)

Polypropylene is widely used in packaging materials, household products, and automotive components. Due to its relatively high stiffness and thermal resistance, PP has been extensively investigated as an asphalt modifier.

Research indicates that PP can improve Marshall stability, stiffness, and resistance to permanent deformation. However, excessive PP contents may increase mixture brittleness and reduce flexibility. Therefore, optimization of polypropylene dosage is necessary to achieve a balance between strength and cracking resistance [3].

2.4.3 Polyethylene Terephthalate (PET)

Polyethylene terephthalate is commonly found in beverage bottles, food packaging, and textile products. Because of its higher melting temperature, PET is frequently incorporated using the dry process, where it acts as a reinforcing material within the asphalt mixture.

Numerous studies have reported improvements in mixture stability, stiffness, and rutting resistance following PET incorporation. However, the performance of PET-modified mixtures depends strongly on particle size, dosage, and processing conditions. Appropriate mixture design is therefore essential to maximize its benefits [10].

2.4.4 Cross-Linked Polyethylene (XLPE)

Cross-linked polyethylene (XLPE) is widely used as an insulation material in electrical power cables and industrial wiring systems due to its excellent thermal stability, mechanical strength, and electrical insulation properties. Unlike conventional thermoplastics, XLPE possesses a cross-linked molecular structure that prevents it from melting and being reprocessed through traditional recycling methods. Consequently, large quantities of waste XLPE generated from cable manufacturing and end-of-life electrical infrastructure are often classified as non-recyclable waste.

In recent years, researchers have investigated the incorporation of waste XLPE into asphalt materials as an alternative recycling route. Studies have reported that XLPE can improve the stiffness and mechanical performance of asphalt mixtures while providing a sustainable solution for managing cable insulation waste. Compared with conventional recycled plastics such as PE, PP, and PET, research on XLPE-modified asphalt remains relatively limited. Nevertheless, its potential for valorizing difficult-to-recycle plastic waste has attracted increasing interest within sustainable pavement engineering [11].

2.4.5 Mixed and Non-Recyclable Plastic Wastes

Growing attention has recently been directed toward the use of mixed and non-recyclable plastic waste. These materials typically consist of contaminated plastics, multilayer packaging, and mixed polymer streams that are unsuitable for conventional recycling processes.

The incorporation of mixed plastic waste into asphalt mixtures offers significant environmental benefits by diverting waste from landfills and incineration. Several studies have reported improvements in stability, deformation resistance, and durability. However, variability in composition and melting behaviour remains a major challenge, requiring careful material characterization and mixture design [2].

Overall, the available literature demonstrates that different plastic types can successfully enhance asphalt performance when appropriately incorporated. While PE, PP, and PET remain the most extensively studied materials, increasing research attention is being directed toward non-recyclable and mixed plastic waste due to their potential environmental and sustainability benefits [1].

2.5 Plastic Incorporation Methods

The performance of plastic-modified asphalt materials depends not only on the characteristics of the plastic waste used but also on the method employed for its incorporation into the asphalt system. Over the past three decades, researchers have developed several techniques for introducing recycled plastic waste into asphalt binders and mixtures. Among these techniques, the wet process and the dry process are the most widely adopted and extensively studied.

The choice of incorporation method significantly influences the interaction between plastic particles and asphalt materials, affecting workability, mixture homogeneity, mechanical performance, durability, and production requirements. Factors such as plastic type, melting temperature, particle size, dosage, and production conditions play important roles in determining the suitability of each method.

Although both approaches have demonstrated promising results, each presents distinct advantages and limitations. Consequently, understanding the mechanisms associated with each incorporation technique is essential for optimizing the use of recycled plastic waste in asphalt pavements [3].

2.5.1 Wet Process

The wet process involves the direct blending of plastic waste with the asphalt binder before mixing with aggregates. In this approach, plastic particles are introduced into the hot binder under controlled temperature and mixing conditions, allowing partial or complete interaction between the plastic and the bituminous matrix. The resulting product is commonly referred to as a plastic-modified binder.

The effectiveness of the wet process largely depends on the ability of the plastic material to soften, melt, swell, or disperse within the asphalt binder. Low-melting thermoplastics such as polyethylene (PE) and polypropylene (PP) are particularly suitable for this method because they can interact more readily with the binder during mixing. The extent of interaction is influenced by factors such as mixing temperature, mixing duration, shear conditions, and plastic particle characteristics [7].

One of the principal advantages of the wet process is the improved modification of binder properties. Numerous studies have reported increases in softening point, viscosity, stiffness, and resistance to permanent deformation following the incorporation of recycled plastics through wet blending. These improvements are generally attributed to the formation of a modified binder structure in which plastic particles interact with the bituminous components, enhancing resistance to high-temperature deformation.

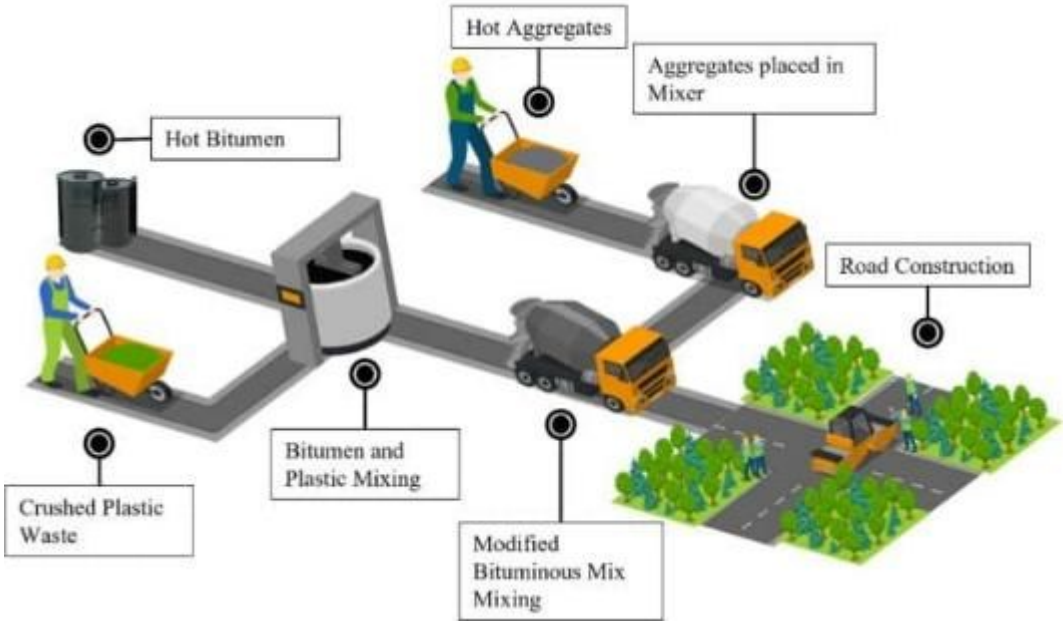

Figure 2.1: The wet process scheme. [3]

The wet process also provides greater control over the modification of binder rheological properties. Since the plastic is incorporated before aggregate mixing, researchers can evaluate the behaviour of the modified binder independently through conventional binder characterization tests. This capability has contributed to the widespread use of the wet process in laboratory investigations aimed at understanding plastic–bitumen interaction mechanisms [12].

Despite its advantages, the wet process presents several technical challenges. One of the most important concerns is compatibility between plastic materials and asphalt binder. Certain plastics may not fully dissolve or disperse within the binder, leading to phase separation during storage or transportation. This issue can result in non-uniform binder properties and inconsistent pavement performance.

Storage stability is another significant challenge associated with wet-modified binders. Differences in density and chemical characteristics between plastics and bitumen may promote separation over time, particularly at elevated temperatures. To address this problem, some studies have investigated the use of compatibilizers, chemical additives, or modified processing conditions to improve binder homogeneity [7].

In addition, the wet process often requires specialized mixing equipment, higher energy consumption, and greater process control than conventional asphalt production. These requirements may increase production costs and limit large-scale implementation in certain regions. Nevertheless, the wet process remains one of the most effective methods for achieving substantial modifications of binder properties and continues to be widely investigated in both laboratory and field studies.

Several researchers have reported that wet-process plastic-modified binders exhibit improved resistance to rutting, and greater durability compared with conventional binders. These findings suggest that the wet process can provide significant engineering benefits when appropriate plastic materials and processing conditions are employed [12].

2.5.2 Dry Process

The dry process is an alternative method for incorporating plastic waste into asphalt mixtures and has gained considerable attention due to its relative simplicity and practicality. Unlike the wet process, where plastic is blended directly with the asphalt binder, the dry process involves adding

plastic particles directly to the heated aggregates before the introduction of the binder. The plastic material may partially melt, soften, or coat the aggregate particles depending on its physical properties and the production temperature employed.

The dry process was initially developed as a means of simplifying the incorporation of recycled plastics into asphalt mixtures while avoiding some of the compatibility and storage stability issues associated with wet-modified binders. Because the plastic is added during mixture production rather than binder preparation, this method generally requires fewer modifications to conventional asphalt plants and production procedures.

One of the principal advantages of the dry process is its ability to accommodate a wider variety of plastic waste materials. Plastics with relatively high melting temperatures, which may not readily disperse within asphalt binders, can often be successfully incorporated through dry mixing. This characteristic is particularly beneficial when utilizing mixed or non-recyclable plastic waste streams that contain different polymer types [6].

Figure 2.2: The dry process scheme. [3]

During the dry incorporation process, plastic particles interact with both the aggregate skeleton and the asphalt binder. Depending on the plastic type and production conditions, the material may act as a reinforcing component, a partial aggregate substitute, or a modifier that improves the interfacial bonding between aggregates and binder. These mechanisms contribute to enhanced mechanical performance frequently reported in plastic-modified asphalt mixtures produced through the dry method.

Numerous studies have demonstrated that dry-process plastic-modified asphalt mixtures exhibit improved Marshall stability, increased stiffness, enhanced rutting resistance, and reduced susceptibility to permanent deformation. In many cases, researchers have also observed improvements in moisture resistance and durability. These benefits are commonly attributed to the reinforcing effect of plastic particles and their contribution to the internal structure of the asphalt mixture [9].

Another important advantage of the dry process is its operational simplicity. Since plastic waste is introduced directly during asphalt mixture production, the method typically does not require specialized binder modification equipment. This reduces production complexity and facilitates implementation in conventional asphalt plants. Consequently, the dry process is often considered more economically attractive and easier to adopt on an industrial scale [13].

Despite these advantages, several challenges remain associated with dry-process incorporation. One important concern is the uniform distribution of plastic particles throughout the mixture. Inadequate mixing may result in localized concentrations of plastic material, potentially affecting mixture homogeneity and performance consistency. Furthermore, the effectiveness of the dry process depends strongly on particle size, plastic morphology, mixing sequence, and production temperature.

The determination of optimum plastic content is also critical. While moderate additions of plastic waste generally improve mechanical performance, excessive quantities may adversely affect workability and compaction characteristics. High plastic contents may reduce mixture flexibility and increase the likelihood of cracking under certain conditions. Therefore, careful mixture design is required to maximize performance benefits while maintaining adequate constructability [2].

Another challenge relates to the variability of waste plastic materials. Since waste streams may contain different polymer types and contamination levels, the resulting asphalt mixtures can exhibit variations in performance. Appropriate material characterization and quality control procedures are therefore essential when implementing dry-process plastic modification on a large scale.

In recent years, the dry process has received increasing attention from researchers and transportation agencies due to its practicality and potential for large-scale waste utilization. Several

field applications have demonstrated satisfactory pavement performance, supporting the feasibility of using recycled plastic waste as a sustainable modifier for asphalt mixtures. As a result, the dry process is often regarded as one of the most promising approaches for integrating non-recyclable plastic waste into pavement construction [6].

2.5.3 Comparison of Wet and Dry Processes

The wet and dry processes are the two main methods used for incorporating recycled plastic waste into asphalt materials. The key difference lies in the stage at which the plastic is introduced. In the wet process, plastic is blended directly with the asphalt binder before mixture production, whereas in the dry process, plastic particles are added to heated aggregates during mixing [7].

The wet process provides greater control over binder modification and allows direct evaluation of changes in rheological properties such as viscosity, penetration, and softening point. As a result, it is widely used in laboratory studies focused on binder performance. However, this method may face compatibility and storage stability issues and often requires specialized equipment and higher processing costs [12].

In contrast, the dry process is generally simpler and more practical for large-scale implementation. It requires fewer modifications to existing asphalt plants and can accommodate mixed or high-melting plastic wastes. Studies have shown that dry-process mixtures can achieve improvements in stability, stiffness, rutting resistance, and moisture resistance comparable to those obtained through wet modification [6].

The selection of an appropriate incorporation method depends on factors such as plastic type, desired pavement performance, available production facilities, and economic considerations. While the wet process is preferred when significant binder modification is required, the dry process is often considered more suitable for industrial applications due to its simplicity, lower cost, and ability to utilize heterogeneous plastic waste streams [2].

Overall, both incorporation methods have demonstrated the ability to improve asphalt performance while promoting plastic waste valorization. Nevertheless, the growing emphasis on circular economy strategies and large-scale waste utilization has contributed to increasing interest in the dry process, particularly for the incorporation of non-recyclable and mixed plastic waste streams.

This trend is reflected in numerous recent studies that identify the dry method as one of the most promising approaches for future sustainable pavement applications [9].

Table 2.1. Comparison between wet and dry incorporation methods for recycled plastic waste in asphalt mixtures [6], [7]**.**

Aspect	Wet Process	Dry Process
Plastic addition stage	Added directly to asphalt binder	Added directly to heated aggregates
Main modification mechanism	Binder modification	Mixture modification
Suitable plastic types	Mainly low-melting thermoplastics	Wide range of plastic materials
Storage stability issues	Possible	Generally absent
Equipment requirements	Higher	Lower
Production complexity	Higher	Lower
Industrial implementation	Moderate	High
Binder characterization	Directly possible	Limited
Use of mixed plastic waste	More difficult	More feasible
Overall practicality	Moderate	High

2.5.4 Factors Influencing Plastic Incorporation

The effectiveness of plastic waste incorporation in asphalt materials depends on several factors related to the plastic characteristics, production conditions, and mixture design. These factors influence the interaction between plastic particles, asphalt binder, and aggregates, ultimately affecting pavement performance [3].

One of the most important parameters is the type of plastic used. Different polymers such as PE, PP, PET, and XLPE exhibit different melting temperatures, stiffness levels, and compatibility with asphalt materials, resulting in varying performance outcomes.

Plastic dosage is another critical factor. Moderate plastic contents generally improve stability, stiffness, and rutting resistance, whereas excessive amounts may reduce workability and increase cracking susceptibility. Therefore, identifying optimum plastic content is essential.

Particle size and shape also affect performance. Smaller particles typically provide better dispersion and interaction with asphalt materials, while larger particles may act as reinforcing elements but can reduce mixture homogeneity if not properly distributed [9].

Processing conditions, particularly mixing temperature and mixing duration, play a significant role in achieving effective plastic incorporation. Adequate temperatures and mixing procedures are necessary to ensure proper melting, dispersion, and interaction between the plastic and asphalt components.

Compatibility between plastic materials and asphalt binder is especially important in wet-process modification. Poor compatibility may lead to phase separation and reduced long-term stability, while improved compatibility contributes to better performance and durability.

Finally, aggregate characteristics, traffic loading and environmental exposure influence the long-term behaviour of plastic-modified asphalt mixtures. Consequently, careful optimization of material selection, processing conditions, and mixture design is required to maximize engineering performance and ensure sustainable pavement applications [6].

2.6 Effect of Plastic Waste on Asphalt Mixture Properties

The incorporation of recycled plastic waste into asphalt mixtures has been widely investigated due to its potential to improve pavement performance while providing a sustainable solution for plastic waste management. Previous studies have shown that plastic modification can influence several mixture properties, including stability, rutting resistance, cracking resistance, moisture susceptibility, stiffness, and long-term durability. The extent of these improvements depends on factors such as plastic type, dosage, incorporation method, and mixture composition [6].

2.6.1 Rutting Resistance

Rutting is a common pavement distress caused by permanent deformation under repeated traffic loading. Many studies have shown that plastic-modified asphalt mixtures exhibit greater resistance to rutting than conventional mixtures. This improvement is mainly associated with increased mixture stiffness and enhanced resistance to deformation at elevated temperatures.

Wheel tracking and repeated load tests frequently report lower rut depths in plastic-modified mixtures, particularly when polyethylene-based plastics are used. However, excessive plastic contents may result in overly stiff mixtures and should therefore be avoided. Overall, recycled plastic waste has proven effective in improving high-temperature pavement performance [6].

2.6.2 Cracking Resistance

Cracking is one of the most critical factors affecting pavement service life. Research indicates that recycled plastic waste can improve crack resistance by reinforcing the asphalt matrix and delaying crack initiation and propagation. Plastic particles may act as stress-distributing elements, allowing the mixture to absorb greater amounts of energy before failure.

Several studies have also reported improved fatigue performance for plastic-modified asphalt mixtures. However, the relationship between plastic content and cracking resistance is not always linear. Excessive plastic additions may increase stiffness to a level that reduces flexibility and increases the risk of cracking. Therefore, maintaining a balance between stiffness and ductility remains essential [9].

2.6.3 Moisture Susceptibility

Moisture susceptibility refers to the loss of strength and durability caused by water infiltration and stripping of the asphalt binder from aggregate surfaces. The hydrophobic nature of most plastic materials can improve resistance to moisture damage by reducing water penetration and enhancing binder–aggregate adhesion.

Research involving HDPE, LDPE, PET, and mixed plastic waste streams have generally reported improved moisture resistance compared with conventional mixtures. Higher tensile strength ratio (TSR) values and lower strength losses after moisture conditioning have frequently been observed. These findings suggest that plastic modification can contribute to enhanced pavement durability under wet environmental conditions [2].

2.6.4 Stiffness and Durability

Plastic-modified asphalt mixtures generally exhibit greater stiffness than conventional mixtures due to the reinforcing effect of plastic particles and improved binder properties. Increased stiffness contributes to better load distribution, improved rutting resistance, and enhanced structural performance. Nevertheless, excessive stiffness may increase susceptibility to cracking, highlighting the importance of optimizing plastic dosage [11].

Durability is influenced by resistance to fatigue, moisture damage, and permanent deformation. Several studies have reported improved long-term performance and satisfactory mechanical behaviour for plastic-modified asphalt mixtures. In addition, recent investigations have shown that

some plastic-modified asphalt materials can undergo multiple recycling cycles while retaining acceptable engineering properties.

Overall, the available literature indicates that recycled plastic waste can significantly improve the performance and durability of asphalt mixtures when appropriately incorporated. These improvements support the potential use of non-recyclable plastic waste as a sustainable modifier for transport infrastructure applications [1].

2.7 Environmental Aspects

2.7.1 Microplastics

Microplastics are plastic particles smaller than 5 mm that can be generated through the degradation and fragmentation of larger plastic materials. Their accumulation in the environment has raised concerns regarding ecological and human health impacts.

The incorporation of recycled plastic waste into asphalt mixtures has been proposed as a means of encapsulating plastic particles within the bituminous matrix, potentially reducing environmental release. Although pavement wear and ageing may contribute to particle generation over time, current studies generally indicate that properly designed plastic-modified asphalt mixtures do not produce significantly higher microplastic emissions than conventional pavements. Nevertheless, further long-term investigations are required to better understand their environmental behaviour [2].

2.7.2 Emissions During Production

The production of plastic-modified asphalt mixtures may generate emissions such as volatile organic compounds (VOCs) and particulate matter due to heating and mixing processes. Emission levels depend primarily on plastic type, incorporation method, and production temperature.

Current research suggests that commonly used plastics such as PE and PP can be incorporated without significant additional emissions when appropriate temperatures are maintained. Proper temperature control and operational practices are therefore essential to ensure environmental sustainability and worker safety during production [3].

2.7.3 Leaching Behaviour

Leaching refers to the release of chemical substances from a material into surrounding water. In plastic-modified asphalt mixtures, concerns mainly relate to the potential release of additives and contaminants contained within recycled plastic waste.

Most laboratory studies have reported low contaminant concentrations in leachates, indicating that the asphalt matrix effectively encapsulates plastic particles and limits their mobility. However, leaching behaviour may vary depending on plastic composition, ageing conditions, and environmental exposure. Consequently, leaching assessment has become an important component of environmental evaluation and is increasingly used to assess the suitability of plastic-modified asphalt systems for sustainable infrastructure applications. [5].

2.8 Research Gaps

Numerous studies have demonstrated that recycled plastic waste can improve the performance of asphalt mixtures by enhancing stability, stiffness, rutting resistance, and durability. However, several important knowledge gaps remain.

Most existing research has focused on recyclable plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), while non-recyclable and mixed plastic waste streams have received considerably less attention. The behaviour of these materials in asphalt mixtures remains insufficiently understood, particularly due to their variability in composition and properties [2].

Although improvements in mechanical performance have been widely reported, limited information is available regarding the long-term performance and environmental behaviour of asphalt mixtures containing non-recyclable plastic waste. Furthermore, environmental aspects such as microplastic generation, emissions during production, and contaminant leaching remain relatively underexplored.

In particular, the environmental performance of plastic-modified asphalt mixtures requires further investigation through leaching assessments to ensure their safe and sustainable use in transport infrastructure applications [5].

Therefore, this research focuses on the mechanical and environmental assessment of Hot Mix Asphalt mixtures modified with non-recyclable plastic wastes. Particular emphasis is placed on

the evaluation of volumetric and mechanical properties, including bulk density, air void content, Indirect Tensile Stiffness Modulus (ITSM), and Indirect Tensile Strength (ITS), together with environmental evaluation through leaching tests.

2.9 Summary

This chapter reviewed the available literature related to the use of recycled plastic waste in asphalt materials. The review covered the characteristics of Hot Mix Asphalt, commonly used plastic types, and the principal methods of plastic incorporation. The effects of plastic waste on asphalt mixture performance, including stability, rutting resistance, cracking resistance, moisture susceptibility, and stiffness, were discussed, together with environmental aspects such as microplastic generation, emissions during production, and leaching behaviour.

Overall, the literature indicates that recycled plastic waste can enhance pavement performance while providing a sustainable approach for waste management. However, important knowledge gaps remain regarding the use of non-recyclable plastic wastes and their environmental behaviour. These gaps provide the basis for the present study, which focuses on the mechanical and environmental assessment of Hot Mix Asphalt mixtures modified with non-recyclable plastic wastes.

3. MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter presents the materials used and the experimental procedures adopted to evaluate the mechanical and environmental performance of Hot Mix Asphalt (HMA) mixtures modified with non-recyclable plastic waste. The study was designed to investigate the feasibility of incorporating shredded cable insulation waste into asphalt mixtures using the dry process and to assess its influence on mixture properties.

The materials used in this research consisted of conventional bitumen, mineral aggregates, and non-recyclable plastic waste. Aggregate characterization tests were conducted to determine the physical and mechanical properties of the aggregates before mixture preparation. The asphalt mixtures were designed using the selected aggregate gradation and optimum binder content.

Three mixture types were investigated, consisting of a conventional control mixture and two plastic-modified mixtures containing 4% and 8% plastic waste. Specimens were prepared using a Superpave Gyratory Compactor with 100 gyrations. The experimental program included the determination of bulk density, air void content, Indirect Tensile Strength (ITS), Indirect Tensile Stiffness Modulus (ITSM), and leaching behaviour. The adopted methodology was intended to provide a comprehensive assessment of the suitability of non-recyclable plastic waste for sustainable pavement applications.

3.2 Materials

3.2.1 Bitumen

Conventional paving bitumen was used as the binder material for the preparation of the Hot Mix Asphalt mixtures. The binder was supplied by a producer located in Northern Italy and was used for both the conventional and plastic-modified mixtures to ensure consistency throughout the experimental program. The bitumen was heated to the required mixing temperature of 160 °C prior to mixture production to ensure adequate coating of the aggregate particles and satisfactory workability during mixing and compaction. Although the exact binder grade could not be confirmed, the same binder was used for all mixtures investigated in this study.

Figure 3.1: Bitumen used for Hot Mix Asphalt mixture preparation

3.2.2 Aggregates

Mineral aggregates constituted the major component of the asphalt mixtures used in this study. Limestone aggregates were selected for the production of both conventional and plastic-modified mixtures. The aggregate blend was established based on the target gradation obtained from the granulometric curve to satisfy mixture design requirements.

The aggregate mixture consisted of 32% limestone aggregate with a particle size of 0–4 mm, 28% limestone aggregate with a particle size of 4–8 mm, 30% limestone aggregate with a particle size of 8–12 mm, and 10% limestone filler. These proportions were selected to achieve the desired particle size distribution and ensure adequate mixture performance.

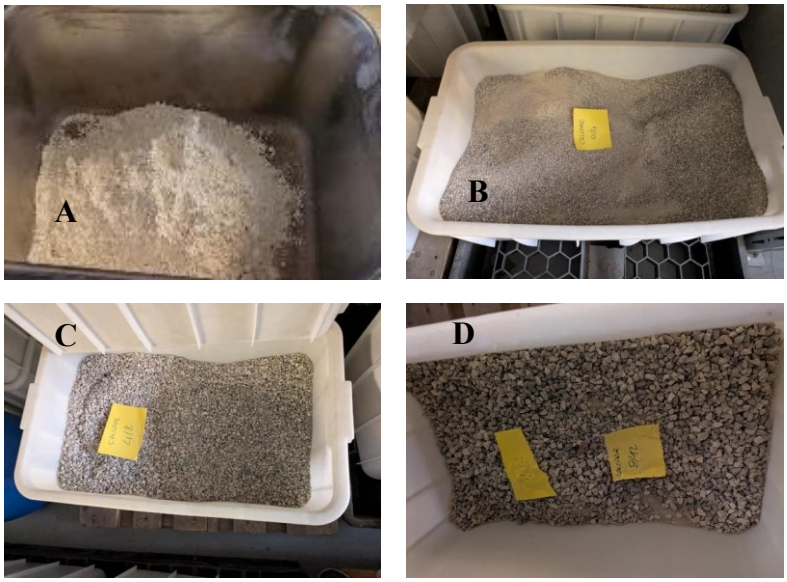

Figure 3.2: (A) Filler (B) Limestone aggregate 0–4 mm (C) Limestone aggregate 4–8 mm (D) Limestone aggregate 8–12 mm

Prior to mixture preparation, the aggregates were characterized through particle size distribution, specific gravity and water absorption, sand equivalent, flakiness index, shape index, and Los Angeles abrasion tests.

3.2.3 Non-Recyclable Plastic Waste

The plastic waste used in this study consisted of shredded electrical cable insulation waste obtained from an electrical cable recycling company located in the Veneto Region, Italy. During the recycling process, copper is recovered from end-of-life electrical cables, while the remaining plastic insulation is normally discarded as waste. The material was supplied for this research to investigate its potential reuse in Hot Mix Asphalt (HMA), thereby supporting circular economy principles through the valorization of an industrial waste stream.

The material was supplied in shredded form, with particle sizes smaller than 4 mm and was incorporated into the asphalt mixtures using the dry process. The exact polymeric composition of the cable insulation waste was not determined; therefore, throughout this study, the material is referred to as shredded cable insulation waste rather than as a specific polymer, as cable insulation may consist of different polymeric materials (e.g., XLPE, PVC, PE, and rubber-based compounds).

For the volumetric calculations, the density of the shredded cable insulation waste was estimated from published literature because its exact polymeric composition and corresponding density were not available. The adopted value therefore represents an assumed representative density for the investigated material.

Figure 3.3: Shredded cable insulation waste used in this study.

3.3 Aggregate Characterization

Aggregate characterization was carried out to evaluate the physical and mechanical properties of the materials used in the asphalt mixtures. The tests were performed in accordance with the relevant European standards to ensure that the aggregates satisfied the requirements for asphalt pavement applications. The characterization program included particle size distribution, specific gravity and water absorption, sand equivalent, flakiness index, shape index, and Los Angeles abrasion tests.

3.3.1 Particle Size Distribution

Particle size distribution analysis was carried out in accordance with BS EN 933-1:2012, Tests for Geometrical Properties of Aggregates – Part 1: Determination of Particle Size Distribution – Sieving Method. Representative aggregate samples were reduced to the required test portion and dried to constant mass. The material was then subjected to sieving using a series of standard sieves arranged in descending order of aperture size.

The mass of material retained on each sieve was determined and expressed as a percentage of the original dry mass. The cumulative percentage passing each sieve was subsequently calculated to obtain the particle size distribution of the aggregate fractions. The grading curves obtained were used to evaluate the aggregate gradation and to verify compliance with the specified grading requirements for Hot Mix Asphalt mixtures.

Figure 3.4: Sieving of aggregates to determine particle size distribution.

3.3.2 Specific Gravity and Water Absorption

The particle density and water absorption characteristics of the coarse aggregates (4–8 mm and 8–12 mm fractions) were determined in accordance with BS EN 1097-6:2022, Tests for Mechanical and Physical Properties of Aggregates – Part 6: Determination of Particle Density and Water Absorption. The pycnometer method was employed to determine the bulk specific gravity and water absorption values required for asphalt mixture design and volumetric calculations.

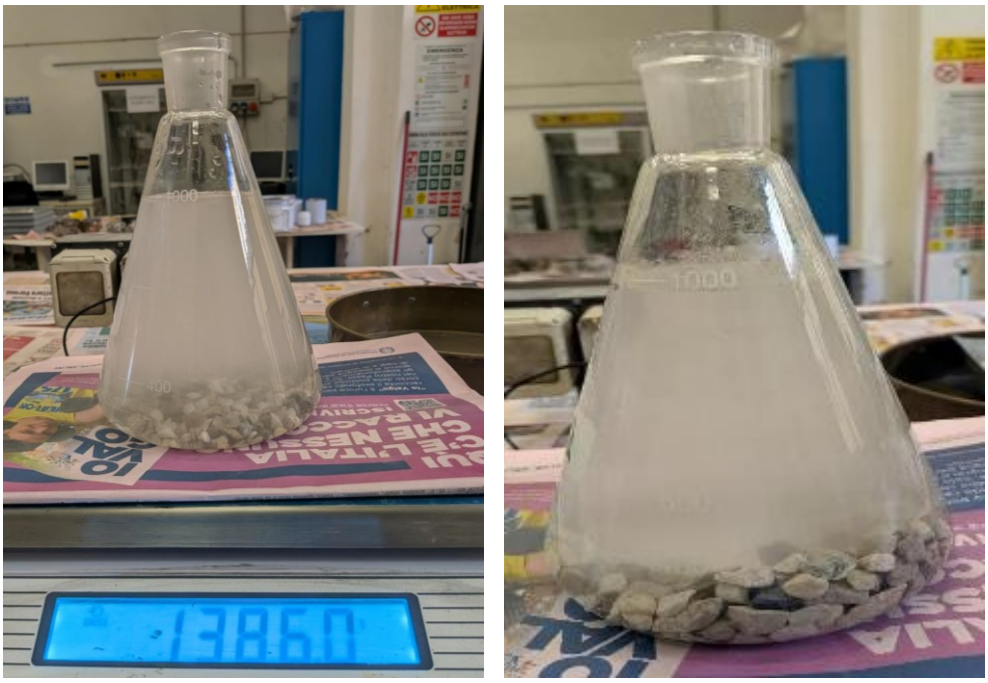

Figure 3.5: Experimental setup for pycnometer density test.

Representative samples of each aggregate fraction were immersed in water for 24 ± 0.5 h. After soaking, the aggregates were removed from the water and brought to the saturated surface-dry (SSD) condition by carefully wiping the particle surfaces with a cloth. The saturated surface-dry mass was then determined, followed by the measurement of the submerged mass in water and the oven-dry mass after drying to constant mass. These measured masses were used to calculate the bulk particle density and water absorption in accordance with the equations specified in BS EN 1097-6:2022. The obtained values were subsequently used in the volumetric analysis and mix design of the Hot Mix Asphalt mixtures.

3.3.3 Sand Equivalent

The cleanliness of the fine aggregate was evaluated by the sand equivalent test in accordance with BS EN 933-8:2012+A1:2015, Tests for Geometrical Properties of Aggregates – Part 8: Assessment of Fines – Sand Equivalent Test. The test was performed on the 0/4 mm aggregate fraction in accordance with Annex A of the standard to assess the presence of clay-like particles and fine contaminants.

Two test specimens were prepared from the aggregate sample and introduced into graduated cylinders containing washing and flocculating solution. After a soaking period, the cylinders were mechanically shaken to disperse the fine particles. The specimens were subsequently washed using the prescribed washing tube, allowing the fine particles to remain suspended while the sand particles settled to the bottom of the cylinders.

Figure 3.6: Determination of Sand Equivalent

Following a settling period of 20 min, the height of the suspension (h_1) and the height of the sediment (h_2) were measured using the test plunger assembly. The sand equivalent value was calculated as the ratio of the sediment height to the total suspension height, expressed as a percentage. The average value obtained from the two test specimens was reported as the sand equivalent value of the aggregate. The measured sand equivalent value was used to evaluate the cleanliness and suitability of the fine aggregate for use in Hot Mix Asphalt mixtures.

3.3.4 Flakiness Index

The flakiness index test was performed in accordance with BS EN 933-3:2012, Tests for Geometrical Properties of Aggregates – Part 3: Determination of Particle Shape – Flakiness Index. The aggregate sample was first reduced and dried to constant mass. The material was then separated into the required particle size fractions using standard test sieves. Each size fraction was subsequently sieved through the corresponding bar sieve with a slot width equal to half of the upper sieve size (Di/2), ensuring complete separation of flaky particles.

The flakiness index was determined as the ratio of the mass of particles passing the bar sieves to the total mass of the aggregate tested, expressed as a percentage. This test was conducted to evaluate the proportion of flaky particles and to assess the suitability of the aggregates for asphalt mixture applications.

Figure 3.7: Bar Sieves used for Flakiness Index

3.3.5 Shape Index

The shape index test was carried out in accordance with BS EN 933-4:2008, Tests for Geometrical Properties of Aggregates – Part 4: Determination of Particle Shape – Shape Index, to evaluate the geometric characteristics of the coarse aggregate particles. Aggregate samples were dried to constant mass and separated into the required size fractions by sieving. For each size fraction, the particle length (L) and thickness (E) were assessed using a particle slide gauge where necessary.

Particles having a dimensional ratio of L/E greater than 3 were classified as non-cubical particles and separated from the remaining aggregate. The shape index (SI) was determined as the mass of

non-cubical particles expressed as a percentage of the total dry mass of the particles tested. The measured shape index value was used to assess the suitability of the aggregates for asphalt mixture production.

Figure 3.8: Grain size caliper used for Shape Index

3.3.6 Los Angeles Abrasion

The resistance of the coarse aggregates to fragmentation was evaluated using the Los Angeles abrasion test in accordance with BS EN 1097-2:2020, Tests for Mechanical and Physical Properties of Aggregates – Part 2: Methods for the Determination of Resistance to Fragmentation. The test was performed to assess the ability of the aggregate particles to resist degradation under mechanical impact and abrasion.

Prior to testing, the aggregate sample was sieved to obtain the required test fraction. A test portion with a total mass of 5000 ± 50 g was prepared by combining 3000 g of the 11.2 mm fraction and 2000 g of the 10 mm fraction. The prepared test portion was placed in the Los Angeles drum together with the specified steel ball charge.

The drum was rotated for 500 revolutions, during which the aggregate particles were subjected to repeated impact and abrasion by the steel ball charge. After completion of the test, the material was discharged from the drum and sieved using the 1.6 mm sieve. The material retained on the 1.6 mm sieve was washed, dried, and weighed. The Los Angeles coefficient was then calculated based on the difference between the initial test portion mass and the final dried mass retained on the 1.6 mm sieve. The obtained coefficient was used to evaluate the fragmentation resistance of the aggregates and their suitability for asphalt mixture production.

Figure 3.9: Experimental setup for Los Angeles

3.4 Mixture Design

The asphalt mixtures used in this study were designed to evaluate the influence of non-recyclable plastic waste on the mechanical and environmental performance of Hot Mix Asphalt. The mixture design was based on the selected aggregate gradation and optimum binder content to ensure adequate volumetric and mechanical characteristics.

3.4.1 Aggregate Gradation

The aggregate blend was established using the particle size distribution results obtained from the sieve analysis. Four aggregate fractions were combined to satisfy the target grading requirements for Hot Mix Asphalt mixtures. The selected aggregate composition consisted of 32% limestone aggregate with particle size 0–4 mm, 28% limestone aggregate with particle size 4–8 mm, 30% limestone aggregate with particle size 8–12 mm, and 10% limestone filler. The resulting gradation curve provided a well-graded aggregate structure suitable for asphalt mixture production.

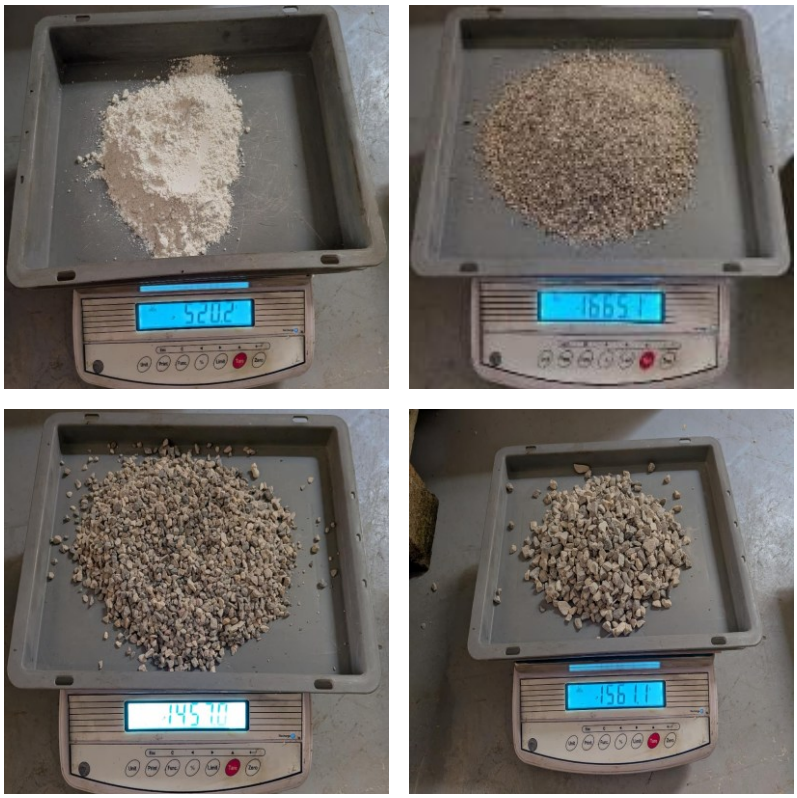

Figure 3.10: Aggregate fractions for sample preparation

3.4.2 Optimum Binder Content

The optimum binder content (OBC) was established through a preliminary mixture design using specimens compacted with the Superpave Gyratory Compactor (SGC). Trial mixtures were prepared with bitumen contents of 4.5%, 5.5%, and 6.5% (by total mixture weight), with four specimens prepared for each binder content. Based on the combined assessment of volumetric and mechanical properties, an optimum binder content of 5.4% was selected and subsequently used throughout the experimental program.

Three asphalt mixtures were then prepared using the selected optimum binder content. A conventional Hot Mix Asphalt mixture without plastic addition was used as the control mixture, while two plastic-modified mixtures containing 4% and 8% shredded cable insulation waste were produced using the dry incorporation method. The selected plastic contents were chosen to investigate the effect of plastic dosage on the mechanical performance and environmental behaviour of the asphalt mixtures.

3.5 Preparation of Plastic-Modified Asphalt Mixtures

3.5.1 Dry Incorporation Method

The plastic-modified asphalt mixtures were prepared using the dry incorporation method. In this approach, shredded cable insulation waste was added directly to the heated aggregate blend before the addition of bitumen. The shredded cable insulation particles were smaller than 4 mm. Two plastic contents, namely 4% and 8%, were investigated and compared with a conventional mixture without plastic addition.

The dry process was selected because of its simplicity and suitability for incorporating non-recyclable plastic waste. This method allows the plastic particles to interact with the aggregate skeleton and asphalt binder during mixing without requiring modification of the binder before mixture production.

3.5.2 Mixing Procedure

The preparation of the asphalt mixtures was carried out under controlled laboratory conditions. Prior to mixing, the aggregate fractions were heated in an oven at 160°C for a minimum period of two hours. The mixing container was also preheated to 160°C to minimize temperature loss during mixture preparation. Bitumen was heated separately to 160°C to ensure adequate fluidity and workability.

The heated aggregates were transferred into the mixing container, and the mineral filler was added. For the plastic-modified mixtures, the required amount of shredded cable insulation waste was introduced into the aggregate blend before adding the binder. Subsequently, bitumen corresponding to the optimum binder content of 5.4% was added and mixing was continued until a homogeneous coating of the aggregates was achieved.

After mixing, the loose asphalt mixture was conditioned in an oven at 160°C for approximately 30 minutes. The mixture was then remixed and prepared for compaction.

Figure 3.11: Sample mixing using the dry method

3.5.3 Specimen Compaction

Specimens were compacted using a Superpave Gyratory Compactor (SGC). Prior to compaction, the mold components and compaction accessories were heated to 160°C and lubricated to facilitate specimen extraction. Filter papers were placed at the top and bottom of the mold before introducing the loose mixture.

Approximately 1250 g of asphalt mixture was placed into a 100 mm diameter mold and compacted using a vertical pressure of 2.9 bar and an internal angle of gyration of 1.25°. A total of 100 gyrations were applied to each specimen. After compaction, the specimens were removed from the mold, labelled, and allowed to cool to room temperature before further testing.

Figure 3.12(a): Sample preparation for compaction

Figure 3.12(b): Compacted samples from Superpave gyratory compactor

3.6 Experimental Program

The experimental program comprised volumetric characterization, mechanical performance evaluation, and environmental assessment of conventional and plastic-modified Hot Mix Asphalt (HMA) mixtures. The laboratory testing program included bulk density and air void content determination, Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Strength (ITS), and leaching tests. These tests were conducted to evaluate the influence of shredded cable insulation waste on the volumetric characteristics, mechanical properties, and environmental performance of the asphalt mixtures.

3.6.1 Bulk Density and Air Void Content

The bulk density of compacted asphalt specimens was determined in accordance with BS EN 12697-6, while the air void content was calculated in accordance with BS EN 12697-8. Prior to testing, the specimens were immersed in water for approximately 24 h to achieve a saturated condition. The submerged mass, saturated surface-dry (SSD) mass, and dry mass of each specimen were measured. The bulk density was then calculated from these measurements and used together with the maximum theoretical density of the mixtures to determine the air void content.

The obtained bulk density and air void values were used to assess the degree of compaction and the volumetric characteristics of the asphalt mixtures.

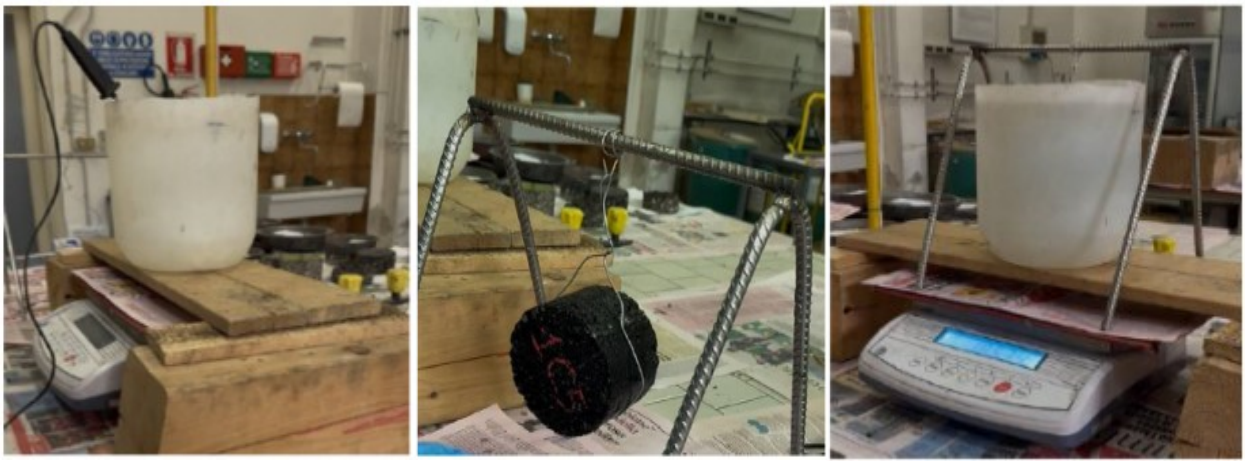

Figure 3.13: Experimental setup for Bulk density and Air voids

3.6.2 Indirect Tensile Stiffness Modulus (ITSM)

The stiffness characteristics of the asphalt mixtures were evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test in accordance with BS EN 12697-26. Before testing, the specimens were conditioned at 25°C to ensure a uniform temperature throughout the sample. Each cylindrical specimen was positioned within the loading frame and subjected to repeated diametral loading pulses. The horizontal deformation induced by the applied load was measured using displacement transducers, and the stiffness modulus was calculated automatically by the testing software.

The ITSM test is non-destructive; therefore, the same specimens were subsequently used for Indirect Tensile Strength testing. The resulting stiffness modulus values were used to compare the rigidity and load-spreading capability of the conventional and plastic-modified asphalt mixtures.

Figure 3.14: Indirect Tensile Stiffness Modulus (ITSM) testing of an asphalt specimen.

3.6.3 Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test was performed in accordance with BS EN 12697-23 to evaluate the tensile properties of the asphalt mixtures. The cylindrical specimens were positioned horizontally between loading strips and subjected to a continuously increasing compressive load applied along the vertical diametral plane until failure occurred.

Figure 3.15: Experimental setup for Indirect Tensile Strength (ITS).

The maximum applied load at failure was recorded and used to calculate the indirect tensile strength of each specimen. The ITS values were used to assess the resistance of the asphalt mixtures to tensile cracking and to evaluate the influence of plastic waste incorporation on mixture strength.

3.6.4 Leaching Test

An environmental assessment of the asphalt mixtures was carried out through leaching tests based on BS EN 12457-2. Following completion of the mechanical testing program, the asphalt specimens were crushed and sieved to obtain particles smaller than 4 mm. The prepared material was then subjected to leaching analysis to determine the potential release of contaminants from the mixtures.

The concentrations of selected elements in the leachate were measured and compared with relevant environmental criteria. The results were used to assess the environmental suitability of

incorporating shredded cable insulation waste into asphalt mixtures and to evaluate the sustainability of the proposed material.

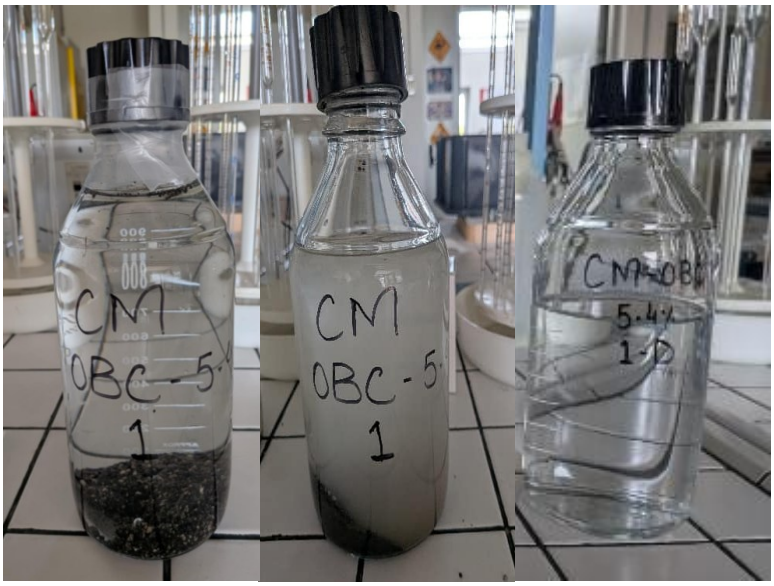

Figure 3.16: Stages of the batch leaching test.

3.7 Test Matrix

The experimental program consisted of volumetric, mechanical, and environmental evaluations performed on conventional and plastic-modified Hot Mix Asphalt mixtures. Three mixture types were investigated, including a control mixture and mixtures containing 4% and 8% shredded cable insulation waste. The laboratory testing program included bulk density, air void content, Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Strength (ITS), and leaching tests.

Table 3.1: Summary of the experimental program.

Mixture ID	Plastic Content (%)	Bulk Density	Air Voids	ITSM	ITS	Leaching
Control	0	✓	✓	✓	✓	✓
PMA4	4	✓	✓	✓	✓	✓
PMA8	8	✓	✓	✓	✓	✓

3.8 Summary

This chapter presents the materials and experimental procedures adopted in the present study. The characteristics of the constituent materials, including bitumen, limestone aggregates, and non-recyclable plastic waste, were described together with the aggregate characterization tests and mixture design process. The preparation of conventional and plastic-modified Hot Mix Asphalt mixtures using the dry incorporation method was outlined, followed by the specimen compaction procedure and the experimental program used to evaluate the volumetric, mechanical, and environmental performance of the mixtures. The methodology described in this chapter provides the basis for the analysis and discussion of the experimental results presented in the following chapter.

4. PERFORMANCE OF PLASTIC-MODIFIED HOT MIX ASPHALT MIXTURES

4.1 Introduction

This chapter presents and discusses the results obtained from the experimental program conducted on conventional and plastic-modified Hot Mix Asphalt mixtures. The influence of shredded cable insulation waste on the volumetric, mechanical, and environmental properties of the mixtures is evaluated by comparing the performance of the control mixture with those containing 4% and 8% plastic waste.

The chapter begins with the characterization results of the aggregates used in the study, followed by the analysis of volumetric properties and mechanical performance, including the Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS). The experimental findings are compared and discussed to evaluate the feasibility of utilizing non-recyclable plastic waste as a sustainable modifier for Hot Mix Asphalt mixtures.

4.2 Aggregate Characterization Results

The physical and mechanical properties of the aggregates were evaluated prior to asphalt mixture preparation to ensure their suitability for Hot Mix Asphalt applications. The characterization program included particle size distribution, specific gravity and water absorption, sand equivalent, flakiness index, shape index, and Los Angeles abrasion tests. The results obtained are presented and discussed in the following sections.

4.2.1 Particle Size Distribution

Particle size distribution analysis was conducted to establish the aggregate gradation used in the mixture design. The selected aggregate blend consisted of 32% limestone aggregate with particle size 0–4 mm, 28% limestone aggregate with particle size 4–8 mm, 30% limestone aggregate with particle size 8–12 mm, and 10% limestone filler. The resulting gradation curve provided a well-graded aggregate structure suitable for Hot Mix Asphalt production. The selected gradation ensured adequate particle interlock and contributed to achieving the desired volumetric and mechanical properties of the mixtures.

Table 4.1: Sieve Analysis Results for the 0–4 mm Limestone Aggregate Fraction

Test Sample M1 = 1500 gram				
Sieve Size	**Retained weight on sieve (g) R**	**Percentage retained on sieve (R / M1) × 100**	**Cumulative Percent Retained Σ (R / M1 × 100)**	**Cumulative Percent Passing 100 − Σ (R / M1 × 100)**
5 mm	0	0.00	0.00	100.00
4 mm	5	0.33	0.33	99.67
2 mm	360.5	24.03	24.37	75.63
1 mm	464.5	30.97	55.33	44.67
500 µm	315	21.00	76.33	23.67
250 µm	199	13.27	89.60	10.40
125 µm	124	8.27	97.87	2.13
63 µm	29	1.93	99.80	0.20
Pan (<0.063 µm)	2.5	-	-	-

Table 4.2: Sieve Analysis Results for the 4-8 mm Limestone Aggregate Fraction

Test Sample M1 = 1505.5 gram				
Sieve Size	**Retained weight on sieve (g) R**	**Percentage retained on sieve (R / M1) × 100**	**Cumulative Percent Retained Σ (R / M1 × 100)**	**Cumulative Percent Passing 100 − Σ (R / M1 × 100)**
10 mm	0	0.00	0.00	100.00
8 mm	165	10.96	10.96	89.04
6.3 mm	405	26.90	37.86	62.14
5 mm	512.5	34.04	71.90	28.10
4 mm	296	19.66	91.56	8.44
2 mm	103	6.84	98.41	1.59
1 mm	15	1.00	99.40	0.60
500 µm	3.5	0.23	99.63	0.37
250 µm	1	0.07	99.70	0.30
125 µm	2	0.13	99.83	0.17
63 µm	1	0.07	99.90	0.10
Pan (<0.063 µm)	0.5	-	-	-

Table 4.3: Sieve Analysis Results for the 8-12 mm Limestone Aggregate Fraction

Test Sample M1 = 3100 gram				
Sieve Size	**Retained weight on sieve (g) R**	**Percentage retained on sieve (R / M1) × 100**	**Cumulative Percent Retained Σ (R / M1 × 100)**	**Cumulative Percent Passing 100 − Σ (R / M1 × 100)**
14 mm	0	0.00	0.00	100.00
12.5 mm	73.5	2.37	2.37	97.63
10 mm	1171	37.77	40.15	59.85
8 mm	1121.5	36.18	76.32	23.68
6.3 mm	455	14.68	91.00	9.00
5 mm	88.5	2.85	93.85	6.15
4 mm	14.5	0.47	94.32	5.68
2 mm	23	0.74	95.06	4.94
1 mm	43	1.39	96.45	3.55
500 µm	35.5	1.15	97.60	2.40
250 µm	32.5	1.05	98.65	1.35
125 µm	32.5	1.05	99.69	0.31
63 µm	7	0.23	99.92	0.08
Pan (<0.063 µm)	2	-	-	-

Table 4.4: Aggregate Composition Adopted for the Preparation of the Asphalt Mixtures

Sample Fraction	**Percentage of single sieve pass based on the curve**								**%**
	SIEVES UNI EN (opening in mm)								
	16	12.5	8	4	2	0.5	0.25	0.063	
Limestone 0/4	100.0%	100.0%	100.0%	99.7%	75.6%	23.7%	10.4%	0.2%	**32**
	32	32	32	31.8944	24.202	7.584	3.328	0.064	
Limestone 4/8	100.0%	100.0%	89.0%	8.4%	1.6%	0.4%	0.3%	0.1%	**28**
	28	28	24.931	2.3632	0.4452	0.1036	0.084	0.028	
Limestone 8/12	100.0%	97.6%	23.7%	5.7%	4.9%	2.4%	1.4%	0.1%	**30**
	30	29.289	7.104	1.704	1.482	0.72	0.405	0.024	
Filler	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	96.0%	67.1%	**10**
	10	10	10	10	10	10	9.6	6.71	
Total	100.00	99.29	74.04	45.96	36.13	18.41	13.42	6.83	**100**

Table 4.5: Aggregate grading limits for mixture design.

Envelope from technical specification			
Sieve Size	**MIN %**	**%**	**MAX%**
16 mm	100	*100.00*	100
12.5 mm	90	*99.29*	100
8 mm	70	*74.04*	88
4 mm	40	*45.96*	58
2 mm	25	*36.13*	38
0.5 mm	10	*18.41*	20
0.25 mm	8	*13.42*	16
0.063 mm	6	*6.83*	10

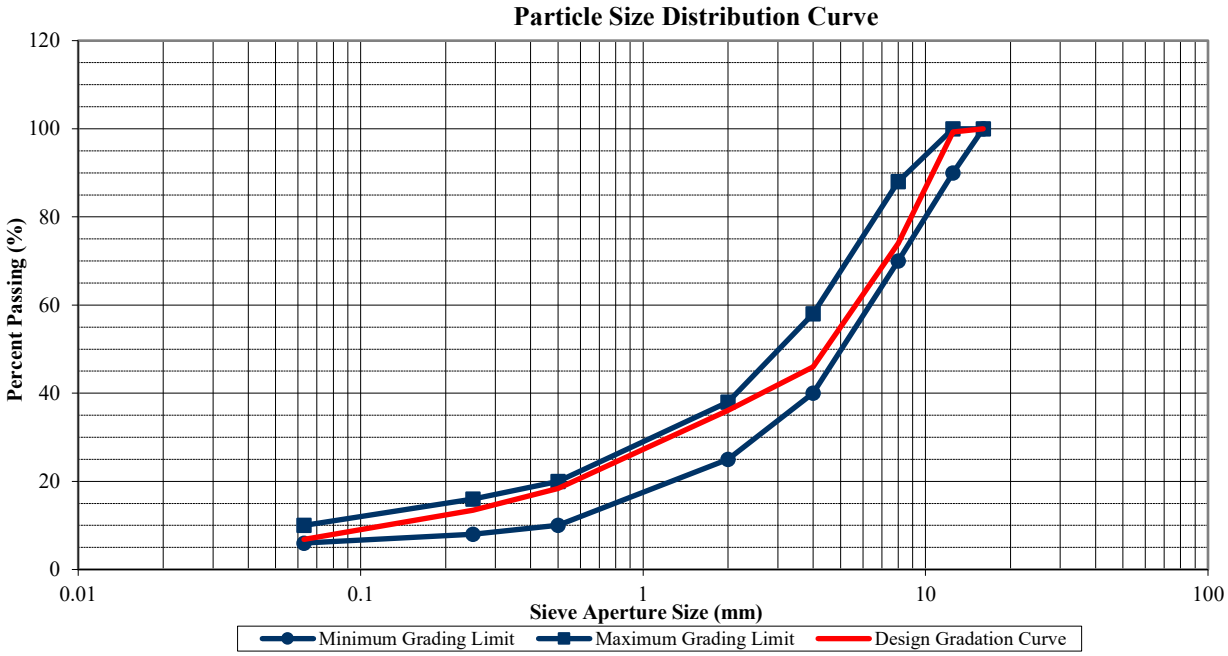

Figure 4.1: Aggregate Gradation Curve Used for Asphalt Mixture Design.

4.2.2 Specific Gravity and Water Absorption

The specific gravity and water absorption tests indicated that the aggregates possessed suitable density characteristics and relatively low water absorption values. The measured water absorption values ranged approximately between 1.0% and 1.2%, while the bulk specific gravity values varied from approximately 2.58 to 2.74 g/cm³. These results indicate that the aggregates exhibit limited moisture absorption and possess adequate density characteristics for asphalt mixture applications. Low water absorption is beneficial for minimizing moisture-related damage and improving the durability of asphalt pavements.

Table 4.6: Specific Gravity and Water Absorption Characteristics of the Limestone Aggregate.

Description	Units	Limestone fraction 4-8	Limestone fraction 8-12
Mass of Aggregate Sample	gram	150.2	150.4
Mass of empty pycnometer	gram	299	299.5
Mass of pycnometer + Aggregate	gram	449.2	449.8
M1: Saturated Surface-Dry aggregate mass	gram	151.4	150.9
M2: Mass of pycnometer + Aggregate + water	gram	1386	1388.1
M3: Mass of pycnometer+ water	gram	1289.2	1295.1
M4: Mass of oven-dry sample	gram	149.6	149.4
ρw: Water density	[g/cm³]	1.000	1.000
Calculated Results			
ρa: Apparent particle density	[g/cm³]	2.833	2.649
ρdry: Bulk particle density (oven -dry)	[g/cm³]	2.740	2.580
ρssd: Saturated surface-dry (SSD) particle density	[g/cm³]	2.773	2.606
WA: Absorption capacity	%	1.20	1.00

4.2.3 Sand Equivalent

The sand equivalent test yielded a value of 91, indicating a low content of clay-like particles and fine contaminants. This high sand equivalent value reflects the cleanliness of the fine aggregate fraction and suggests favourable aggregate quality. Clean aggregates contribute to improved adhesion between the aggregate surface and the asphalt binder, thereby enhancing mixture durability and moisture resistance.

Table 4.7: Sand Equivalent Test Results (SE) — BS EN 933-8:2012:2015

Limestone Fraction 0-4 mm		
Parameter	**Specimen 1**	**Specimen 2**
h_1 — Total suspension height (mm)	10.6	11.2
h_2 — Sediment height (mm)	9.6	10.2
SE (10) =$(h_2/h_1) \times 100$	91	91
Difference = $\lvert SE_1 - SE_2 \rvert$		0

4.2.4 Flakiness Index

The flakiness index values obtained for the 4–8 mm and 8–12 mm limestone aggregate fractions were 13% and 14%, respectively. These relatively low values indicate that the aggregates contained a limited proportion of flaky particles. Aggregates with low flakiness indices generally exhibit improved particle interlock and enhanced resistance to deformation, which contributes positively to the mechanical performance and durability of Hot Mix Asphalt mixtures.

Table 4.8: Flakiness Index determination for the 4–8 mm limestone fraction.

Sample mass M = 1505.5 g				
Particle size fraction (d/D)	**Mass R_i (g)**	**Nominal width of slot (mm)**	**Mass m_i (g)**	**FI_i (%)**
8/10	165	5	43.5	26.36
6.3/8	405	4	58	14.32
5/6.3	512.5	3.15	50	9.76
4/5	296	2.5	30	10.14
$M_1 = \sum R_i$	1378.5	$M_2 = \sum m_i$	181.5	
$FI = (M_2/M_1)*100$	13			

Table 4.9: Flakiness Index determination for the 8-12 mm limestone fraction.

Sample mass M = 3088 g				
Particle size fraction (d/D)	**Mass R_i (g)**	**Nominal width of slot (mm)**	**Mass m_i (g)**	**FI_i (%)**
12.5/16	73.5	8	10.5	14.29
10/12.5	1171	6.3	202.5	17.29
8/10	1121.5	5	147	13.11
6.3/8	455	4	49	10.77
5/6.3	88.5	3.15	10	11.30
4/5	14.5	2.5	2.5	17.24
$M_1 = \sum R_i$	2924	$M_2 = \sum m_i$	421.5	
$FI = (M_2/M_1)*100$	14			

4.2.5 Shape Index

The shape index test produced a value of 7%, indicating that the aggregates possessed favourable particle shapes. The relatively low shape index suggests that the aggregate particles exhibited satisfactory geometric characteristics, which are beneficial for achieving adequate compaction and good load distribution within the asphalt mixture.

Table 4.10: Shape Index for 8–12 mm limestone aggregate fraction.

Sample mass M = 294.5 g			
Particle size fraction (d/D)	**Mass M_1 (g)**	**Mass M_2 (g)**	**Shape Index SI (%) (M_2/M_1) *100**
8-12 mm	275	19.5	7

4.2.6 Los Angeles Abrasion

The Los Angeles abrasion test resulted in a coefficient of 24, demonstrating that the aggregates possessed good resistance to wear and fragmentation. This relatively low abrasion value indicates that the aggregates are sufficiently durable to withstand mechanical stresses and traffic loading conditions. Consequently, the aggregates used in this study were considered suitable for the production of Hot Mix Asphalt mixtures.

Table 4.11: Los Angeles Abrasion Results for Limestone Aggregates

Parameter	**Symbol**	**Mass (g)**	**Description**
Initial dry mass of test portion	m_1	5002.3	Before test – Fraction 11.2 and 10 mm mixed (5000 ± 50 g)
Dry mass retained on 1.6 mm sieve after fragmentation	m_2	3780.2	After test – combined dried mass retained on 1.6 mm sieve
Los Angeles Coefficient (%)	LA	**24**	Formula: LA = ((m_1 – m_2) / m_1) *100

4.3 Volumetric Properties

The volumetric properties of asphalt mixtures play an important role in determining their structural integrity, durability, and resistance to environmental effects. Bulk density and air void content were evaluated to investigate the influence of shredded cable insulation waste on the internal structure and compaction characteristics of the mixtures. Average values obtained for the control mixture and the plastic-modified mixtures containing 4% and 8% plastic waste are presented and discussed in the following sections.

4.3.1 Compaction Behaviour (K-Value)

The average K-values obtained from the gyratory compaction curves are presented in Figure 4.2. The control mixture exhibited an average K-value of 4.32%, while the mixtures containing 4% and 8% shredded cable insulation waste exhibited average K-values of 4.67% and 3.41%, respectively.

The K-value represents the slope of the relationship between air void content and the natural logarithm of the number of gyrations during compaction. Consequently, it provides an indication of the compaction behaviour of the asphalt mixtures during the gyratory compaction process.

Among the investigated mixtures, the 4% plastic mixture exhibited the highest average K-value of 4.67%, which was only slightly higher than that of the control mixture 4.32%. This suggests that the addition of 4% shredded cable insulation waste had little influence on the compaction characteristics of the asphalt mixture. In contrast, increasing the plastic content to 8% reduced the average K-value to 3.41%, indicating a lower rate of air void reduction during gyratory compaction. Overall, a more noticeable reduction in the K-value was observed when the plastic content was increased to 8%.

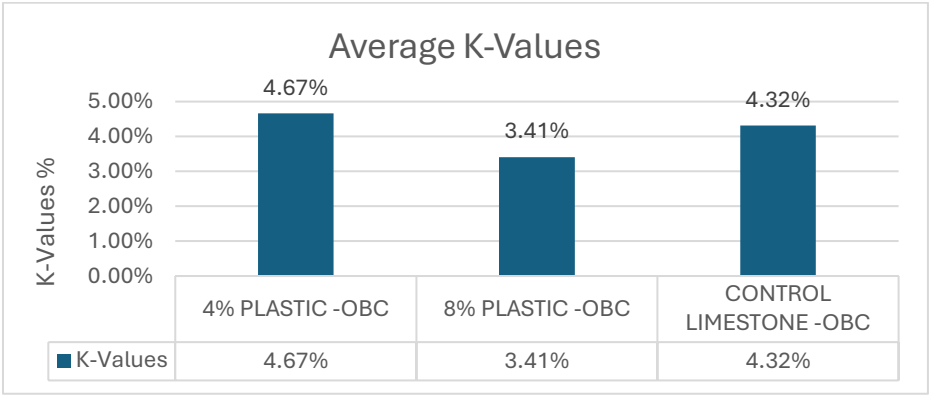

Figure 4.2: Comparison of average K-values of asphalt mixtures.

4.3.2 Bulk Density

The average bulk density values obtained for the investigated mixtures are presented in Tables 4.12–4.14. The control mixture exhibited an average bulk density of 2.463 Mg/m³, while the incorporation of shredded cable insulation waste resulted in a gradual reduction in bulk density, with average values of 2.358 Mg/m³ and 2.273 Mg/m³ for the mixtures containing 4% and 8% plastic, respectively.

As shown in Figure 4.3, the control mixture exhibited the highest average bulk density, while the addition of shredded cable insulation waste reduced the bulk density of the asphalt mixtures. The reduction was relatively small for the 4% plastic mixture but became more pronounced when the plastic content was increased to 8%.

The reduction in bulk density can be attributed to the lower density of the plastic particles compared with mineral aggregates. In addition, the presence of plastic particles affected the packing characteristics of the aggregate skeleton, thereby reducing its packing efficiency. This effect became more pronounced with increasing plastic content, resulting in lighter mixtures with a less compact internal structure.

Table 4.12: Bulk density values of the control mixtures.

CONTROL LIMESTONE -OBC 5.4%- Bulk Density (Pbssd)							
Sample Code	**m1 (dry weight) [g]**	**m2 (wet weight) [g]**	**m3 (SSD weigh) [g]**	**Pw [Mg/m3]**	**Water temperature [° C]**	**Pbssd (Mg/m3)**	**Average Pbssd (Mg/m3)**
Control Limestone-5.4%B- 1	1241.0	739.0	1243.0	0.997	23.70	2.456	2.463
Control Limestone-5.4%B- 2	1242.0	743.0	1243.5	0.997	23.70	2.475	
Control Limestone-5.4%B- 3	1243.0	742.5	1245.5	0.997	23.70	2.465	
Control Limestone-5.4%B- 4	1247.5	743.0	1249.5	0.997	23.70	2.457	

Table 4.13: Bulk density values of 4% Plastic samples.

4% Plastic Mixture – Bulk Density (Pbssd)							
Sample Code	**m1 (dry weight) [g]**	**m2 (wet weight) [g]**	**m3 (SSD weigh) [g]**	**Pw [Mg/m3]**	**Water temperature [° C]**	**Pbssd (Mg/m3)**	**Average Pbssd (Mg/m3)**
4% PLASTIC - 1	1250.5	728.0	1254.0	0.997	23.70	2.371	2.358
4% PLASTIC - 2	1250.0	726.0	1254.0	0.997	23.70	2.361	
4% PLASTIC - 3	1251.5	723.0	1256.0	0.997	23.70	2.342	
4% PLASTIC - 4	1250.0	727.0	1254.5	0.997	23.70	2.364	
4% PLASTIC - 5	1252.0	726.5	1256	0.997	23.70	2.358	
4% PLASTIC - 6	1251.5	725.5	1256	0.997	23.70	2.353	

Table 4.14: Bulk density values of 8% Plastic samples.

8% Plastic Mixture - Bulk Density (Pbssd)							
Sample Code	**m1 (dry weight) [g]**	**m2 (wet weight) [g]**	**m3 (SSD weigh) [g]**	**Pw [Mg/m3]**	**Water temperature [° C]**	**Pbssd (Mg/m3)**	**Average Pbssd (Mg/m3)**
8% PLASTIC - 1	1247.5	701.5	1256	0.997	23.70	2.244	2.273
8% PLASTIC - 2	1251	702.0	1261.5	0.997	23.70	2.230	
8% PLASTIC - 3	1245.5	712.0	1249.5	0.997	23.70	2.311	
8% PLASTIC - 4	1250.5	705.0	1256.5	0.997	23.70	2.262	
8% PLASTIC - 5	1252.5	712.0	1260	0.997	23.70	2.280	
8% PLASTIC - 6	1251	714.5	1255	0.997	23.70	2.309	

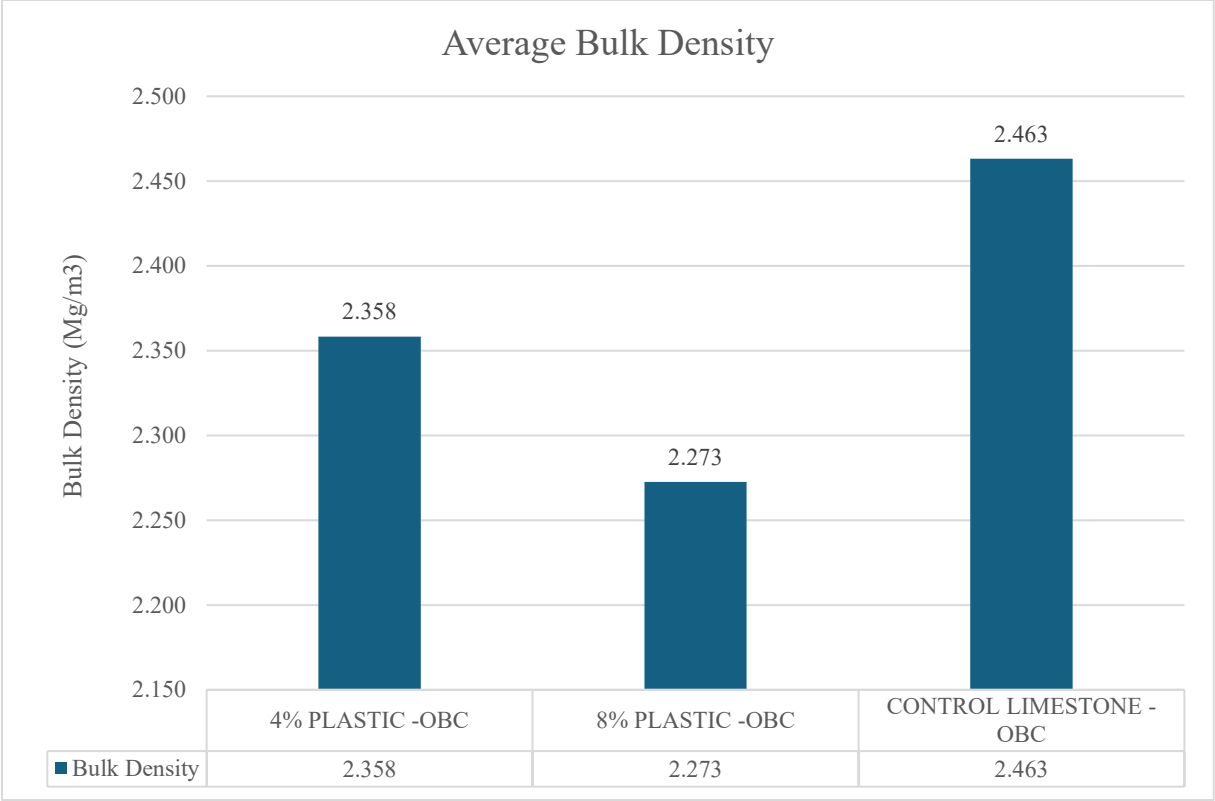

Figure 4.3: Comparison of average bulk density of the investigated asphalt mixtures.

4.3.3 Air Void Content

The average air void contents obtained for the investigated mixtures are summarized in Table 4.15. The control mixture exhibited an average air void content of 3.05%, whereas the mixtures containing 4% and 8% shredded cable insulation waste exhibited average air void contents of 3.19% and 3.15%, respectively.

As shown in Figure 4.4, only slight differences in air void content were observed among the mixtures investigated. The 4% plastic mixture exhibited the highest average air void content, while the 8% plastic mixture showed a slightly lower value, remaining close to that of the control mixture. Although the bulk density decreased with increasing plastic content, this reduction did not result in a proportional increase in the final air void content.

Overall, the incorporation of shredded cable insulation waste resulted in only minor changes in the air void content of the asphalt mixtures. All mixtures remained within a narrow range of air voids (3.05–3.19%), indicating that the selected plastic contents did not adversely affect the volumetric characteristics of the mixtures under the investigated laboratory conditions.

Table 4.15: Air void contents of investigated mixtures.

Sample Code	Bulk Density ρbssd (Mg/m3)	Maximum density ρ_{mc} (Mg/m3)	Void %	Average Void %
Control mixture-5.4%B- 1	2.456	2.541	3.33%	3.05%
Control mixture-5.4%B- 2	2.475		2.58%	
Control mixture-5.4%B- 3	2.465		2.98%	
Control mixture-5.4%B- 4	2.457		3.30%	
4% Plastic - 1	2.371	2.436	2.65%	3.19%
4% Plastic – 2	2.361		3.06%	
4% Plastic – 3	2.342		3.86%	
4% Plastic – 4	2.364		2.97%	
4% Plastic – 5	2.358		3.18%	
4% Plastic - 6	2.353		3.40%	
8% Plastic - 1	2.244	2.346	4.36%	3.15%
8% Plastic – 2	2.230		4.95%	
8% Plastic – 3	2.311		1.50%	
8% Plastic – 4	2.262		3.61%	
8% Plastic – 5	2.280		2.84%	
8% Plastic - 6	2.309		1.61%	

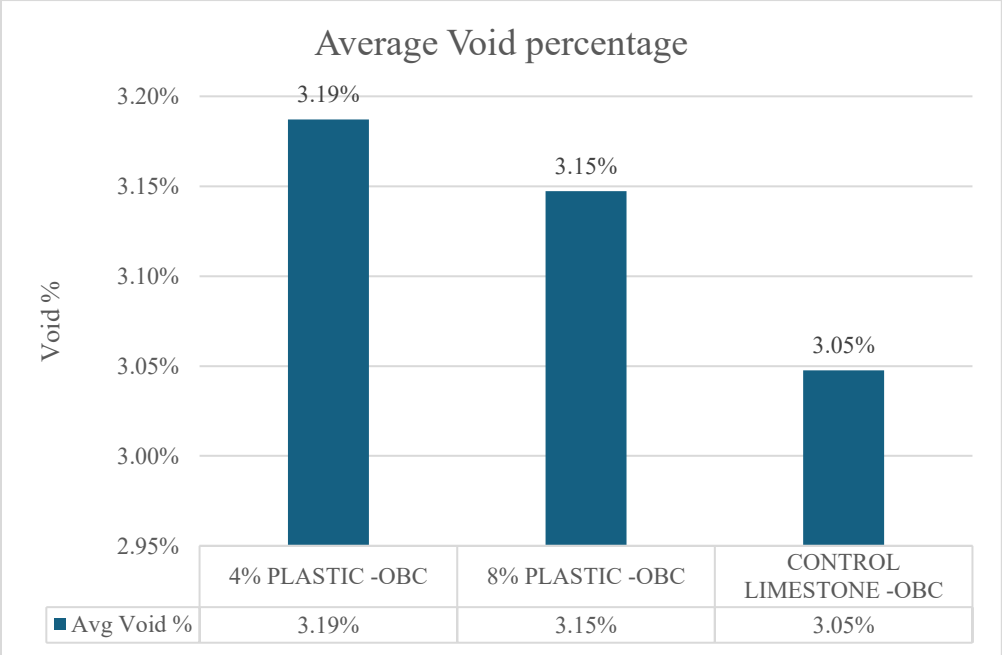

Figure 4.4: Comparison of average air void contents for the investigated mixtures.

4.4 Stiffness Characteristics

4.4.1 Indirect Tensile Stiffness Modulus (ITSM)

The stiffness characteristics of the asphalt mixtures were evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test conducted at 25°C. The stiffness modulus represents the ability of an asphalt mixture to resist deformation and distribute traffic loads within the pavement structure. The average ITSM values obtained for control and plastic-modified mixtures are presented in Table 4.16.

The control mixture exhibited an average stiffness modulus of 859 MPa. The incorporation of shredded cable insulation waste resulted in a noticeable reduction in stiffness, with average stiffness modulus values of 389 MPa and 332 MPa obtained for the mixtures containing 4% and 8% plastic, respectively. Compared with the control mixture, the stiffness modulus decreased by approximately 55% for the 4% plastic mixture and 61% for the 8% plastic mixture.

The relatively low stiffness modulus obtained for the control mixture may be associated with the soft consistency of the bitumen used in the experimental program. Although the binder grade was not formally verified, visual observations during mixture preparation and discussions with laboratory personnel suggested that the binder exhibited behaviour closer to a 70/100 penetration grade than a conventional 50/70 paving bitumen. Consequently, the ITSM values should be interpreted comparatively within the scope of the present study.

Table 4.16: Indirect Tensile Stiffness Modulus (ITSM)

Sample code	Stiffness Modulus (MPa)	ITSM Average (MPa)
Control mixture-5.4%B- 1	1183	859.00
Control mixture-5.4%B- 2	1076	
Control mixture-5.4%B- 3	543	
Control mixture-5.4%B- 4	634	
4% Plastic - 1	353	388.67
4% Plastic - 2	523	
4% Plastic - 3	277	
4% Plastic - 4	396	
4% Plastic - 5	301	
4% Plastic - 6	482	
8% Plastic - 1	168	331.50
8% Plastic - 2	169	
8% Plastic - 3	606	
8% Plastic - 4	500	
8% Plastic - 5	318	
8% Plastic - 6	228	

The incorporation of shredded cable insulation waste further reduced the stiffness of the asphalt mixtures. Since the average air void contents of all mixtures remained similar (3.05–3.19%), the reduction in stiffness cannot be attributed solely to changes in volumetric properties. Instead, the decrease is likely associated with the relatively flexible nature of the shredded plastic particles and the weaker interaction between the plastic and the bituminous matrix when incorporated using the dry process. These factors may have reduced the overall rigidity of the mixtures, resulting in lower stiffness modulus values.

Furthermore, increasing the plastic content from 4% to 8% produced an additional reduction in stiffness, indicating that higher proportions of shredded cable insulation waste further decreased the resistance of the mixtures to elastic deformation. This trend suggests that, under the conditions investigated, increasing plastic content had a progressively greater influence on reducing mixture stiffness.

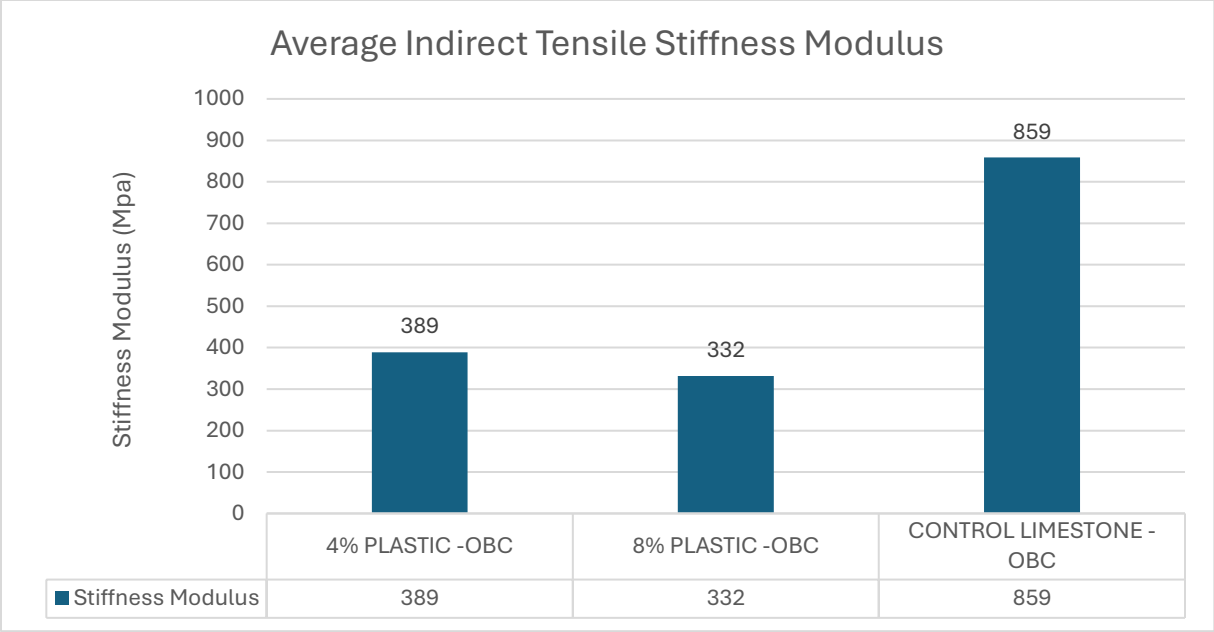

Figure 4.5: Comparison of average Indirect Tensile Stiffness Modulus (ITSM) of investigated asphalt mixtures.

Overall, the results indicate that the incorporation of shredded cable insulation waste reduced the stiffness characteristics of the investigated asphalt mixtures. Although the plastic-modified mixtures exhibited similar air void contents to the control mixture, the progressive reduction in stiffness with increasing plastic content highlights the importance of optimizing plastic dosage to achieve an appropriate balance between environmental sustainability and mechanical performance.

4.5 Tensile Strength

4.5.1 Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test was performed to evaluate the tensile properties and cracking resistance of the asphalt mixtures. The average dry ITS values obtained for the control and plastic-modified mixtures are presented in Table 4.17.

The control mixture exhibited the highest average dry ITS value of 1.02 MPa. The incorporation of shredded cable insulation waste reduced the tensile strength of the asphalt mixtures, with average ITS values of 0.62 MPa and 0.45 MPa obtained for the mixtures containing 4% and 8% plastic, respectively. Compared with the control mixture, the tensile strength decreased by approximately 39% for the 4% plastic mixture and 56% for the 8% plastic mixture.

Table 4.17: Indirect Tensile Strength (ITS) results for dry asphalt specimens tested at 25°C.

Sample code	d_{mean} (mm)	h_{mean} (mm)	P_{max} (kN)	ITS (MPa)	Average ITS (MPa)	Displacement (mm)
4% Plastic - 1	100.30	67.75	6.359	0.60	0.62	3.803
4% Plastic - 3	100.67	68.85	6.371	0.59		4.103
4% Plastic - 5	100.39	68.69	7.442	0.69		3.560
8% Plastic - 1	100.85	71.05	4.865	0.43	0.45	4.822
8% Plastic - 2	102.19	71.88	4.454	0.39		5.616
8% Plastic - 6	100.54	69.94	5.986	0.54		5.175
Control mixture-5.4%B- 2	100.21	64.42	10.171	1.00	1.02	3.541
Control mixture-5.4%B- 3	100.45	64.42	10.523	1.04		3.015

Table 4.18: Indirect Tensile Strength (ITS) results for water-conditioned specimens at 40°C.

Sample code	d_{mean} (mm)	h_{mean} (mm)	P_{max} (kN)	ITS (MPa)	Average ITS (MPa)	Displacement (mm)
4% Plastic – 2	100.51	68.36	2.168	0.20	0.24	4.321
4% Plastic – 4	100.47	67.77	2.795	0.26		4.054
4% Plastic – 6	100.57	68.49	2.691	0.25		4.249
8% Plastic – 3	100.52	70.26	2.348	0.21	0.20	5.707
8% Plastic – 4	100.60	71.25	2.338	0.21		5.423
8% Plastic – 5	100.63	71.95	2.220	0.20		5.257
Control mixture-5.4%B- 1	100.28	64.97	3.801	0.37	0.34	4.052
Control mixture-5.4%B- 4	100.07	65.24	3.197	0.31		4.484

The reduction in tensile strength cannot be attributed solely to changes in air void content, as all mixtures exhibited similar average air void contents (approximately 3.1%). Instead, the reduction is likely associated with the incorporation of shredded cable insulation particles, which may have weakened the internal bonding between the aggregate skeleton and the bituminous binder when incorporated using the dry process. Consequently, the mixtures exhibited lower resistance to tensile loading as the plastic content increased.

In addition to the reduction in tensile strength, the average displacement at failure increased from 3.28 mm for the control mixture to 3.82 mm and 5.20 mm for the mixtures containing 4% and 8% plastic, respectively. This increase indicates that the plastic-modified mixtures underwent greater

deformation before failure, suggesting a more flexible response under tensile loading. Although increased flexibility may improve strain tolerance, it was accompanied by a substantial reduction in tensile strength.

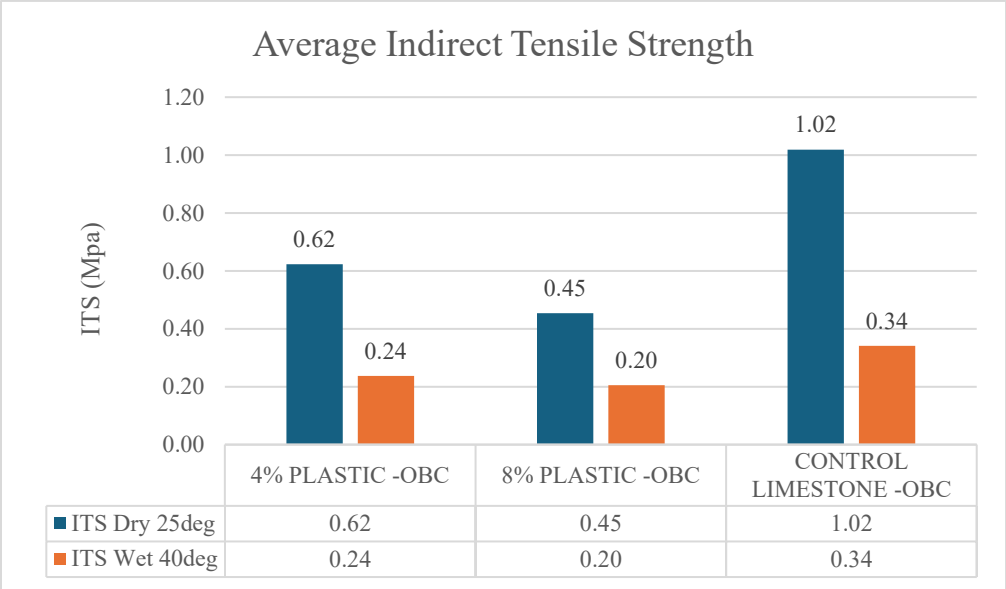

Figure 4.6: Comparison of average Indirect Tensile Strength (ITS) of investigated asphalt mixtures under dry and water-conditioned testing conditions.

The indirect tensile strengths of the water-conditioned specimens tested at 40°C are presented in Table 4.18. As expected, the conditioned specimens exhibited lower tensile strengths than the corresponding dry specimens due to the combined influence of moisture conditioning and the higher testing temperature. The average conditioned ITS values were 0.34 MPa, 0.24 MPa, and 0.20 MPa for the control, 4% plastic, and 8% plastic mixtures, respectively. Similar to the dry ITS results, tensile strength decreased with increasing plastic content, indicating that the incorporation of shredded cable insulation waste reduced the resistance of the mixtures to tensile loading under the conditioning and testing conditions adopted in this study.

Overall, the results indicate that the incorporation of shredded cable insulation waste reduced the indirect tensile strength while increasing the deformation at failure of the asphalt mixtures. The control mixture exhibited the greatest resistance to tensile loading, whereas the mixture containing 8% plastic showed the lowest tensile strength and the highest displacement, indicating that excessive plastic incorporation adversely affected the tensile performance of the mixtures.

4.6 Overall Discussion

The experimental results demonstrate that the incorporation of shredded cable insulation waste influenced the volumetric and mechanical behaviour of the Hot Mix Asphalt mixtures. The aggregate characterization confirmed that the limestone aggregates possessed suitable physical and mechanical properties for asphalt mixture production, including favourable particle shape, low flakiness, high cleanliness, and good resistance to fragmentation. The selected aggregate gradation also satisfied the specified grading envelope, providing a suitable aggregate skeleton for mixture preparation.

The incorporation of shredded cable insulation waste reduced the bulk density of the asphalt mixtures because of the lower density of the plastic particles compared with the mineral aggregates. However, only minor changes in air void content were observed, with all mixtures exhibiting average air void contents of approximately 3%. This indicates that, despite the reduction in density, the selected plastic contents did not significantly affect the overall compactability or volumetric characteristics of the mixtures.

In contrast, the mechanical properties were considerably influenced by the addition of plastic waste. Both the Indirect Tensile Stiffness Modulus (ITSM) and the Indirect Tensile Strength (ITS) decreased progressively with increasing plastic content. The reduction in stiffness and tensile strength is considered to be primarily associated with the relatively flexible nature of the shredded cable insulation particles and their interaction with the bituminous matrix when incorporated using the dry process. Since the air void contents remained similar for all mixtures, the observed reductions in mechanical performance cannot be attributed solely to changes in volumetric properties.

The displacement measured during the ITS test increased with increasing plastic content, indicating that the plastic-modified mixtures exhibited greater deformation before failure. This behaviour suggests that the incorporation of shredded cable insulation waste increased the flexibility of the mixtures while simultaneously reducing their resistance to tensile loading. Although increased flexibility may improve the ability of asphalt mixtures to accommodate strain, excessive reductions in stiffness and tensile strength may adversely influence pavement performance under traffic loading.

Overall, the experimental results indicate that shredded cable insulation waste can be successfully incorporated into Hot Mix Asphalt mixtures using the dry process. Nevertheless, increasing the plastic content from 4% to 8% resulted in a further reduction in mechanical performance without providing a corresponding improvement in volumetric characteristics. Therefore, among the mixtures investigated, the 4% plastic mixture exhibited a more balanced performance and appears to represent a more suitable plastic content for further investigation and potential engineering applications.

4.7 Summary

This chapter presents the experimental results obtained for the aggregate characterization, volumetric properties, and mechanical performance of conventional and plastic-modified Hot Mix Asphalt mixtures incorporating shredded cable insulation waste.

The aggregate characterization confirmed that the limestone aggregates satisfied the required physical and mechanical properties for asphalt mixture production. The selected aggregate gradation complied with the specified grading limits and provided a suitable aggregate skeleton for mixture preparation.

The incorporation of shredded cable insulation waste reduced the bulk density of the asphalt mixtures, while only minor variations in air void content were observed among the investigated mixtures. In contrast, both the Indirect Tensile Stiffness Modulus and the Indirect Tensile Strength decreased with increasing plastic content, whereas the displacement at failure increased, indicating a more flexible but mechanically weaker mixture.

Overall, the results demonstrate that the addition of shredded cable insulation waste influenced the mechanical behaviour of asphalt mixtures more significantly than their volumetric characteristics. Although all plastic-modified mixtures remained suitable for laboratory evaluation, increasing the plastic content beyond 4% resulted in a noticeable reduction in stiffness and tensile strength. The environmental performance of the investigated mixtures is evaluated in the following chapter through laboratory leaching tests.

5. ENVIRONMENTAL ASSESSMENT

5.1 Introduction

The use of waste-derived materials in asphalt mixtures has attracted increasing attention as a sustainable approach for reducing landfill disposal and promoting circular economy principles. However, the incorporation of recycled materials into pavement applications requires an evaluation of their environmental performance to ensure that harmful substances are not released into the surrounding environment during service life.

One of the principal environmental concerns associated with recycled materials is the potential leaching of contaminants when exposed to water. Although bituminous binders generally act as an encapsulating medium that limits the mobility of chemical constituents, the possible release of contaminants from asphalt mixtures containing waste materials must be assessed experimentally.

In the present study, the environmental performance of conventional and plastic-modified Hot Mix Asphalt (HMA) mixtures was evaluated through laboratory leaching tests. The objective was to investigate the potential release of selected heavy metals from mixtures containing shredded cable insulation waste and to assess their environmental suitability. The measured leaching results were subsequently compared with the regulatory concentration limits specified in Italian Ministerial Decree D.M. 186/2006 (Allegato 3) to evaluate the environmental performance of the investigated mixtures.

5.2 Leaching Behaviour

5.2.1 Leaching Test Procedure

Leaching tests were conducted in accordance with the principles of BS EN 12457-2. Following completion of the mechanical testing, the asphalt specimens were crushed and sieved, and the fraction passing the 4 mm sieve was retained for leaching analysis.

Approximately 91–92 g of material was weighed for each sample and transferred into glass bottles. Subsequently, 1 L of distilled water was added to each bottle, resulting in a liquid-to-solid ratio of approximately 11 L/kg. The bottles were tightly sealed and placed vertically on a laboratory shaker for 24 h to ensure continuous contact between the asphalt material and the leaching solution.

Figure 5.1: (A) Prepared samples before agitation (B) Samples after 24 hr of agitation (C) Leachate after vacuum filteration

After the agitation period, the bottles were removed from the shaker and allowed to stand for a short period to facilitate the settlement of coarse particles. Following settlement, the liquid phase was separated from the solid residue by vacuum filtration. The collected eluates were transferred into clean containers and subsequently analyzed for selected heavy metals, including barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), vanadium (V), and zinc (Zn).

Two replicate samples were tested for each mixture type, including the control mixture, the mixture containing 4% and 8% of shredded cable insulation waste. The average values obtained from the replicate tests were used for the environmental assessment.

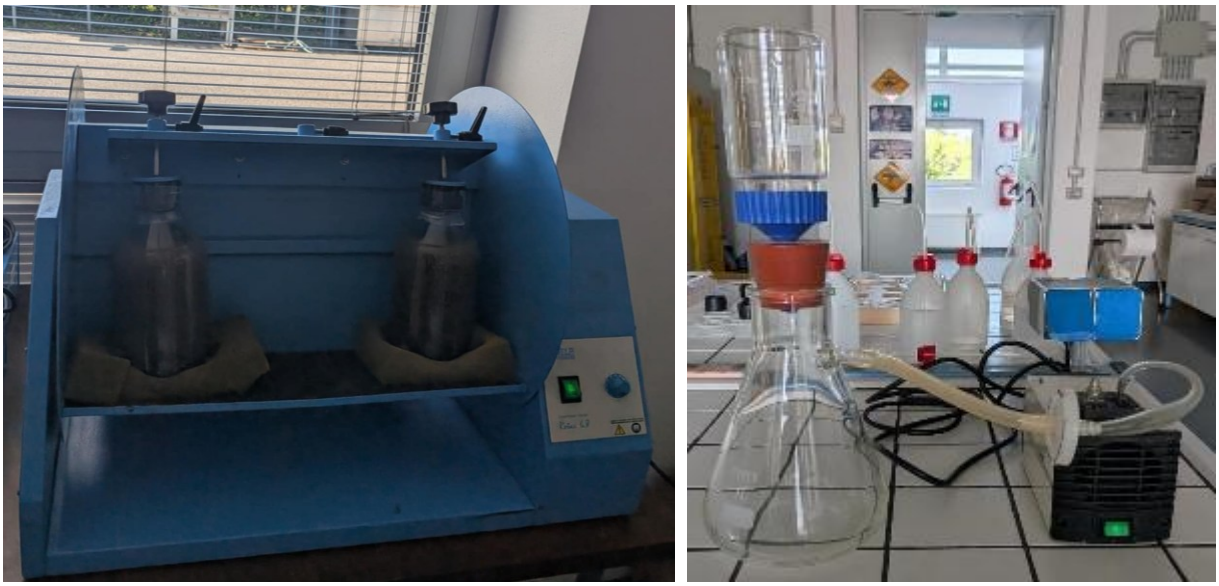

Figure 5.2: Experimental setup for the leaching test, including the laboratory shaker and vacuum filtration apparatus.

5.2.2 Leaching Results

The concentrations of selected heavy metals measured in the eluates are presented in Table 5.1. The reported values represent the average concentrations obtained from the replicate tests for each mixture.

The results indicate generally low concentrations of all investigated elements. Most metals were below the analytical detection limit of 10 µg/L for all mixtures. Detectable concentrations were primarily observed for barium, vanadium, and zinc.

Among the analyzed elements, zinc exhibited the highest concentration, reaching 28.6 µg/L in the mixture containing 8% shredded cable insulation waste. However, the measured concentrations remained relatively low for all investigated mixtures. The results further indicate that the incorporation of cable insulation waste did not result in substantial increases in heavy metal release compared with the control mixture.

Table 5.1: Heavy metal concentrations measured in the leachates.

Leaching Test Results								Average		
Sample		Control Mixture -OBC-5.4%	Plastic 4%	Plastic 8%	Control Mixture-OBC-5.4%-D	Plastic 4%-D	Plastic 8%-D	Control Mixture-OBC-5.4%	Plastic 4%	Plastic 8%
Weight (g)		91.2	91.6	91.2	91.2	91.4	91.2	91.2	91.5	91.2
Components (µg/L)	Ba	< 10	< 10	11.7	< 10	10.4	12.6	< 10	**10.4**	**12.2**
	Be	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Cd	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Co	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Cr	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Cu	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Ni	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	Pb	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
	V	11.5	11.6	10.6	12.2	11.2	< 10	**11.9**	**11.4**	**10.6**
	Zn	17.5	< 10	28.6	< 10	< 10	< 10	**17.5**	< 10	**28.6**

The generally low concentrations observed in the leachates suggest that the asphalt matrix effectively restricted the mobility of the investigated elements. The bituminous binder appears to provide an encapsulating effect that limits direct contact between the waste particles and the leaching medium, thereby reducing contaminant release.

5.2.3 Comparison with Regulatory Limits

The average concentrations of the investigated heavy metals measured in the leachates were compared directly with the regulatory concentration limits specified in Italian Ministerial Decree D.M. 186/2006 (Allegato 3). Since the analytical results were reported in units of µg/L, the regulatory limits originally expressed in both mg/L and µg/L were converted to a common unit (µg/L) to facilitate direct comparison. The comparison is presented in Table 5.2.

The measured concentrations of all investigated elements were generally well below the corresponding regulatory concentration limits. Barium concentrations ranged from 10.4 to 12.2 µg/L, considerably lower than the regulatory limit of 1000 µg/L. Similarly, zinc concentrations ranged from below the analytical detection limit to 28.6 µg/L, remaining substantially below the regulatory limit of 3000 µg/L. Vanadium concentrations ranged from 10.6 to 11.9 µg/L, which is also well below the regulatory limit of 250 µg/L.

Table 5.2: Comparison of leaching results with regulatory limits.

Sample		Control Mixture-OBC-5.4%	Plastic 4%	Plastic 8%	Regulatory Concentration Limit (µg/L)
Weight (g)		**91.2**	**91.5**	**91.2**	
Components (µg/L)	**Ba**	< 10	10.4	12.2	1000 µg/L
	Be	< 10	< 10	< 10	10 µg/L
	Cd	< 10	< 10	< 10	5 µg/L
	Co	< 10	< 10	< 10	250 µg/L
	Cr	< 10	< 10	< 10	50 µg/L
	Cu	< 10	< 10	< 10	50 µg/L
	Ni	< 10	< 10	< 10	10 µg/L
	Pb	< 10	< 10	< 10	50 µg/L
	V	11.9	11.4	10.6	250 µg/L
	Zn	17.5	< 10	28.6	3000 µg/L

The concentrations of beryllium, cobalt, chromium, copper, nickel, and lead were either below or equal to the analytical detection limit of 10 µg/L, indicating negligible release of these elements from both the control and plastic-modified asphalt mixtures. No significant increase in heavy metal release was observed following the incorporation of shredded cable insulation waste, demonstrating that the addition of 4% and 8% plastic waste did not adversely affect the environmental performance of the mixtures under the laboratory conditions investigated.

Cadmium concentrations were reported below the analytical detection limit of 10 µg/L. However, since the regulatory concentration limit specified in D.M. 186/2006 is 5 µg/L, compliance for cadmium cannot be conclusively verified based on the available analytical detection limit. Nevertheless, cadmium was not detected in any of the investigated mixtures.

Overall, the comparison indicates that the concentrations of the investigated heavy metals remained substantially below the applicable regulatory concentration limits. These findings suggest that the asphalt binder effectively encapsulated the shredded cable insulation waste, limiting the mobility of potentially hazardous constituents and providing favourable environmental performance under the laboratory conditions considered in this study.

5.3 Summary

This chapter presents the environmental assessment of conventional and plastic-modified Hot Mix Asphalt (HMA) mixtures containing shredded cable insulation waste. Laboratory leaching tests were conducted on crushed asphalt specimens to evaluate the potential release of selected heavy metals.

The measured concentrations of the investigated elements were generally low, with most metals remaining below the analytical detection limit. Detectable concentrations were primarily observed for barium, vanadium, and zinc; however, the measured values remained well below the applicable regulatory concentration limits. Comparison with the concentration limits specified in Italian Ministerial Decree D.M. 186/2006 (Allegato 3) indicated that the investigated mixtures complied with the regulatory requirements for all assessed elements. However, compliance for cadmium could not be conclusively verified because the analytical detection limit exceeded the regulatory concentration limit.

Overall, the results indicate that the incorporation of shredded cable insulation waste did not result in significant heavy metal release and that the asphalt binder effectively restricted contaminant mobility through encapsulation. Consequently, the investigated plastic-modified asphalt mixtures demonstrated favourable environmental performance and showed potential as a sustainable alternative for the utilization of non-recyclable cable insulation waste in pavement applications.

6. CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

This study investigated the feasibility of incorporating shredded non-recyclable cable insulation waste into Hot Mix Asphalt (HMA) mixtures using the dry process. Conventional HMA was compared with mixtures containing 4% and 8% shredded cable insulation waste to evaluate the influence of plastic addition on the volumetric, mechanical, and environmental performance of the asphalt mixtures.

The aggregate characterization confirmed that the limestone aggregates satisfied the relevant specification requirements for asphalt mixture production. The selected aggregate gradation also complied with the specified grading limits, providing a suitable aggregate skeleton for the preparation of both conventional and plastic-modified mixtures.

The incorporation of shredded cable insulation waste reduced the bulk density of asphalt mixtures because of the lower density of the plastic particles compared with the mineral aggregates. However, only minor differences in air void content were observed among the investigated mixtures, indicating that the selected plastic contents had a limited influence on the volumetric characteristics of the mixtures.

The mechanical performance of the asphalt mixtures was influenced by the incorporation of shredded cable insulation waste. Both the Indirect Tensile Stiffness Modulus (ITSM) and the Indirect Tensile Strength (ITS) decreased with increasing plastic content, while the displacement at failure increased. These results indicate that the addition of plastic produced mixtures with greater deformability but reduced stiffness and tensile resistance. Among the investigated mixtures, the 4% plastic mixture exhibited a more balanced performance than the mixture containing 8% plastic.

The environmental assessment demonstrated favourable leaching behaviour for both conventional and plastic-modified asphalt mixtures. Laboratory leaching tests indicated generally low concentrations of the investigated heavy metals, with most elements remaining below the analytical detection limit. Comparison with the regulatory concentration limits specified in Italian Ministerial Decree D.M. 186/2006 (Allegato 3) showed that the measured concentrations were substantially below the applicable limits for the assessed elements. These findings indicate that the

asphalt binder effectively encapsulated the shredded cable insulation waste and limit the release of potentially hazardous constituents under the laboratory conditions investigated.

Overall, the results demonstrate that shredded cable insulation waste can be incorporated into Hot Mix Asphalt mixtures using the dry process without causing significant environmental concerns under laboratory conditions. However, increasing the plastic content reduced the mechanical performance of the mixtures, indicating that careful optimization of plastic dosage is required. Based on the results obtained in this study, the mixture containing 4% shredded cable insulation waste provided a more favourable balance between environmental acceptability and engineering performance than the mixture containing 8% plastic.

6.2 Limitations of the Study

The present study was conducted under controlled laboratory conditions and should therefore be interpreted within the scope of experimental program undertaken. Several limitations should be acknowledged.

The density of the shredded cable insulation waste was estimated from published literature because direct laboratory measurement of the material density was not available during the study. Although this assumption enabled the volumetric calculations to be completed, determination of the actual density of the plastic waste would improve the accuracy of future analyses.

The mechanical evaluation was limited to bulk density, air void content, Indirect Tensile Stiffness Modulus (ITSM), and Indirect Tensile Strength (ITS). Other important pavement performance characteristics, including rutting resistance, fatigue performance, low-temperature cracking resistance, and long-term ageing behaviour, were beyond the scope of present investigation.

In addition, the environmental assessment was based on short-term laboratory leaching tests. Although the results demonstrated favourable environmental performance, long-term field exposure, weathering, traffic loading, and ageing may influence contaminant release over the service life of asphalt pavements.

6.3 Recommendations for Future Research

Based on the findings of this study, the following recommendations are proposed for future research:

- Determine the physical properties of shredded cable insulation waste, including its particle density and chemical composition, prior to mixture design.
- Investigate additional plastic contents between 4% and 8% to identify the optimum dosage for balancing mechanical and environmental performance.
- Evaluate the influence of shredded cable insulation waste on additional pavement performance properties, including rutting resistance, fatigue life, moisture susceptibility, and low-temperature cracking.
- Assess the long-term environmental performance of plastic-modified asphalt mixtures through extended leaching studies under ageing and field exposure conditions.
- Field trials to evaluate the in-service performance of plastic-modified asphalt mixtures under actual traffic and environmental conditions.

The findings of this study contribute to the growing body of knowledge on the sustainable utilization of non-recyclable plastic waste in road construction and demonstrate the potential of shredded cable insulation waste as an alternative material for Hot Mix Asphalt applications when appropriate mixture design and plastic dosage are adopted.

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