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Innovative Modified Stone Mastic Asphalt Concretes Containing Composite Poly-functional Fibres for Eco-friendly Paving Applications

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Esame finale anno 2019

To my supportive family

A B S T R A C T

In the present research, a complete study was carried out investigating the effectiveness of novel cellulose-based poly-functional fibres in enhancing the mechanical and performance properties of a virgin and 25% RAP containing Stone Mastic Asphalt (SMA). Therefore, there could be a significant economic advantage and a well-balanced solution between eco sustainability and technology in using RAP in SMA, if it could be used without sacrificing the excellent performance of SMA mixtures. The fibres modification was carried out by adding mineral (glass) fibre, a type of Plastomeric polymer and/or powdered tire rubber. The mix of mineral fibres and rubber with polymeric component was supposed to perform similarly to the regular bitumen modifiers improving the dynamic/mechanical performance of the bituminous binders. The fibrous component contributes to further improving the rheological and thixotropic behaviour of the bituminous mastic. The test program included numerous tests in both binder and mixture-scale in addition to primary microscopic analysis providing a wide range of data to achieve a complete understanding of fibre interaction with binder and its performance in asphalt mixtures. For this purpose, four different cellulose-based fibres (with and without powdered crumb inside), a 50/70 penetration graded neat bitumen, and a 10/40-70 SBS PmB were used to produce the bituminous compounds and mixtures to be investigated through the experimental works. Overall, the results indicate the possibility of modifying asphalt mixtures via modified fibres and the superiority of rubberized fibres in comparison to those of non-rubberized. However, the rubberized mixtures needed enough digestion and interaction temperature and time. In addition, it has been found that while the substitution of 25% virgin materials with RAP could enhance some of the dynamic mechanical properties of SMA, the low-temperature thermal cracking sensitivity increased for all the tested RAP containing mixtures with different fibres rather than the type of modification.

Keywords:

Recycled Asphalt Pavement (RAP); Polymer modified bitumen (PmB); Stone Mastic Asphalt (SMA); Modified fibre; Rubberized fibre; Mechanical and performance properties; Thermal cracking sensitivity.

A C K N O W L E D G M E N T

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INTRODUCTION AND OVERVIEW

CHAPTER 1 INTRODUCTION AND OVERVIEW

1.1 Foreword and Background

Sustainable pavements for heavy-duty roads

Demands for high-performance pavements due to ever-increasing traffic loads become more crucial considering the sustainability principles. In addition, the problem becomes more complicated once severe climate aggravates the rate of erosion in some regions. Hence, conventional Hot Mix Asphalts (HMA) with neat bitumen cannot respond to the current inevitable heavy traffic flow loadings. Although the term, heavy-duty pavement has been defined differently in many countries, European Asphalt Pavement Association (EAPA) defines it as the roads, which carry at least 10% to 20% Heavy Goods Vehicles (HGV) and HGV lanes that carry 3000 to 5000 HGVs/day, crawler lanes carrying 0.3 million 80 kN standard axles/year or sites that have static loads of over 1 N/mm² [1]. For such occasions, Stone Mastic Asphalt (SMA) mixtures are known as a primary alternative construction material for heavy-duty load highway pavements due to its inherent structure. During the decades SMA mixtures have been introduced to asphalt pavement construction industries with reportedly superior mechanical and performance properties in comparison to the conventional HMA. SMA has been applied on heavily trafficked roads, on airports, both on runways and taxiways, in harbour areas and for industrial use e. g. loading and unloading zones, parking lots and etc. In particular high rutting resistance, lower noise emission and improved moisture sensitivity performance are some of the remarkable characteristics of SMA mixture. SMA can be paved in several thicknesses well-suited for all needs of redesigning, repair works and rehabilitation. Good initial skid resistance and an improved optical appearance plus the possibilities of adding pigments or coloured aggregates make SMA also attractive pavements.

In this respect, the development of different types of Polymer modified Binders (PmB) and stabilizing fibres, could improve the low tensile strength of SMA mixture, made it an ideal durable asphalt mixture for highway pavements. On the other side, despite many identified advantages of SMA mixtures, the needed high bitumen content, high-quality coarse aggregates, and stabilizing fibres made the initial construction costs higher in comparison to conventional HMA mixtures. Therefore the use of waste materials can be the most convenient way of reducing the primary production costs.

From another point of view, the tripartite concept of sustainability in terms of environment, economic and social/technical principles (Fig.1.1) for the extended highway networks has prompted to use more than ever waste materials and apply new technologies in pavement industry aimed for more durable pavements. Regarding pavement materials, Reclaimed Asphalt Pavement (RAP), End of Life Tires (ELT), waste plastics, and industry fillers have been some of the practiced efforts during the last decades. Among the introduced materials, RAP and ELTs have been more interests of decision makers due to rapidly increasing costs of bitumen and limited landfill spaces considering the environmental principles.

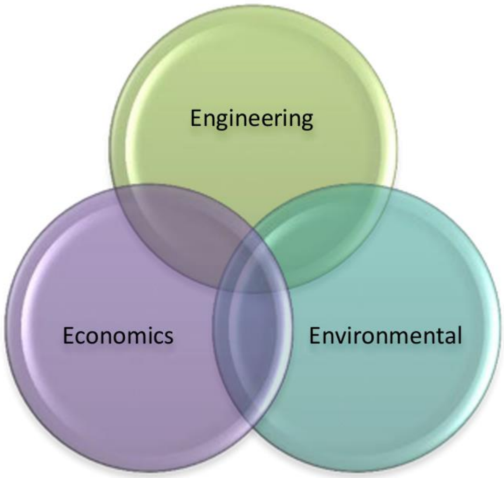

Fig. 1.1. The three key benefits of recycled/reused materials in road pavements and sustainability [2].

With the successful experience of the last two decades and development of different effective rejuvenators, nowadays the RAP portion in the asphalt mixtures increased significantly. Both laboratory and practical data reported acceptable and in some cases even improved values for recycled asphalt mixtures except for the minor concerns on the imposed stiffness and later reduced fatigue resistance. The methods of compensating the aged, stiff binder and ensuring adequate pavement performance include the use of rejuvenator or softening additives, use of soft virgin binder grade and increase in total mixture binder content. In overall, using RAP reduces the amount of costly new asphalt binder required in the production of asphalt paving mixtures. However for higher RAP content (above 25%), design and production take extra effort, but the savings in using the higher RAP contents significantly outweigh the added costs [3].

Similar to RAP, at one time, the push to use tires in asphalt seemed to primarily be just a means of getting rid of piles of scrap tires. But now, the emphasis of using tires in asphalt binder is to improve pavement performance. There are mainly three adopted methods developed for creating rubberized asphalt pavements:

- *Dry process;* refers to mixing crumb rubber into the mixture as a small part of the aggregates, filler or additive rather than blending the rubber with the liquid asphalt. This process is normally only applicable to hot mix applications.

- *Wet process;* refers to blending or reacting the crumb rubber with the liquid asphalt at elevated temperatures before incorporating the resulting binder for use in an asphalt paving or surfacing application.
- *Terminal blending* of rubberized asphalt. For this, tire rubber is blended into the asphalt binder at the asphalt terminal or refinery and shipped to the asphalt production plant as a finished binder, with no additional handling or processing required. The tire rubber is incorporated into the asphalt to provide styrene butadiene carbon black and aromatic oils yielding a stable, homogenous material.

Each of these methods will result in rubberized asphalt pavements with different properties and different performances [2]. Agencies need to understand these differences so they can make a choice on the type of process that will perform best for their desired application.

Fibres, former stabilizers, new modifiers

Early decades were known as binder drainage control solution especially for the gap and open-graded asphalt mixtures, nowadays fibres are expected to provide adjacent benefits in addition to its stabilizing roles. Scientific efforts made understanding the mechanism of fibre in different types of asphalt mixtures and binders led to introduce a new generation of fibres known as poly-functional fibres. These types of fibres are usually a mix of two or more reinforcing materials such glass, plastics, rubber, and low softening point polymers. These ultra-treated fibres, namely Modified Fibres (MFs) work as modifiers, producing Modified Asphalt mixtures (MAs) with improved mechanical and performance properties as well as their mixture stabilizing genuine. The technique provides an opportunity to benefit the individual feature of each material together. For instance, while glass fibre has low potential in binder absorption, the presence of it can make a three-dimensional network with the binder and further improvements. On the contrary, it has been shown that cellulose fibres with high potentials of bitumen absorption have no or marginally effects on the mechanical properties of asphalt mixtures (in particular open and dense-graded mixtures).

From another perspective, the production of modified asphalt mixtures is very flexible: it can take place at any given moment to the degree of modification required. This allows the asphalt producer to organize raw materials in the most efficient way possible [4]. In practice, the modified fibres partially or completely replace the use of modified bitumen and, in addition, are specialized depending on the type of work and specifications. For this reason, they are considered an innovative improvement in work offers.

In addition, the concept of blended fibre pellets provided a new technique for incorporating the useful waste materials in asphalt mixtures. Incorporation of waste glass powder, ELTs, and some by-product materials are some of the potential eco-friendly materials. Overall to date the few valid successful reports available on the use of poly-functional fibres in modifying asphalt mixtures are quite promising. While the use of fibres in dense and open-graded mixtures is common, opportunities exist to use the poly-functional fibres with other benefits more than binder drainage control.

1.2 Problem Statement

The increasing demand for sustainable asphalt products requires a move towards the higher use of cost-effective and green alternatives, including the use of high asphalt binder replacement from using RAP and new eco-friendly modification approaches. While nowadays incorporation of RAP into asphalt mixtures is a common green strategy, as for SMA has not defined yet. This is due to the concerns related to the tensile properties and durability of recycled SMA as well as to continuous grading of RAP aggregates.

On the other hand, while the effectiveness of different kinds of PmBs on the asphalt pavement performance is undeniable, several technical deficiencies have been reported as well as high costs and environmental impacts related to production procedure and implementation of PmBs. From the technical point of view, every type of modification is well suited for specific application temperature range and may not act out of it. The problem will get more significant with the severe climates experiencing radical min/maximum temperatures. This may consider as one of the deficiencies of PmBs form technical point of view.

In addition, considering the environmental aspects, manufacturing, storing, and the use of PmBs consume a considerable amount of energy. Regarding the PmB manufacturing, high temperature (depend on the type of polymer) is usually needed with shear mixers producing a homogenous compatible structure. As for asphalt mixture production with PmBs, the high viscosity of PmBs requires a high temperature for reducing the viscosity needed for producing homogenous asphalt mixtures.

As a new approach, direct incorporation of additives such as low softening point polymers and poly-functional fibres into asphalt mixtures was recently introduced and found effective reported in few existing research and field practices in this regard. In particular, as for gap-graded and open-graded mixtures, the idea is to modify the fibres to benefit more than stabilizing characteristics. This could be achieved by adding polymers and modifiers to the stabilizing agent of fibres, make it as a poly-functional system aimed for improving mechanical/performance properties of asphalt mixtures besides binder drainage control. It is believed that the polymeric component performs an action similar to the modifiers increasing the complex modulus. The fibrous component contributes to further improving the rheological and thixotropic behaviour of the bituminous mastic, giving a better distribution of the binder and an increase of the film thickness on the aggregates, with consequent increase of the stability and the mechanical characteristics of the final mix. Known as Modified Asphalt (MA) technology, the direct addition of additives offers logistic advantages and therefore cost benefits. In addition, poly-functional fibres make storage of PmB binders on asphalt production plants unnecessary or avoid high investments in a range of storage tanks for various bitumen types. In some cases, high energy costs for hot storage of modified bitumen are avoided or significantly reduced. These result in a considerable economic, energy and time saving, and allows the application even in the most remote places, not equipped with industrial facilities.

However, despite many studies on PmB modification of different types of asphalt mixtures, there has been a lack of researches on the efficiency of direct addition of these poly-functional systems into asphalt mixtures. Studies on the latest research works on fibre-reinforced asphalt mixtures show that the relative benefits and issues with these various types of fires were not well-documented. This is mainly due to scholars' interest to follow sophisticated laboratory protocols and normalized specifications regarding modified asphalts rather than employing off-standardized approaches.

1.3 Objectives

The scope of the research work presented herein includes:

- providing a synthesis on reviewing the existing literature and the most recent scientific research works on the asphalt concrete modification/reinforcement via a new generation of fibres, innovations and proven findings in this respect.

- Investigating the feasibility of asphalt mixture modification via composite polymer-added fibres and comparing the tests results with commonly used PmB mixtures.

- Development of a full-scale study to compare and characterise a commonly used SMA mixture produced with SBS PmB and conventional fibres with SMA mixtures modified with composite fibres containing plastomeric polymer by conducting a full-scale experimental program.

- Examining the effectiveness of rubberized fibres with ELTs as a new eco-friendly approach beyond the commonly used dry and wet method, aiming for developing a more economical and practical alternative.

- Study the SBS/Rubber interaction in mixtures produced with SBS PmB and rubberized poly-functional fibres.

- Evaluate the mechanical and performance properties of SMA mixtures containing RAP aggregates, modified via binder or fibre.

1.4 Research Plan

The presented research was conducted in four main stages, as shown in Fig. 1.2 as a comprehensive laboratory scale research. The experimental plan included a primary stage of mix design, which completed by prequalification tests. The mechanical and performance tests on optimized mixtures were divided into binder and mixture scales as well as primary stage microscopic analysis on fibres micro-structure and texture. The tests have been organised in order to provide a wide range of test temperature.

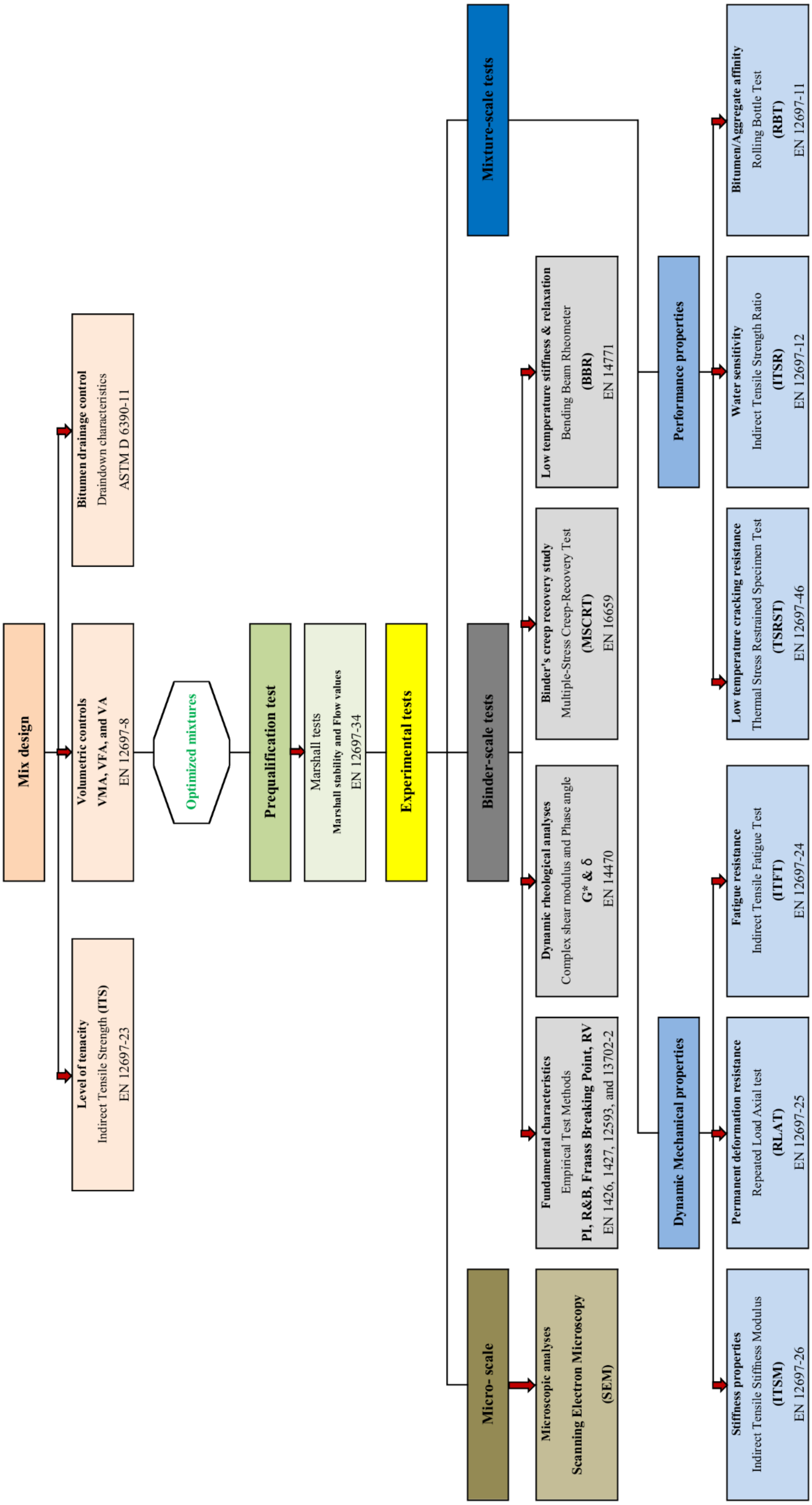

Fig. 1.2. Experimental plan.

1.5 Thesis Organization

Information in this report is presented as follows:

Chapter One introduces the background of the topic (different asphalt modification strategies, Polymer modification and fibre modification) and a problem statement. In this chapter, the research objectives and hypotheses are presented, the adopted methodology is outlined, and the significance of the research is presented.

Chapter Two explores the state of the practice regarding the use of fibre additives in asphalt mixtures. It discusses about the past research and studies that have been related to asphalt mixture modification, mainly gap-graded mixtures. It provides information relevant to the modified Stone Mastic Asphalt (SMA) properties shown with experimental works and field experiences. In continuing it discusses the polymer types, which have been used in binder modification, advantages and disadvantages of various polymers, and effects of waste rubber in asphalt mixtures. This chapter is concluded by presenting a review on stabilizing fibres and state-of-the-art on asphalt mixture modification via fibre and reinforcing fibres.

Chapter Three outlines all the adopted materials and experimental works and procedures in addition to sample preparation methods and test specimens for this research. In this respect, firstly some of the fundamental characteristics of all the adopted materials were provided as well as brief explanation on mechanical and performance tests' standard procedure and test apparatus.

Chapter Four deals with the specimen/sample preparation methods and adopted mix design procedure. Adopted aggregate gradation, compaction methods, and volumetric controls were addressed in detail.

Chapter Five, This chapter is presented as a series of journal papers. The contributions of the candidate and the co-authors for the papers comprising chapter 5 are hereby set forth. Hence the results and analysis is provided within five papers.

Chapter six provides a summary of key findings via concluding remarks from all the previous chapters as well as some suggestions for future studies on asphalt mixtures' fibre-modification/reinforcement and the new generation of fibres based on the information gathered in this study.

Chapter 1 References

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CHAPTER 2

LITERATURE REVIEW

CHAPTER 2 LITERATURE REVIEW

2.1 The State-of-the-Knowledge and the State-of-the-Practice

This synthesis assembles and summarizes the available literature on SMA's engineering features, fibre resources and effectiveness in enhancing the asphalt mixtures' mechanical/performance properties and is concluded with the rubberized mixtures characteristics.

2.2 SMA vs. Conventional Dense-Graded HMA

SMA originally developed in Germany decades ago, is by far the most accepted type of Hot Mix Asphalt for heavily loaded pavements and harsh climates. SMA is best explained as a two-component HMA, which comprises a coarse aggregate skeleton derived from a gap-graded gradation and a high bitumen content mortar. These two components combined address the concerns of both mixture stability and durability. SMA can provide an extremely high rut-resistant and durable HMA mixture as compared with dense-graded asphalt mixture. This improvement is realized through the formation of a stone-to-stone aggregate skeleton in SMA. The major difference between conventional mixes and SMA is in its structural skeleton [1]. SMA has high percentage about 70 to 80 % of coarse aggregates in the mix. This increases the interlocking of the aggregates and provides better stone to stone contact which serves as a load carrying mechanism in SMA and hence provides better rut resistance and durability. On the other hand, conventional mixes contain about 40 to 60 % coarse aggregate (see Fig. 2.1 & 2.2). They do have the stone to stone contact, but it often means the larger grains essentially float in a matrix composed of smaller particles, filler and asphalt content. The stability of the mix is primarily controlled by the cohesion and internal friction of the matrix which supports the coarse aggregates.

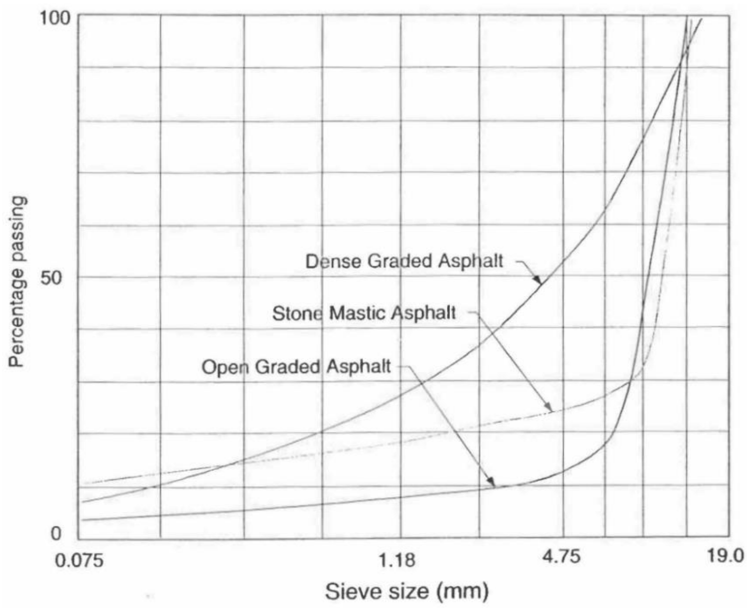

Fig. 2.1. Typical grading curves of different types of asphalt mixtures [2].

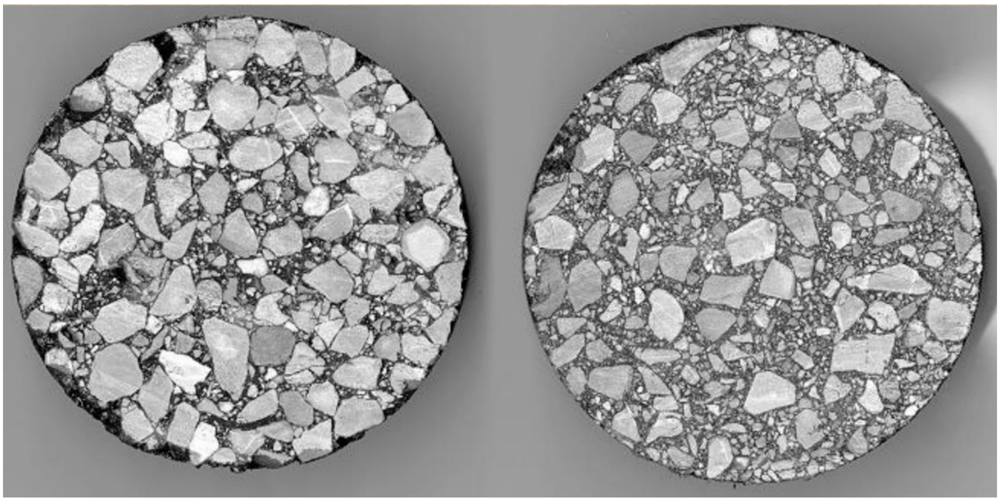

Fig. 2.2. Typical SMA vs. Dense-graded HMA cross section view [3].

The second difference is the binder content which lies between 5 to 6 % for conventional mixes. Below this, the mix becomes highly unstable. Above this percent will lead to an abrupt drop of stability because the binder fills all the available voids and the extra binder makes the aggregates to float in the binder matrix. The SMA uses very high percent of binder > 6.5 percent which is attributed to the filling of more amount of voids present in it, due to a high coarse aggregate skeleton. The high bitumen content contributes to the longevity of the pavements.

The third difference is the use of stabilizing additives in SMA mixtures, which is attributed to filling up of a large number of voids in SMA so as to reduce the drain down due to the presence of high bitumen content. On the contrary, there is no stabilizing agent in conventional mixes since the bitumen content is low (compared to SMA), which only serves the purpose of filling the moderate amount of voids and binding the aggregates.

SMA mixtures' benefits

The main functional characteristics of SMA mixtures compared with conventional dense-graded mixtures are:

- *Improved pavement performance*; remarkable rutting resistance, reduced ravelling probably due to higher binder content compared to conventional mixtures. The results from practical experiences proved the suitability of SMA for heavy load duty pavements such as truck/container terminals and intersections and high stressed pavements such as highly trafficked motorways.

- *Noise reduction*; many previous acoustic research works showed that the substitution of dense-graded mixtures by SMA leads to noise reduction from 2.5 dB up to 7 dB [4 & 5]. Taking into account that the reduction rate greatly depends on the Nominal Maximum Aggregate Size (NMAS) of the mixture and the speed, the higher the speed, the more reduction in noise was reported.

- *High skid resistance performance*; although SMA is not an Open-graded friction course (OGFC), the rough surface provides safer friction coarse in particular for motorways. In addition, SMA similar to OGFC surfaces has less water spray in comparison with conventional mixtures in wet conditions.

- *Wet night visibility*; comparing the SMA surface texture with the conventional mixtures, it provides less light reflection in wet condition.

SMA manufacturing cost considerations

In comparison to conventional HMA, SMA is complex. The materials required are premium, and the costs associated with SMA are at least commensurate. Based on the reported economic analysis, SMA manufacturing costs are higher than conventional Dense graded mixtures [5 & 6]. It is deemed that this higher cost is related to recommend polymer modified bitumen, fibres and high-quality aggregates (taking account the stone on stone connections). While the use of SMA entails higher initial costs, studies have shown that SMA mixtures used in pavement rehabilitation or as the surface layer for new construction can outperform conventional hot-mix asphalt mixtures. However, the life-cycle cost analysis within many pieces of researches have shown that SMA is more cost effective considering the long-term maintenance and rehabilitation costs during the life service length [7-10]. Experience from Germany, where SMA was developed in the 1960s, already has shown that a performance life of 20-30 years is not exceptional including the use of SMA on heavily trafficked roads like the Autobahns.

The overall advantages of SMA pavements can be shown by a life-cycle-cost analysis but it can be justified by using an approach based on the initial costs. The theoretically required lifespan to obtain equal annual costs for SMA and AC is 25% longer assuming the price of SMA laid 120% of the price of HMA per m^2. Given that the lifespan increase of at least 5 to 10 years can be obtained and additional advantages covered earlier are gained it is clear that the choice of SMA is a good investment [5].

2.3 RAP Containing SMAs

While the challenge of using RAP into dense-graded mixture goes to increase the portion as much as possible without compromising pavement's performance and technical characteristics, the use of RAP in specific mixtures such as Stone Matrix Asphalt (SMA) is not common practice. Almost most of the conducted research and practical experiences have proven that the higher initial manufacturing cost of SMA mixtures, for which recycled SMA mixtures could be considered as an economical alternative. This is due to the high-performance levels required and to the premium materials needed for such a mixture, SMA may be significantly more expensive than conventional

HMA. Combining SMA technology with RAP would potentially reduce the production costs and make this material environmentally sustainable when the superior fatigue performance is preserved [11].

However, the use of RAP into SMA mixtures is under scepticism and is needed to be investigated to provide an SMA mixture that is both durable and economical. This is mainly because the effect of RAP on the aggregate and asphalt properties is uncertain. One of the concerns with blending RAP into an SMA mixture is the uncertainty of whether the RAP aggregate conforms closely to the physical requirements of virgin aggregate because more stringent requirements are specified for SMA aggregates.

In a research on 25% RAP aggregate containing SMA, lower Los Angeles abrasion loss and higher Indirect Tensile Stiffness-ITS (for both conditioned and unconditioned samples for moisture susceptibility testing) were recorded in comparison to the control virgin SMA [12]. However, besides these, the research also showed a lower fatigue properties for SMA mixtures containing higher than 30% RAP. In this case, with a research conducted by NCAT [13], almost similar results were obtained. In addition to the higher tensile strength, which could be expected due to imposed stiffness and decreased fatigue life for the SMA mixtures containing more than 20% RAP, no statistical effects on rutting performance were recorded. It is noteworthy that in both research works no significant change in thermal cracking potential was seen.

2.4 SMA Technically Drawbacks and Fibre Role

A lot of research work has been reported on the performance and mechanical properties of SMA mixtures and its rutting resistance superiority and in particular for the heavy duty pavements. However, besides the proven rutting resistance and durability (due to high binder content), conventional dense-graded mixtures showed higher tensile strength and higher fatigue life in comparison to the SMA mixtures in several research works [14-18]. This is generally referred to the inherent structure of dense-graded asphalt mixtures, which leads to better interlock of mixture's constituent in comparison with the gap-graded skeleton of SMA mixtures.

Although SMA is not nearly as strong in tension as it is in compression, SMA tensile strength is important in pavement applications. On the other hand, the tensile properties of bituminous mixtures are of interest to pavement engineers because of the problems associated with cracking. In this case, PmBs and fibre-reinforcement are some of the suggested solutions for increasing the tensile properties of the gap-graded nature of SMA mixtures. Many research and field experiences showed that while the addition of fibres is not effective on permanent deformation of SMA mixture, it can improve the tensile properties providing a three-dimensional network through the high bitumen contended mastic of SMA mixtures.

Regarding the SMA tensile properties, two types of modification approaches with Polymer modified Binders and fibres have been introduced. The use of fibres in asphalt mixes dates back many decades. While the earliest role of fibres in asphalt was controlling the bitumen drainage and stability of open-graded and gap-graded mixtures, the later use of fibres developed as asphalt modifier as well as the asphalt mixture stabilizer. In this case, several pieces of researches have shown that while fibres (mainly cellulose fibres) have no effect on rutting performance of open graded and gap-graded mixtures [19-21], they can strengthen the dense-graded mixes to both rutting and cracking potentials [22]. In fact, the effectiveness of fibres on asphalt mixture properties greatly depend on the fibre's origin. While cellulose-based fibres have a great potential in draindown control, the synthetic and mineral fibres were showed improvements on tensile properties and durability by creating a network through the mastic [23 & 24].

On the other hand, besides fibre-reinforced SMA mixtures, PmBs were also found to be effective for improving some of the SMA's mechanical and performance properties. Several research studies comparing the SMA mixes containing fibres and PmBs concluded the superiority of PmBs on mixtures' properties comparing to basic cellulose fibres [19 & 25]. However, as a stabilizing additive, the fibres showed superior performance in comparison to those of mixtures containing only PmB.

2.5 Fibres

While the primary advantage of the using fibres is essentially stabilizing the mixture and prevent bleeding of asphalt during hot weather service, they are also considered to play a key role in mechanical and performance properties of different types asphalt mixtures. Moreover, the increased use of OGFCs and SMAs in roadway construction has presented different purposes for fibres in asphalt mixtures aiming to reinforcing properties. Fibres are reportedly used to provide the following benefits [26 & 27]:

- Increased tensile strength resulting in increased resistance to cracking
- Reduced severity of cracking when it did happen
- Increased fatigue resistance
- Increased rutting resistance as a result of lateral restraint within the mixture
- Increased abrasion resistance
- Higher asphalt content leading to increased durability
- And potential lower life cycle costs arising from longer service life.

However the aforementioned functions are greatly depended on the type of the mixture and fibre source. In summary, there are two main uses for fibres:

I. To prevent bitumen draindown in gap- and open-graded mixes, and
II. To strengthen dense-graded asphalt mixes to resist rutting and cracking [28].

Despite the fibre and mixture type, the main function of fibre in asphalt mixtures are to deliver additional tensile strength in the resulting asphalt concrete and to increase strain energy absorption of the asphalt mix in order to inhibit the formation and propagation of cracks which can decrease the structural integrity of the road pavement [29].

On the other side, the addition of fibres may increase the air void of AC mixture, thereby requires more compaction efforts to achieve the same density of unmodified AC mixture [26]. This is one of the reasons that controlling the fibre content is always crucial.

So far, many kinds of fibres had been applied in asphalt concrete. These fibres included three main resources of natural fibres, mineral fibres and synthetic fibres. However, the most frequently used fibres to prevent binder drainage in asphalt binders are cellulose fibres in a 0.3% generally and mineral fibres (slag wool, rock wool) added in a 0.4%. As a stabilizing additive, the main role of the fibres is to prevent the relatively high percentages of asphalt binder from draining from the mixture. Since then, fibres used as stabilizers include mainly cellulose and mineral fibres [23].

Fibres can generally be purchased in two forms: loose fibres and pellets. Fibres in a dry, loose state come packaged in plastic bags or in bulk. Fibres can also be pelletized. The pellets are added at the RAP collar of the drum mix plant or directly into the pug mill of a batch plant. The heat from the aggregates causes the pellet binder to become fluid allowing the fibre to mix with the aggregate. Some pelletized fibres contain a small amount of asphalt cement that must be accounted for in the overall asphalt content of the mixture.

Different types of fibres

A wide variety of fibre types has been used in asphalt mixtures, including cellulose, mineral, synthetic polymers and glass fibres as well as some less common fibres like recycled fibre materials such as newspaper, carpet fibres and recycled tire fibres have also been used. These fibres can be divided into two main group of synthetic and natural fibres. While Synthetic fibres include glass, carbon, and polymer fibres; natural fibres include a wide variety of materials used as stabilizing fibres in asphalt mixtures mainly divided into three groups of plant, animal, and mineral fibres. Fig. 2.3 exhibits these categories in details.

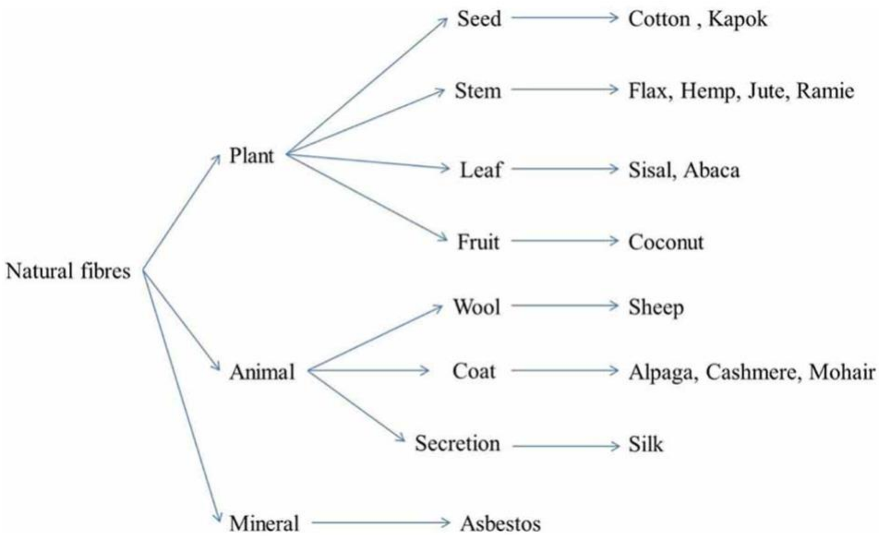

Fig. 2.3. Classification of natural fibres [30].

The different types of fibres have benefits and shortcomings regarded to their genuine micro-structure (see Fig. 2.4) that makes them better suited for some applications than others. For example, while cellulose fibres are not strong in tension, they are potentially absorbent and can hold bitumen, therefore they are well suited for reducing the draindown in open-graded mixes, but not for reinforcing dense-graded asphalt mixtures improving the tensile properties [29].

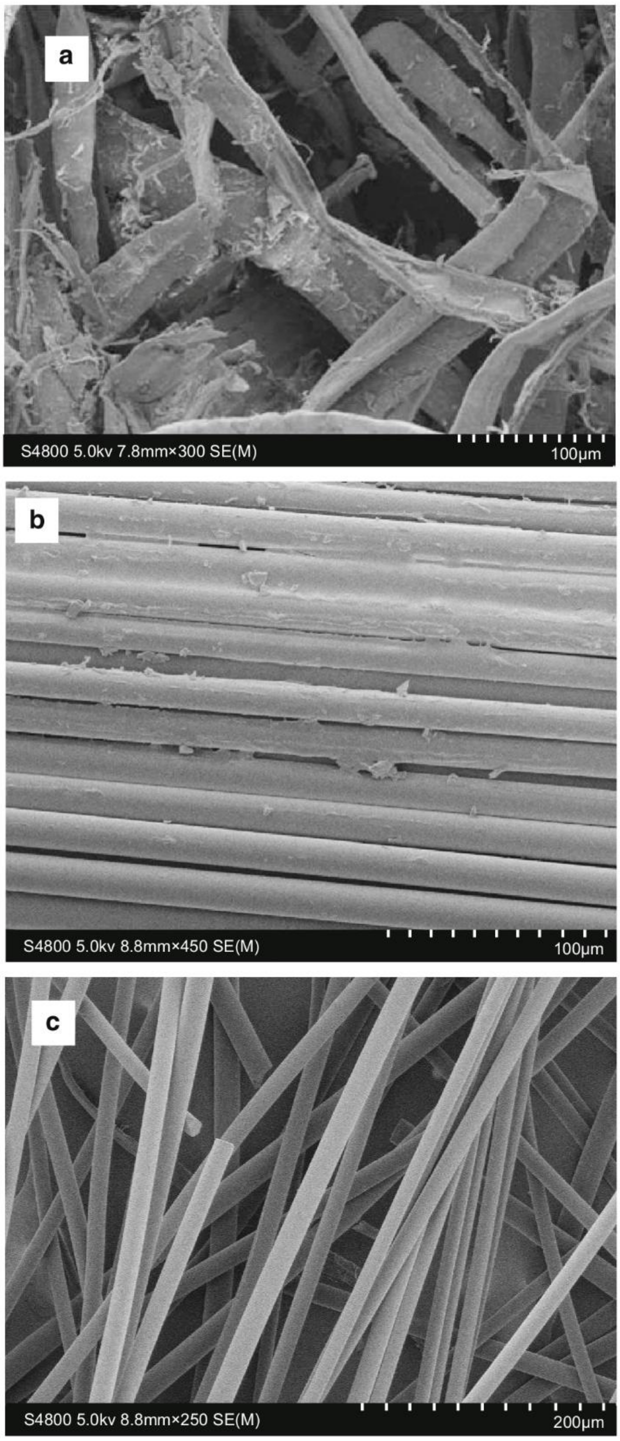

Fig. 2.4. Typical SEM images of different fibres [31].

Table 2.1 summarizes some of the reported benefits and drawbacks of some of the common fibres. While a great deal of research has been conducted on the use of fibres in asphalt mixtures, the results of these research works have been mixed specially regarding the use of fibres in dense-graded asphalt mixtures. This is why in some cases fibres have reportedly improved the rutting and cracking of binders and mixtures and in the other cases, there have been no significant improvements.

Table 2.1. Reported benefits and disadvantages of common fibre types [28].

Fiber Type	Reported Advantages	Reported Disadvantages
Cellulose	• Stabilizes binder in open- and gap-graded stone matrix asphalt (SMA) mixtures. • Absorbs binder, allowing high binder content for more durable mixture. • Relatively inexpensive. • May be made from a variety of plant materials. • Widely available. • May be from recycled materials such as newsprint.	• High binder absorption increases binder cost. • Not strong in tensile mode.
Mineral	• Stabilizes binder in open- and gap-graded SMA mixtures. • Not as absorptive as cellulose. • Electrically conductive fibers have been used for inductive heating for deicing purposes or to promote healing of cracks.	• Some may corrode or degrade because of moisture conditions. • May create harsh mixes that are hard to compact and may be aggressive, causing tire damage if used in surfaces.
Polyester	• Resists cracking, rutting, and potholes. • Increases mix strength and stability. • Higher melting point than polypropylene. • High tensile strength.	• Higher specific gravity means fewer fibers per unit weight added. • Cost-effectiveness not proven/varies.
Polypropylene	• Reduces rutting, cracking, and shoving. • Derived from petroleum, so compatible with asphalt. • Strongly bonds with asphalt. • Disperses easily in asphalt. • Resistant to acids and salts. • Low specific gravity means more fibers per unit weight added.	• Lower melting point than some other fiber materials requires control of production temperatures. • Begins to shorten at 300°F. • Cost-effectiveness not proven/varies.
Aramid	• Resists cracking, rutting, and potholes. • Increases mix strength and stability. • High tensile strength. • May contract at higher temperature, which can help resist rutting.	• Cost-effectiveness not proven/varies.
Aramid and polyolefin	• Controls rutting, cracking, and shoving. • Combines benefits of aramid and polyolefin (polypropylene) fiber types.	• Cost-effectiveness not proven/varies.
Fiberglass	• High tensile strength. • Low elongation. • High elastic recovery. • High softening point.	• Brittle. • Fibers may break where they cross each other. • May break during mixing and compaction. • Cost-effectiveness not proven/varies.

2.5.1.1 Plant-based fibres

Natural cellulose-based fibres offer low-cost, low density composite reinforcement with good strength and stiffness. Because of their annual renewability and biodegradability, natural fibres have recognized as environmentally-friendly alternatives to synthetic fibres in the last two decades. These fibres have been used in limited local areas. They may be derived from wood materials (such as jute, flax, and straw), leaves (such as sisal), seeds or they may have fruit basis; such as coir, cotton, coconut or palm. Fig. 2.5 exhibits the details on plant fibre classification.

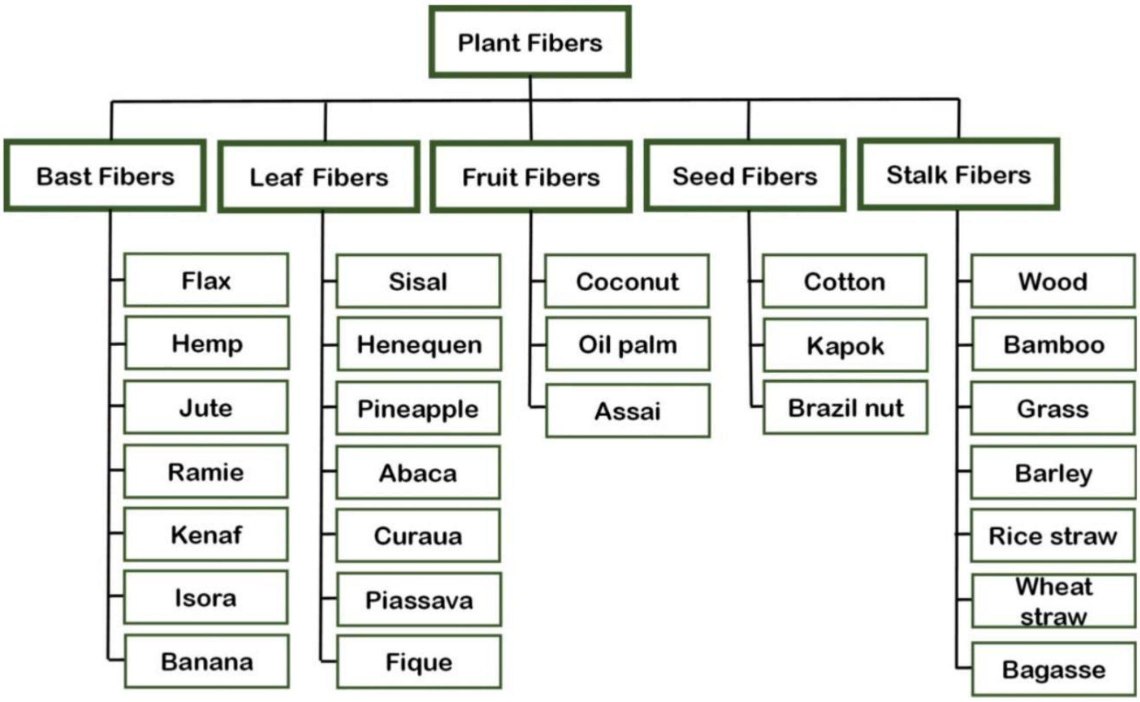

Fig. 2.5. Classification of plant fibres [32].

According to Fig. 2.5 the fibres are classified based on their location in the plant. Fig. 2.6 represents some of the most common natural fibres used in asphalt production. Plant fibres are composed of cellulose and hemicellulose (sugar-based polymers), lignin (a complex polymer of aromatic alcohols), pectin (complex set of polysaccharides), structural water, and wax or oil. Since cellulose is the principal chemical component of plant fibres, with varying amount of hemicellulose and lignin, they are often referred to as lignocellulosic or cellulosic. The use of natural fibres provides benefits to the environment with respect to the degradability and utilisation of natural materials. Plant-based natural fibres are lignocellulosic in nature and hence they are composed of cellulose, hemicelluloses, lignin, pectin and waxy substances. The structural composition and chemical structure of fibres are presented in Table 2.2.

Table 2.2. Structural composition of natural fibres [33].

Name of the fibres	Cellulose (wt.%)	Lignin (wt.%)	Hemicellulose (wt.%)	Pectin (wt.%)	Wax (wt.%)	Micro-fibrillar/spiral angle (°)	Moisture content (wt.%)
Bast fibres							
Jute	61–71.5	12–13	13.6–20.4	0.2	0.5	8.0	12.6
Flax	71	2.2	18.6–20.6	2.3	1.7	10.0	10.0
Hemp	70.2–74.4	3.7–5.7	17.9–22.4	0.9	0.8	6.2	10.8
Ramie	68.6–76.2	0.6–0.7	13.1–16.7	1.9	0.3	7.5	8.0
Leaf fibres							
Sisal	67–78	8.0–11.0	10.0–14.2	10.0	2.0	20.0	11.0
Pineapple leaf fibre	70–82	5–12	–	–	–	14.0	11.8
Seed fibres							
Cotton	82.7	0.7–1.6	5.7	–	0.6	–	33–34

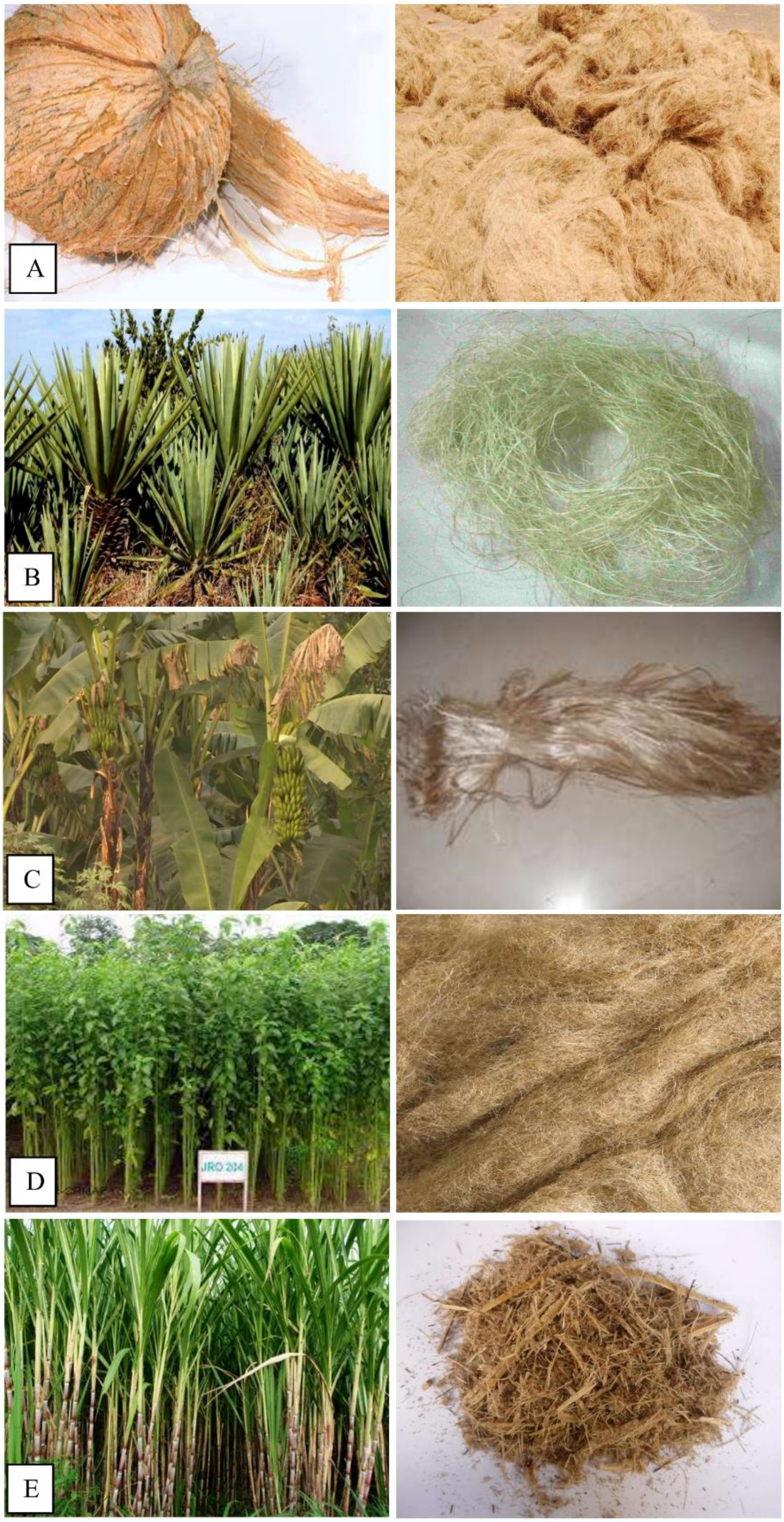

Fig. 2.6. Some of the Natural fibres. A) Coconut fibre, B) Sisal fibre C) Banana fibre D) Jute fibre E) Sugarcane fibre.

From the microstructural point of view, the structure of the natural fibres was of paramount interest for researches since it could be considered as a determinant factor in functional properties of fibres as well as other physical properties, in particular in composite materials such as asphalt concrete. Fig. 2.7 represents the microstructure and surface properties of some of natural fibres. However, the physical parameters measured are typically spread over a broader range of values, reflecting variability in chemical composition, crystallinity, diameter, and cross-sectional shape, strength, and stiffness from fibre to fibre, and even from one section of the fibre to another.

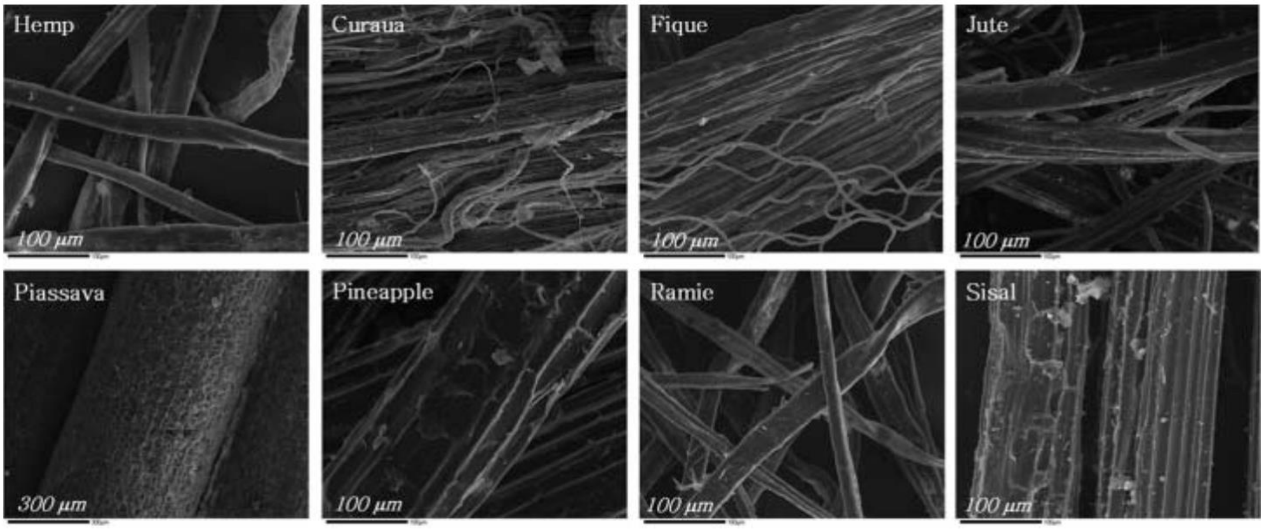

Fig. 2.7. Micro structural characteristics of natural fibres via Scanning Electron Microscopy (SEM) images [32].

Table 2.3. Typical physical and mechanical properties of natural fibres [32].

Fibers	Density [g/cm^3]	Elastic modulus [GPa]	Elongation at break [%]	Tensile Strength: Strength [MPa]	Tensile Strength: Specific strength
Bamboo	0.6–1.1	11–17	NA	140–230	127–383
Coconut	1.15	4–6	15–40	131–175	114–152
Cotton	1.5–1.6	5.5–12.6	7–8	287–597	179–398
Flax	1.54	28–85	1–4	345–2000	224–1300
Hemp	1.47	17–70	1.6	368–800	250–544
Jute	1.44	10–30	1.5–1.8	393–773	273–537
Kenaf	1.2	14–53	1.6	240–930	200–775
Nettle	1.51	25–87	2.1–2.5	560–1600	370–1060
Ramie	1.5–1.56	27–128	1.2–3.8	400–1000	256–667
Sisal	1.45–1.5	9–22	2–7	350–700	233–483
E-glass	2.5	70	2.5	2000–3500	800–1400
Carbon	1.4	230–240	1.4–1.8	4000	2860

Inconsistency in the properties of lignocellulosic fibres requires the application of rigorous quality control so that uniformity in the resulting composite may be achieved. If variability in the fibre-to-fibre mechanical properties is controlled, then theories and models developed for traditional, synthetic fibre composites may also be applied to those containing natural fibres. However, in spite of this shortcoming regarding the natural plant fibres, there are engineering benefits by using them as fibres in asphalt mixtures. Table 2.4 summarizes some of the state-of the art on the use of natural fibres in different types of asphalt mixtures.

Table 2.4. Summary of state-of-the-practice on natural fibres.

Source	Fibre	Mixture	Bitumen	Test methods	Major Outcome
S. P. Hadiwardoyo, 2013 [34]	Coconut fibres 0.75 (on the weight of mixture)	Dense-graded Asphalt concrete	60/70 Neat bitumen	• Optic im. • Empirical tests • Marshall	• Coconut fibre reduced the penetration grade and ductility of the bitumen but increased the softening point. • 0.75% Coconut fibre increased the Marshall stability 10-15% • The mixture's temperature should be kept below of its flash point
M. A. Sani et al., 2011 [35]	Coconut coir and Kenaf fibre 0.3 (on the weight of aggregates)	Dense-graded Asphalt concrete	80/100 Neat bitumen	• Cantabro Abrasion Loss • Marshall	• Coir fibre and kenaf fibre increases the Marshall Stability • Cantabro abrasion loss of the mixture containing coir was better than the Kenaf fibre containing mixtures
S.S. Awanti, et al., 2013 [36]	Coconut coir fibre and cellulose fibre 0.3 (on the weight of mixture)	Stone Mastic Asphalt (SMA)	VG 30	• Draindown • TSR • ITFT	• Lower draindown comparing to mixture containing cellulose fibre • overall, the SMA mixture containing coir fibre was better than that of containing cellulose fibre
C.S. Bindu et al. 2014 [37]	Coir, Sisal, banana, and waste plastic 0.3 (on the weight of mixture)	Stone Mastic Asphalt (SMA)	60/70 Neat bitumen	• Draindown test	• coir fibre found to be better for bitumen drainage control comparing to the Sisal and Banana fibres • 0.7% found to be the optimum amount of plastic fibre for obtaining the draindown limit
N. Kumar R et al., 2016 [38]	Sisal 0.3 (on the weight of mixture)	Stone Mastic Asphalt (SMA)	60/70 Neat bitumen	• Draindown test • Marshall	• It was observed that only 0.28% addition of sisal fibre significantly improves the Marshall properties of SMA mixes • The drain down characteristics of the SMA mixes with 0.28 Sisal fibre met the specification limit
R. S. Dikshith, 2012 [39]	Banana 0.3 (on the weight of aggregates)	Stone Mastic Asphalt (SMA)	60/70 Neat bitumen	• Marshall stability and Flow	• Banana fibre showed increases the Marshall Stability. However it was not significant • 0.3% was found as optimum fibre content of mixtures
P. Kumar, 2004 [40]	Jute fibre 0.3 (on the weight of mixture)	Stone Mastic Asphalt (SMA)	60/70 Neat bitumen	• Moisture susceptibility • Hamburg wheel tracking	• Same TSRs for the SMA with jute fibre and SMA with synthetic fibre was recorded • SMA with jute fibre may be suitable for gap graded bituminous mixes as supported by lower permanent deformation however the difference was insignificant

Besides the benefits regarding the use of natural fibres in asphalt mixtures, there are some major limits, which restricted the use of these fibres commonly in asphalt mixture production. The hydrophilicity of natural fibres results in high moisture absorption and weak adhesion to hydrophobic matrices. However natural fibres can be treated in order to improve their adhesion to matrix materials. Additionally, most natural fibres have low degradation temperatures (~200°C), which makes them incompatible high mixing and curing temperatures. This also restricts natural fibre composites to relatively low-temperature applications. There are several other challenges, such as large variability of mechanical properties, lower ultimate strength, lower elongation, problems with nozzle flow in injection moulding machines, bubbles in the product and poor resistance to weathering presented by natural fibres [33].

2.5.1.2 Cellulose fibres

Cellulose fibres are plant-based fibres obtained most commonly from a woody plant, however some are obtained from the waste newspaper. The effectiveness of cellulose fibres in preventing binder draindown in porous and SMA asphalt mixtures was demonstrated by many experimental and field research works. Addition of cellulose fibre to SMA does not chemically modify the bitumen used; rather, it enhances performance of the finished product by allowing the use of higher bitumen contents that tend to thicken and bulk the aggregate coating. The surface characteristics and the structure of cellulose Fibre assists the bitumen to maintain a high viscosity and avoid binder drainage during storing, transportation and laying. The thicker coating of bitumen around each stone also reduces long-term oxidation, ageing and moisture penetration [31]. Besides the benefits of cellulose fibres it should be noted that they can be damaged by high temperature and it is important that they do not come in contact with aggregates or drum mix gases at a temperature greater than 200°C. Such restrictions do not apply to mineral fibres such as rockwool and glass fibre [2].

2.5.1.3 Mineral fibres

In general, mineral fibres have been the preferred fibres of many road administrations for use in OGFC mixes. While Cellulose has better stabilizing capacity than mineral fibres, it is not used as frequently as mineral fibres. This is due to concerns that the organic cellulose fibres may absorb water and, therefore, be susceptible to moisture damage in the field, in spite of some researches showing comparable results [42]. As a commonly used mineral fibres, it is thought that adding glass fibre to the asphalt mixture enhances the mixture’s strength and fatigue characteristics while increasing the ductility. It is believed that due to their excellent mechanical properties, glass fibres might offer excellent potentials for asphalt modification [43].

2.5.1.4 Synthetic fibres

The 1980s brought more research on the use of synthetic fibres to prevent, or at least retard, cracking in HMA pavements (e.g., reflective cracking). The most commonly used synthetic fibres are polyester, polypropylene, aramid. Such these polymers have different melting points, which need to be considered when adding to HMA. The use of synthetic fibres was explored for reinforcement due to high tensile strengths and durability. In this respect, a research by Freeman et al. concluded that polyester fibres, while increasing the optimum asphalt content, provided reinforcement of the HMA mixtures tested. The polyester fibres not only increased mixture toughness but also significantly reduced the moisture susceptibility of the mixes by producing higher tensile strength ratios than the control mixture without fibres [44].

2.5.1.5 Waste or recycled fibres

The increasing importance of sustainability in construction has led to increased interest in reusing materials that would otherwise be disposed of, including waste fibres from a variety of sources. Waste carpet fibres, plastic wastes, and tire fibres are the most common recycled fibres with some favourable results in enhancing asphalt mixtures properties.

2.5.1.6 Innovative modified fibres

Besides the aforementioned stabilizing/reinforcing fibre resources, several mixtures of cellulose fibre and various modifiers are also available. These types of compounds have been produced mainly bearing in mind that: binder stabilization and a change in specific characteristics of the mix [45]. These compositions enable the simultaneous feeding of mixtures with a stabilizing agent and modifier additive. These poly-functional fibres are usually produced in granulated form, which makes dosage production control easier. These composite products may be produced by the combination of one or two different natural/mineral resources or by addition of any type of polymers and recycled materials. While it is generally accepted that a polymer additive may substantially improve the performance of the mixtures, cellulose fibre is typically regarded as having only a marginal improvement on the performance of SMA during its lifetime. In this case, the commonly used cellulose fibre pellets have recently been further modified by the addition of a polymer. The addition of polymer into bitumen typically modifies its viscosity of binder giving it improved temperature susceptibility.

Natural and synthetic rubbers as fibre

2.5.1.7 Rubber as fibre - experimental records

Through the decades of introducing ELT's rubber to pavement industry, the better understanding of the potential physical and rheological effects increased the variety of rubber practice alternatives in pavement technology. Besides the effectiveness of rubberized binders /mixtures (via both wet process and dry process) in improving the mechanical and performance properties of the final rubberized product, the well-recognized swelling properties (shown in Fig. 2.8) of CR led to considering it as a great source of draindown control material and mixture stabilizer. However, there are just a few research works concentrating on stabilizing potentials of CR (dry process) and rubberized binders (wet process). In this respect, the recent research work of the author on the feasibility of CR in draindown control of a typical porous asphalt showed comparable results [46] with commonly used fibres. In this study, dry processed mixture was compared with mixtures containing cellulose-based loose and granulated fibres (pelletized shape-bitumen treated). The results showed that the rubberized mixtures are of great potentials of daindown control. It is noteworthy that a higher daindown was recorded for the mixtures containing pelletized fibres in comparison to the rubberized mixture. Similarly, a study on rubberized porous asphalt found that the use of the rubber modified binder was effective in minimizing the binder draindown and was comparable to the addition of 0.3% cellulose fibres to the mix [47].

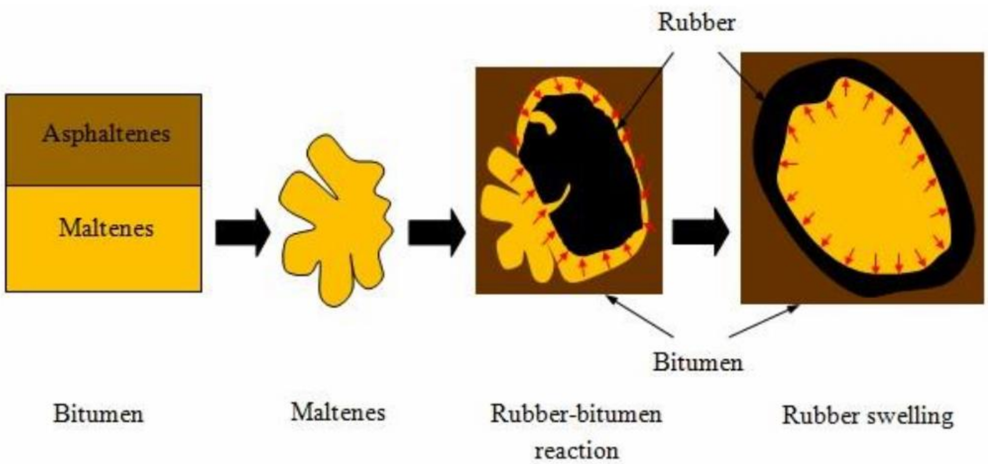

Fig. 2.8. Schematic of rubber swelling in rubber-bitumen interaction [48].

In addition to stabilizing characteristics, the idea of adding CR into gap-graded mixtures is to benefit the elastic properties, which could be achieved by rubber particles distributed through the mixture (theoretically shown in Fig. 2.9).

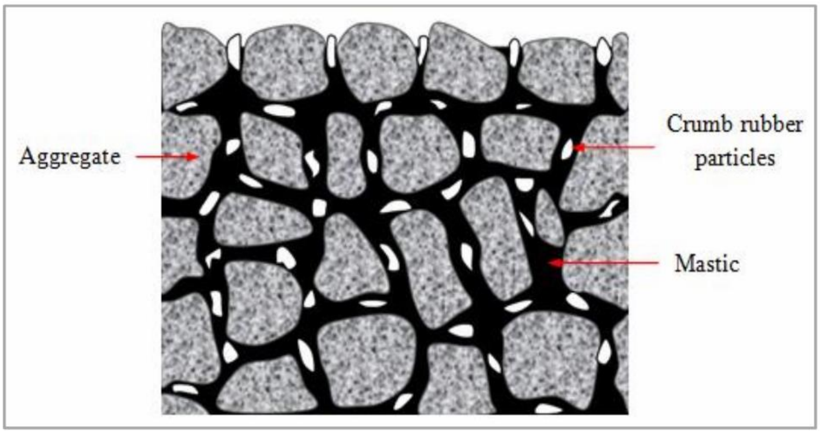

Fig. 2.9. Rubber particles distribution within a gap graded rubberised mixtures [49].

Specifically considering SMA mixtures, the dry method of incorporating CR into gap-graded mixtures was initially targeted at controlling the effects of snow and ice on the pavement surface. The resulted rubberised mixture was expected to have the advantages of breaking up ice and providing better skid resistance during icy conditions than conventional asphalt mixtures. The effectiveness of such application later was proved within several research works and field data observations.

CR as mixture stabilizer has been investigated in some experimental work. In this respect the earliest research works compared the 3 to 13mm crumb rubber with commonly used cellulose and polyester fibre with the same known quantity of 0.3% [21]. The results showed the great potentials of CR in binder drainage control of SMA with providing a comparable draindown rate of the mixture containing cellulose fibres. It is noteworthy that even if the recorded draindwon was slightly higher than those of cellulose fibre containings, the SMA mixture containing CR showed improved tensile properties. In another research work, SMA mixtures made with SBS PmB containing fibre were compared with rubberized SBS PmB. The results showed the superiority of rubberized SBS PmB in binder drainage control and higher permanent deformation resistance [50]. Considering the SMA mixtures, the efficiency of CR in draindown control was also observed for the SMA mixtures containing 30% of combined CR and Low-Density Polyethylene-LDPE (30% CR+70% LDPE, approximately 10% CR on the weight of binder) flakes. It is noteworthy that the CR concentration less than this showed an insignificant effect on binder drainage and further performance and mechanical properties [51]. In line with these aforementioned research works, in an experimental work, the effectiveness of Crumb Rubber Modified Binder (CRMB) in binder drainage was shown comparing the SMA mixtures consisted of natural fibre and neat bitumen [52]. The key finding of this study, like as most of the previous research works, was the improved mixture performance and in particular tensile properties besides draindown control.

2.5.1.8 Optimum rubber content and rubberized mixture properties

The effectiveness of using rubber in asphalt binders and mixture varies widely depending on the mixture type, production processing method, quantity of rubber, incorporation method, and the adopted production variables. Regarding the CR production and processing there are two main methods for processing, scrap tyres, namely ambient granulating and cryogenic grinding (see Fig. 2.10).

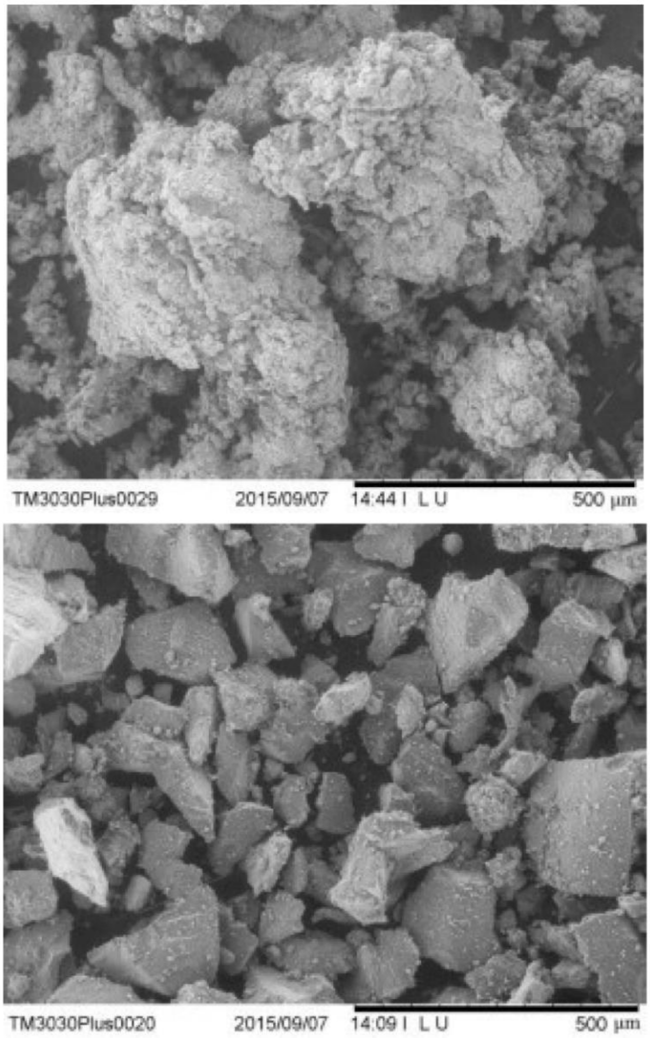

Fig. 2.10. SEM of crumb rubber (top) ambient granulating synthetic tyre rubber (bottom) cryogenically crushed synthetic tyre rubber [53].

Both processes essentially reduce the size of the tyre and separate the steel belting and fibre from the rubber compound. The ambient granulating using a cracker mill process is currently the most common and most productive means of producing crumb rubber. The process comprises a series of granulators for tearing the scrap tyres, screeners, conveyors, and various magnets for steel removal. The end product of the cracker mill process is an irregularly shaped particle with a large surface area, ‘spongy surface’ and varies in size. Cryogenic grinding is accomplished at extremely low temperatures (-87 to -198°C) by submerging the scrap tyre in liquid nitrogen. Below the glass transition temperature, the rubber is very brittle and easily fractured to the desired size (0.85 mm to 6 mm) [48]. The surface of rubber obtained from cryogenic grinding is glass-like with a lower surface area and elastic recovery compared to ambient granulated crumb rubber of similar gradation. Ambient granulated crumb rubber results in a higher binder viscosity than any of the modified binders produced with an equal amount of cryogenic crumb rubber [54 & 55]. This is possible due to the very high surface area and irregular shape of the ambient rubber particles which permits a faster reaction of the bitumen with the rubber than when cryogenic rubber is utilised.

Among them probably the most important factor is the optimum percentage of rubber in binder/mixture. Many research works have been conducted comparing the performance and mechanical properties of mixtures containing different amounts of rubber. However it greatly depends on the application method (dry or wet) and binder’s characteristics. Regarding to the rubberized bitumen, ASTM D6114 defines asphalt rubber (rubberized bitumen) as material consisting of the virgin binder and a minimum of 15% CR.

Besides the CR concentration, the binder/rubber interaction also plays a key role in the effectiveness of the final product. It is generally believed that the lack of interaction between CR and binder is the reason for some inconsistencies experienced via dry process. Nonetheless, the problem could be removed with considering enough conditioning time through the asphalt mixture production.

In addition to CR quantity and the binder/rubber interaction time needed for rubber digestion, it was found that the properties of pure bitumen used to produce rubberized binder/mixture also are very important to the quality of the final product. Softer bitumen with higher lightweight fraction gives a higher swelling rate to the rubber particles and thus displays a better high and low-temperature properties compared to harder bitumen with the same amount of rubber modification.

Table 2.5. Summary of some of the findings on rubberized asphalt mixtures.

Source	Process Method-Mix Type	Used Binder & OBC	Optimum Rubber Content	Test Methods	Major Outcomes
H.T. Tai Nguyen et al. 2017 [56]	Dry-process AC & SMA	Neat 60/70 5 & 5.5% (on the weight of total mix)	1.5-2% (on the weight of total mix)	• Marshall • Hamburg wheel tracking • ITS	• The CR contributes to the significant improvement in the Marshall stability and rutting resistance • At the optimal content of CR, the rutting resistance of dry processed mixtures was as good as that of SBS and CR modified mixtures using wet process
A. Subhy et al. 2017 [57]	Dry-process SMA	Neat 35/50 5.6% (on the weight of total mix)	0.6% (on the weight of total mix)	• ITSM • RLAT • ITFT	• The addition of rubber by dry process increased the stiffness modulus • While dry-processed SMA showed superior rutting performance, still the wet-processed SMA outperformed all the tested mixtures • Low fatigue life at 100με and better fatigue life at 50με comparing to control mix. Overall, wet-processed mix outperformed all the mixtures.
J.L. Feiteira Dias et al. 2014 [58]	Dry-process Gap-graded	Neat 35/50 8-9% (on the weight of total mix)	17-21.8% (on the weight of bitumen)	• Stiffness • 4-point ben. fatigue • wheel tracking	• Dry processed mixes were less sensitive to high temperatures than the reference mix without rubber. However the stiffness moduli were slightly lower than those made by wet process method. • Comparable fatigue performance recorded for both dry processed and wet processed mixtures
A. Cetin, 2013 [59]	Dry-process Porous asphalt	Neat 50/70 6.50%	10% (on the weight of OBC)	• Permeability • Cantabro • ITS • Stiffness	• Increasing the CR size and content significantly reduced the permeability, • Increasing the CR size and content more than 10% reduced the ITS values
F. Moreno et al. 2011 [60]	Dry-process Gap-graded	Neat 50/70 6.50%	0.5-1% (on the weight of total mix)	• TSR • Wheel tracking	• increasing the CR content more than 1% resulted in considerable reduced density • 45 min. was recorded as the optimum digestion time for CR • The amount of CR had great impact on Moisture Sen. and plastic def.
F. Moreno et al. 2010 [61]	Dry-process Gap-graded	Neat 50/70 4-5% (on the weight of agg.)	< 1% (on the weight of total mix)	• Marshall	• The mechanical performance of the mixes was affected by variations in the digestion time • The addition of CR improved permanent deformation resistance • Digestion time of 90 Min. @ 165±5°C led to best results
F. Hernández-Olivares, 2009 [62]	Dry-process Semi dense-graded	Neat 60/70 5.50%	1% (on the weight of total agg.s)	• Marshall • Wheel tracking • Moisture Sen.	• The higher rubber content than optimum led to rubber agglomeration • Depending on maturation time (conditioning time) the presence of rubber resulted in better resistance to plastic deformation and durability • laboratory wheel tracking were not consistence to the field samples
N.S. Mashaan, 2014 [63]	Wet-process No Mixture scale tests	Neat 80/100 -	16% (on the weight of bitumen)	• Bitumen conventional test • Dynamic shear test	• Due to high viscosity and the ease of pavement manufacturing and laying, 20% and above is not suitable • even if the presence of 4% CR could make changes to the base bitumen, the recorded differences were not significant
H. Wang, 2012 [64]	Wet-process No Mixture scale tests	PG 64-22 -	10-20% (on the weight of bitumen)	• Rotational Viscosity • BBR • RTFOT	• The addition of CR can significantly improve the viscosity of binders • The addition of CR into asphalt binder can reduce the creep stiffness • Finer CR resulted in higher viscosity at high temp. and lower creep stiffness at low temp.
B.Vural Kök et al. 2011 [65]	Wet-process Dense-graded HMA	AC 160/220 -	8%(on the weight of bitumen)	• Bitumen conventional and Dynamic shear Tests • Marshall	• Higher stiffness modulus were recorded with 8% CR added modified mixtures exhibited performance similar to the 4% SBS modified mixture and had a 50% higher stiffness modulus value than the base mix. • 8%-CR modification was determined as the most suitable content according to both binder and mixture tests

Table 2.5. Continuing.

Source	Process Method-Mix Type	Used Binder &OBC	Optimum Rubber Content	Test methods	Major Outcome
C. Sangiorgi et al. 2017 [46]	Dry-process Porous asphalt	SBS PmB 45/80-70 6.00%	1.00% (on the weight of Aggregates)	• Permeability • Cantabro • ITS • ITSM	• Lower porosity for the mixtures containing CR when compared to the ref. mixtures. • Improved thermal sensitivity in terms of ITSM modulus. • Comparable ITS values with those of not containing CR. • Addition of CR improved ravelling properties in terms of Cantabro test
C. Sangiorgi et al. 2018 [66]	Dry-process SMA	SBS PmB 45/80-70 7.5% and 8.5%	0.75% and 1.2% (on the weight of Aggregates)	• ITS • ITSM • Skid resis. • Noise analysis	• Higher ITS and ITSM results for the SMA containing 0.75% CR and comparable values for the SMA mixture containing 1.2% CR when compared to the ref. Mixture. • Addition of CR reduced the emission of noise if compared to Ref. SMA layer. • The ref. mixture performed better that CR containing SMAs in terms of skid parameters.
M. Losa et al. 2012 [67]	Both dry and wet process Gap-graded	SBS PmB 45/80-70 8.5% for wet and 9% for dry processed	1.8% for wet and 2.0% for dry processed (on the weight of Aggregates)	• ITS • MR • Skid resis. • Noise analysis	• Both mixtures showed similar ITS values. • Wet processed mixture showed higher macrotexture values when compared to dry mixture. • Acoustic measurements showed no meaningful difference between the mixtures. • Comparable MR recorded for the both mixtures.

2.5.1.9 Rubberized binder and mastic's properties

Besides the bitumen drainage control, the addition of CR to the binder/mixture has many technical benefits shown by many research works (some of them summarized in table 2.5). However, these advantages greatly depend on the binder characteristics and mixture properties. When CR is added to bitumen, even in relatively small quantities, the rheological behaviour of the resulting binder is often dramatically different from that of the un-rubberized bitumen. Empirical test methods do show decreased penetration index and increased softening point depending on the base bitumen characteristics and CR concentration. Besides these, fundamental rheological testing can be used to accurately define the rheological response of rubberized binders and mastics, over a very wide range of temperature. As a commonly seen effect, the addition of CR will result in thermal sensitivity improvements even for the binders already modified with SBS PmB. In this case, a research work studied the effects of CR addition on mastics made with SBS PmB. The results in terms of complex modulus and phase angle master curves (Fig. 2.11) showed that the addition of CR improves the thermal sensitivity of mastic at both low and high temperatures in addition to evident visco-elastic improvements at linear visco-elatic region [68].

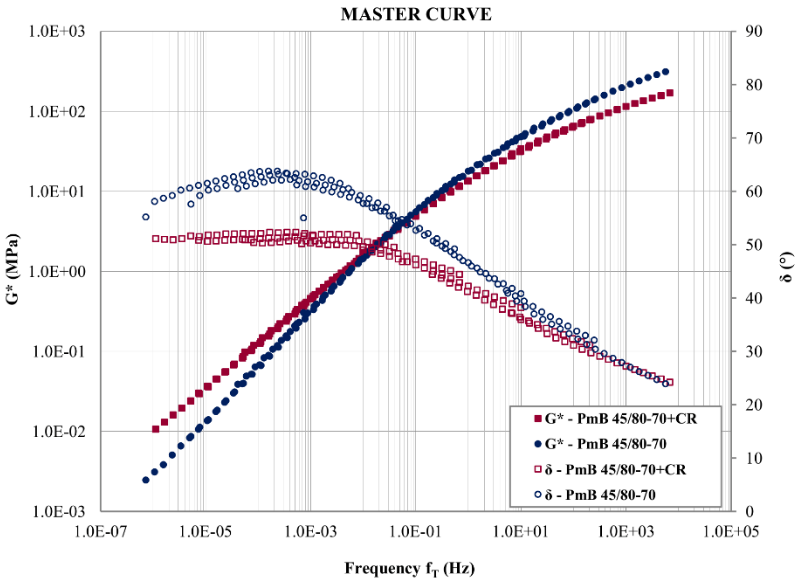

Fig. 2.11. G* and Phase angle master curves of mastics made with SBS PmB with and without CR addition [68].

In the same research, the mastics' properties (with and without CR) were investigated out of the linear visco-elastic region by means of Multiple-Stress Creep-Recovery Test (MSCRT). The results represented in Fig. 2.12 showed that as could be expected the addition of CR rubber could enhance the elastic properties (see Fig. 2.13) comparing to the mastic without CR in it.

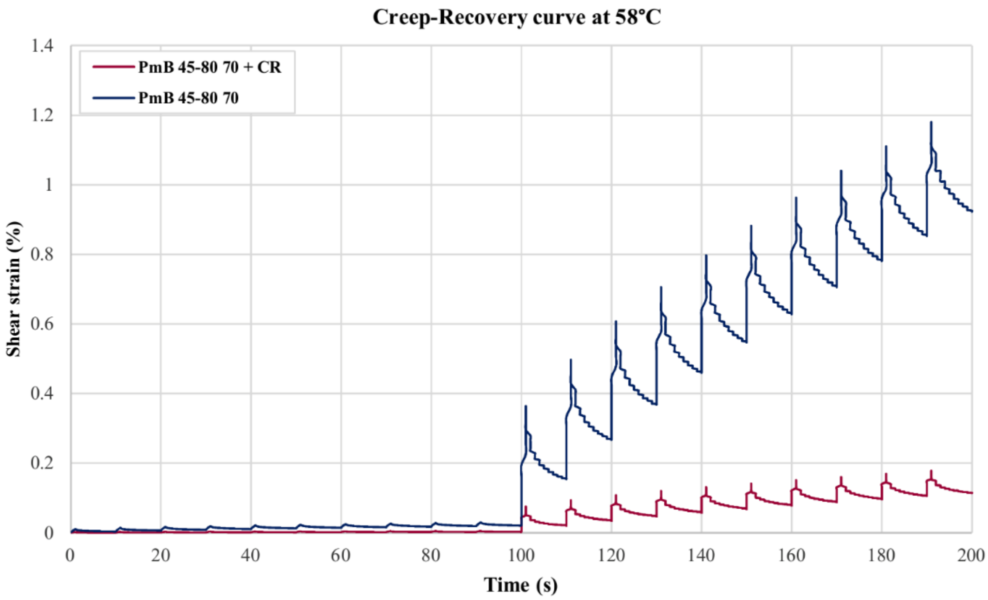

Fig. 2.12. Creep-Recovery curves of mastics made with SBS PmB with and without CR addition [68].

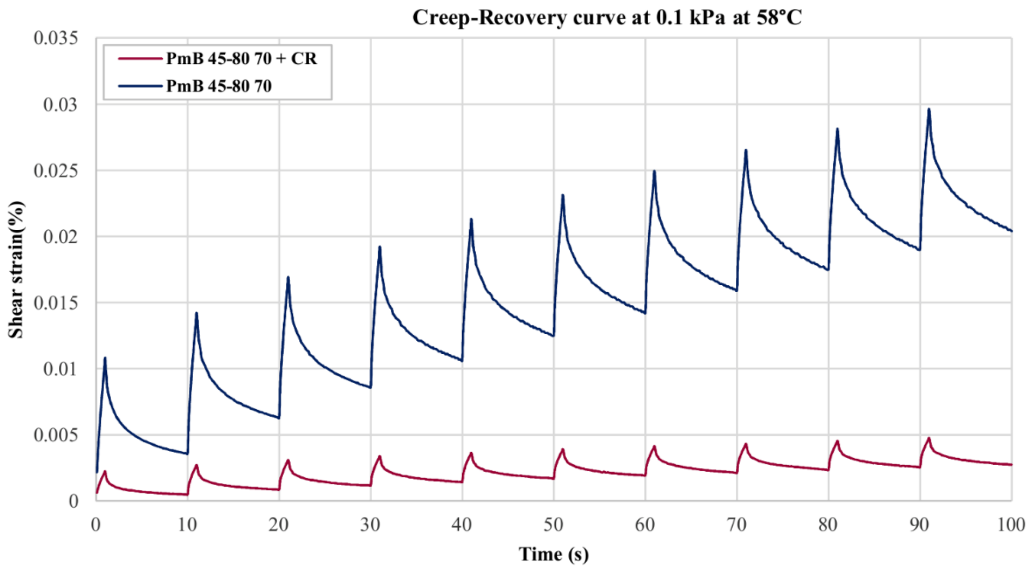

Fig. 2.13. Creep-Recovery curves of mastics made with SBS PmB with and without CR addition at 0.1 kPa [68].

Fibres' shapes and forms

Fibres may be supplied in bulk or packaged in plastic film that melts on contact with hot aggregates. Considering the form, fibres may be loose or pelletized to improve ease of handling [2]. Loose fibres may be pressed into pellets to keep the fibres together without or with a binding agent. Some types of pelletized fibres contain a bituminous binder that must be considered in the mix design. These fibres are known as bitumen-treated fibres are shown in Fig. 2.14. Compared with pure fibre pellets, much shorter premixing times are required with bitumen-coated fibre pellets. In addition, bitumen-coated fibre pellets are not sensitive against humidity.

Fig. 2.14. From left to right: Loose cellulose fibre, Bitumen treated cellulose fibre, and fine crumb tyre rubber. Scale coin diameter: 23.25 mm.

It is believed that Pelletized fibre have numerous benefits comparing to loose fibres including:

- More homogenous distribution in the mixer;

- No agglutination of the fibres within the mix;
- Improved handling on account of lower volume packaging;
- And space-saving storage through the optimal use of palettes.

Besides the aforementioned benefits of pelletized fibres compared to loose fibres, some deficiencies have been reported in experimental research works and field experiences. In this respect, some research works shown the superiority of loose fibres in draindown control when compared to solely granulated fibres and bitumen treated ones [44]. In addition field experiences showed the importance of adequate pre- and post-mixing times for full effectiveness of the pellets [69].

2.6 Polymer-modified Bitumen (PmB)

PmB overview

Pavements designed and constructed for heavy-duty traffic and extreme weather conditions require specially designed engineered bitumen grades. The rheological behaviour of asphalt-polymer blends is of great interest because it is closely related to the performance of pavements. By changing the characteristics of normal bitumen with the addition of a polymer, (elastomeric nature or plastomerics, etc.), it could be possible to obtain a bitumen that allows the mixture to be more cohesive, with much more strength and significant higher resistance to parameters like fatigue and permanent deformation. However, it should be noted that the efficient performance of polymer modification should fulfil the needed bitumen binder viscosity through the temperature. Fig. 2.15 represents how a typical pavement use PmB differs from neat bitumen.

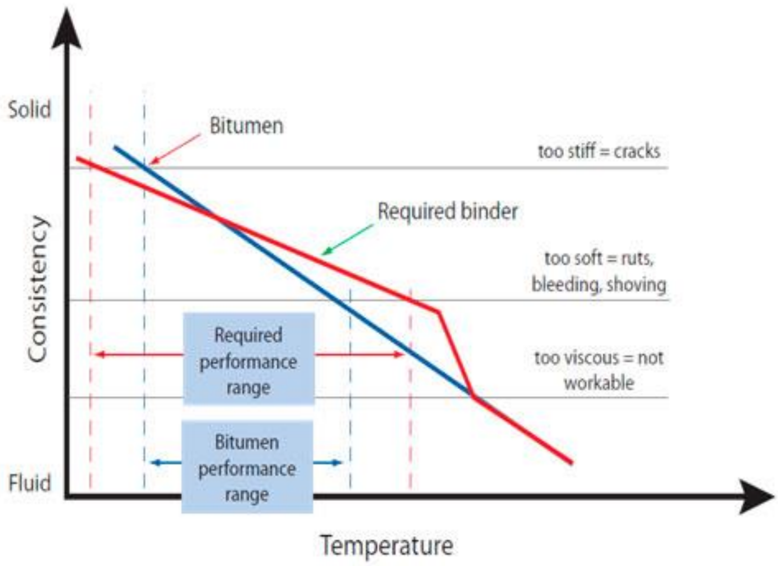

Fig. 2.15. Typical PmB and neat bitumen viscosity vs. temperature [70].

Overall, the increase in the amount of bitumen modifiers can primarily attributed to the following factors:

- Ever-increasing demand on asphalt pavements resulted in high traffic volumes/loads with higher tire pressure, increased significantly the need of more rutting resistant pavements.
- Most of non-modified bitumen binders do not meet the specifications' requirements in regions with extreme climate conditions.
- Environmental and economic pressures to dispose of some waste materials and industrial by products (such tire, glass, sulphur, and etc.) as additives in asphalt pavements.
- Administrative willingness to pay higher costs for pavements with a longer service life to reduce the risks of premature distresses.

Bitumen polymer modification pros and cons

Among the polymers introduced as for bitumen modification, elastomers and plastomers are commonly used in pavement manufacturing and in particular for heavy duty pavements. From the functional point of view, elastomers enhance the strength of bitumen at high temperature as well as elasticity at low temperature and the plastomers enhance strength but not elasticity [4 & 70]. The polymers from both main categories were reported to lead to some improved properties of bitumen, such as higher stiffness at high temperatures, higher cracking resistance at low temperatures, better moisture resistance or longer fatigue life. Although these polymers all improve bitumen properties to some extent, there are still some drawbacks limiting the future development of bitumen polymer modification, such as high cost, low ageing resistance and poor storage stability of polymer modified bitumen (PMB). Researchers attempted various ways to remove these drawbacks. Table 2.6 summarizes some of the reported advantages and drawbacks of the road pavement polymer modified bitumen.

Polymers' resources

Polymers are macromolecules made by chemically reacting many (poly) smaller molecules (monomers) with one another to from long chains of cluster. Copolymers consist of a combination of two different monomers that can be in a random or block arrangement. For instance, polystyrene is a hard, brittle plastic whereas polybutadiene is soft and rubbery if these two distinctive monomers are randomly mixed and react together a new polymer, called copolymer is formed with varying properties depending on the molar ration of the monomers incorporated into the chain [72].

Table 2.6. Road pavements' PmBs pros and cons remarks (updated from [71]).

Polymer	Advantages	disadvantages
Ethylene-Vinyl-Acetate (EVA)	Outstanding compatibility Minimal viscosity changes Thermally stable at normal mixing and handling temperatures. Low cost, as compared to block copolymers	No improvement in elastic recovery
Styrene-butadiene block co pol. (SBS)	Higher flexibility at low temperatures Better flow and deformation resistance at high temperatures Strength and very good elasticity. Increase in rutting resistance	High cost Reduced penetration resistance Higher viscosity at layout temperatures
Natural Rubber	Better rutting resistance Higher ductility Higher elasticity and properties under cyclical loads.	Sensitive to decomposition and oxygen absorption. Too high molecular weight (low compatibility).
Reclaimed Tire Rubber	Rubber disposal, Low material cost Potential fatigue resistance improvement Reduced reflective cracking Longer durability	needs for high temperature and long digestion time If not de-vulcanized it may act as a flexible filler

Many polymers have been used as binder modifiers, and they can be classified into five groups consisted of polymers used as bitumen modifiers (1) thermoplastic polymers, (2) natural and synthetic rubbers, (3) thermoplastic rubbers, and (4) thermosetting polymers. Thermoplastics tend to harden during cooling and soften during heating whereas thermosets cannot revert to a fluid state upon heating. The details are shown in Table 2.7. From these polymers two types of polymer are generally used to modify bitumen for road construction: plastomers and elastomers. EVA (Ethene-Vinyl-Acetate) and PE (Polyethylene) are examples of commonly used plastomers and SBS copolymers (Styrene-Butadiene-Styrene) is the most used elastomer (Fig. 2.16). Basically, plastomers increase the viscosity and stiffness of the bitumen. Elastomers also improve the elastic behaviour of the bitumen. The specifications and standards of most countries focus solely on the use of SBS, however, the use of elastomers, plastomers and other materials are highly beneficial in the design of specific binders [73].

Fig. 2.16. EVA (Ethene-Vinyl-Acetate) on the left vs. SBS (Styrene-Butadien-Styrene).

Table 2.7. Main categories of bitumen modification polymers [74].

Thermoplastics	Polyethylene (PE) Polypropylene (PP) Ethylene-Vinyl-Acetate (EVA) PVC
Natural and Synthetic Rubbers	SBR Natural Rubber Polydiolefins Recalimed Tire Rubber
Thermoplastic rubbers	Styrene-butadiene-block copolymer (SBS) Styrene-isoprene block copolymer (SIS)
Thermosets	Epoxy resins
Mixed systems	

Plastomer polymers

Plastomers form a rigid three-dimensional network improving rigidity and providing permanent deformation resistance under loading [74]. However, the utilization of plastomers in asphalt mixtures are limited. Common thermoplastics used in asphalt modification include polyethylene (PE), polypropylene (PP), poly vinyl chloride (PVC), polystyrene (PS), and ethylene vinyl acetate (EVA).

Polyethylene which can be found in in three forms; Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Linear Low-Density Polyethylene (LLDPE), is the most common plastomer. In addition, polyolefin group includes: polypropylene, Ethylene-propylene-copolymers, and EVA [71]. EVA is a plastomer, which is copolymer obtained by copolymerization of ethylene and vinyl acetate. Even though it is considered as a potential bitumen modifier, there are some shortcomings of which the phase separations is of more importance. For instance, some of the plastomers (for example EVA) melt at high temperature. When added to bitumen they appear as small droplets that are dispersed in the bitumen. The bigger the volume of the polymer in the bitumen, the more it will (positively) affect the properties of the bitumen. However, it is greatly depends on the type of the polymers and bitumen origin. Sometimes the polymer is added directly to the asphalt mixture in an asphalt plant. In this case, the polymer has almost no time to interact with the bitumen and therefore will not show a significant influence on mixtures properties. Besides, it is unlikely that a homogeneous end product is obtained. Altogether the improvement of the asphalt properties will be significantly less than with a proper polymer modified bitumen with the same polymer content. [75]. However, some important factors, including the characteristics of the bitumen and the polymer themselves, the content of polymer and the manufacturing processes, determine the final properties of polymer modified bitumen (PmB) [76].

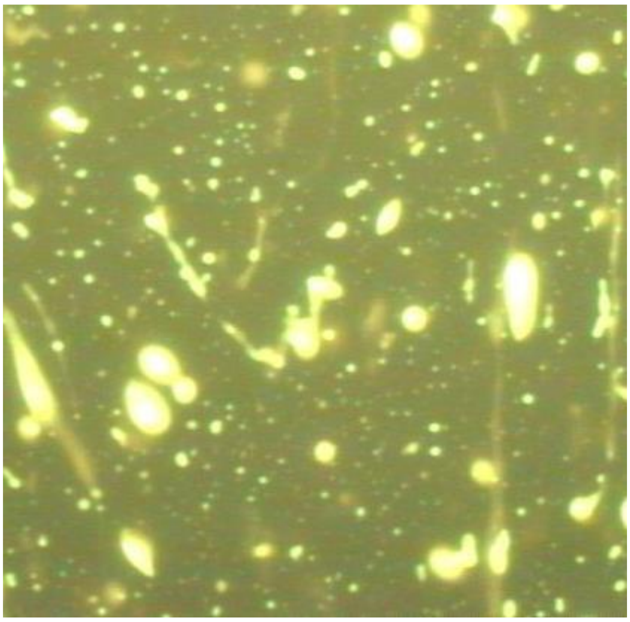

Fig. 2.17. Low EVA content and phase seperation [75].

Level of bitumen polymer modification

In the bitumen modification via polymers, depend on the quantity of polymer and the developed bitumen/polymer system, the level of modification can be divided into low polymer content, polymer content around 5%, and sufficiently high polymer content. In the low polymer content, the bitumen is the continuous phase of the system and the polymer, which less than 4% is dispersed through it. For the modified bitumen containing around 5% polymer, the system may show microstructures in which the two phases are continuous and interlocked. Such systems are generally difficult to control and pose stability problems. As for sufficiently high polymer content bitumen, more than 7% in general, if the bitumen and polymer are correctly chosen. The polymer phase is the matrix of the system. In this case, the polymer is the continuous phase and the asphalt is therein dispersed. Fig. 2.17 typically represents the differences between bitumen/polymer phases by means fluorescence images of a modified bitumen containing Ethylene Vinyl Acetate (EVA). The properties of such a system are fundamentally different from those of a bitumen and depend essentially on those of the polymer. These materials are usually employed for roofing [73].

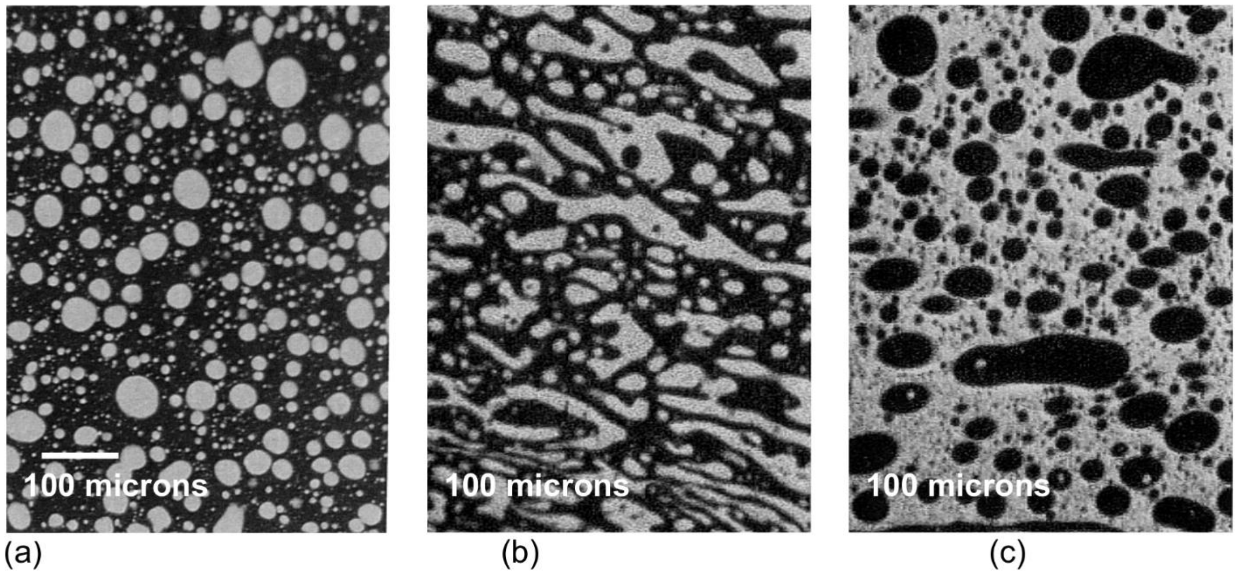

Fig. 2.17. Fluorescence images of PmB containing a) 3% EVA, b) 5% EVA, and c) 7% EVA [77].

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CHAPTER 3

MATERIALS AND METHODS

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3.1 Materials

Virgin fine and coarse aggregates

The first step in the mix design procedure is to select aggregates that meet specification requirements. For the current study, the composition of the 12mm SMA mixtures produced consists of: fine (4/8mm) and coarse (8/12mm) porphyry aggregates shown in Fig. 3.1 and limestone sand. For the SMA mixtures, the aggregate properties are extremely important since the stone-on-stone contact is the essential backbone of SMA mixtures. Therefore aggregates' hardness and shape for SMA mixtures are more important than conventional HMA mixtures. The physical and chemical properties of aggregates result from the geologic origin and mineralogy of the potential source and its subsequent weathering. On the other hand, many of the properties of aggregates relate to grain size and surface texture. In the following, some of the aforementioned properties are briefly discussed for the porphyry aggregates in general.

Fig. 3.1. Fractionated 4/8 vs. 8/12 porphyry aggregates.

3.1.1.1 Mineralogy of porphyry

Porphyry is a reddish-brown to purple igneous rock containing large phenocrysts of various minerals embedded in a fine-grained matrix. The main chemical component is silica, while other major components are iron, potassium and aluminium oxides. Porphyry is rich in the following minerals: quartz, sanidine, plagioclase, and to a lesser extent, pyroxenes and glass matrix.

3.1.1.2 Physical and mechanical characteristics of porphyry

The mechanical characteristics deemed to be important for asphalt mixtures and in particular for SMA construction. Table 3.1 points out the physical and mechanical characteristics of porphyry aggregates adopted in this study.

Table 3.1. Porphyry aggregates given physical and fundamental properties [1].

Test	Standard	Value
Apparent Particle Density (Mg/m³)	EN 1097-6	2.63
Los Angeles Coefficient (LA)	EN 1097-2	15
Water Absorption (%)	EN 1097-6	1.4
Aggregate Abrasion Value (AAV)	EN 1097-8	1.6
Polished Stone Value (PSV)	EN 1097-8	52
Resistance to Breakage (MPa)	EN 1926	82

Reclaimed Asphalt Pavement (RAP) aggregates

The recycling of existing asphalt pavement materials produces new pavements with considerable savings in the material resource, cost, and energy. For this research work two differently fractionated RAP aggregates (different stockpiles based on different size) were used as fine and coarse RAP aggregates shown in Fig. 3.2.

Fig. 3.2. Fine and coarse RAP aggregates before and after binder extraction.

As the first and most important step in the design of any recycled HMA, the properties of RAP aggregate and RAP binder were determined. The basic required properties of RAP materials included: binder viscosity, bitumen content and particle size distribution of aggregates. For this purpose, the binder of the RAP aggregates was extracted for the main following reasons:

i. *RAP aggregates grain distribution*, which was determined by sieving analysis of RAP aggregates before and after binder extraction providing Black and White grading curves represented in Fig. 3.3. These were needed for determining the final grading of the mixture and the job mix formula. In this experimental work, RAP was added at a rate of 25% of total aggregate weights.

ii. *RAP aggregate type*, which, in particular, is important for SMA mixture stone-on-stone skeleton. Such this type of RAP is not desirable if the aggregate does not meet specified requirements for the new HMA.

iii. *Aged bitumen content determination*, which should be considered as the existing recoverable bitumen binder for the mixtures containing RAP.

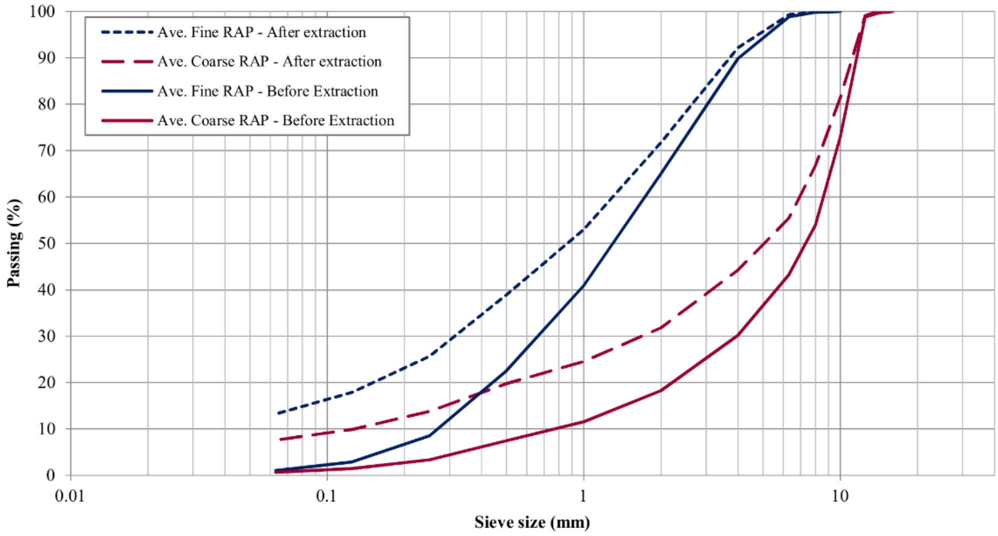

Fig. 3.3. Fine and coarse RAP grain distribution before and after binder extraction (Black and White curves).

Filler

SMA, as typically defined, requires a relatively high content of asphalt cement and mineral filler mastic to bind together the large aggregate particles. Limestone-based fillers are the most commonly used in the construction of asphalt pavement, especially with granitic-based aggregates. Limestone filler is a product obtained from the fine grinding of limestone and contains a high degree of calcium carbonate (min. 90%). Handling, storing, and introducing the mineral filler into the SMA mixture are of paramount importance for proper mix production.

Binders

Polymer modified Bitumen (PmBs) are widely used in the pavement construction to improve the mechanical performance of pavement materials and allow them to fulfil their design requirements. Among the polymer modifiers for asphalt binder, Styrene-Butadiene-Styrene (SBS) copolymer modified bitumen are usually used in SMAs. Styrenic block copolymers commonly termed thermoplastic rubbers due to their ability to combine both elastic and thermoplastic properties, can be produced by a sequential operation of successive polymerisation of styrene butadiene styrene (SBS). At suitable SBS concentration, a continuous polymer phase is formed throughout the bitumen and significantly modifies the base bitumen properties.

In the present experimental work, two different bitumens including a 40/50 penetration graded bitumen and a 10/40-70 SBS polymer modified Bitumen (PmB) were used. Some of the physical characteristics of both bitumens were provided in Table 3.2 and 3.3.

Table 3.2. Given neat bitumen physical properties.

Measured properties	Unit	Value	Standard
Penetration @25°C	0.1 mm	50-70	EN 1426
Softening Point (R&B)	°C	46-54	EN 1427
Flash Point	°C	≥250	EN 2592
Dynamic Viscosity @ 60 °C	Pa.S	≥145	EN 12596
Fraass Breaking Point	°C	≤-8	EN 12593

Table 3.3. Given SBS modified bitumen physical properties.

Measured properties	Unit	Value	Standard
Penetration @25°C	0.1 mm	10-40	EN 1426
Softening Point (R&B)	°C	≥70	EN 1427
Flash Point	°C	≥250	EN 2592
Dynamic Viscosity @ 160 °C	Pa.S	≥0.4	EN 13702/2
Force ductility @ 10 °C	J/cm^2	≥3	EN 13589

Rejuvenating agent

In High RAP containing mix design, both the high and low temperature pavement performance need to be enhanced to ensure that premature failures do not occur. While both rejuvenator and recycling agent improve the cracking resistance, but there are differences between rejuvenator and recycling agent and their respective benefits. Rejuvenating agents affect both the physical and chemical properties of the virgin asphalt binder and the RAP binder in the mix design.

They add the following benefits:

1. Improve the low-temperature PG grade and increase crack resistance of AC;
2. Improve workability/compaction of the RAP containing mixtures;
3. Restore the aromatic resins to the high RAP asphalt binder that were lost due to oxidative field aging
4. Do not cause continuous age softening of the RAP asphalt binder which could lead to increased rutting potential
5. Reduce the high-temperature Performance Grade (PG)

On the other hand, the recycling agents are also capable of reducing the viscosity and improving the low-temperature properties of the high RAP binder. Here’s where they differ from a rejuvenating agent:

1. A recycling agent does not add the aromatic resins to balance the properties of the high RAP binder and repair the oxidative aging.

2. Without the aromaticity restored, the high RAP mix design will exhibit premature rutting due to continued age softening of the RAP binder.

It is worth mentioning that, regarding the use of rejuvenating agents, it is not only important to have a balanced mix design regarding volumetric, but also to ensure that the design will provide long-term performance without increased rutting and/or premature cracking.

In this experimental work, a waste vegetable (WV) oil-based rejuvenator was used. Table 3.4 provides the technical identification (physical properties) of the used rejuvenator. It is noteworthy that, the recommended dosage of rejuvenator by the producer was considered as an optimum dosage, which was 0.15% by weight of RAP in the mixture.

Table 3.4. Rejuvenating agent’s given physical properties.

Properties	Unit	Value	Appearance
Appearance	-	viscous liquid	
Minimum operating temp.	°C	≥ -5	
Density @ 25°C	g/cm³	0.77 – 0.79	
Flash point	°C	≥90	
Viscosity @25°C	Pa.S	30-40	

Fibres

While the primary role of fibres as stabilizing additives was to prevent the bitumen draindown of the mixture, here the effectiveness of composite modified fibres on mixture mechanical and performance properties has been studied. For this purpose, 4 novel cellulose-based fibres were investigated including the followings:

I. A cellulose-based mineral fibre (glass) added fibre. The mineral component (structural) is supposed to forms a three-dimensional network and plays a role of micro-reinforcement in the matrix of binder.
II. A cellulose-based fibre mainly composed of cellulose and high amount of waste tire rubber (60-70%). It contains also a minor portion of mineral (glass) fibres.
III. A cellulose-based fibre containing mineral fibre (glass) and a plastomeric polymer. The compound were deemed to increase the viscosity and micro-structural reinforcement of the bitumen film.
IV. A cellulose-based fibre composed of cellulose and waste tire rubber and plastomeric polymer (40-50%).

Fig 3.4 represents the cellulose, mineral and polymer, which were used for producing the different composite fibres in this study and as well as the room temperature appearance of the four composite fibres before and after grinding. It is worth mentioning that grinding the fibres was necessary for producing a homogenous mix through the laboratory scale works.

Fig. 3.4. Appearance of fibres before and after mixing as composite fibre in pellet and grinded form. Scale coin diameter: 23.25 mm.

3.2 Methods

In the following sections, the applied tests during each of the defined phases of the research plan is briefly described. This contains the explanation on adopted test methods and calculations according to the considered standards, as well as a concise introduction on the apparatus and test machines.

Dynamic rheological analysis

3.2.1.1 Dynamic rheological parameters

Significance and use

The rheological characterisation of bitumen has traditionally been based on measurements of viscosity, penetration, ductility and softening point temperature. These measurements are generally not sufficient to thoroughly describe the rheological and failure properties of bitumen needed to relate bitumen properties to mixture properties and to pavement performance, particularly for PMBs. In order to accurately relate binder properties to pavement performance, it is necessary to undertake more fundamental testing of bitumen.

At present the most commonly used method of fundamental rheological testing of bitumen is by means of dynamic mechanical methods using oscillatory-type testing, generally conducted within the region of linear viscoelastic (LVE) response. These oscillatory tests are usually undertaken by means of Dynamic Shear Rheometers (DSRs, shown in Fig. 3.5), which apply oscillating shear stresses and strains to samples of bitumen sandwiched between parallel plates at different loading frequencies and temperatures.

Test procedure

In the present research, in all the binder scale tests, the first stage was dedicated to producing bituminous samples and compounds with considering the practical field asphalt mixture procedure. For this, the laboratory blends were prepared by blending the ground (powdered) fibres into hot bitumen and stirred manually. Considering the needed time for rubber digestion into bitumen besides the practical conditioning time (The time for transportation of asphalt concrete) the sample preparation included the following steps:

- Blending the ground fibre with hot bitumen for 5 minutes at 170± 5˚C, depending on the type of bitumen
- Mixing manually the blend at 160±5˚C

The general rheological characteristics of the binders in this study were measured under the following test conditions:

- Mode of loading: controlled-strain;
- Temperatures: 22 to 82˚ with 6-degree steps;
- Frequencies: 0.01–40 Hz (eleven values);
- Parallel plate geometries: 25mm diameter with a 1mm gap
- Strain amplitude: within LVE response 0.4 – 10.0%

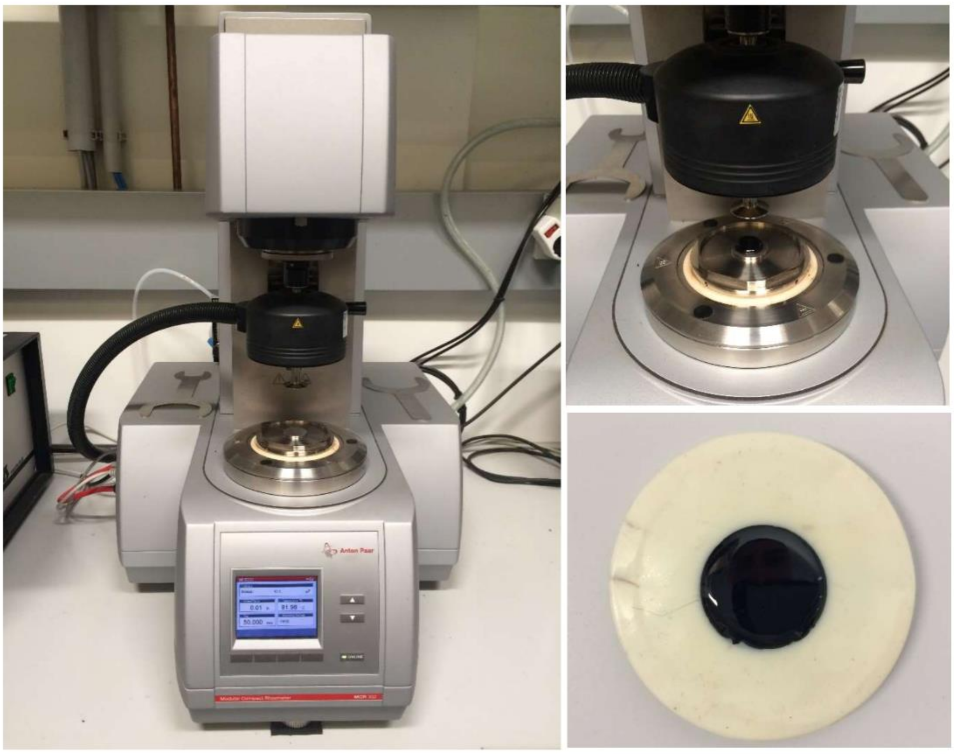

Fig. 3.5. Dynamic Shear Rheometers (DSR) and test sampling at UNIBO Lab-Roads.

Calculations and output data

The principal viscoelastic parameters that were obtained from the DSR consisted of the complex shear modulus (G*) and phase angle (δ). G* is defined as the ratio of maximum (shear) stress to maximum strain and provides a measure of the total resistance to deformation when the bitumen is subjected to shear loading. It contains elastic and viscous components, which are designated as the (shear) storage modulus (G') and (shear) loss modulus (G'') respectively. These two components are related to the complex (shear) modulus and to each other through the phase (or loss) angle (δ) which is the phase, or time, lag between the applied shear stress and shear strain responses during a test. The phase angle, defined above as the phase difference between stress and strain in an oscillatory test, is a measure of the viscoelastic balance of the material's behaviour [2].

$$G^* = \frac{|\tau_{max} - \tau_{mix}|}{|\gamma_{max} - \gamma_{mix}|} \tag{3.1}$$

With τ_{max} and γ_{max} having the following expressions:

$$\tau_{max} = \frac{2\, T_{max}}{\pi r^3} \text{ (Pa)} \tag{3.2}$$

$$\gamma_{max} = \frac{\theta_{max}\, r}{h} \tag{3.3}$$

where:

τ_{max} = absolute value of the peak-to-peak shear stress (Pa)

γ_{max} = absolute value of the peak-to-peak shear strain (%)

T_{max} = maximum applied torque (load) (Pa)

r = radius of specimen plate (mm)

θ_{max} = maximum deflection angle (rad)

h = specimen height (mm)

Here for the current research, The DSR rheological data has also been presented in the form of complex shear modulus and phase angle isochronal graphs, comparing the stiffness and viscoelastic behaviour of the fibre added compounds besides neat bitumen. It is worth mentioning that in order to investigate on the importance of the load frequency the isochronal graphs were produced considering 1.59 Hz and 10 Hz as frequency representing the medium and high frequencies respectively.

3.2.1.2 Binder creep recovery test

Significance and use

The rutting potential of asphalt binders is characterized in the laboratory using Superpave rutting parameter (G*/Sinδ) and Multiple-Stress Creep-Recovery (MSCR) tests. However many researchers have reported that Superpave rutting parameter may not correlate well with the field performance as this parameter is determined at very low stress an in linear viscoelastic range, while rutting occurs out of this range. The MSCR test uses the well-established creep and recovery test concept to evaluate the binder's potential for permanent deformation. It produces lab results that are closely correlated with actual mix performance.

Test procedure

For the current research, MSCR tests were carried out following the European standard EN 16659 using the Dynamic Shear Rheometer (DSR) with parallel plates of 25 mm diameter and a gap of 1 mm. The test temperature of 58°C was adopted in this test, and the obtained results were compared with the primary Superpave rutting parameter through the test 1-second creep load is applied to the asphalt binder sample. After the 1-second load is removed, the sample is allowed to recover for 9 seconds. The test is started with the application of a low stress (0.1 kPa) for 10 creep/recovery cycles then the stress is increased to 3.2 kPa and repeated for an additional 10 cycles.

Calculations and output data

The MSCR test is conducted at two stress levels: 0.1 and 3.2 kPa, and non-recoverable creep compliance (Jnr) and recovery (R) values are determined for a selected asphalt binder. The J_{nr} value is calculated as the ratio between the average non-recoverable strain for 10 creep and recovery cycles, and the applied stress for those cycles (shown in Fig. 3.6). Several studies observed a better correlation between J_{nr} estimated at 3.2 kPa and rutting performance of asphalt mixes in field and laboratory [3]. A lower J_{nr} indicates that asphalt binder is highly rut resistant and vice versa. In addition to Jnr, recovery (R) of asphalt binder can be estimated using MSCR test, which can further be used to evaluate rutting performance of asphalt binder. A higher R value is desirable for asphalt binder so it has the capability to return back to its original shape after unloading.

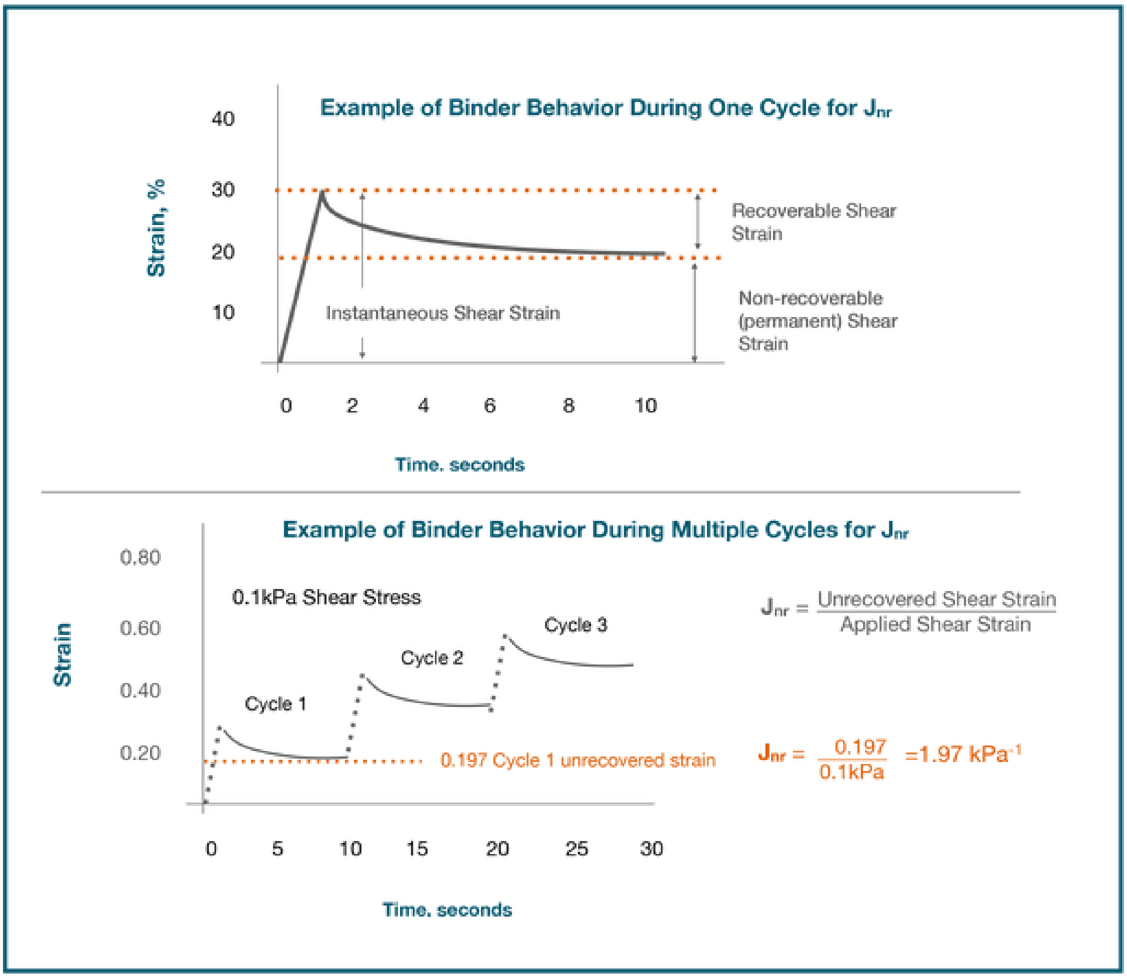

Fig. 3.6. Typical MSCR curve. Strain vs. time.

Bending Beam Rheometer (BBR)

Significance and use

Cracking due to low-temperature stresses is the dominant failure mode in asphalt pavements built in cold climates. This distress manifests as a set of almost parallel surface-initiated transverse cracks of various lengths and widths. Among the few test methods been introduced for investigating the binder low-temperature properties, BBR testing is the most common and non-destructive test, which focuses on the stiffness and the relaxation behaviour of the binder. This test makes it possible to determine different critical indicative parameters for the low-temperature behaviour of the bitumen. The purpose of BBR test is to make sure that asphalt binders do not become too stiff and brittle at low temperature, since it can contribute to transvers cracking in HMA pavements [4]. The BBR is used to measure the mid-point deflection, in three-point bending, of a beam of a bituminous binder.

Test procedure

The BBR is used to perform low-temperature creep tests on beams of asphalt binders conditioned at the desired temperature for 1 h in ethanol (C_2H_6O). The BBR is flexural stiffness test. From the applied load and resulted deflection, the creep stiffness of the asphalt binder is calculated. In analysing the BBR data, another quantity called m-Value is also calculated. The m-value is the log log of the creep curve at a given loading time. These parameters give an indication of an asphalt binder's ability to resist low temperature cracking. A sample of asphalt binder is moulded into a beam measuring 6.25 x 12.5 x 127 mm (see fig. 3.7). This sample is then simply supported at two points 102 mm apart in a controlled temperature fluid bath. The beam is then loaded at the midpoint by a 100 g load that, under normal gravity conditions, produces 0.98 N of force. The beam deflection is measured at 8, 15, 30, 60, 120, and 240 seconds.

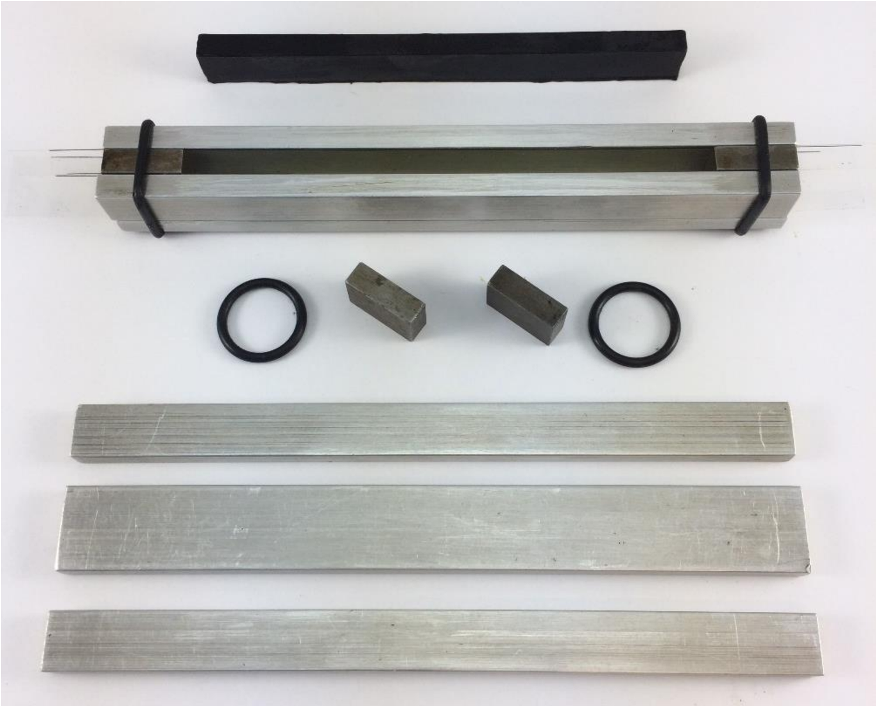

Fig. 3.7. BBR mould configuration and ready bitumen beam after demoulding.

Calculations and output data

From the dimensions of the test specimen, the measured test load, and the test specimen deflection the stiffness of the test specimen at any specific loading times is calculate using following equation:

$$Sm(t) = PL3/\ 4bh3\delta(t) \tag{3.4}$$

where:

Sm (t) is flexural creep stiffness at time t (MPa);

P is measured test load (mN);

L is span length (mm);

b is width of test specimen (mm);

h is depth of test specimen (mm);

, and δ (t) is deflection of test specimen at time t.

Indirect Tensile strength (ITS)

Significance and use

The Indirect Tensile Strength (ITS) test also known as the splitting test is a common test using for asphalt mix design and characterization. In asphalt mixtures, the mineral skeleton (aggregates) affords the compression strength, and the bitumen and mastic cohesion, deliver the tenacity (furthermore the bitumen/aggregates adhesion) [5]. Given that the tensile characteristics of asphalt mixtures are indicators of cracking potentiality, it is considered as a fundamental parameter of rutting [6], thermal and fatigue cracking resistance. In addition, ITS value is directly depended on the tenacity reached by aggregate/filler and bitumen bonding level [7] hence ITS value is considered a reliable comparative parameter.

Test procedure

The following steps followed according to European standard test method, EN 12697-23:

- Gyratory-compacted specimen production (see section 4.2.1)
- Recording the height and diameter of each specimen
- Storing the specimens at least 2 hours at 25˚C. After being sure about the temperature, the specimen was carefully placed on the lower loading strip of apparatus shown in Fig. 3.9
- Lowering top loading strip slowly into light contact with the specimen
- controlling the two loading strips to remaining parallel to each other during testing

- Applying the load at a constant speed of deformation of (50 ± 2) mm/min and record the peak vertical load at failure of the specimen (see Fig. 3.8).

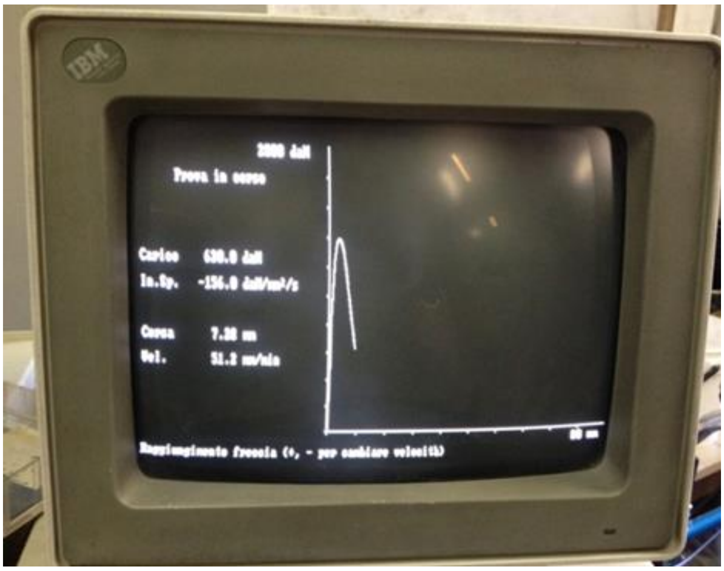

Fig. 3.8. Load-deformation screen capture at ITS test.

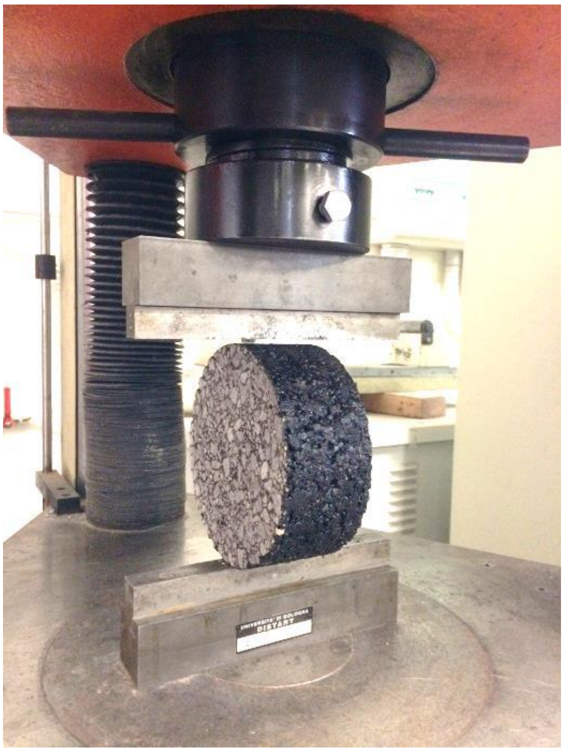

Fig. 3.9. Mounted specimen between loading strips for ITS test.

Calculations and output data

Tensile strength of the compacted bituminous mixture is determined using following formula:

$$ITS = \frac{2P}{\pi DH} \quad (3.5)$$

where:

ITS is Indirect Tensile Strength, express in (GPa);

P is the peak load, expressed in (kN);

D is diameter of specimen, expressed in (mm);

, and H is the height of the specimen expressed in (mm).

Marshall Stability and Flow

Significance and use

Marshall Method despite its shortcomings, is still probably the most widely used mix design method in the world probably since it is a simple and inexpensive test. Marshall Stability is related to the resistance of bituminous materials to distortion, displacement, rutting and shearing stresses. The stability is derived mainly from internal friction and cohesion. Cohesion is the binding force of binder material while internal friction is the interlocking and frictional resistance of aggregates. As bituminous pavement is subjected to severe traffic loads from time to time, it is necessary to adopt bituminous material with good stability and flow [8]. In the present research, the Marshall Method was used as the prequalification test, to assure on optimized mixture throughout the primary mix design.

Test procedure

The following steps shown in Fig. 3.10 followed according to European standard test method, EN 12697-34:

- Making the Marshall compacted specimens (see section 4.2.2). For the current test 75 blows have been chosen, considering a heavy load duty pavement. It is worth mentioning that the compacted specimens shall be demoulded ensuring that they are cooled in air to avoid any danger of deformation
- Immersing the demoulded specimens on their flat surface in the water bath at 60°C for at least 40 min
- Removing the test specimen from the water bath and placing it centrally on its sides between Marshall apparatus shields
- Applying the load to the test specimen to achieve a constant rate of deformation of (50 ± 2) mm/min

Fig. 3.10. A) Proportionated materials for a Marshall specimens. B) Marshall compacted specimens. C) Conditioning the specimens at 60˚C. D) UNIBO Marshall apparatus.

Calculations and output data

According to Fig. 3.11 Marshall stability value is the total load that causes failure of the specimen at 60°C while the Flow value is the total amount of deformation (rounded to the nearest 0.1 mm) that occurs up to the points the load start decreasing (failure point). It is noteworthy that the European approach for Marshall Stability and Flow, EN 12697-34 defines three different levels of flow value also described in Fig. 3.11.

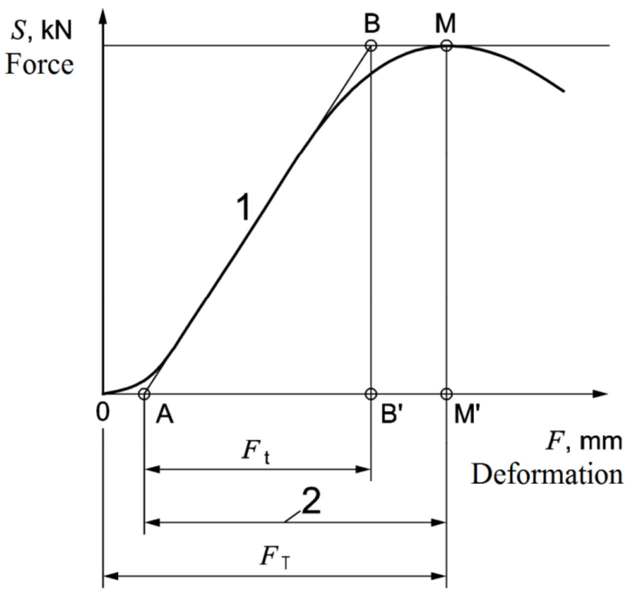

Fig. 3.11. Graphical depiction of the definitions for stability (S), flow (F), tangential flow, Ft, and total flow, F_T according to EN 12697-34.

Indirect Tensile Stiffness Modulus (ITSM)

Significance and use

Knowledge of the stiffness of bituminous mixtures is obviously a key element for the analysis and rational structural design of flexible pavements [9]. At normal traffic flow speeds and pavement temperatures, asphalt mixtures act almost elastically, therefore, its elastic stiffness is a measure of its resistance to bending and relatively its loads spreading ability [10]. In literature, ITSM is also considered as an indicator for the structural properties of mixtures as it is related to the capacity of the mixture to traffic loads bearing [11]. In addition, given that the ITSM values greatly depend on test temperature, the results often consider for thermal sensitivity analysis of asphalt mixtures. Hence stiffness of asphalt mixtures is an essential parameter in the evaluation of induced load, temperature stress and distribution of deformities in the pavement structure [12 & 13].

Test procedure

Asphalt mixture stiffness can be measured by various test procedures described in EN 12697-26 (annex C). The test was performed using the servo-hydraulic Universal Testing Machines UTM shown in Fig. 3.12. The test equipment comprises the loading system, incorporating a pneumatic load actuator, a steel load frame, a load cell and two loading strips. The deformation measurement system, including two Linear Variable Differential Transducers (LVDTs), mounted on a rigid frame clamping the test specimen; and the recording equipment, comprising an interface unit connected to a personal computer which monitors and records the electrical signals from the load actuator and LVDTs.

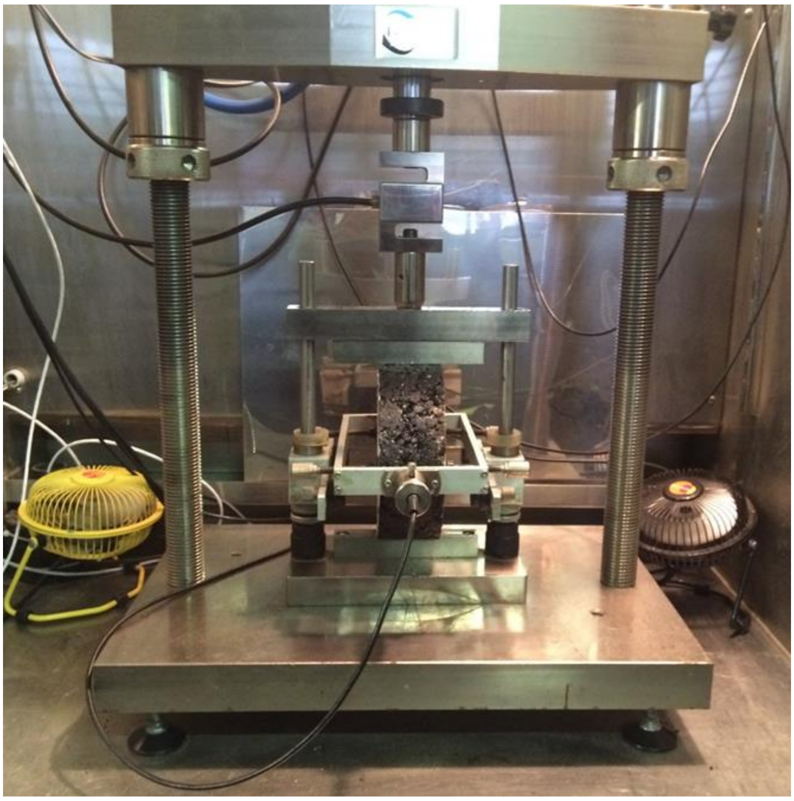

Fig. 3.12. ITSM test configuration.

The load applies a repeated load pulses with rest period. The load shall have a Haversian waveform shown in Fig. 3.13 or close to it.

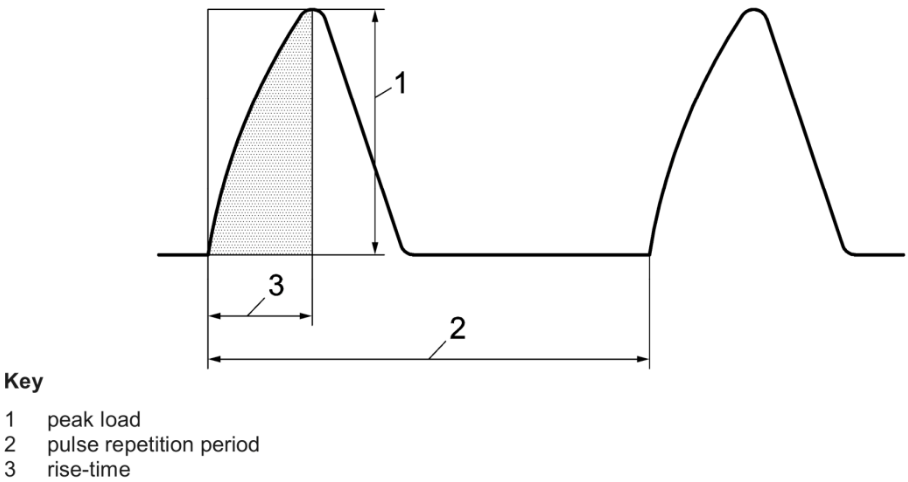

Fig. 3.13. Graphical representation for ITSM test loading characteristics according to EN 12697-26.

Calculations and output data

According to EN 12697-26 Annex C, calculation of the Modulus is based on the average of 5 load pulses, shown in Fig. 3.14.

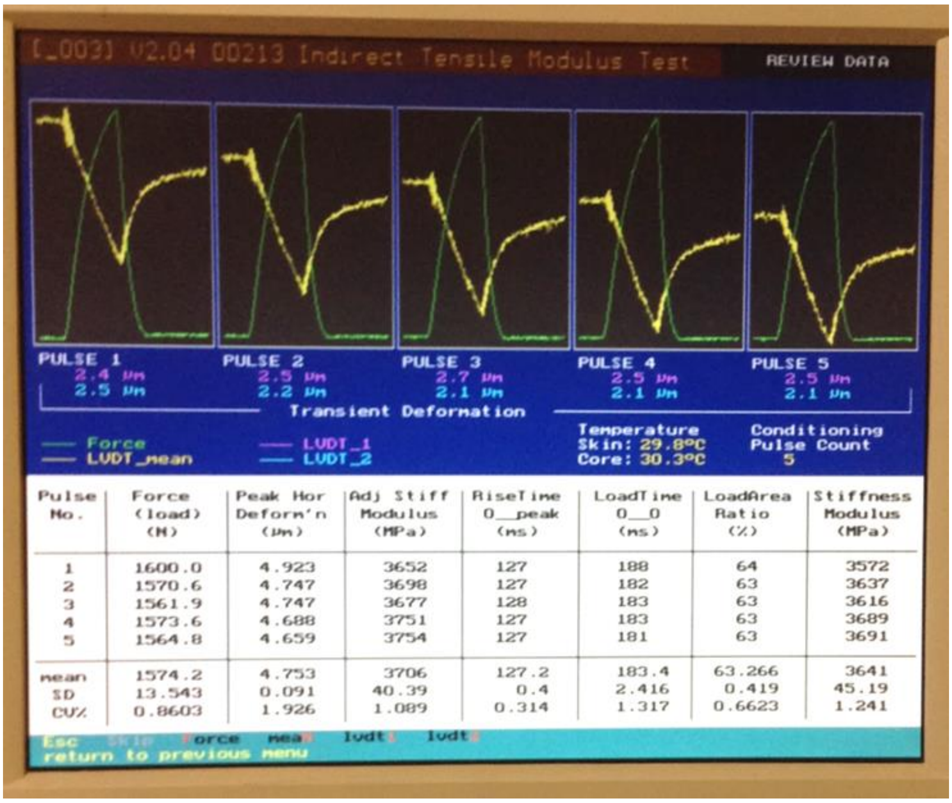

Fig. 3.14. ITSM screen capture after 5 load pulses.

The modulus is determined with the well-known equation:

$$E = \frac{F \times (\upsilon + 0{,}27)}{(z \times h)} \qquad (3.6)$$

Where:

E is the measured stiffness modulus, expressed in Mega Pascal (MPa);

F is the peak value of the applied vertical load, expressed in Newton (N);

z is the amplitude of the horizontal deformation (see Fig. 3.13) obtained during the load cycle, expressed in millimetres (mm);

h is the mean thickness of the specimen, expressed in millimetres (mm);

, and *v* is the Poisson's ratio, here used 0.35.

Repeated Load Axial Test (RLAT)

Significance and use

Rutting is a common failure form for flexible pavements in which material under the wheel path flows and densifies to form a depression or rut. Two major mechanisms of rutting are *densification* (compaction) due to the repeated loading and *plastic shear deformation* due to the repeated action of shear and tensile stress. If a pavement has been well compacted during construction, further densification during rutting is unlikely, and permanent deformation is principally due to shear flow [14]. The direct uniaxial cyclic compression configuration termed the permanent deformation properties by applying Repeated Load Axial Test known as RLAT. Besides the attractions of RLA test; including the simplicity, relatively low cost and straightforward procedure, and experimentally derived empirical results showed that RLA test is able to discriminate effectively different mixtures in terms of permanent deformation close to practical results. In addition, it presented good correspondence with other relative tests like Wheel Tracking test [5]. A variety of loading systems has been used to measure mixture response in repeated loading, ranging from relatively simple mechanical or pneumatic systems to more complex electro-hydraulic systems. More sophisticated systems generally include a testing chamber that permits careful control of temperature as well as the application of repeated load confining pressure coordinated with the vertical repeated load.

Test procedure

The test method is to determine the creep characteristics of the bituminous mixtures by means of a cyclic uniaxial compression test with some confinement. In this test, a cylindrical specimen is subjected to a cyclic axial stress. To achieve a certain confinement, the diameter of the loading plate is lower than that of the sample. The test to which reference was made was the EN 12697-25 Method A.

A cylindrical specimen with a diameter of 150 mm, maintained at an elevated temperature of conditioning (40°C), is placed between two parallel plates. The top plate has a diameter of 100 mm (because of a certain, inclination, in reality the area of the specimen subjected to stress has a diameter of 96 mm). There is no additional pressure applied lateral containment. The sample must be placed well centred with the test axle between the two plates. Two displacement transducers are positioned on the load plate, facing one another. Then a preload for 10 minutes (600 s) is applied. Immediately after that ended the step of preloading, the cyclic loading is applied with a series of pulses (1 ± 0.05) s.

Fig. 3.15. RLA test's configuration.

Calculations and output data

During the RLAT the change of the height of the sample is measured at the specific application of the load values. From this, the cumulative axial deformation (permanent deformation) of the specimen is determined as the function of the number of load applications. Results are presented in a graph (typically shown in Fig. 3.16) which involves an initial elastic part, followed by plastic deformation. The graph shows on the ordinate the accumulated deformation (in percent), while the abscissa axis shows pulses on a logarithmic scale. The first part of the graph is basically linear and represents the elastic deformation with the initial settling of the voids of the specimen, while the subsequent part is the plastic deformation that is the part of the permanent deformation, unrecoverable once removed the applied load. The permanent deformation performance of the asphalt mixtures was quantified by the ultimate percentage strain after 3600 cycles.

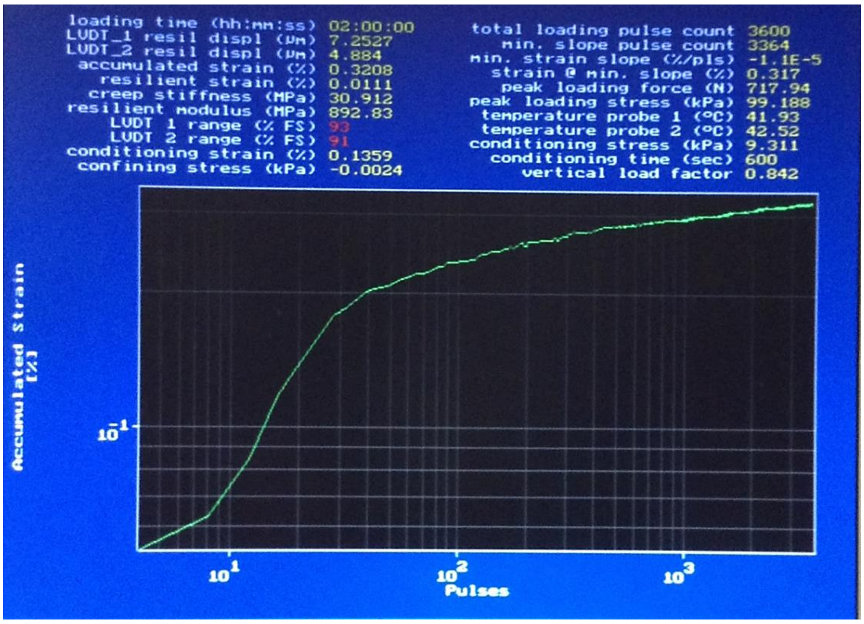

Fig. 3.16. Typical screen capture of strain-load pulse graph in Repeated Load Axial Test (RLAT).

Indirect Tensile Fatigue Test (ITFT)

Significance and use

Fatigue is one of the main failure modes of the asphalt pavement’s structure, which results in degradation of the bound pavement materials and finally the whole pavement structure. Two phases of the degradation process occur during fatigue cracking. The first phase corresponds to degradation resulting from damage that is uniformly distributed throughout the material. This phase is manifested by the initiation and propagation of a network of micro-cracks that results in decreased rigidity (stiffness modulus) of the material. The second phase starts with the coalescence of these micro-crack’ and the appearance of macro-cracks, which propagate within the material. These two phases are typically referred to as crack initiation and crack propagation [15]. It generally appears in the form of alligator or map cracking that is initially confined to localized zones and spreads at an increasing rate.

The fatigue behaviour of bituminous materials is measured in the laboratory under either controlled stress or strain conditions by different test configurations. Controlled stress is more widely used since it reproduces site conditions in which load is applied to the pavement structure and is the mode from which fatigue design equations are deduced [16]. In this mode, a repeated stress or load of constant amplitude is applied to a sample which causes the stiffness to eventually decrease and, thus, the resulting strain will increase.

From another perspective, several methods and test configurations have been developed for the fatigue testing of asphalt mixtures included repeated flexural beam, cantilever flexural, and indirect tensile tests graphically shown in Fig. 3.17 are usually used.

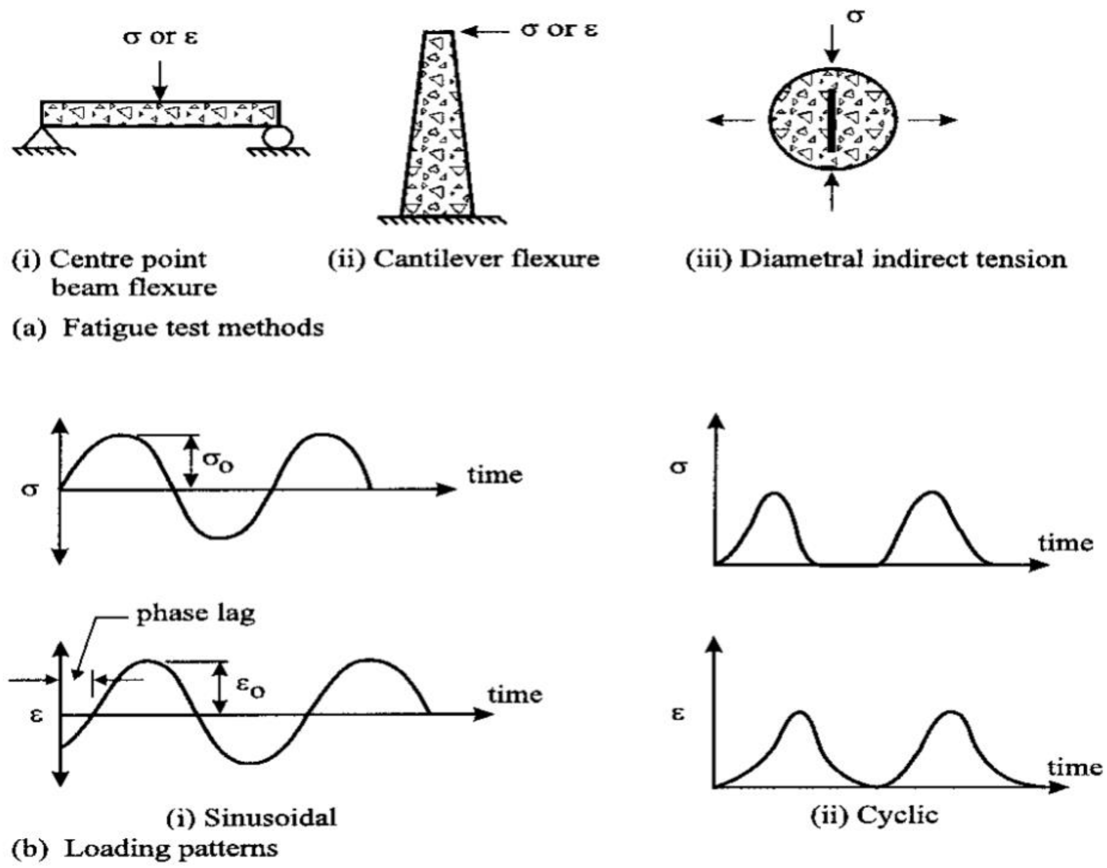

Fig. 3.17. Some well-known fatigue tests for bituminous materials and their loading patterns [16].

Indirect Tensile Fatigue Testing (ITFT) is a method commonly used to assess the fatigue resistance properties of asphaltic mixtures. The method's main characteristic is that the force applied on the testing specimen is a constant load pulse that generates a steady (constant) horizontal stress in the specimen, thus letting the resulting strain increase as the asphalt mixture specimen fails through fatigue damage.

Test procedure

In this study, ITFT was carried out in controlled stress mode according to EN 12697-24. For indirect tensile fatigue test, the extensometers measure the lateral deformation of specimens. The specimen was exposed to a repeated load with a load signal through the vertical diametrical plane shown in Fig. 3.18.

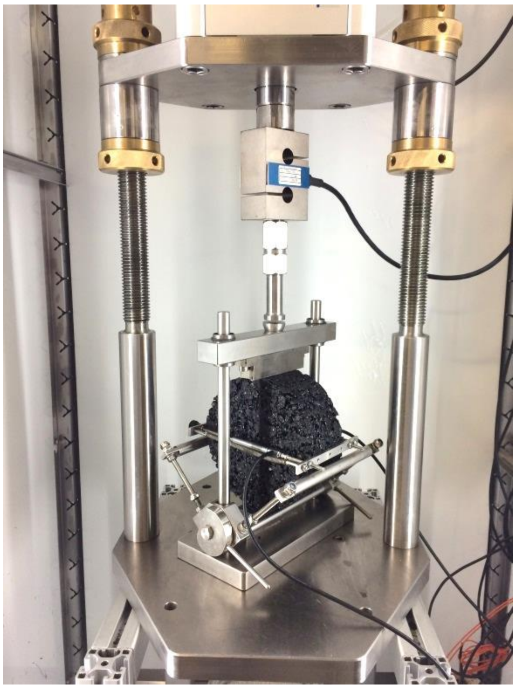

Fig. 3.18. Indirect Tensile Fatigue Test (ITFT) configuration and specimen placement settings.

This loading develops a relatively uniform tensile stress perpendicular to the direction of the applied load, which induces permanent deformation leading to failure of the sample by splitting along the central part of the vertical diameter. During the test, the stress and material stiffness were monitored continually (Fig. 3.19) and recorded at the preselected intervals using computer data. In this research study, three cyclic loading forces were used (200, 250, and 300 kPa). The fatigue life is defined as the number of load application when the complex stiffness modulus has decreased to half the in initial value $N_{f/50}$. Complex stiffness modulus is considered after 100 load applications.

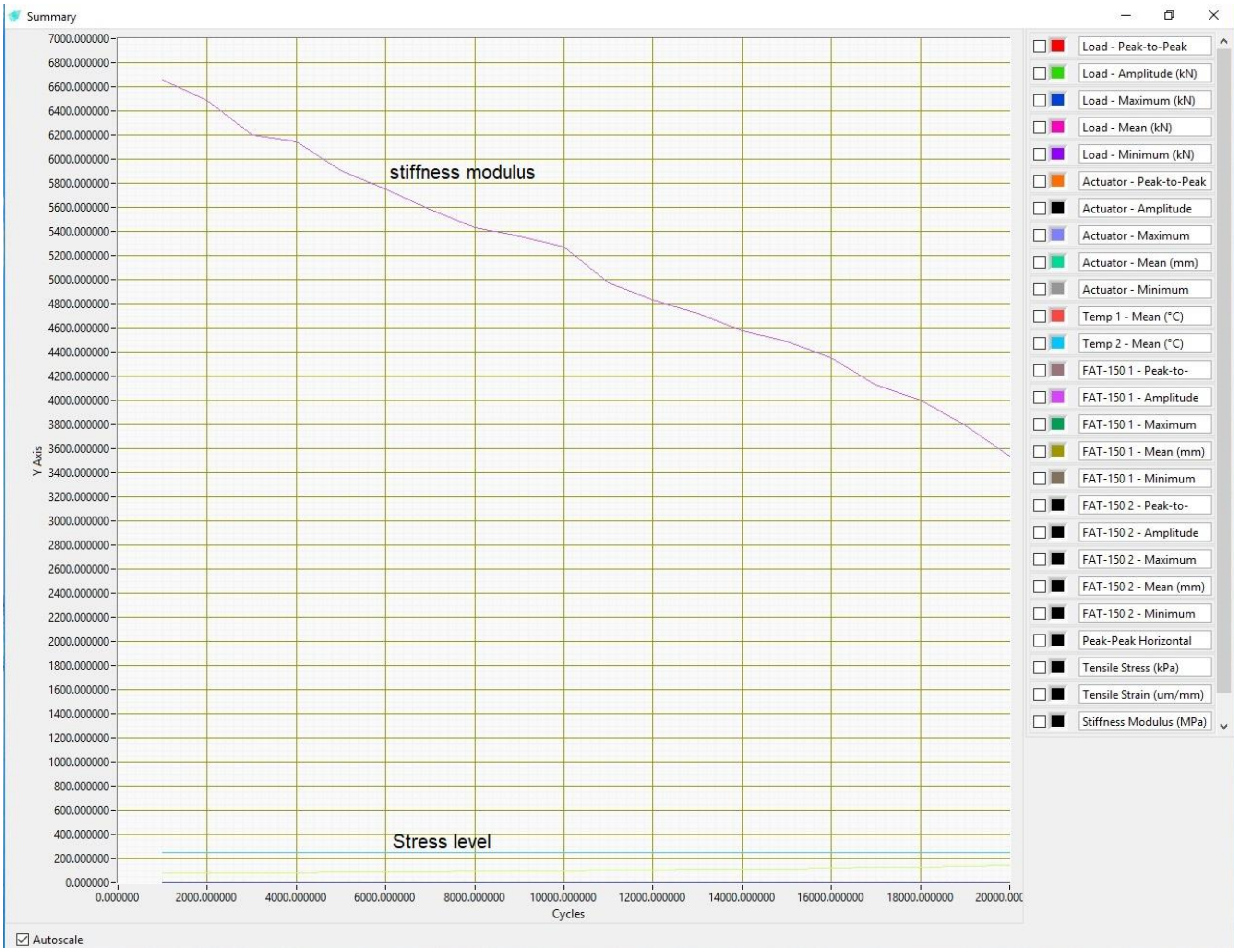

Fig. 3.19. Screen capture, monitoring the initial and momentary stiffness of material.

The ITFT tests were performed using the following conditions:

- Test temperature: 20˚C
- Poisson's ratio: 0.35
- Loading condition: controlled-stress
- Loading rise-time: 120 ms
- Failure indication: decreased stiffness modulus to half value after 100 cycles

Calculations and output data

The test specimen was subjected to different levels of stress, for a regression analysis on a range of values. This allowed the development of the fatigue relationship between the number of cycles at failure (NF) and initial tensile strain. The tensile strain and stress at the centre of the specimen shall be calculated using the following formulae:

$$\sigma = \frac{2F}{\pi \times t \times \emptyset} \tag{3.7}$$

$$\varepsilon = \left(\frac{2\,\Delta H}{\emptyset}\right) + \left[\frac{1+3\upsilon}{4+\pi\times\upsilon-\pi}\right] \tag{3.8}$$

$$\varepsilon_o = 2.1\frac{\Delta H}{\emptyset} \tag{3.9}$$

$$S_{mix} = \frac{\sigma s}{\varepsilon s}\times(1+3\upsilon) \tag{3.10}$$

Where:

σ is the horizontal tensile stress at the centre in (MPa);

F is the measured force in (N);

t is the specimen thickness in (mm);

$\emptyset$ is the specimen diameter in (mm);

ε is the horizontal strain (µm/m);

ΔH is the horizontal deformation in (mm);

ε_o is the resilient horizontal tensile strain between load impulses;

And S_{mix} is the stiffness modulus, in (MPa).

Considering the principle definitions the fracture life is calculated by the following equation:

$$\text{Nf} = k \times \left(\frac{1}{\varepsilon_o}\right)^n \tag{3.11}$$

where:

N_f is the number of load applications;

k and n are material constants;

And ε_o is the tensile strain in µε at the centre of the specimen

Thermal Stress Restrained Specimen Test (TSRST)

Significance and use

Low-temperature cracking is the most prevalent distress found in asphalt pavements built in cold weather climates. As the temperature drops the restrained pavement tries to shrink. The tensile stresses build up to a critical point at which a crack is formed. Thermal cracks can be initiated by a single low-temperature event or by multiple warming and cooling cycles and then propagated by further low-temperatures or traffic loadings. Thermal cracking can be divided into two modes of distress: low temperature cracking and thermal fatigue cracking. While Low-temperature cracking results from extremely cold temperatures; thermal fatigue cracking results from daily temperature cycles. Low-temperature cracking is attributed to tensile stresses induced in the asphalt concrete pavement when the temperature drops to an extremely low-temperature. If the pavement gets cooled, tensile stresses develop as a result of the pavement's tendency to contract in the meanwhile the contact friction between the pavement and the base layer resists the contraction. If the tensile stress equals the strength of the mixture at that temperature, a micro-crack develops at the surface of the pavement. Under repeated temperature cycles, the crack penetrates the full depth and across the asphalt concrete layer. The primary pattern of low-temperature cracking is transverse to the direction of traffic and is regularly spaced at intervals of approximately 30 m for new pavements to less than 3 m for older pavements. If the transverse crack spacing is less than the width of the pavement, longitudinal cracking may occur, and a block pattern can develop [17]. The Thermal Stress Restrained Test (TSRST) has been developed to evaluate the thermal cracking resistance of asphalt concrete mixtures.

Test procedure

The test is carried out by cooling an asphalt concrete specimen at a specified rate (usually 10˚C) while keeping the specimen length constant. For this, a beam or cylindrical specimen epoxied to end platens is mounted in the load frame, which is enclosed by the cooling cabinet as shown in Fig. 3.20. Two or four Linear Variable Differential Transformers (LVDTs) monitor changes in the length of the specimen, while the load cell monitors the tensile load.

Fig. 3.20. Mounted specimen and placed dummy specimen for TSRST.

Calculations and output data

The TSRST results are reported in terms of the temperature at fracture and the maximum stress at failure. Fig. 3.21 shows a typical TSRST graph.

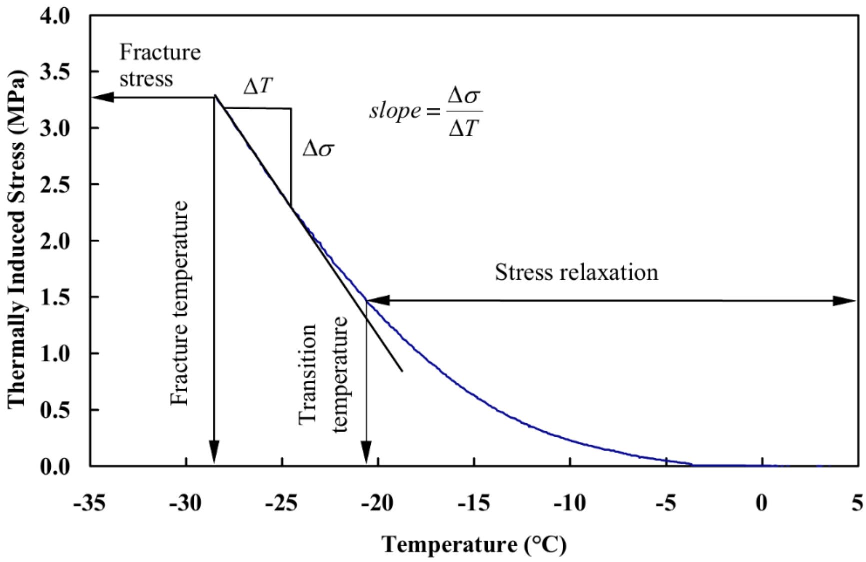

Fig. 3.21. Schematic representation of TSRST typical curve and parameters.

The thermally induced stress gradually increases as the temperature decreases at a constant rate of cooling until the specimen fractures. At the breakpoint, the stress reaches its maximum value, which is referred to as the fracture strength, with a corresponding fracture temperature. The transition temperature divides the curve into two parts-relaxation and non-relaxation. As the temperature approaches the transition temperature, the asphalt cement becomes stiffer and the thermally induced stresses are not relaxed beyond this temperature. Due to the prohibited thermal shrinkage, cryogenic stress is built up in the specimen. The results are the progression of the cryogenic stress over the temperature (T) and the failure stress, failure at the failure temperature $T_{failure}$ [18].

Indirect Tensile Strength Ratio (ITSR)

Significance and use

One of the factors that lead to premature failure of pavements is moisture sensitivity. The presence of moisture in bituminous mixes can either initiate new distresses or aggravate existing distresses. In moisture-induced damage, the bond between bitumen and aggregate gets weakened in the presence of water, leading to aggregate stripping or ravelling [19]. The moisture damage can be detrimental if combined with other factors, such as freeze-thaw cycling [20]. Moisture damage can be defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture [21]. Premature failure may result due to stripping when critical environmental conditions act together with poor and/or incompatible materials and traffic [22]. Due to the detrimental effect of moisture damage, it is important to test the susceptibility of an asphalt mixture to moisture damage. The moisture damage resistance of mixes is evaluated in terms of the effect of moisture on different mix parameters such as stability, indirect tensile strength, stiffness (resilient modulus, dynamic modulus), rutting, and fatigue characteristics. Numerous tests have been used to evaluate moisture susceptibility of HMA; some are tests for asphalt binder, while others are for asphalt mixtures. The tests for asphalt mixtures are divided into tests for loose mixes and tests for compacted mixes.

Within the framework of European test methods, the determination of the indirect tensile strength ratio (ITSR) is put forward as a measure in order to assess the water sensitivity of asphalt mixtures, which applied for the present study.

Test procedure

The test has been done following the basis on EN 12697-12 standard method A, however, it is worth mentioning that here we did not apply a vacuum to obtain an absolute (residual) pressure. Hence, subsets of specimens were subjected to dry conditioning while the corresponding specimens were conditioned by immersing into the water at 40˚C for 72 h (Shown in Fig. 3.22). Before running the tensile strength test the wet subset was stored in the water bath at 25˚C for 2h. The specimens were then subjected to indirect tensile strength immediately after just drying the surface of the specimens. The ITS values were determined by loading the specimens at a constant rate (50 mm/min) and measuring the force required to break them. The tensile strength of the conditioned specimens was then compared with the dry conditioned specimens to determine the tensile strength ratio (ITSR).

Fig. 3.22. Conditioning of wet subset for ITSR.

Calculations and output data

The tensile strength ratio is calculated as follows:

$$ITSR = 100 \times \frac{\text{ITS wet}}{\text{ITS dry}} \quad (3.12)$$

where:

ITSR is the indirect tensile strength ratio, in percent (%);

ITS wet is the average indirect tensile strength of the wet group, in kilopascals (kPa), rounded to three significant figures;

And *ITS* dry is the average indirect tensile strength of the dry group, in kilopascals (kPa), rounded to three significant figures.

Rolling Bottle Test (RBT)

Significance and use

The adhesion between bitumen and aggregates is of paramount importance for asphalt mixtures since it has been confirmed that weak bond-strength results in a premature failure of the pavement [23]. In addition, the adhesion between aggregate and binder was identified as one of the most important parameters influencing moisture sensitivity [24]. In order to extend the service life of the pavement, several countries have implemented national requirements of the mandatory addition of adhesion promoters in asphalt mixes, to secure and maintain the adhesion and durability of asphalt pavements over time. However, it has been shown that the adhesion between bitumen and aggregate also depends on the chemical nature of the components and therefore the source of the bitumen and type of aggregate. Other aggregate-properties such as surface texture, shape, porosity and absorption will also influence the adhesion [25]. Others factors are related to mixture design and layer construction (air voids content, film thickness, permeability and drainage) or environmental factors (temperature, pavement age, freeze-thaw cycles and presence of ions in the water) [26, 27].

Number of test methods is available to estimate the affinity between aggregates and bituminous binders. The standardized European approach to quantify the affinity between aggregate and bitumen is the rolling bottle test.

Test procedure

The Rolling Bottle Test (RBT) was conducted in accordance with EN 12697-11 with minor modifications based on practical procedure also considered in mixture scale tests. Fig. 3.23 shows the applied procedure steps.

1. Aggregates, only material retained between the 8 and 11 mm sieve was used for conducting the rolling bottle tests. To prepare samples for testing, dust-free aggregate samples weighing 510 g heated up to 175±5˚C then mixed with the proportionated amount of each fibre for at least 5 minutes.
2. Heated binder (temperature was depended on the type of bitumen, neat bitumen or SBS PmB) added to the mixed aggregates and fibre.
3. Aggregates, fibre, and bitumen mixed until getting fully bitumen covered aggregates.
4. Then after the proportionated limestone filler added to all material.
5. After mixing all the materials, the materials stored in the oven at 160±5˚C, simulating the practical conditioning for 25 minutes.

6. Coated aggregate particles as the individual, loose particles were spread on silicon paper for 18 h at room temperature.
7. 150±2 g of aggregates transferred into the bottles previously approximately 50% filled with distilled water of 5˚C. The glass rod placed in the bottles and filled with water.
8. The bottles finally placed on the rolling apparatus.

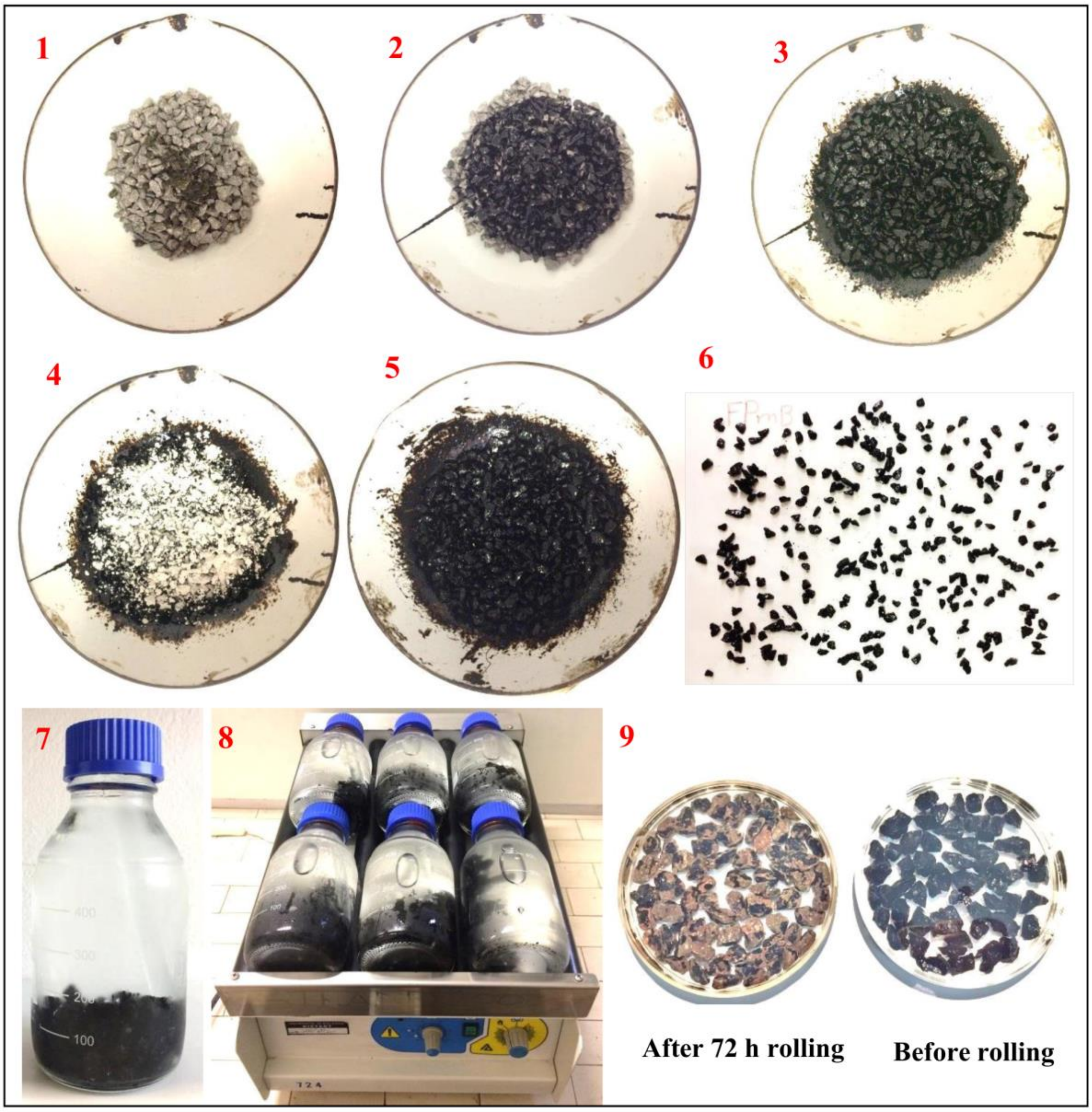

Fig. 3.23. Rolling bottle test procedure.

Calculations and output data

As mentioned before, RBT consists in placing bitumen-coated aggregates in a bottle filled with de-ionized water and then placing it in a rolling machine, which subjects the material to a mechanical stirring action in the presence of water. After defined time steps, normally 6, 12, 24, 48, and 72 h, at least two independent operators (in this research 3) visually estimate the residual degree of bitumen coverage of the particles immersed under water and under concentrated lights using the scale set in the standard as shown in Fig. 3.24. The presence of water helps the operators observe the aggregates better. It also represents a simple, rapid and low-cost test for an indication of the affinity between aggregate and bitumen. Fig. 3.25 show a sample after rotation period under water, investigating the binder coverage.

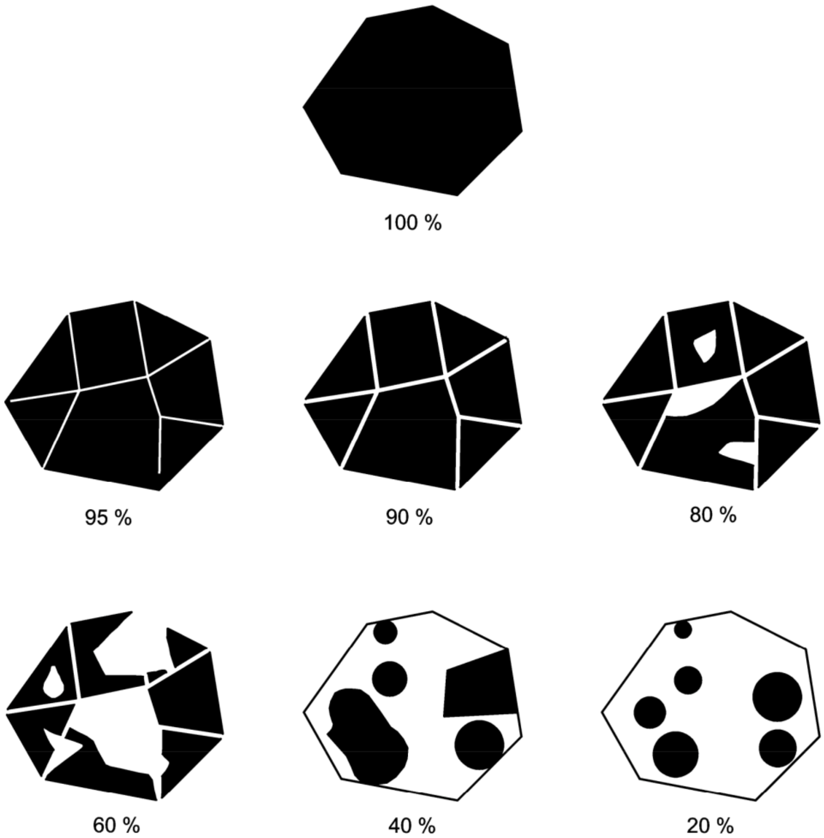

Fig. 3.24. Reference for estimation of degree of bitumen coverage according to EN 12697-11.

Fig. 3.25. Aggregates after rolling, immersed under water and under light for observing the bitumen coverage.

At the end of the test, the degree of bitumen coverage of the aggregate particles is estimated by visual observation of at least two independent observers and recorded to the nearest 5%.

Chapter 3 References

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CHAPTER 4

MIX DESIGN AND PREQUALIFICATION TESTS

CHAPTER 4 MIX DESIGN AND PREQUALIFICATION TESTS

4.1 Specimen Production and/or Sample Preparation Methods

4.1.1 Totally virgin mixtures

One of the most influential variables in determining the performance-based properties of the asphalt mixtures is the specimen fabrication method. Researchers and practitioners have always recognised that results obtained from testing of binders and mixtures can be vastly different and that differences in the methods used to produce asphalt concrete specimens for laboratory testing can influence the measured material properties and predicted performance. Considering the extended experimental plan and the defined tests, different specimens, by means of adopted compaction method and specimen geometry were produced for the presented research work.

As the first stage, once satisfactory aggregate materials have been identified, the aggregate gradation and the optimum asphalt cement content are selected. Gradation is perhaps the most important property of an aggregate mix. It affects almost all the important properties of asphalt concrete mixtures including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. Therefore, gradation is a primary consideration in the asphalt mix design [1]. This is accomplished by first selecting an appropriate aggregate blend. The blended gradation should comply with the gradation specified to provide an aggregate skeleton with a stone-on-stone contact and furnish a mixture that meets the minimum VMA requirement. Table 4.1 provides the considered gradation band represented in Fig. 4.1 (from Italian Specifications of Autovie Venete [2]) considering the nominal maximum aggregate sizes (NMAS) of 12 mm

Table 4.1. Applied aggregate gradation band.

Sieve Size (mm)	Lower/Upper limit* (%)	Cut surface appearance
12	100/100	
10	81/100	
8	60/80	
4	30/52	
2	22/34	
1	16/26	
0.5	11/21	
0.063	8/14	

* From Italian specifications, Autovie Venete

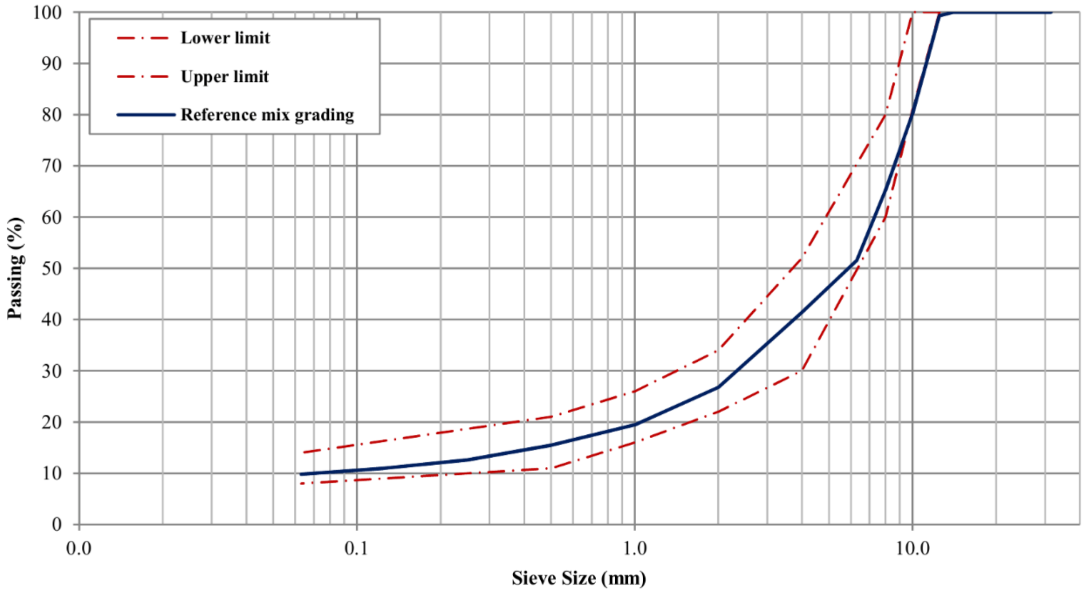

Fig. 4.2. SMA applied grading curve and grading band.

As the first stage of mixture production, the job mix formula of the components were determined according with this gradation band for both mixtures with and without RAP containing mixtures. Table 4.2 provides the job mix formula of the mixtures.

Table 4.2. Job mix formula of aggregates and filler.

Mixture	Proportion (%)					
	Sand	Porphyry 4/8	Porphyry 8/12	Fine RAP	Coarse RAP	Filler
Mixture without RAP	21	22	47	0	0	10
Mixture with RAP	5	24	38	12	13	8

The overall procedure and chronology (shown in Fig. 4.2) of producing asphalt mixtures were:

1a) Heating the proportionated virgin aggregates (4/8, 8/12 porphyry, and lime stone sand) according to job mix formula, up to 170±5°C;

1b) Heating the RAP aggregates up to 100±5°C;

2) Adding fibre to aggregates and mix for a minute;

3) Adding RAP to the mixtures containing RAP;

4) Adding the hot binder to mix (binder temperature depend on the binder type; for modified 180±5°C and for neat bitumen 170±5°C);

5) Mixing all the compound and wait for a minute;

6) Adding filler to mix;

7) Mix all the material until get to uniform mix;

8) Condition the samples for 30 minutes hours at 150°C in oven. Using conditioning method were intended to simulate what happens in the plant;

9) and compacting the sample with any compaction apparatus.

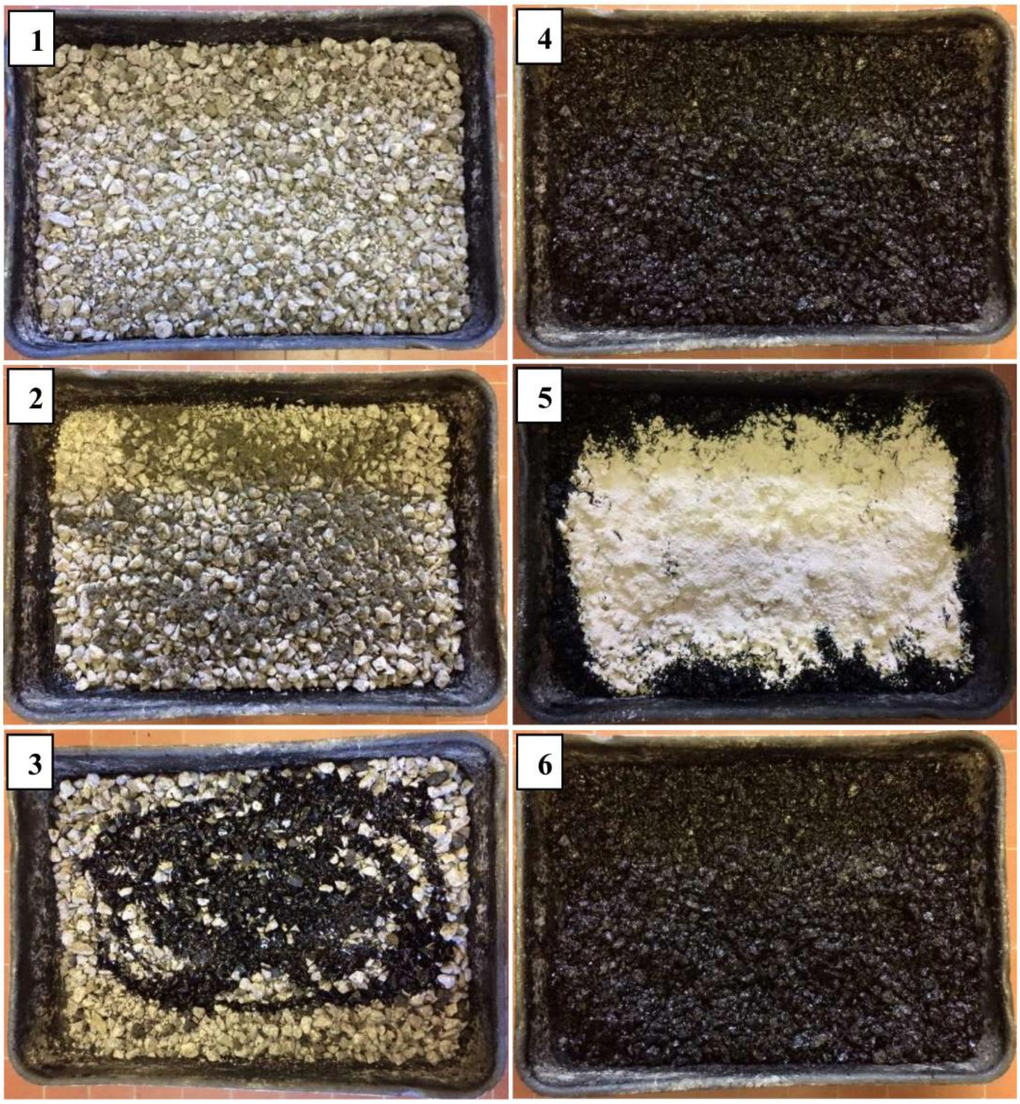

Fig. 4.2. Mixing steps. 1) Heating the fine and coarse aggregates; 2) Adding and mixing the fibre with heated aggregates; 3 & 4) Adding and mixing the binder; 5 & 6) Adding and mixing filler.

It is worth mentioning that regardless of the material compaction methods (explained in the following), the chronology of mixture preparation was the same due to not impose any additional influence on experimental tests.

4.1.2 25% RAP containing mixtures

For the mixtures containing RAP aggregates, the primary stage goes to binder extraction which is needed for the further aged binder characterization as well as RAP aggregate properties. Fig. 4.3 shows the binder extraction set up and the used RAP filter and the Table 4.3 presents the extraction table of coarse RAP in this study. Within binder extraction, the recoverable amount of binder in RAP was considered 4% on the weight of RAP aggregates, which was considered through the mix design procedure.

Fig. 4.3. Binder extraction machine, applied in this research (on the left) and extraction filter on the right.

Table 4.3. RAP aged binder calculation.

RAP Sample	I	II
Filter + Asphalt mixture weight (RAP)	616.3	682.6
Empty filter weight	51.0	57.7
Asphalt mixture weight (RAP)	565.3	624.9
Extracted material (RAP clean aggregates) + Filter weight	591.4	656.4
Extracted material weight (RAP clean aggregates)	540.4	598.7
Extracted bitumen weight (aged bitumen)	24.9	26.2
Bitumen % on the weight of aggregates	4.6	4.4
Total weight of extracted material	1139.1	
Total weight of asphalt mixture (RAP)	1190.2	
Total weight of extracted bitumen (RAP clean aggregates)	51.1	
Bitumen % on the weight of asphalt mixture (RAP)	4.29	
Bitumen % on the weight of asphalt mixture (RAP clean aggregates)	4.49	

The process and chronology as for totally virgin mixtures were adopted for producing the RAP containing mixtures. It is noteworthy that controlling the heating temperature of RAP aggregates is of utmost importance. For this reason, while the virgin aggregates were heated up to 170±5°C, the RAP aggregates heated up to 100°C and under controlled time, avoiding possible further ageing.

For the RAP containing mixtures, the rejuvenating agent was also added to these mixtures to recover the aged binder of RAP. The rejuvenator was added to the bitumen first and then mixed with materials. For this purpose, the proportionated rejuvenator was mixed with the heated bitumen and manually stirred until having a homogenous compound.

4.2 Compaction Methods

4.2.1 Gyratory Compaction

In the presented research work, all laboratory compacted test specimens (except for TSRST and Marshall Test) were fabricated using a gyratory compactor. The specimens were compacted with 150 mm in diameter and variable in height (depending on the test) and then were cut to achieve the final tests' specimens with a target air voids content.

European Standard EN12697-31, specifies the method for compaction of cylindrical specimens of bituminous mixtures using a gyratory compactor. The gyratory compactor is a mechanical compaction device comprised of a reaction frame, rotating base, and motor; loading system, loading ram, and pressure gauge; height measuring and recordation system, mould and base plate. Such compaction is achieved by combining a rotary shearing action and a vertical resultant force applied by a mechanical head. The method is used for:

a) Determination of the air voids content of a mixture for a given number of gyrations or derivation of a curve density (or void content) versus number of gyrations;
b) Preparation of specimens of given height and/or at a predetermined density, for subsequent testing of their mechanical properties.

Mixing and compaction temperatures are chosen according to asphalt binder properties so that compaction occurs at the same viscosity level for different mixes. Key parameters of the used gyratory compactor (see Fig. 4.4) are:

- Sample size: 150 mm diameter cylinder. The heights varied for the different tests
- Load: flat and circular with a diameter of 149.5 mm corresponding to an area of 175.5 cm^2
- Compaction pressure: typically, 600 kPa
- Number of blows: 100

- Simulation method: the load is applied to the sample top and covers almost the entire sample top area

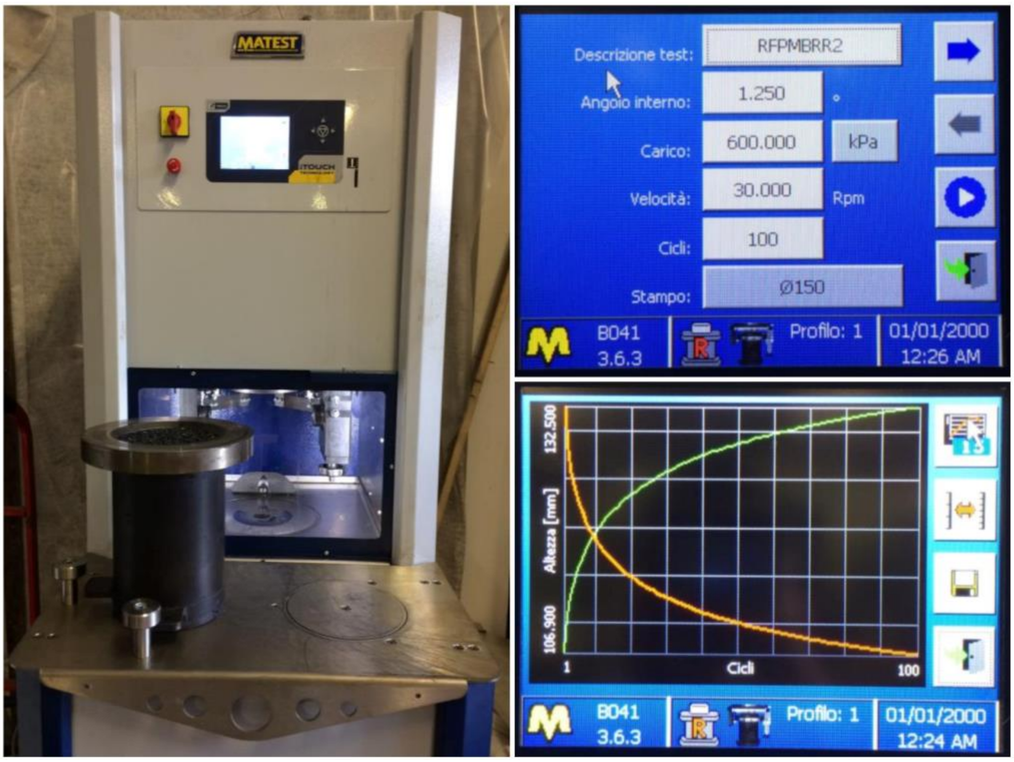

Fig. 4.4. Gyratory compactor at UNIBO laboratory of paving materials; applied settings, and height/density monitoring along with the test.

4.2.2 Marshall compaction

The coarse aggregate, fine aggregate, and the filler material should be proportioned so as to fulfil the previously determined mix design. The required quantity of the mix is taken so as to produce compacted bituminous mix specimens of thickness 63.5 mm approximately. 1200 g of aggregates and filler are required to produce the desired thickness. The same mixing chronology, which was mentioned in section 4.1 was adopted for preparing the mixture. Following the mixing procedure, the aggregates heated to a temperature of 170±5°C while the compaction mould assembly kept pre-were heated to the temperature of 100°C. The bitumen was heated to the needed temperature based on the bitumen type. The required amount of bitumen added to the heated aggregate and thoroughly mixed followed by adding and mixing all with filler. After keeping the samples for 30 minutes of conditioning time at 150±5°C, the mixture was placed in a mould and compacted with 75 blows. The sample was taken out of the mould after a few minutes using the sample extractor. Fig. 4.5 shows the Marshall hammer and the extracted Marshall compacted specimens.

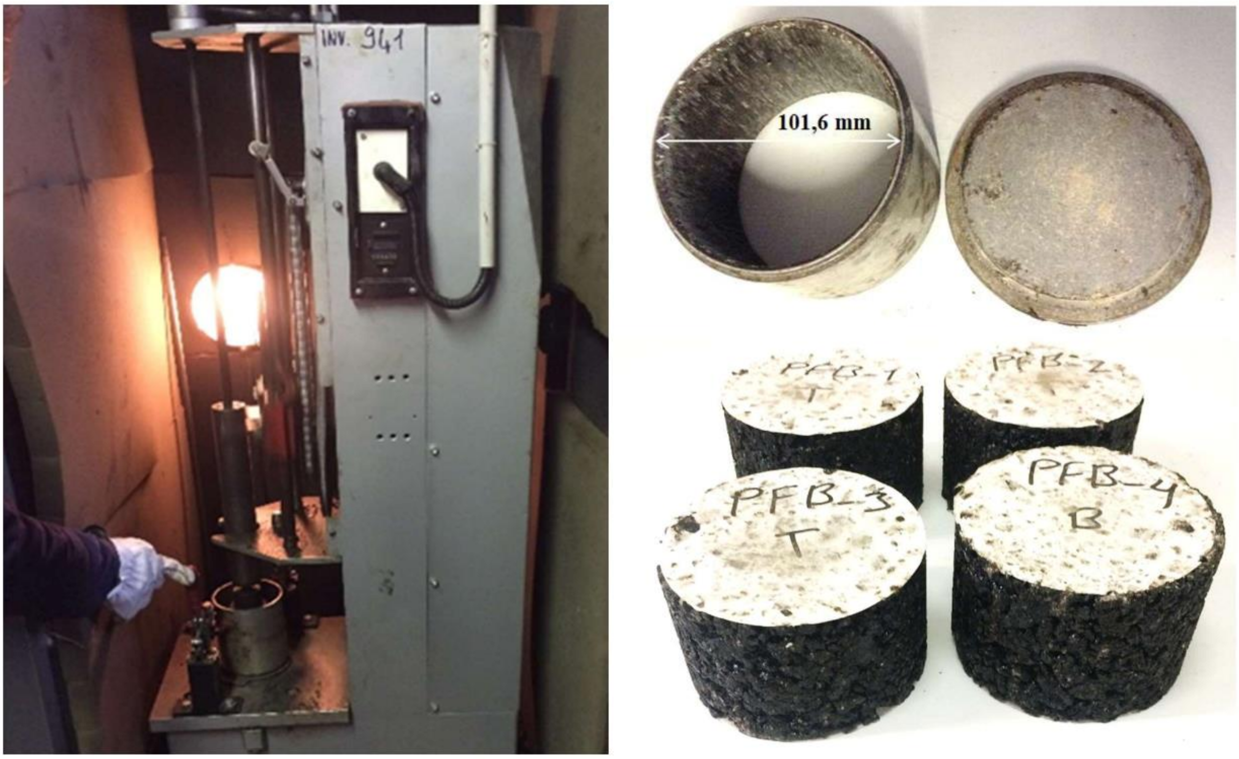

Fig. 4.5. Marshall hammer at UNIBO laboratory of paving materials; Marshall moulds and demoulded specimens.

4.2.3 Roller compaction

The roller compactor was designed to emulate the action of actual site, compromises a pivoted steel roller segment, which forced into contact with the hot mixture by a vertically mounted pneumatic actuator. Asphalt slab roller compactor compact asphalt slabs to target mixture densities using loads that are equivalent to those of full-scale compaction equipment. The mixture is placed in the mould and compacted to a predetermined density. The density is determined on a weight-to-volume basis for the specific mixture being compacted and for the specific air void level required.

Asphalt slab roller compaction is considered to be the method of laboratory specimen compaction that results in slabs of asphaltic paving materials with properties that most closely simulate those of materials in the highway. Literary, a number of benefits have been mentioned for roller compaction. The following are significant findings: (a) rolling compaction is practical for the production of asphalt concrete test specimens in a research laboratory; (b) large numbers of specimens of various geometries can be produced on a daily basis; (c) slab width, length, and thickness are easily varied; and (d) the equipment and procedure can easily accommodate the fabrication of pavement layers such as overlays (e.g., open-graded mixture over a dense-graded mixture) [3].

The compaction complied with EN 126970-33 standard with the electromechanically operated apparatus shown in Fig. 4.6. Slab compactors feature a compacting system by roller segment head.

The roller segment freely moves by simple friction for better compaction uniformity. A brushless motor or stepper motor moves vertically the roller segment under displacement control. The vertical load is applied orthogonally to the axis of the travel motion. The mould carriage moves back and forth by linear movement. The longitudinal (major) mould dimension correspond to the compaction direction so it is possible to obtain specimens of the proper length complying with Standards.

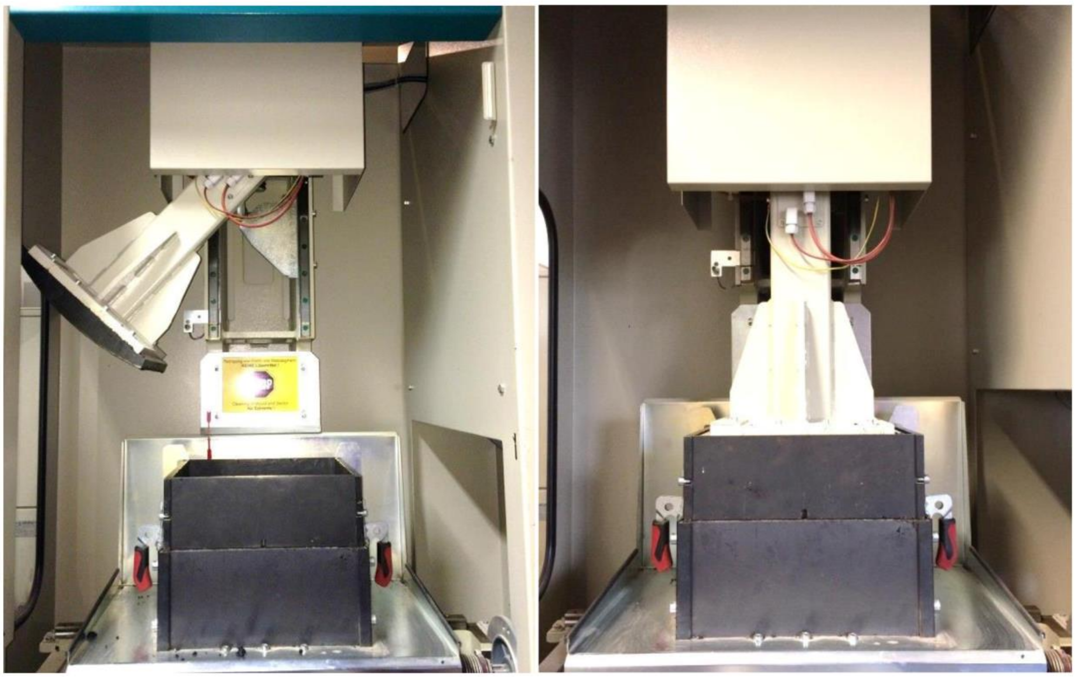

Fig. 4.6. Roller compactor at TU Wien, institute of transportation laboratory.

4.3 Mix Design and Primary Tests

The design of asphalt concrete mixture involves the selection and proportioning of materials to obtain the desired properties in the final product. In the design of asphalt concrete mixtures used in pavement construction, the constituents are rationally selected and blended aiming for minimizing principal pavement distresses such as fracture, distortion and disintegration. This section is dedicated to adopted mix design procedure and binder optimization. Overall, the objective of the bituminous mix design is to determine a cost effective blend and gradation of aggregates and bitumen that yields a mix having:

- Sufficient bitumen to ensure a durable pavement;
- Sufficient mix stability to satisfy the demands of traffic without distortion or displacement;
- Sufficient voids in the total compacted mix to allow a slight amount of bitumen expansion due to temperature increase without flushing, bleeding, and loss of stability;
- And adequate workability to facilitate the laying of the mix without segregation.

However, Asphalt mixture characteristics which favour different aspects of performance often conflict. For example low binder content are generally beneficial for resistance to deformation while high binder content enhance durability and resistance to fatigue cracking. Hence, the mix design is therefore usually a compromise.

In particular, regarding the SMA mixtures, the mix design consists of two part. A coarse aggregate skeleton and binder rich mortar. The rationale in SMA mix design is first to develop an aggregate skeleton with a coarse aggregate-on-coarse-aggregate contact that is generally referred to as the stone-on-stone contact. The second part of the mix design rationale is to provide sufficient mortar of the desired consistency. Satisfactory mortar consistency and, thus, good SMA performance requires a relatively high asphalt cement content. For this reason, the voids in the mineral aggregate (VMA), or the design asphalt cement content, must exceed some minimum requirement [4]. According to the adopted mix design method, NAPA recommended procedure, five steps are required to obtain a satisfactory SMA mixture, as shown in Fig. 4.7.

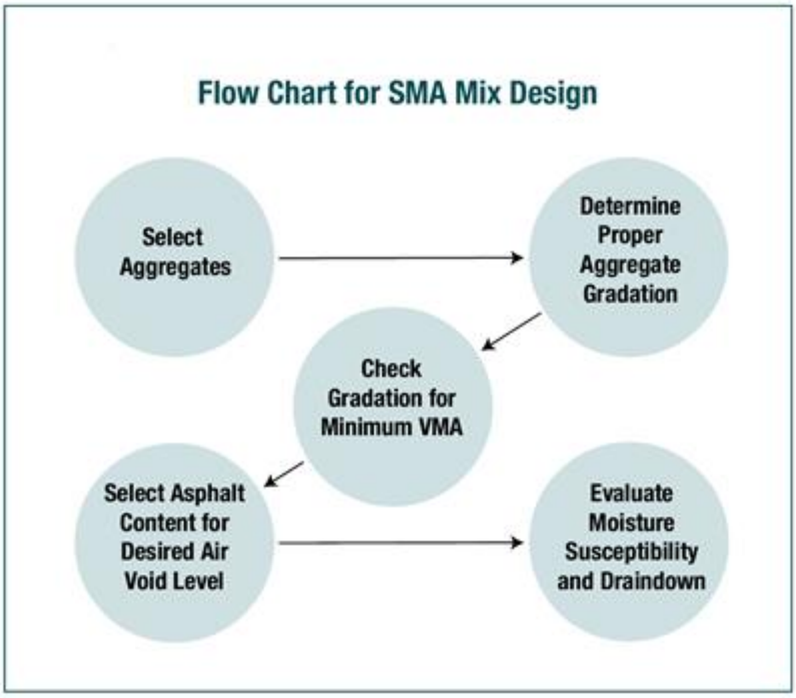

Fig. 4.7. NAPA recommended procedure for SMA mix design [4].

The first step in the mixture-design process is to select aggregates that meet specification requirements. Aggregate hardness and shape are even more important than in conventional dense-graded mixtures. See chapter 3, for further details on porphyry aggregates used in this study as coarse aggregates. Once satisfactory aggregate materials have been identified, the optimum aggregate gradation is selected. This is accomplished by first selecting an appropriate aggregate blend considering the Nominal Maximum Aggregate Size used and ranges. For this research 12mm was considered as NMAS and the adopted gradation was complied with an Italian specification (See section 4.1). The following sections dedicated to later steps of SMA mix design recommended by NAPA.

4.3.1 Volumetric controls

After the first and second step of SMA mix design, volumetric controls is the next stage. For this purpose, the blended aggregates, are combined with a different percentage of bitumen binders and compacted (here gyratory compaction, gyration number: 100). In addition to the voids, then after the samples were compacted and allowed to be cool down they are were removed from the moulds for being tested aiming for determining their bulk specific gravity. The National Center for Asphalt Technology-NCAT (performance evaluation of SMA pavements) suggests that; choosing the asphalt content to produce an air void content near 4 %, will provide protection against fat spots after laying down and provides better rut resistance. However, the range of 4 to 8% was an acceptable air void content according to the local specifications (Autovie Venete) adopted in this research. It is noteworthy that using different compaction methods lead to achieving slightly different volumetric values summarized in Table 4.4, however, the values complied with the specification limits.

Table 4.4. Volumetric analysis.

Property	Compaction method	
	Gyratory compaction	Marshall Compacted
Bitumen binder (%)	6	6
VMA (%)	14	14
VA (%)	4-5.5	4.15-5.5
Agg. apparent density	2.626	2.626
Ave. mix density	2.399	2.298

4.3.2 Tensile properties

Once the gradation is controlled, it will likely be necessary to adjust the asphalt. In this case, additional samples were prepared using the selected gradation and various bitumen binder contents. In the present research, the optimum asphalt cement content was chosen considering the required voids in the mixtures and Indirect Tensile test values, representing the overall properties of the mixtures. SMA is not as strong in tension as it is in compression, SMA tensile strength is important in pavement applications [5]. Therefore, the values of indirect tensile strength were used to evaluate the relative quality of bituminous mixtures in conjunction with laboratory mix design, testing and for estimating the resistance to cracking. Low-temperature cracking, fatigue and rutting are the three major distress mechanisms. A higher tensile strength corresponds to a stronger cracking resistance. At the same time, mixtures that are able to tolerate higher strain prior to failure are more likely to resist cracking than those unable to tolerate high strains [6]. The indirect tensile test, although not new in concept and theoretical development, found meaningful acceptability for the design and analysis of asphalt mixtures only within the last decade. Its principal advantage is its ability to predict fracture strength. It is also capable of evaluating the elastic properties and fatigue characteristics of asphalt mixtures [7].

The indirect tensile test involves loading a circular disc or a cylindrical specimen with compressive loads along two opposite generators, thus creating a stress condition in which failure occurs by splitting along the loaded plane (see chapter 3 for more details). For the present research, two asphalt binders and four different fibres have been used producing a series of SMA mixtures using same aggregate gradations. The mixtures were named by letters and numbers to facilitate the results presentation. Table 4.5 summarizes the mixtures' components adopted in this study.

Table 4.5. Summary of the mixtures' details and applied ID.

Mixture ID	Mix details
FPmB	[Cellulose + Glass Fibre] 0.3% + SBS PmB
RFPmB	[Rubberized Cellulose + Glass Fibre] 0.3% + SBS PmB
PFB	[Cellulose + Glass + Plastomeric polymer Fibre] 0.4% + Neat Bitumen
RPFB	[Rubberized Cellulose + Glass Fibre + Plastomeric polymer] 0.5% +Neat Bitumen
FPmBRR	[Cellulose + Glass Fibre] 0.3% + SBS PmB + RAP (25%) + Rejuvenator
RFPmBRR	[Rubberized Cellulose + Glass Fibre] 0.3% + SBS PmB + RAP (25%) + Rejuvenator
PFBRR	[Cellulose + Glass + Plastomeric polymer Fibre] 0.4% +Neat Bitumen + RAP (25%) + Rejuvenator
RPFBRR	[Rubberized Cellulose Fibre + Glass + Plastomeric polymer] 0.5% + Neat Bitumen + RAP (25%) + Rejuvenator

Note: The percentage is on the weight of aggregates

As for the primary stage of mix design, the Optimum Binder Contents (OBCs) of the mixtures were determined based on the data obtained from one of the mixtures of made with SBS PmB (FPmB) and one from the mixtures made with neat bitumen (PFB). For this purpose, asphalt mixture containing different binder content (5.5, 6, and 6.5%) were made and have been compared by ITS values. Fig. 4.8 represents the ITS values of each mixtures corresponding to their bitumen content.

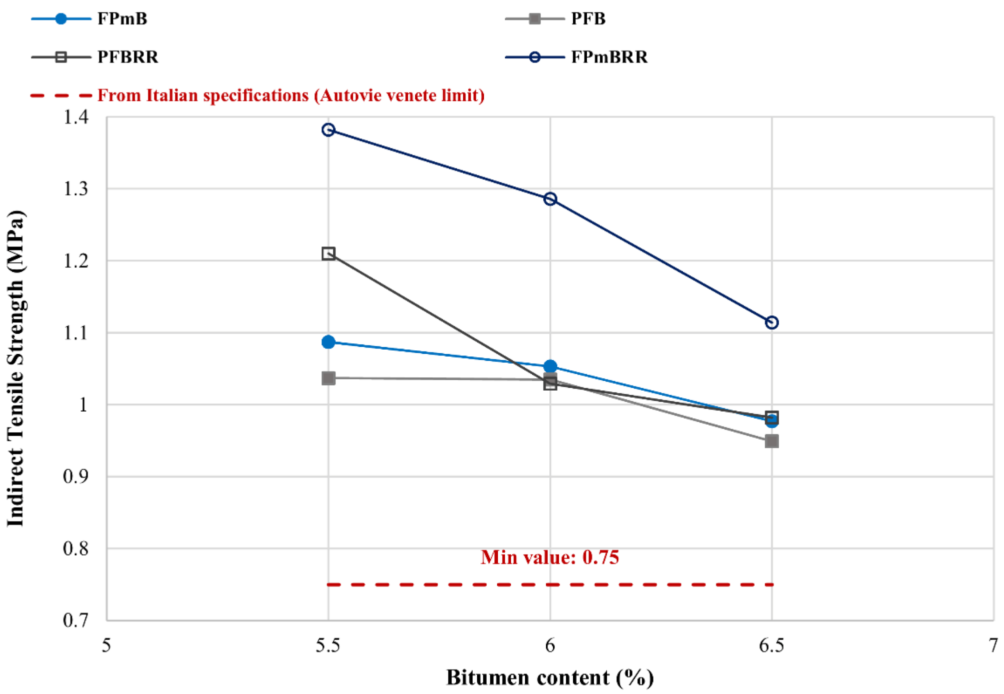

Fig. 4.8. ITS values vs. binder content for SMA mix design.

According to the graph, all the mixtures fulfilled the minimums required by the considered Italian specifications. It can be seen that while the difference between the mixtures containing 5.5% and 6% bitumen is not significant for the total virgin mixtures, the difference for the 25% RAP containing mixtures is consistent. However, Increasing the binder content more than 6.0% decreased the ITS value for all the mixtures. Accordingly, at this stage 6.0% was chosen as the OBC for all the mixtures even if the ITS values for the mixtures containing 5.5% were higher 6%. This is because of the following reasons:

1. The difference between the ITS values of mixtures containing 5.5% and 6% was not significant.
2. Considering the overall performance properties, workability and durability of the mixtures, a higher bitumen content is always advised for the SMA mixtures. This is related to the gap-graded nature of the SMA structure, which leads to high striping potentials, low durability and lower moisture susceptibility.
3. The mixtures containing 5.5% did not fulfil the required further volumetric values of the considered specifications.

It is worth mentioning that since all the fibres were cellulose-based fibres being used in identical SMA mixtures, 6% OBC was considered for all the mixtures. The differences in the percentage of used fibres supposed to act as an additive/modifier rather than a stabilising agent. On the other hand, the test results could be comparable with reducing the variables between the mixtures, concentrating on the direct changes made by fibres.

4.3.3 Draindown control

According to the NAPA definition [4], draindown is considered to be the portion of the mixture (included both fines and binder) that is being separated from the sample as a whole and flows downward through the mixture. The draindown control is more important for the gap-graded and open-graded mixtures rather than conventional dense graded mixtures. The test is used through the mix design of asphalt mixtures to control OBC and also whether the binder stabilizer is efficient or not. Within SMA mixtures, the high amount of binder content leads to high susceptibility of bitumen binder drain off from the aggregates. Hence, for the present research, the driandown test method developed in ASTM D6390-11 was applied to simulating the practical temperature to observe the draindown potentials. In this case, a sample of the previously optimized mixtures (in terms of ITS values and volumetric results) mixture was placed in a wire basket, which was positioned on a plate of known weight. The sample, basket, and plate (shown in Fig. 4.9) were placed in an oven for a 1h at 175±5˚C (Fig. 4.10). At the end of the heating period, the basket containing the sample was removed from the oven along with the plate and thereafter the weight of the plate was determined. The amount of draindown is considered to be that portion of the material that separates itself from the sample as a whole and is deposited outside the wire basket. The material that drains may be composed of either binder or a combination of binder and fine aggregate. Finally, the draindown percentage was calculated according to the following simple formula:

$$Draindown = \frac{(D-C)}{(B-A)} \times 100 \quad (4.1)$$

where:

A is mass of the empty wire basket;

B is mass of the wire basket and sample;

C is mass of the empty catch plate or container;

And D is mass of the catch plate or container plus drained material.

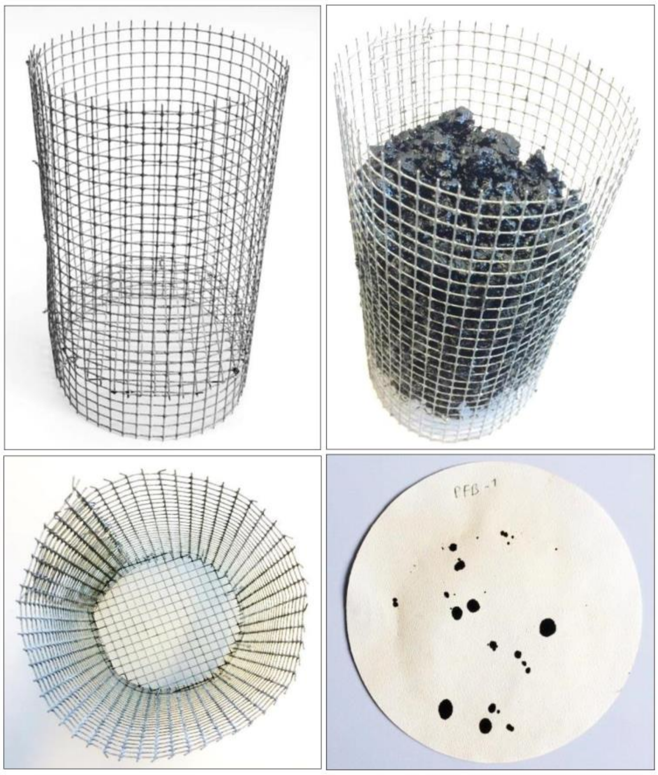

Fig. 4.9. UNIBO draindown test apparatus and the test plate after finishing the test.

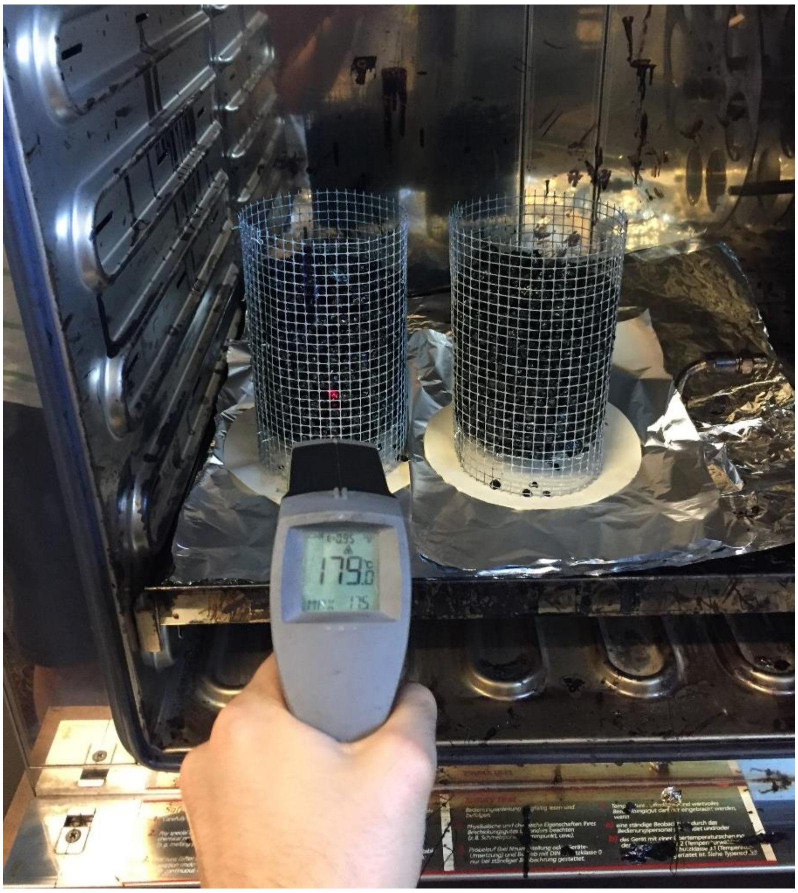

Fig. 4.10. Controlling the temperature of un-compacted mixture during draindown test.

Accordingly the test has been done for the optimized mixtures, however, the recorded drain down rate was far less than the specification's requirement. A sample of recorded draindown, shown in Fig. 4.9 demonstrates the efficiency of the fibres on the draindown control. For the mixtures containing 0.4% PF (Cellulose-based mineral fibre and Plastomeric polymer added) recorded draindown was reduced to approximately 0.1%, which satisfies the limits (0.3%) of both NAPA [8] and National Centre for Asphalt Technology (NCAT) [9].

4.4 Prequalification Controls

In the present research, besides the aforementioned procedure applied for mix design, the Marshall method was also implemented as for the initial integrity control of the optimized mixtures. In this method, the resistance to plastic deformation of the Marshall compacted cylindrical specimens of a bituminous mixture is measured when the specimen is loaded diametrically at a deformation rate of 50 mm per minute. For the details on the adopted test procedure see chapter 3. There are two major features of the Marshall method of mix design: density-voids analysis and stability-flow tests. The Marshall stability of the mix is defined as the maximum load carried by the specimen at a standard test temperature of 60°C. The flow value is the deformation that the test specimen undergoes during loading up to the maximum load. The obtained test results were then compared with the requirements of the considered Italian specifications through the mix design (Marshall Stability > 8kN and Marshall Rigidity > 2.5 kN/mm)

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CHAPTER 5

EXPERIMENTAL WORKS, RESULTS AND ANALYSIS

CHAPTER 5 EXPERIMENTAL WORK, RESULTS AND ANALYSIS

5.1 Analysis Framework

The following sections included the papers, which published in peer review journals representing the complete results and analysis of the tests, which were carried out in this research work.

I. S. Eskandarsefat, G. Dondi, C. Sangiorgi, Recycling asphalt pavement and tire rubber: A full laboratory and field scale study, Construction and Building Materials.

This paper consisted of a full-scale (Laboratory and field data) on the application of the dry-method for a dense-graded mixture containing 30%RAP aggregates. The paper made a comprehensive understanding of rubberized mixtures, mix design, mechanical and performance characteristics, and the interaction of RAP and rubber. Same RAP aggregates and rejuvenator of the following research on modified SMAs were used in this study.

II. S. Eskandarsefat, B. Hofko, C. Sangiorgi, C.O. Rossi, Fundamental and rheological properties of bituminous binders containing novel cellulose-based poly-functional fibres, Composites Part B: Engineering.

This paper provided a wide knowledge of fundamental data on physical and rheological characteristics of the neat bitumen and SBS PmB in presence of modified fibres. The paper included both empirical test methods and dynamic rheological test ones via Dynamic Shear Rheometer (DSR). Besides these, considering the importance of microstructural properties of fibres, a microscopic analysis was carried out exploring the differences in microstructures of the materials and their role in the materials' properties (Fibres).

III. S. Eskandarsefat, G. Dondi, C. Sangiorgi, Modified recycled SMA mixtures, Polymer modified Fibres vs. Polymer modified Bitumen, Construction and Building Materials.

This paper included the applied mix design procedure, prequalification tests, and a complete laboratory scale tests on the optimized modified SMAs. The analysis of the tests' results were done in the light of the knowledge gathered by literature review and the first paper's analysis. This strategy could help whether, the mixture type or the type of modification was dominant.

IV. S. Eskandarsefat, B. Hofko, C. Sangiorgi, A comparison study on low-temperature properties of Stone Mastic Asphalts modified with PmBs or modified fibres, submitted to International Journal of Pavement Engineering.

As a complete research work and since the tensile properties and cracking potential of SMAs are of paramount importance, this paper consisted of low-temperature experimental work and analysis.

The tests included both binder and mixture-scale tests by means of Bending Beam Rheometer (BBR) and Thermal Stress Restrained Specimen Test (TSRST), respectively.

5.2 Paper I

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Recycling asphalt pavement and tire rubber: A full laboratory and field scale study

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HIGHLIGHTS

- Increased ITS values for the mixtures containing crumb rubber.
- Decreased thermal sensitivity of mixtures containing RAP by adding fine crumb rubber.
- Adding crumb rubber could improve skid resistance properties in terms of both macro and micro texture.
- No remarkable tire/pavement noise emission recorded through the acoustic investigation by means of CPX measurements.

GRAPHICAL ABSTRACT

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ABSTRACT

The present research deals with the influence of fine Crumb Rubber (CR) incorporation on the mechanical and performance characteristics of dense graded asphalt mixtures including 30% Reclaimed Asphalt Pavements (RAP) by means of both laboratory-scale and in situ tests. In the laboratory phase, the mixtures were evaluated in terms of Indirect Tensile Strength (ITS), moisture sensitivity, Indirect Tensile Stiffness Modulus (ITSM) and Repeated Load Axial Test (RLAT). Experimental tests indicated that while the difference of RLAT results were insignificant, the ITS values and the ITSM modulus changed in an effective way. On the other hand, the in-situ investigations on texture by means of sand patch and British pendulum provided testimonies to the effectiveness of CR in recycled dense graded mixtures. Finally, the tire/pavement noise emission measurements of the trial sections by means of Close Proximity (CPX) showed no significant difference between the tested pavements with and without rubber.

1. Introduction

1.1. Background

The recycling of existing asphalt pavement materials produces new pavements with considerable savings in resources and less negative impacts on the environment. Aggregate and binder from the old asphalt pavements are still valuable even though these pavements have reached the end of their service lives. Currently in many construction projects asphalt is: recycled in unbound base layers, used for road shoulders and rural roads, mixed for cold or hot in-place recycling, and added in a relatively small percentage to new Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA).

The limited RAP content in HMA is the result of many questions and confusion among researchers and industry regarding the feasibility of total Reclaimed Asphalt Pavement (RAP) recycling. On the other hand, the maximum amount of reclaimed asphalt is mainly

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1. Introduction

1.1. Background

The recycling of existing asphalt pavement materials produces new pavements with considerable savings in resources and less negative impacts on the environment. Aggregate and binder from the old asphalt pavements are still valuable even though these pavements have reached the end of their service lives. Currently in many construction projects asphalt is: recycled in unbound base layers, used for road shoulders and rural roads, mixed for cold or hot in-place recycling, and added in a relatively small percentage to new Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA). The limited RAP content in HMA is the result of many questions and confusion among researchers and industry regarding the feasibility of total Reclaimed Asphalt Pavement (RAP) recycling. On the other hand, the maximum amount of reclaimed asphalt is mainly limited by the available production technology. In a conventional recycling process, superheated virgin materials indirectly heat the RAP aggregates thus imposes limitations on the amount of RAP that can be used in final mixture. In many previous researches, it has been proved that RAP incorporation in asphalt mixtures is not truly sustainable and cost effective when the RAP portion is reduced in total mass [1]. Along with economic and environmental principles of RAP utilization in asphalt mixtures, it has been found that using RAP could improve the rutting resistance and perform as well as the virgin mixtures regarding the other aspects [2, 3]. Although the recycling of by-product materials is beneficial in most cases by reducing the consumption of virgin materials, the performance of the highway should not be compromised. Studies have shown that the effect of aged binder from RAP on the performance properties of the virgin binder depends upon the level of RAP used in the HMA mixture [3]. Therefore, although it is helpful in reducing the utilization of virgin asphalt binder and improving rutting resistance, the aged binder in RAP is thought to be a potential contributing factor responsible for asphalt pavement thermal and fatigue cracking failures [4]. This is due to the increased mixture stiffness, which is due to the aged binder in the RAP. Conquering this problem, softer asphalt binders or rejuvenating additives can be used to counteract the stiffness of the RAP binder, therefore, enabling the use of higher percentages of RAP in HMA. On the other hand, it has been documented that rejuvenating agents can be carried by Ground Tire Rubber (GTR), because of its absorptive properties, to revitalize the properties of the RAP binder [5]. Major techniques used to process CR in asphalt are divided in dry and wet process. The rubber used in the wet process is usually a fine material with 100% passing the 2 mm, or even smaller sieve, which is added directly into the bitumen to provide the modified binder. Generally, both laboratory and in situ test results show that dry process CR modified mixtures exhibit poor performance or show little improvement compared to wet process or conventional asphalt mixtures [6]. Several laboratory studies have been conducted to determine an appropriate aggregate gradation, design bitumen content or mixture preparation procedure, which shows improved and consistent results for dry process originated mixtures [7-8]. On the other hand, the absence of specialized standards, test methods and practice application manuals (industry scale) resulted in controversies among researchers and clients on incorporation of CR by dry process.

1.2. Objectives

Since the mixtures incorporating both RAP and CR have not yet been evaluated, the objective of this study was to investigate and evaluate the engineering properties of dry method application of fine crumb rubber on mixtures containing 30% of RAP with and without rejuvenating agents. In addition, considering the low elastic properties of mixtures with RAP as a matter of greater fatigue and thermal susceptibility, the research aimed for CR modification effects on mechanical and performance properties. As a comprehensive study the effectiveness of CR on acoustic properties, micro and macro texture of the pavement assessment were the field study objectives of this research.

1.3. Research plan

Fig. 1 represents the different research phases and program developed to provide a comprehensive understanding through the objectives of the research. In order to assess the efficiency of the use of CR in recycled asphalt mixtures, the obtained test results and values have been compared with the relative limits or required values in local and international specifications. It is worth mentioning that, at the mixture scale, three different mixtures were tested: a Dense graded mixture with RAP (DR), a Dense graded mixture containing RAP and rejuvenator (DRR) and a Dense graded mixture containing RAP, rejuvenator and Crumb rubber (DRRCr). These were produced to investigate the feasibility of adding CR in mixtures containing 30% RAP (on the weight of total aggregate).

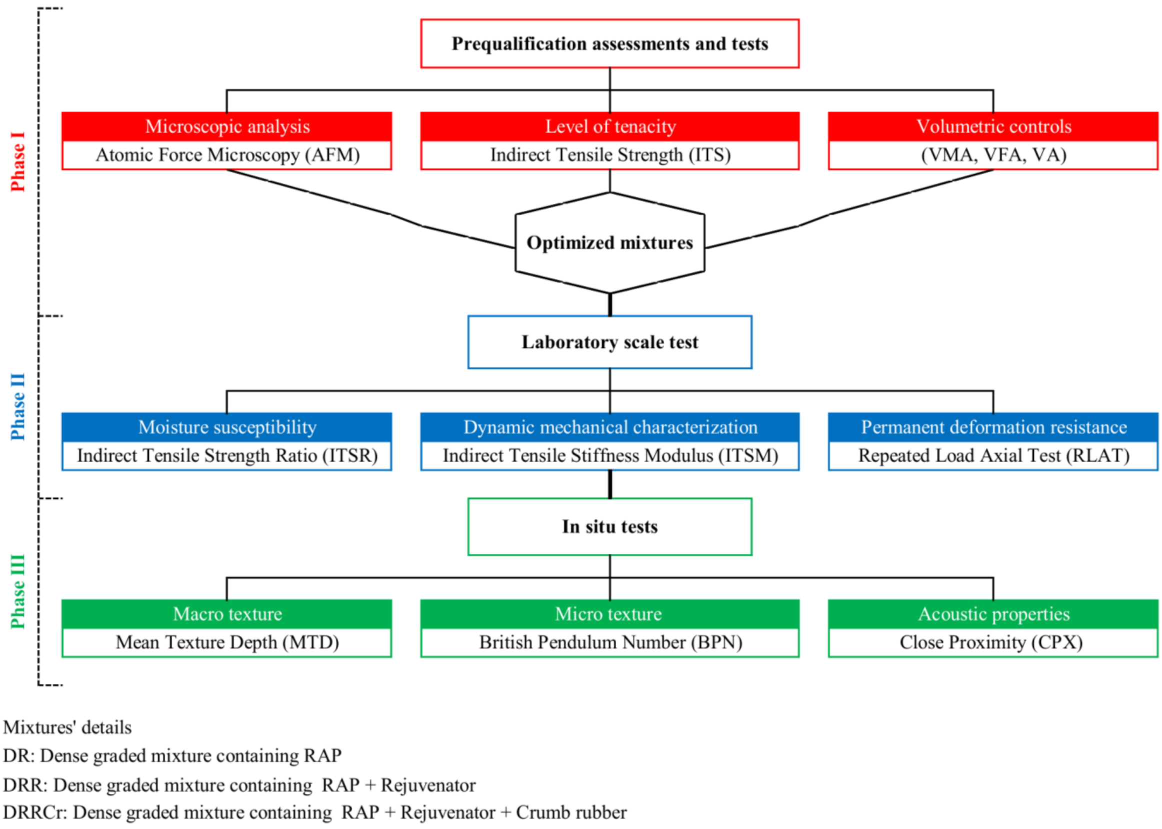

Fig. 1. Research plan.

2. Materials

2.1. Virgin aggregates and RAP

In this paper, RAP passing the 12.5 mm and the 6.3 mm sieves are respectively referred to as coarse RAP and fine RAP. The RAP was taken from the same plant area as the new aggregates to ensure that the aggregates in the RAP have similar properties to the virgin one. Thereafter the qualitative analysis was conducted for both coarse and fine RAP before and after binder extraction. Fig. 2 shows the grading curves of coarse and fine RAP before and after the binder extraction (black and white curves). In this study the combined coarse and fine aggregate gradation comply with two Italian specifications (Province of Bologna [9] and Autostrada del Brennero specifications [10]) prescribed in Table 1. According to the chosen gradation, the RAP mixture contained 25% of fine RAP and 5% of coarse RAP to keep the trial grading similar to fully virgin mixture.

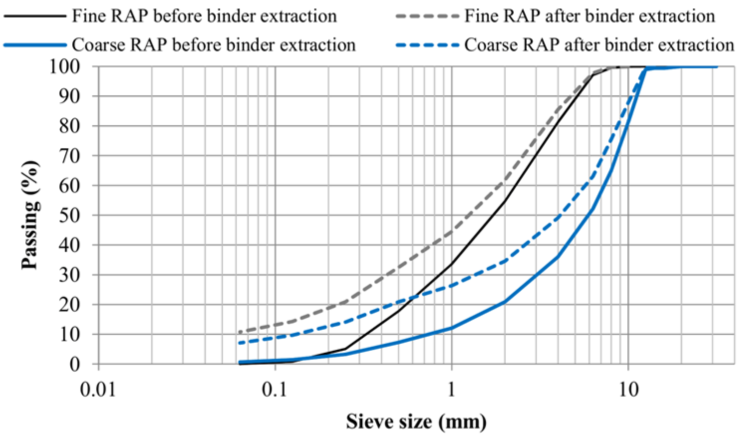

Fig. 2. Grading curves of fine and coarse RAP before and after extraction.

Table 1. Considered gradation limits.

Sieve Size (mm)	**14**	**12.5**	**8**	**4**	**2**	**1**	**0.5**	**0.063**
***Autostrada del Brennero (%)**	100/100	90/100	70/90	43/67	25/45	19/35	13/26	6/11
Sieve Size (mm)	**20**	**15**	**10**	**5**	**2**	**0.4**	**0.18**	**0.075**
***Province of Bologna (%)**	100/100	100/100	70/90	40/60	25/38	11/20	8/15	6/10

* Italian specifications

2.2. Binder

In this research to assess the effectiveness of a soft binder as rejuvenator, a 70/100 pen grade binder was used for both the virgin and RAP mixtures. The primary basic physical parameters of the bitumen are presented in Table 2. For this study, the optimum binder content was determined by ITS test results, which will be discussed later.

Table 2. 70/100 bitumen physical properties.

Measured properties	**Unit**	**Value**	**Standard**
Penetration @25°C	0.1 mm	70/100	EN 1426
Softening Point (R&B)	°C	43-51	EN 1427
Flash Point	°C	≥250	EN 2592
Dynamic Viscosity	Pa.S	≥90	EN 12596
Fraass Breaking Point	°C	≤-10	EN 12593

2.3. Crumb Rubber (CR)

The fine crumb rubber (pulverized) in this research was obtained from tire buffing process. The grain size distribution of crumb rubber is given in Table 3 and Fig. 3 represents fine crumb rubber appearance comparing with limestone filler also used in this research. The amount of crumb rubber was chosen as 1% by weight of the aggregates and was added to the mixture according to the dry process.

Fig. 3. Fine crumb rubber and limestone filler. Scale coin diameter: 23.25mm.

Table 3. Granulometry of CR

Sieve size (mm)	No.	Passing (%)
0.59	# 30	100.0
0.425	# 40	83.0
0.297	# 50	34.3
0.18	# 80	3.2
0.15	# 100	2.4
0.075	# 200	1.1

2.4. Rejuvenator agent

In order to restore the rheological properties of the aged, stiffed binder, the use of rejuvenator or softening agent is considered as a common solution. Another technique for this purpose is to use a soft virgin binder considering that the optimum grade depends on the aged binder properties and on the amount of RAP in the mixture [11]. In this study, soft binder and waste vegetable (WV) oil-base rejuvenator were used separately and also together producing different mixtures to assess the applicability of soft binder as a softening agent. Table 4 provides the technical identification (physical properties) of the used rejuvenator, noteworthy. The recommended dose of rejuvenator by the producer considered as an optimum dose, was 0.15% by weight of RAP in the mixture.

Table 4. Physical properties of rejuvenator agent.

Measured properties	Unit	Value -Description
Appearance	-	viscous liquid
Minimum operating temperature	°C	≥ -5
Density @25°C	g/cm³	0.77 – 0.79
Flash point	°C	≥90
Viscosity @25°C	Pa.s	30-40

3. Prequalification Tests and Mix Design Controls

3.1. Microscopic analysis

3.1.1. Bitumen/rejuvenator interaction

Atomic Force Microscopy (AFM) has been recognized as one of the most powerful approaches to visualize the surface morphologies and mechanical properties of materials at nanoscale. This technique also has been extensively applied in dispersion examines of Nano-metric components in Nano composites and mixtures [12]. Given that, the dispersion state has significant influence on the properties of a compound, the AFM technique was used to observe the morphology, dispersion rate and interaction mechanism of rejuvenator with binder. Depending on the type of measurement (non-contact mode (NCM) or pulsed-force mode (PFM)), the results can be presented either by surface topography image or PFM image with which the mechanical properties can be identified. Through AFM analysis, three phases are typically observed in bitumen AFM images, i.e. catana phase included topographic features known as bee like structures, Peri phase consist of the region surrounding the bee structures, and Para phase as the predominant smooth matrix. Relatively it was found that the catana phase represents the asphaltene fraction, the surrounding region is considered as resins and the smooth matrix is considered as saturates and aromatics [13]. The AFM samples were prepared by placing 20 ± 5 mg of bitumen on a steel plate (12 mm diameter and 0.4 ± 0.08 mm thickness). The plates were kept at 105°C until the sample melted providing smooth surface. Afterward the plates were cooled to the room temperature (~25°C) with cooling rate of 60°C/h. Figs. 4 and 5 display the topography and phase images of virgin bitumen and rejuvenator added bitumen samples respectively. Comparing the topographic images, while for the neat bitumen the catana phase surrounded by peri phase can be obviously distinguished, it is not clear for the sample added rejuvenator. However, both samples are homogenous. A possible explanation can be given by the interaction between rejuvenator and bitumen whereby the smoother morphology have been reported in literature as a result of dissolving asphaltene fraction in presence of rejuvenator [14]. The notable achievement of AFM image analysis is the different para phases when for rejuvenator added sample many uniformly dispersed bright spots were observed. These amorphous stated spots do not have the same structure as catana phase structures. From the chemical perspective, these bright fragments can be recognized as rejuvenator since the used rejuvenator was organic based (vegetable oil) and consist of aliphatic hydrocarbons fatty acids (mostly long chain molecules) and not aromatic extracted materials. Notably within context, the bitumen containing synthetic waxes, which frequently contains fatty acids and are often long chain hydrocarbons, have manifested similar structures and morphology in bitumen [15]. In summary, it can be declared that the addition of the rejuvenator resulted in uniform morphological changes of the neat bitumen, which may be considered as a good dispersion of the rejuvenator.

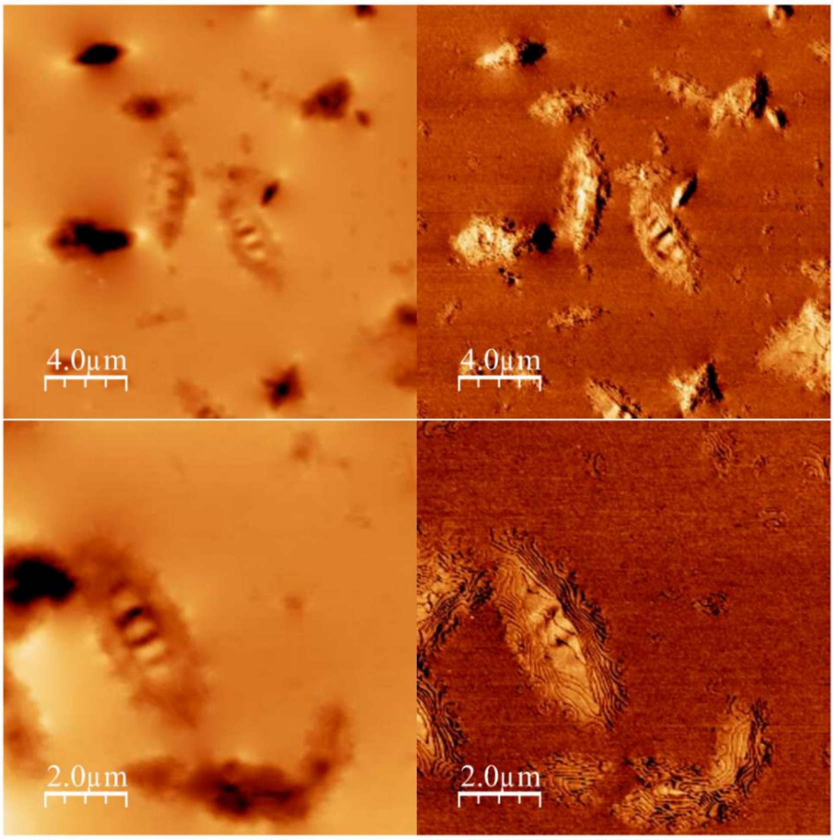

Fig. 4. Virgin bitumen AFM images. Topography images on the left and PFM images on the right.

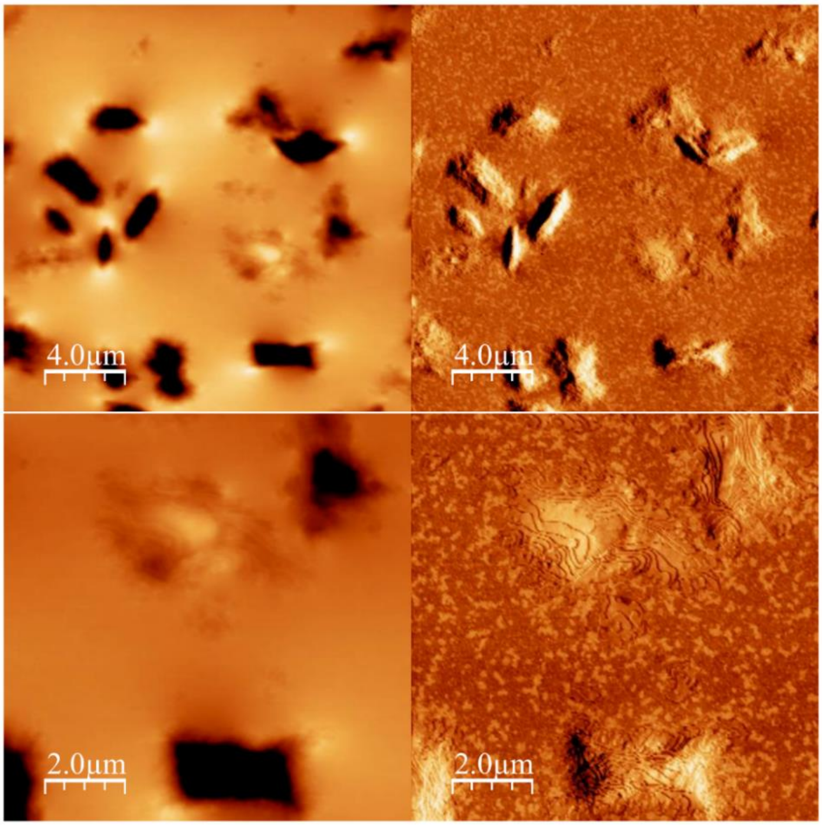

Fig. 5. Rejuvenator added bitumen AFM images. Topography images on the left and PFM images on the right.

3.1.2. CR in mastic

Among the FAQs referred to the rubberized asphalt mixtures by dry process method, the quality of CR digestion and appearance of agglomeration in mastic phase have been always under scepticism. In this respect, while to date several studies have been done on diffusion mechanism and the degree of blending between fresh and RAP binder, the presence of CR and the further interaction in such mixtures has not yet been defined. Hence, bearing in mind the simultaneously presence of RAP and CR, Scanning Electron Microscopy (SEM) images of Three different mixtures including a Dense graded mixture with RAP (DR), a Dense graded mixture with RAP and rejuvenator (DRR) and a Dense graded mixture with RAP, rejuvenator and Crumb rubber (DRRCr) were compared to investigate on the probable CR agglomeration in the mastic phase. SEM images reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials. SEM was utilized in the investigation of the dispensation of CR in the blended aged and virgin binders by evaluating the microstructures of the residue mastics. For this purpose, the samples taken from the mastics of mixtures were cut to provide a smooth surface. By the assessment, their shapes and surface textures were detected comparably. The images represented in Fig. 6 depict similar textures with homogenous compounds and no evidence of CR agglomeration, which was the main aim of the investigation. Based on the data acquired from SEM analysis, CR particles can be clearly detected, which finely interlocked with other mastic particles. This may be considered as the consistency of mastic attribute.

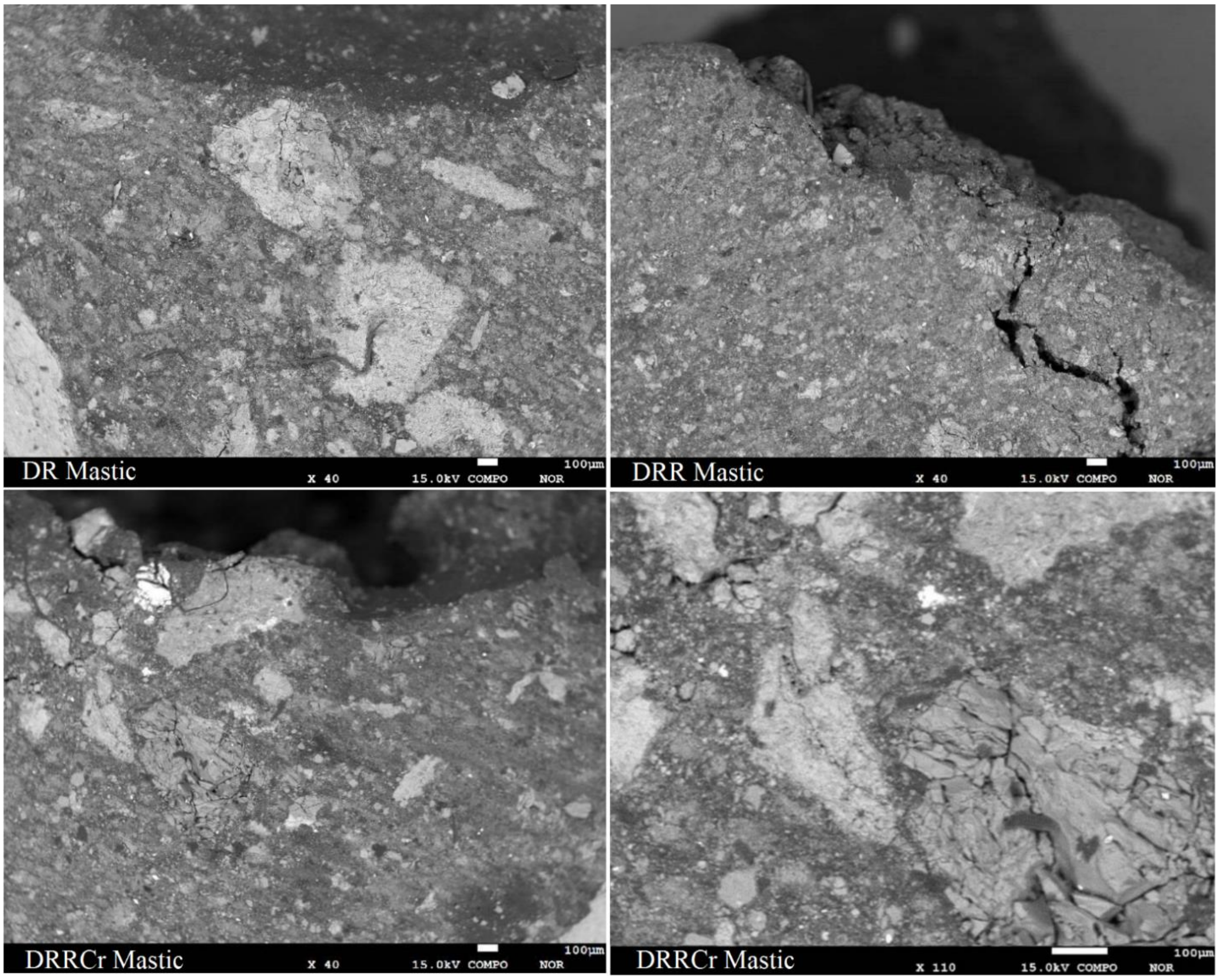

Fig. 6. Cross section SEM images of DR, DRR, and DRRCr mastics.

3.2. Volumetric analysis and level of tenacity

For each mixture, nine 150 mm diameter gyratory compacted specimens (100 gyrations) with different amount of binder were fabricated and tested for Indirect Tensile Strength (ITS) as for optimum binder control mixtures. It is worth mentioning that an average amount of recoverable aged bitumen in RAP, which was previously determined by binder extraction, was considered in binder percentage of each mixture. Therefore, the optimum amount of binder was evaluated considering the ITS results and volumetric analysis. The ITS of the asphalt samples were determined following the EN 12697-23 at 25°C. Based on the ITS results represented in Fig. 7, the optimum binder content for DR, DRR, DRRCr mixtures were considered to be 5.5, 5.5 and 6.0% (including the weight of rejuvenator and by weight of aggregates) respectively. Noteworthy, the type C mode of failure (combination pattern) according to EN 12697-23 was observed for all the tested specimens (Fig. 8). While the brittle materials fail with a single failure line, elastic materials exhibit less localized failure line. Review of the failure modes, the fragmentation in mode C is defined as limited tensile break line and larger areas close to the loading strips.

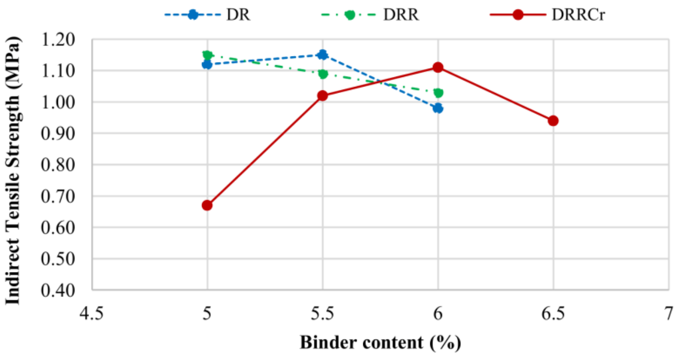

Fig. 7. ITS values vs. binder content, EN 12697-23.

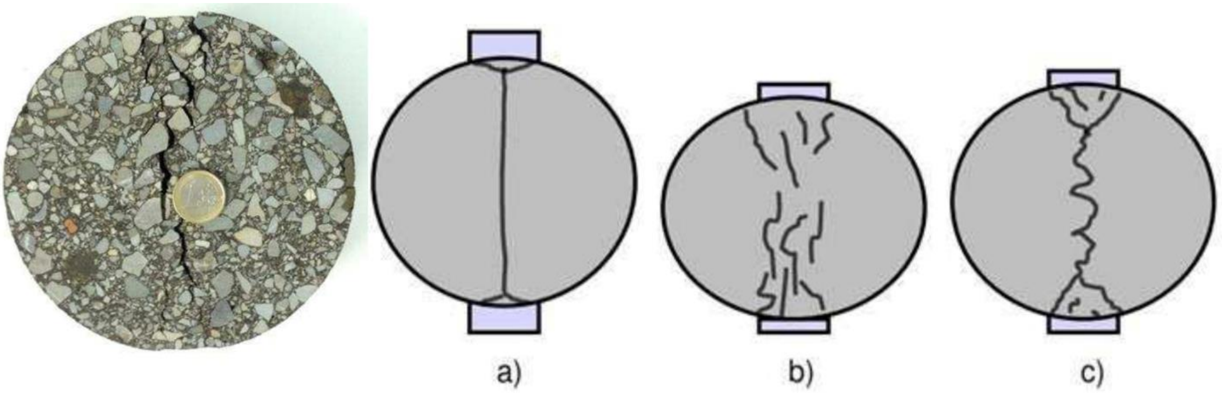

Fig. 8. ITS tested specimen on the left and typical failure modes (EN 12697-23) on the right.

Along with ITS values, Table 5 presents the volumetric parameters compared with the limits required in AASHTO mix design (considering the Nominal maximum aggregate size (NMAS) of 12.5 mm) and common Italian specifications (e.g., Autostrada del Brennero) requirements. It can be clearly seen that the DRRCr mixture fully complied with both specifications.

Table 5. Air voids analysis, EN 12697-8.

Specimen ID	VMA	VA (%)	VFA
DR-1	11.4	1.7	85.2
DR-2	12.7	3.1	75.3
DR-3	12.2	2.6	78.5
Ave. DR	12.1	2.5	79.7
DRR-1	11.3	2.0	82.0
DRR-2	12.0	2.8	76.9
DRR-3	12.0	2.8	76.9
Ave. DRR	11.8	2.5	78.6
DRRCr-1	14.1	3.6	74.4
DRRCr-2	14.0	3.5	75.1
DRRCr-3	13.9	3.4	75.7
Ave. DRRCr	14.0	3.5	75.1
***Limits**	**-**	**3 - 6**	**-**

*Italian specifications (Autostrada del Brennero)

4. Laboratory Scale Tests, Results and Analysis

4.1. Moisture susceptibility

TS test is a test frequently adopted for moisture susceptibility assessment of asphalt mixtures in terms of Indirect Tensile Strength Ratio (ITSR). Moisture susceptibility test data can be used to estimate the potential for long-term stripping and to assess antistripping additives [16]. For the current study, the test procedure followed the EN12697-12 [17] with 2 specimens for both dry and wet conditions. For the wet conditioning, the randomly selected specimens of each mixture were immersed in 40°C water for 3 days, then the ITSR was simply calculated with the ITS values for all the dry and wet specimens conducted at 25°C. Fig. 9 represents the ITS and TSR values of the three different tested mixtures. Based on the results the inclusion of CR increased significantly the dry conditioned ITS value, which resulted in lower ITSR. However, all mixtures provided the target limit of the European standards, 75% and technical specifications.

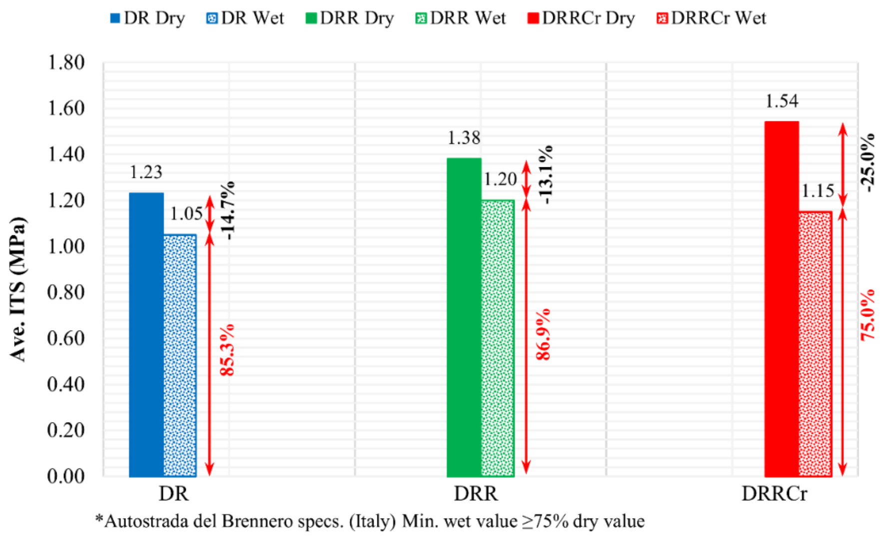

Fig. 9. Dry and wet conditioned specimens Ave. ITS values and ITSR, EN 12697-12.

4.2. Dynamic mechanical characterization

In order to assess the effect of the CR on the mechanical properties of the mixtures, ITSM test was conducted following the EN 12697-26 [18]. The superiority of this test is that it is possible to run the test with both laboratory or field cored samples, which facilitates the monitoring of field practices [19]. The test was performed at three different temperatures: 5, 20 and 35°C with 4 specimens for each temperature. Based on the results shown in Fig. 10, while at the low temperatures the DRRCr mixture had the lowest stiffness modulus at medium and high temperatures, the ITSM results of DRRCr mixture were higher than DR and DRR mixtures. This proves the effectiveness of CR incorporation in thermal sensitivity improvements of the recycled mixture.

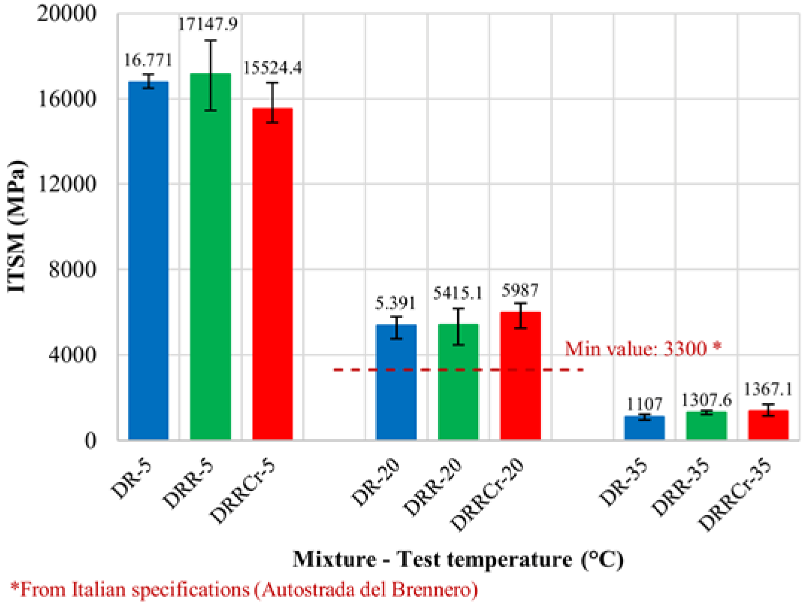

Fig. 10. Ave. ITSM test results, EN 12697-26.

4.3. Permanent deformation resistance

Many previous researches indicated that the incorporation of RAP in the hot mix asphalt mixtures increases the rutting resistance as a result of aged binder presence [20, 21]. However it should be noted that while adding rejuvenator is a common solution for decreasing the imposed stiffness, not paying attention to the optimum dose may increase the permanent deformation potentiality [22]. In this research the permanent deformation resistance of the mixtures was evaluated by means of Repeated Load Axial Test (RLAT) according to EN 12697-25 [23] by measuring and comparing the ultimate strain and strain rate. It has been shown that from the mentioned parameters, the mean strain rate per cycle is more reliable to analyse the permanent deformation properties considering that it is independent of the initial strain experienced through the test [24]. In addition, the strain rate demonstrates the linear span of the tested mixture's deformation behaviour, which is calculated as a linear regression between 1800 and 3600 cycles (the secondary creep stage) [25]. Considering the creep behaviour of materials, the creep curve is divided into three different stages. In the primary stage the strain rate decreases by increasing the load cycles; in the secondary creep stage the strain rate is almost constant and in the tertiary part the strain rate increases severely till the failure point. A schematic representation of the test configuration and the typical creep curve are given in Fig. 11. Table 6, represents the strain rate (le/cycle) and final strain percentage of the tested mixtures after 3600 cycles. It is necessary to determine the position and extent of the linear portion of the curve, therefore in all calculations the regression coefficient R2 was calculated to be not less than 0.95 to certify the linearity of the data included in the calculations. Based on the results although the average final accumulated strains for the DRRCr mixture is marginally higher, the strain rate results are almost the same. The insignificant higher accumulated strain for DRRCr mixture can be related to the higher air voids content comparing to DRR and DR mixtures, however, the DRRCr mixture complied with the required air voids properties. On the other hand, considering the correlation between ITSM values and creep characteristics [26], these results could be expected referring to the difference between the ITSM test results of mixtures at high temperature.

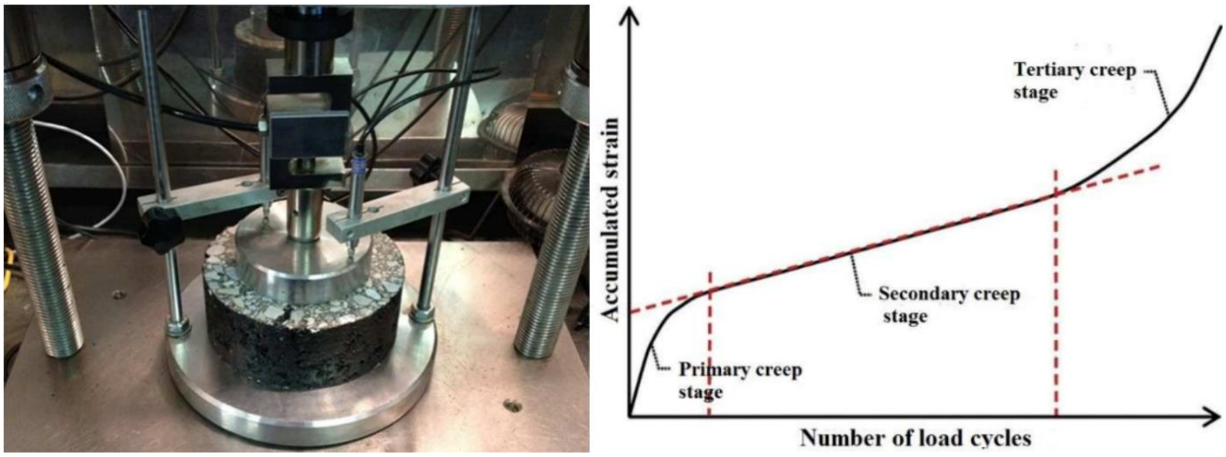

Fig. 11. RLAT set up on the left and typical creep curve under constant load on the right.

Table 6. Asphalt mixtures permanent deformation parameters, EN 12697-25.

Specimen ID	Accumulated strain (%)	Strain rate (μ/cycle)
DR-1	0.566	0.294
DR-2	0.631	0.169
DR-3	0.546	0.187
DR-4	0.510	0.231
DR-5	0.507	0.165
Ave. DR	**0.552**	**0.209**
DRR-1	0.514	0.250
DRR-2	0.480	0.283
DRR-3	0.675	0.194
DRR-4	0.591	0.204
DRR-5	0.410	0.157
Ave. DRR	**0.534**	**0.218**
DRRCr-1	0.649	0.147
DRRCr-2	0.648	0.288
DRRCr-3	0.637	0.261
DRRCr-4	0.756	0.239
DRRCr-5	0.541	0.183
Ave. DRRCr	**0.646**	**0.224**

5. Trial field tests, results and analysis

Two pavements on the same section of a road were selected as trial sites. Within trial practices, since mixing and compaction temperatures shown great effects on both mechanical and performance properties, the temperature of the mixtures have been controlled by means of a thermal camera. Fig. 12 demonstrates the temperature of the mixtures during laying and compaction. The in-situ program consisted of the macro and micro texture evaluation by means of Sand Patch and

British Pendulum tests in addition to Close Proximity (CPX) acoustic measurements on DRR and DRRCr mixtures' trial road sections. Taking into account the unstable values for the newly paved texture and high texture variations in early ages, all the filed investigations have been carried out after 8 months thus included a cold winter season. Alongside with the mechanical properties of asphalt pavement, the key performance properties of the surface layer are mainly related to the texture characteristics including: skid and rolling resistance, riding quality, drainage capability and acoustic properties [27]. It is known that the surface texture is greatly affected by various parameters e.g. aggregates mineralogical characteristics, environmental effects, construction procedure, and the exploitation parameters [28]. Hence, for the current practice the surface texture performance was evaluated controlling the variability in aggregate mineralogy, environmental condition, construction and service.

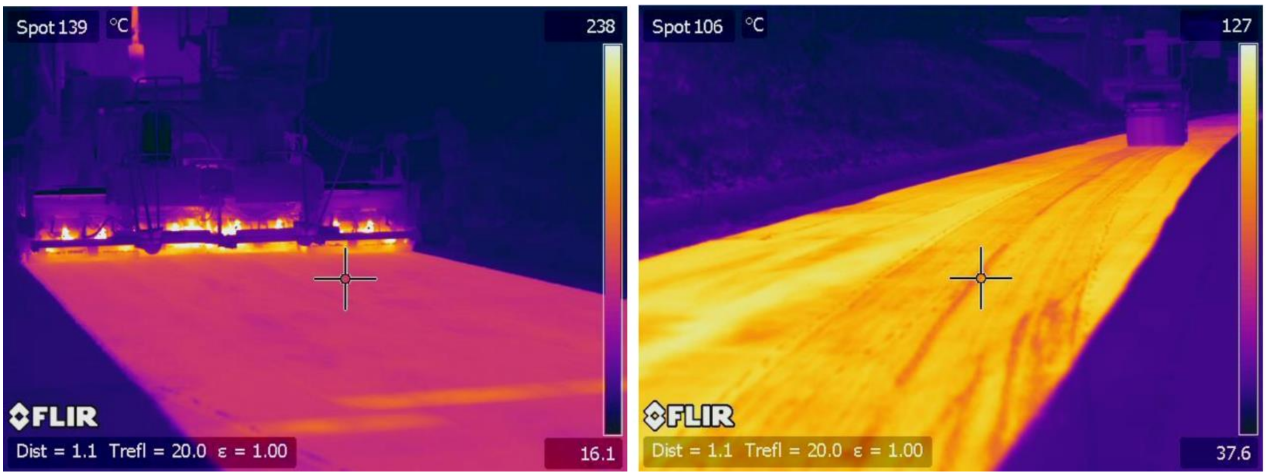

Fig. 12. Mix temperature during laying the material on the left and intermediate rolling temperature on the right.

5.1. Macro texture

Theoretically, pavement surface texture depth is considered as a measure of pavement macro texture. Macro texture plays a key role in the wet weather skid resistance of pavement surface, particularly at higher speeds. Hence, pavements, which are constructed to service vehicles passing at speeds faster than 80 km/h, require adequate macro texture. In addition to friction characteristics, macro texture strongly affects the pavement/tire generated noise level and hydroplaning [29]. In order to examine the pavement macro texture, sand patch test is by far the most commonly prescribed test for in situ practices. The test concept is based on a known volume of material on the surface and subsequent measurement of the total area covered. The test procedure, shown in Fig. 13, was developed to determine an average depth of the pavement surface texture, which greatly represents the macro-texture and skid resistance properties. The macro texture value is frequently recognized in terms of Mean Texture Depth (MTD), which is simply calculated by the following equation:

$$MTD = \frac{4V}{\pi D^2} \quad (1)$$

Where:

MTD is the mean texture depth in (mm);

V is the sample volume in (mm^3);

And D is the average diameter of the area covered by the material in (mm).

Fig. 13.MTD test procedure on DRRCr section surface. Scale coin diameter: 23.25mm.

For the current research, the test was conducted according to the EN 13036-1 standard [30]. Table 7 represents the test values for seven randomly spaced points on the trial sections of DRRCr and DRR mixtures. Comparing the values with the ranges identified in the Italian national standard (CNR BU 94) and the required minimum in Province of Bologna specification, it can be deduced that both pavements complied with the medium valid range and are higher than the minimum required value. Although the difference between the mean values for the two mixtures is not significant, the value for the DRRCr mixture is higher. Notably, considering the results with the void analysis data, it can be seen that the higher the VA and VMA, the greater MTD is, which may be considered as a predication of relative results.

Table 7. Mean texture depth (MTD), EN 13036-1

Test point ID	MTD (mm)	Test point ID	MTD (mm)
DRRCr-1	0.47	**DRR-1**	0.38
DRRCr-2	0.55	**DRR-2**	0.47
DRRCr-3	0.41	**DRR-3**	0.41
DRRCr-4	0.44	**DRR-4**	0.47
DRRCr-5	0.44	**DRR-5**	0.47
DRRCr-6	0.44	**DRR-6**	0.41
DRRCr-7	0.44	**DRR-7**	0.44
Ave. DRRCr	0.45	**Ave. DRR**	0.43
*** CNR BU 94**		**0.4 mm to 0.8 mm**	
**** Province of Bologna**		**≥ 0.4 mm**	
****Autostrada del Brennero**		**≥ 0.3 mm**	

* Italian code

** Italian specification

5.2. Micro texture

There are mainly two approaches to evaluate the skid resistance of pavement surface including statistic and dynamic systems. Among the statistic ones the British Pendulum tester is probably the most widespread equipment for the in situ practices. Beyond the well-known benefits, the inconsistent test values for coarse macro texture surfaces, frequent calibration needs and limited applicability (low speed skidding simulations, by far 10 km/h swing speed) [31] are reported as the drawbacks. The test results are reported as a number (British Pendulum Number), which is a measure of the kinetic energy loss when the rubber slider is dragged on the surface. Table 9 represents the recommended British pendulum values (TRRL, 1969 [32]) for the different classified roadways. For the current research, the micro texture of the DRRCr and DRR surfaces was investigated by means of BPN according to ASTM E303-93 [33] on the seven longitudinally equidistant points. By comparing the test results provided in Table 9, to the suggested required limits by local specification (Province of Bologna [9]) and widely in use values shown in Table 8, it can be seen that both mixtures fulfilled the limits. The interesting point of the results goes to the concordance of the values with the MTD test values. By the achieved data, it can be deduced that in overall the mixtures with CR improved the roadway safety in terms of skid resistance, although the difference is not significant. On the other hand, it should be noted that as it was mentioned earlier, rather than the binder properties, the aggregate characteristics play a major role in pavement texture and in particular for the micro texture properties.

Table 8. Minimum suggested BPN (TRRL, second edition).

Site description	Min. value
Difficult sites : I. Roundabouts II. Bends with radius less than 150m on unrestricted roads III. Gradients, 1 in 20 or steeper, of lengths greater than 100m IV. Approaches to traffic lights on unrestricted roads	60
Motorway, trunk and class 1 roads and heavily trafficked roads in urban areas (carrying more than 2000 vehicles/day)	55
All other sites	45

Table 9. BPN test values.

Test point ID	BPN	Test point ID	BPN
DRRCr-1	59	**DRR-1**	60
DRRCr-2	62	**DRR-2**	58
DRRCr-3	62	**DRR-3**	61
DRRCr-4	60	**DRR-4**	55
DRRCr-5	57	**DRR-5**	51
DRRCr-6	59	**DRR-6**	50
DRRCr-7	60	**DRR-7**	52
Ave. DRRCr	**60**	**Ave. DRR**	**55**
*** Province of Bologna**		**≥ 55**	

* Italian specification

5.3. Acoustic properties

Bearing in mind the environmental issues, tire/pavement noise is the main contributor of traffic noise pollution particularly in urban zones. While many tire/pavement noise studies concentrated on the pavement surface texture, the sound emission is also function of the pavement stiffness properties and sound absorption capability [34, 35]. Within context, it has been proven that, the noise level also greatly depends on pavement type and surface texture. Moreover, the design and pattern of the tire still found to be an effective factor in tire/pavement noise emission and some research have been investigating the integrity of tire pattern for noise investigations [36]. Pavement noise abatement approaches included: using small maximum aggregate size, applying Open Graded Friction Course (OGFC) (porous asphalt with high air voids), and wearing surface course with low stiffness at the tire-pavement interface [37]. In this respect, studies have found that while porous asphalt can diminish the noise emission by sound absorption with connected pores [38], adding CR will reduce the tire/pavement noise by decreasing the contact stiffness of pavement [39]. Here in order to evaluate the noise emission properties, the Close Proximity (CPX) method was has been applied for the two test sections and differences in sound emission were compared. Among the identified approaches for measuring the on-board tire-pavement noise, CPX has been recognized as an effective acoustic measurement method standardized in ISO 11819-2. The technique is based on test tire rolling on the road or the test track surface with microphones placed close to the tire surface, measuring the sound pressure. For this approach, a test vehicle with special reference tire as shown in Fig. 14 was equipped with the microphones. Average measured noise levels of both DRR and DRRCr sections are shown in Table 10 at reference vehicle speeds of 40, 50 and 80 km/h. The analysis of the CPX measurements indicates that the use of fine CR, comparing the surface texture, has less influence on the acoustical behaviour of asphalt pavement. The achieved close values at all the tested speeds could be expected, with considering the effective parameters on tire/pavement noise emissions. Given that, both mixtures had similar mix design and respectively close MTD values (formerly discussed), the only probable effective item was mix stiffness. Hence referring to close stiffness modules particularly high temperature, no significant noise emission difference was seen. Former studies with approximately the same amount of CR also experienced the same conclusions [40].

Fig. 14. CPX tire-pavement noise measurement configuration and tire pattern.

Table 10. Sound emission test results, CPX levels

Pavement section ID	**Level of CPX dB (A)**		
	@ 40/h	**@ 50/h**	**@ 80/h**
DRR	85.9 ± 0.6	89.4 ± 0.6	97.0 ± 0.8
DRRCr	85.9 ± 0.8	89.2 ± 0.9	96.6 ± 1.3

6. Concluding remarks

The present research reports an experimental study concerning the use of CR in a dense graded recycled asphalt mixture. The main scope of the study was to approach an understanding of optimized composition of the different materials utilized in the dense graded HMA that yield desired performance properties. The following conclusions and explanations were determined according to the laboratory tests results and analysis on the different investigated mixtures.

- In comparison with the mixtures without CR, the optimum bitumen content in DRRCr mixture was 0.5% higher. In fact according to the conducted literature survey it was experienced that the incorporation of dry process CR into a mixture will lead to less workability and dry appearance in comparison to the mixture without.
- Voids analysis indicated that addition of a precise amount of fine CR to dense graded mixture would not change the volumetric parameters, which were under scepticism. However, former studies by authors showed that incorporation of fine CR by dry process would reduce the void rates and interconnected voids in porous asphalts.
- The ITSM results at three different temperatures indicated that the addition of CR into asphalt mixtures would decrease their thermal sensitivity, particularly the higher stiffness related to the presence of RAP. Based on the average ITSM values although the modulus decreased at low temperature, at the high and medium temperatures it is comparable with non-CR mixtures.
- Moisture sensitivity assessment by means of ITSR revealed that all the tested mixtures cover the required limit provided in different standards. Regarding the ITS values of dry conditioned specimens, it can be derived that the incorporation of CR indirectly increases the ITS value of mixtures comparing to the not rubberized mixtures, while the ITS values of wet conditioned specimens are close.
- Considering the RLAT results in terms of final accumulated strain and strain rate, it can be deduced that no significant difference was found regarding the creep characteristics of the tested mixtures. This could be expected based on the similar ITSM values at high temperature and the correlation with permanent deformation behaviours.
- An outstanding gain in skid resistance properties of the mixtures with and without crumb rubber was that, subject to the proper mix design and manufacturing controls, CR could improve both macro and micro texture of the mixtures.
- Acoustic properties in terms of CPX measurements showed insignificant difference for the tested trial sections with and without rubber. This could be expected taking account the effective noise abatement factors. Therefore, with similar mix design and final compacted surface texture, and the close stiffness values, the CPX measurements are in line with other data.

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5.3 Paper II

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Fundamental properties of bitumen binders containing novel cellulose-based poly-functional fibres

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ABSTRACT

A series of Fibre-added bitumen compounds were subjected to conventional and rheological tests for investigating the effectiveness of modified fibres in improving the characteristics of bituminous binders. The studied fibres were novel composite cellulose-based poly-functional fibres with and without a plastomeric polymer and crumb rubber content, which blended with neat bitumen or SBS Polymer modified Bitumen (PmB). The test program included a primary stage of microscopic analysis by means of Scanning Electron Microscopy (SEM), for observing these composite fibres' microstructure as well as the empirical test methods, and dynamic rheological analyses using Dynamic Shear Rheometer (DSR). According to the conventional test results, the addition of fibres increased the softening point and viscosity and reduced the penetration. From another perspective, while the addition of rubber decreased the softening point and viscosity, it increased the penetration of compounds in comparison to those containing fibres without rubber content. From the results obtained by Multiple-Stress Creep-Recovery (MSCR) and Frequency Sweep (FS) test, the isochronal graphs of complex modulus and creep-recovery curves showed the same trends in terms of increased stiffness. In addition, the phase angle curves confirm that the presence of rubber decreased the stiffness and increased the elasticity for PmB compounds in comparison to those of reference mixtures containing non-rubberized fibres.

1. Introduction

Recently, the utilization of different types of fibres has become quite a common strategy to control the bitumen darindown of Gap and open-graded asphalt mixtures. However, the increased use of porous asphalts and Stone Matrix Asphalt (SMA) as open and gap-graded mixtures respectively, has presented a different role for the fibres in asphalt mixtures [1]. SMA was designed as a wearing course with especially high resistance to studded tires. This was possible with the stone-on-stone contact of coarse aggregates provided by gap-graded structure of asphalt mixture. This discontinuous grain size distribution in gap and open-graded asphalt mixtures results in some engineering deficiencies as well as bitumen draindown. To overcome this problem the new generation of fibres are modified to improve the performance and mechanical properties of asphalt mixtures. In addition, the mixture is stabilized to avoid the binder drainage during construction and binder bleeding during the extremely high temperature service conditions. Besides the aim of enhancing the mixture's properties, fibres created a new market to reuse some of the waste materials [2].

Many different composite modified fibres such as bitumen-treated fibres, polymer-added fibres, and more recently rubberized fibres have been introduced and experienced to promote their further application. All of these fibres have a cellulose base because it is better at binder absorption compared to mineral fibres [3,4] and proven effectiveness in many experimental studies and field practices [5]. In the literature, most of the studies were carried out on the possible alternatives for the commonly used cellulose fibres considering the economical and eco-friendly principles. The introduction of coconut, banana, sisal, etc. as natural fibres; glass and basalt as mineral fibres and aramid, polyester, and fiberglass as synthetic fibres in addition to recently introduced waste tire rubber and plastics [6&7] are some of these efforts. In this respect, a wide variety of conclusions have been made on the effectiveness of different kinds of fibres. However, most of these conclusions derived from experimental studies on the mixture scale and not in binder scale.

In the mixture scale, besides bitumen draindown control capability,

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In the mixture scale, besides bitumen draindown control capability, the primary functions of fibres are to provide extra tensile strength in the resulting composite and to increase the strain energy absorption [8]. This inhibits the formation and propagation of cracks, which reduces the structural integrity of the asphalt pavement. This effect is more crucial for the porous and SMA mixtures, in which the tensile strength is lower in comparison to conventional dense-graded asphalt concretes because of the characteristics of the structure of these mixtures.

On the other hand, regarding the permanent deformation resistance, the performance of fibres is depended on the mixture type. It has been shown that while the cellulose-based fibres had not got any significant effects on rutting resistance of gap and open-graded asphalt mixtures [9], the addition of waste tire rubber as fibre was effective for these mixtures in most cases [10].

In summary, the main uses of fibres can be divided into two main categories:

1. For the open-graded and gap-graded asphalt mixtures; mainly to control the bitumen draindown and to improve the performances related to tensile properties.

2. For the dense graded mixtures; enhance the rutting resistance [11].

For these purposes, while the natural fibres (mainly plant-based cellulose fibres) are suitable for bitumen draindown control, the synthetic fibres are recommended for improving the tensile strength [12].

In the binder scale, the findings on the effect of cellulose-based fibres on the bitumen physical and rheological properties can be divided based on the test temperature levels. Low-temperature analysis by means of Bending Beam Rheometer (BBR) and intermediate/high-temperature levels mainly by means of Dynamic Shear Rheometer (DSR) are the most common practices. At the low temperatures, the authors' former study [13], in line with the few pieces of research in the literature [14], showed that the binders increased stiffness when different kinds of cellulose fibres were added. However, the same research showed that the rubberized fibres could alleviate the stiffness. On the other hand at intermediate and high temperatures, a research showed that the complex shear modulus of fibre-added bitumen compound was increased, which could result in improved rutting resistance for the binders and in extended scale in the mixtures. Moreover, the addition of various fibres reduced the phase angle of asphalt binders which increases the elastic part in the visco-elastic properties of asphalt binders [15]. It was also shown that the total permanent strain at the creep test was higher for the bitumen samples containing cellulose fibre compared to mineral and synthetic fibres.

The main scope of this paper was to characterize a series fibre-added bitumen compounds by conventional and fundamental tests. This data could be used to evaluate the binder's role in asphalt mixture and compare it to the mixture's structural (mixture type/ aggregate skeleton) characteristics in the final fibre-reinforced asphalt mixtures. In addition, investigation on the feasibility of using End of Life Tire rubbers (ELTs) into asphalt concretes via rubber-added fibres as a new approach was one of the main goals of this research. Overall the novelty of this research goes to the characterisation of composite fibres and theirs' impact of the bitumen binder properties. While to date many research works have been conducted for investigating the effects of different cellulose-based fibres, the newly introduced composite fibres have not been investigated yet. This research work aims for investigating the fibre added bitumens compounds, which is of paramount importance on final asphalt concrete's mechanical and performance properties. Considering the objectives of this research, the experimental plan presented in this paper concentrated on binder's rheological and physical properties with and without the addition of different modified fibres.

2. Materials

2.1. Bituminous binders

In the present experimental work two different bitumens were used; the two were a 40/50 penetration grade bitumen and a 10/40-70 SBS polymer modified Bitumen (PmB). Fig. 1 represents the fluorescence microscopy images of both bitumens showing the SBS dispersion into the modified binder compared with the neat bitumen.

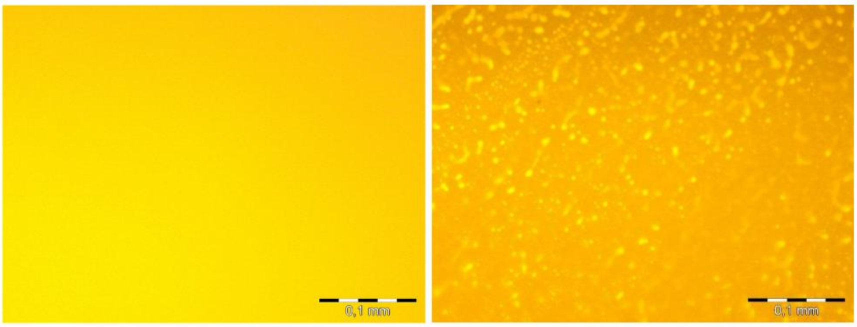

Fig. 1. Binders' fluorescence microscopy images. On the left neat bitumen and on the right SBS PmB.

2.2. Fibres

Four different multifunctional fibres were used in this study (shown in Fig. 2) were:

1. A cellulose-based mineral fibre (glass) added fibre. The mineral component (structural) supposed to form a three-dimensional network and play a role of micro-reinforcement in the binder matrix. In the present research called as (F).

2. A cellulose-based fibre containing mineral fibre (glass) and a plastomeric polymer. The compound was deemed to increase the viscosity and micro-structural reinforcement of the bitumen film. In the present research called as (PF).

3. A cellulose-based fibre mainly composed of cellulose and high amount of waste tire rubber (60-70%). It contains also a minor portion of mineral (glass) fibres. In the present research called as (RF).

4. A cellulose-based fibre composed of cellulose, minor portion of mineral fibre (glass), waste tire rubber, and also a minor portion of plastomeric polymer. In the present research called

as (RPF). It is worth mentioning that the rubber percentage on the weight of fibre is less than RF fibre (40-50%).

The composition of each fibre was chosen based on the individual characteristics of the materials (cellulose, glass powder, crumb rubber and polymer). The ultimate goal was producing a composite fibre with potentials to improve the mechanical and performance properties of asphalt mixture as well as having an acceptable stabilizing properties.

Considering the test scale and providing uniform compounds the pelletized fibres were grinded by mechanical grinding apparatus until become powders. It is noteworthy that, in order to avoid any variables to the results and provide comparable test values, the fibre content kept constant and 7.5% on the weight of bitumen. This may approximately represent the 0.4% on the weight of the total mixture (depending on mix design).

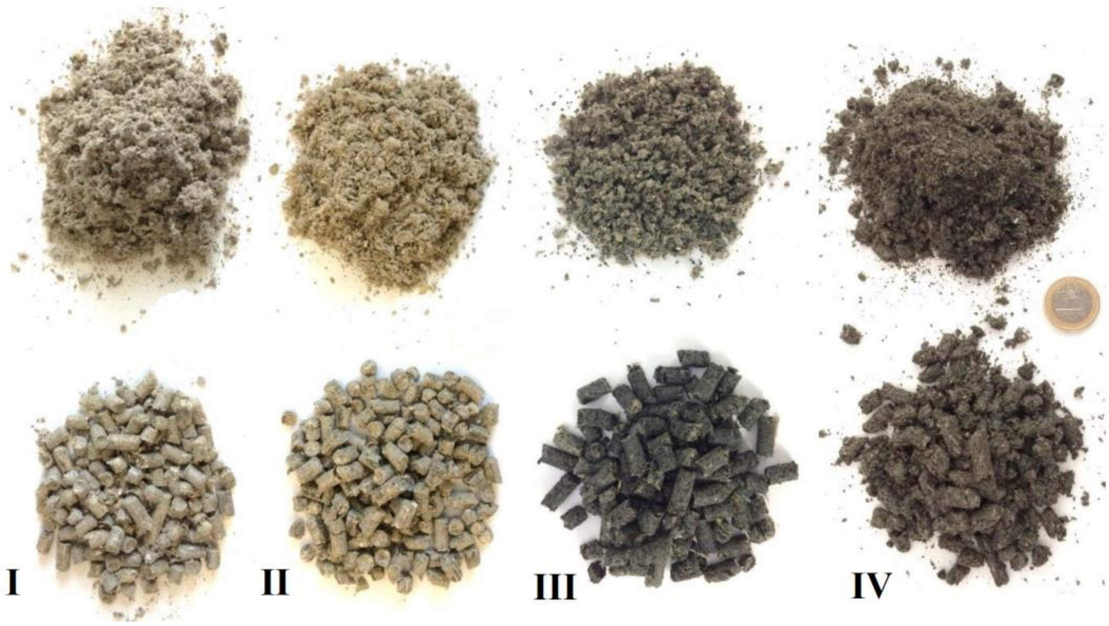

Fig. 2. Appearance of the fibres before grinding on the bottom and after grinding on the top.

3. Methods

3.1. Sample preparation

The laboratory blends were prepared by blending the ground (powdered) fibres into hot bitumen and stirring manually. Considering the needed time for rubber digestion into bitumen besides the practical conditioning time (The time for transportation of asphalt concrete) the sample preparation included the following steps:

- Blending the grinded fibre with hot bitumen for 5 minutes at 170± 5˚C, depending on the type of bitumen

- 25 minutes conditioning and frequently manually mixing the blend at 160±5˚C

The temperatures and the conditioning time were determined and carefully controlled in a way to avoid the imposed aging. It is worth mentioning that, in order to avoid the fibre sedimentation in hot fluid bitumen binder, the samples were prepared in small portions. This degradation was fully considered especially during sample preparation before purring the materials into the moulds.

3.2. Experimental plan

The study plan followed in this research included three phases of Microscopic analysis, empirical test methods, and rheological analysis, described in detail in Fig. 3.

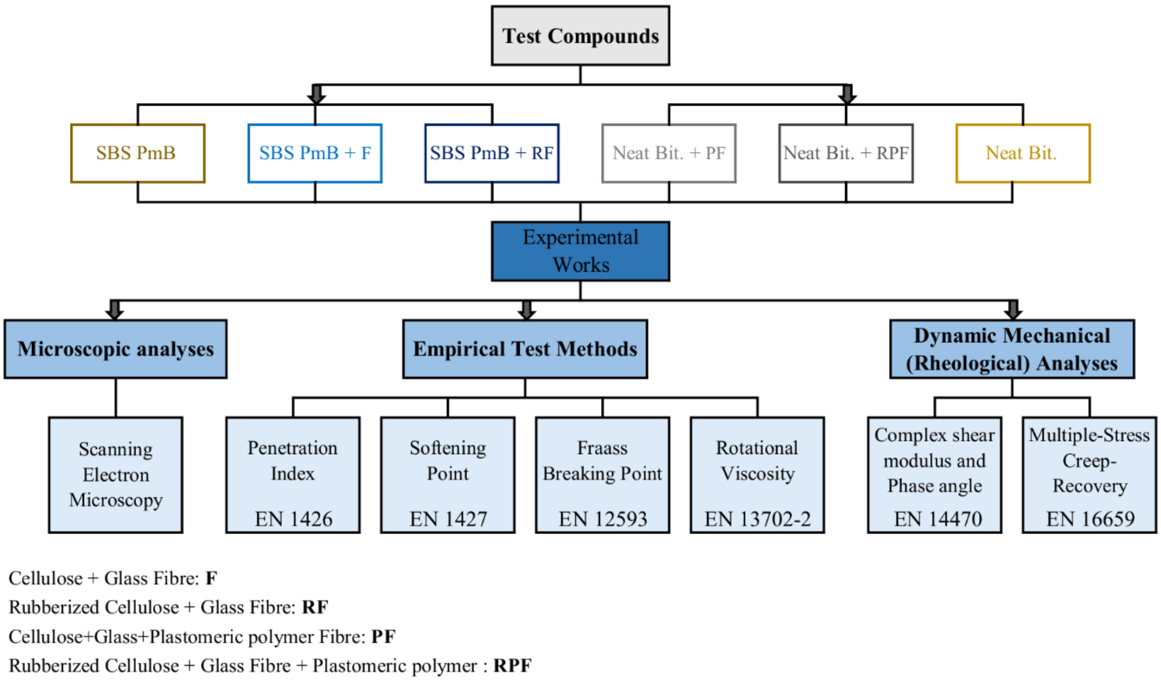

Fig. 3. Research scheme.

4. Results and Discussions

4.1. Microscopic analysis

As the primary stage of the present research, in order to understand the fibres' interaction with bituminous binders and modification/reinforcement mechanism, the microstructure of the fibres was observed by Scanning Electron Microscopy (SEM) shown in Fig. 4 and Fig. 5. It is noteworthy that SEM images were provided for the fibres and not the fibre-added bituminous compounds. A tiny pieces of grinded fibre were observed under SEM, but not from powdered fibres.

Fibres can form a three-dimensional network in bituminous binders, and this network can be retained at high temperature. The difference between the fibres' microstructure would result in different asphalt adsorption [16] and further rheological properties. According to the fibre F (cellulose and glass fibres), it can be seen that the cellulose fibre has an irregular and twisted strip/filament structure with rough surface texture, which is constructive to the adhesion of binder. With this texture, it can also absorb more bitumen and stabilize the asphalt mixtures effectively. In contrary, the mineral fibres can be seen as straight white bars with a smooth surface texture, which results in poor bitumen adsorption. Generally, the mineral fibres are more rigid than the cellulose fibres, and tend to be aligned with no entanglement and fewer absorption properties [3, 15].

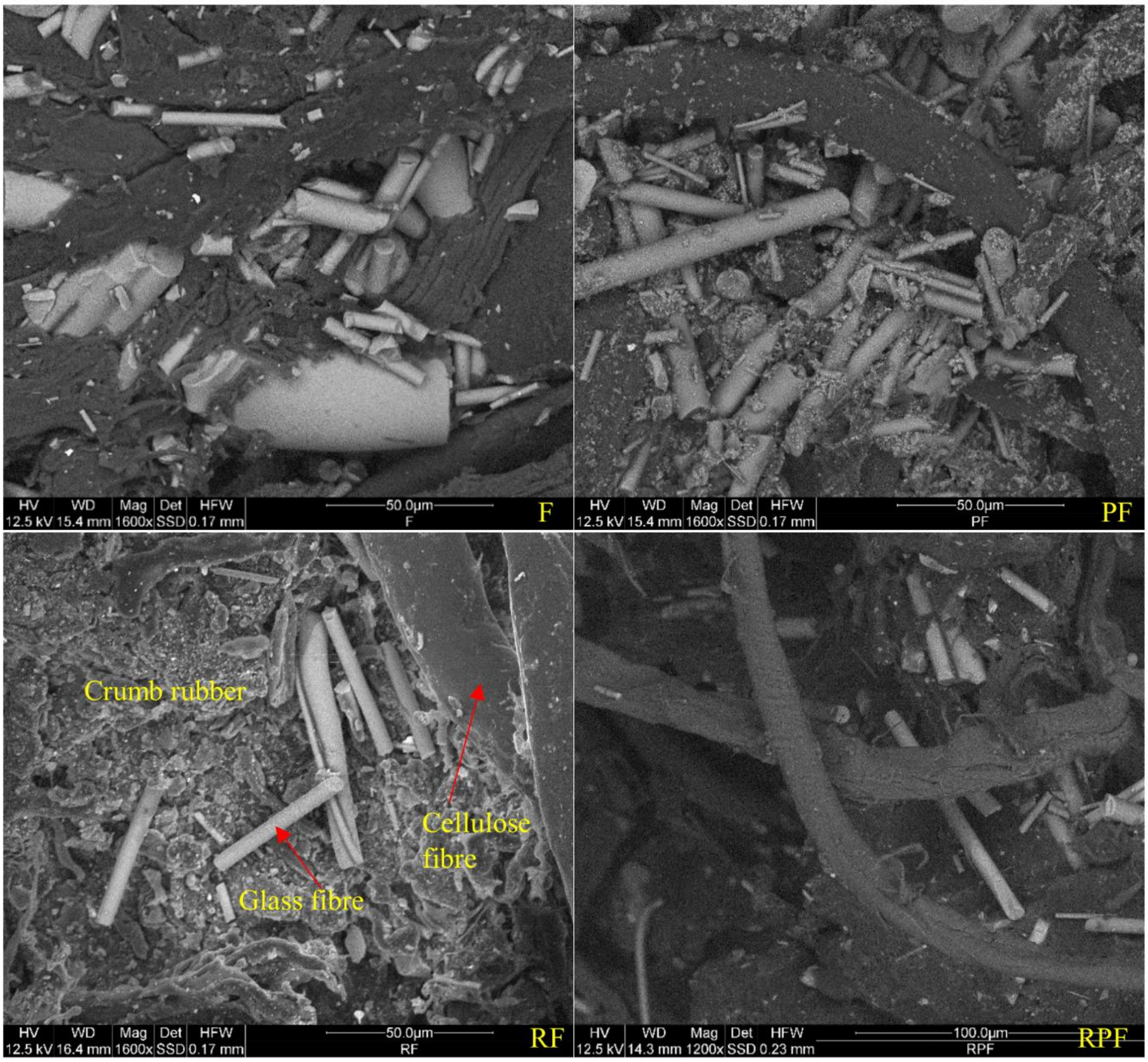

Fig. 4. SEM images of fibres at 1600x magnitude.

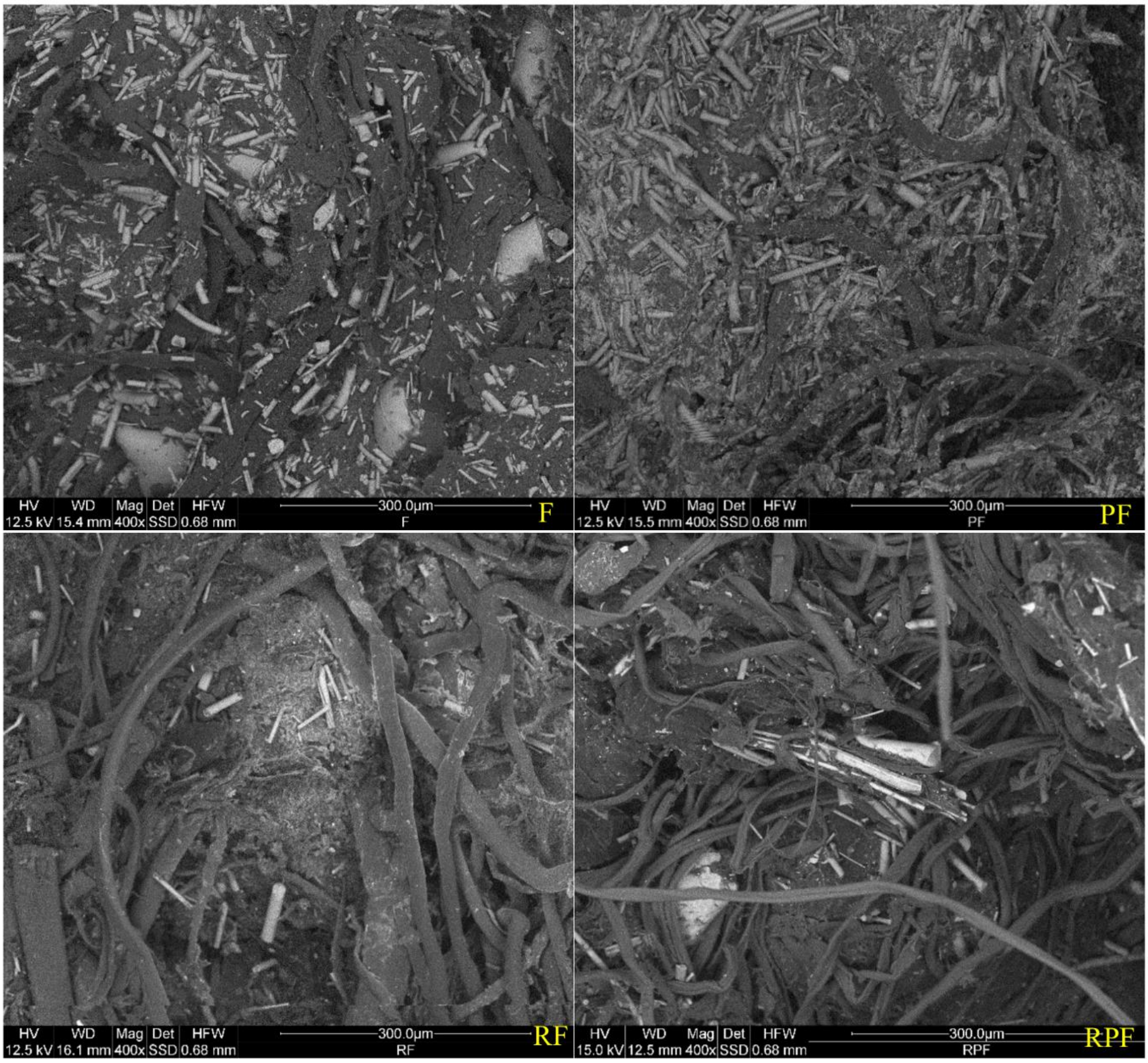

Fig. 5. SEM images of fibres at 400x magnitude.

Fig. 4 and 5. B shows the PF fibre image, which is similar to F fibre's image with more round section filament structure for cellulose fibre instead of strip structures in F fibre image. Here the presence of well-distributed white powdery materials is due to the addition of plastomeric polymer. It seems that the polymer covered the surface of both cellulose and mineral fibre uniformly. Form another point of view, the higher portion of mineral fibre in comparison to the fibre F is noticeable.

Fig. 4 and 5. C. shows the rubberized fibre's (RF) structure and texture. It can be seen that this fibre is a high rubber content fibre with a minor portion of cellulose and mineral fibres. While the cellulose and mineral fibres can be seen as black round-section filaments and white straight bars, respectively, the rubber particles can be seen as irregular-shaped lumps accumulated with high volume of fibre.

Fig. 4 and 5. D represents the RPF fibre microscopic texture. As it can be seen, there is a minor portion of glass fibre shown as white bar-shaped structures, cellulose fibres here can be observed as more twisted strips as well as the rubber, which can be seen same as RF fibre irregular-shaped accumulated lumps similar to RF fibres. Table 1 represents a summary on main characteristics of Fibres' micro-structures.

Table 1. Fibres' microstructure.

Fibre	Fibres' Components											
	Organic (Cellulose)			Mineral (Glass)			Polymer (Plastomer)			Elastomer (Tire rubber)		
	Form	Feature	Texture	Form	Feature	Texture	Form	Feature	Texture	Form	Feature	Texture
F	Irregular twisted	Strip filament	Rough surface	straight	Bar-shaped	Smooth surface	-	-	-	-	-	-
PF	Irregular twisted	round sec. filament	Rough surface	straight	Bar-shaped	Smooth surface	well-distributed powdery material			-	-	-
RF	Irregular twisted	round sec. filament	Rough surface	straight	Bar-shaped	Smooth surface	-	-	-	Irregular-shaped lumps		Dense accumulated
RPF	Irregular twisted	Strip filament	Rough surface	straight	Bar-shaped	Smooth surface	-	-	-	Irregular-shaped lumps		Dense accumulated

4.2. Empirical tests

Penetration

The primary method for bitumen classification in the European standardisation framework is the penetration test at 25°C. The test involves the determination of bitumen consistency expressed as the distance that a standardised steel needle penetrates vertically into a bitumen sample at a specific temperature. The needle load is 100 g, and the loading time equals 5 seconds. The penetration unit is [0.1 mm], which corresponds to the needle penetration depth in the bitumen sample. The penetration represents a quantitative measure of the bitumen response to variation in temperature.

Fig. 6 represents the effect of fibre on the penetration of the two compound groups: neat bitumen and SBS PmB, compared with the virgin binders as the reference material. As it can be seen, for the both neat and modified binder the addition of fibre decreased the penetration index value and with a similar trend. However, the reduction of penetration was more significant for the neat bitumen compounds in comparison to those of SBS PmB ones, this could be correlated to the low viscosity of the neat binder that makes the ease of binder absorption of the fibres. From another point of view, rubberized fibres increased the penetration compared to the compounds with non-rubberized fibres; however, the effect was not remarkable, which could be due to the limited rubber content of the fibres.

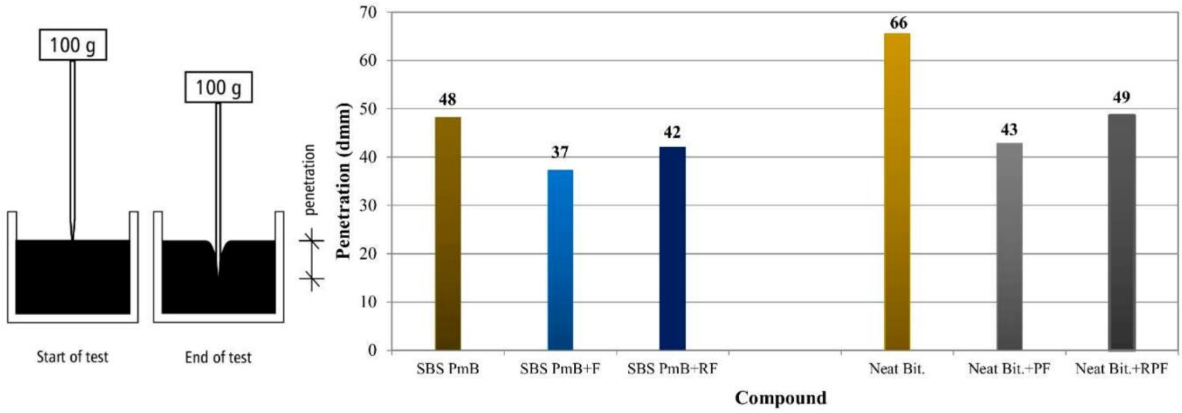

Fig. 6. Penetration test's principle and the average penetration indices.

Softening point

The Softening point of bitumen represents the thermal stability of the bitumen [17]. It means that higher the softening point of bitumen is the higher temperature it needs to reach the same viscosity. The current research introduced the softening point into the bituminous compounds' characterization for investigating the effect of different fibre addition on thermal stability. The test involves the determination of the "conventional" temperature at which asphalt acquires a specific consistency. Bitumen softening point testing is usually performed by the ring and ball method (R&B in short). Two bitumen samples placed in metal rings are heated in a controlled manner in a liquid (distilled water for the expected R&B from 28 to 80°C, glycerine for the R&B from 80 to 150°C), placed in a glass beaker, with each bitumen-filled ring supporting a steel ball. The softening point is adopted as the average temperature at which both bitumen rings soften to the point that each ball, covered in bitumen and overcoming its resistance, travels a distance of 25.0 mm ± 0.4 mm. The result of the softening point test is expressed in (°C).

In terms of softening point the values shown in Fig. 7 indicate that the addition of all the tested fibres increased the softening point of both neat bitumen and SBS PmB. It is worth mentioning that although the same trend was observed for both groups of compounds, the quantitative comparison of the values reveals the significant effect of cellulose + glass fibre (F) on SBS PmB.

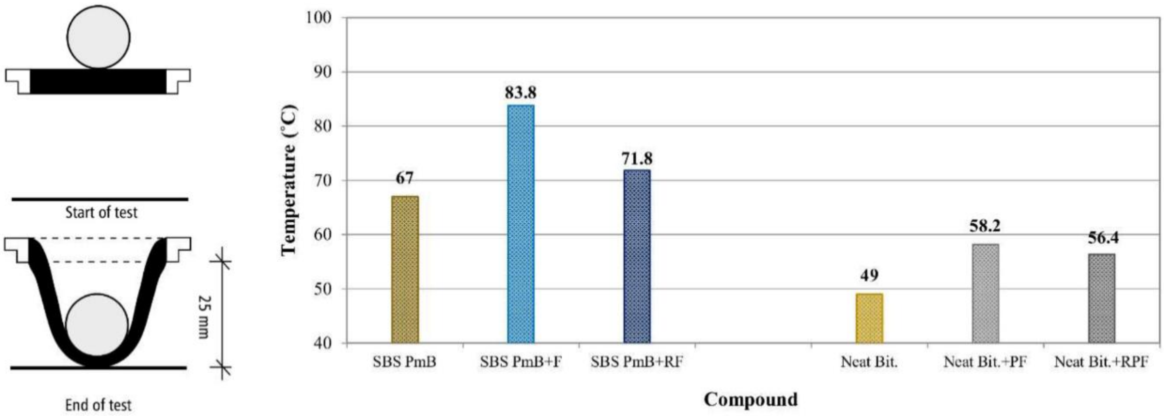

Fig. 7. R&B softening point test's principle and the average softening points.

Rotational viscosity

Viscosity is an important physical property to evaluate the flowability and deformation of bitumen [18]. It is always useful to determine the flow behaviour of the bitumen at high temperatures monitoring the field production and laboratory design by establishing the viscosity-temperature profiles. The Rotational Viscometer (RV) is used to determine the viscosity of asphalt binders in the high-temperature range of manufacturing and construction [19]. The basic RV test measures the torque required to maintain a constant rotational speed (20 RPM) of a cylindrical spindle while submerged in an asphalt binder at a constant temperature with a thermosel temperature control system. This torque is then converted to a viscosity. The RV test values ensure that the asphalt binder is adequately fluid for pumping and mixing [20].

Rotational viscosities for the two compound groups (at 135, 160, and 185˚C) are shown in Fig. 8. The viscosity of asphalt binder at high manufacturing and construction temperatures (above135°C) is important because it can control the pumpability, mixability, and the workability. In the case Superpave specifications determined the dynamic viscosity less than 3 Pa.s at 135 for asphalt mixture pavement. The results show a consistent increase in viscosity with fibre addition for both groups. As with the penetration and softening point tests, the viscosities give a clear indication of the stiffening effect of fibre addition. Comparing the overall conventional test results, the most important achievement was the consistent results and trends for both groups. It can be observed that in line with penetration and softening point, the addition of cellulose + glass fibre (F) to the SBS PmB recorded the highest viscosity among the tested compounds. In this respect, it has been found that the addition of glass fibres decreases the penetration and viscosity, increases softening point, which was referred to the glass fibre surface texture and dimensions (length and width) which help to form a network of fibres, interacting to create a continuous network of fibres through the bitumen

[21]. However, it should be taken into account that the surface adsorption and roughness properties of cellulose fibre increased the effects too.

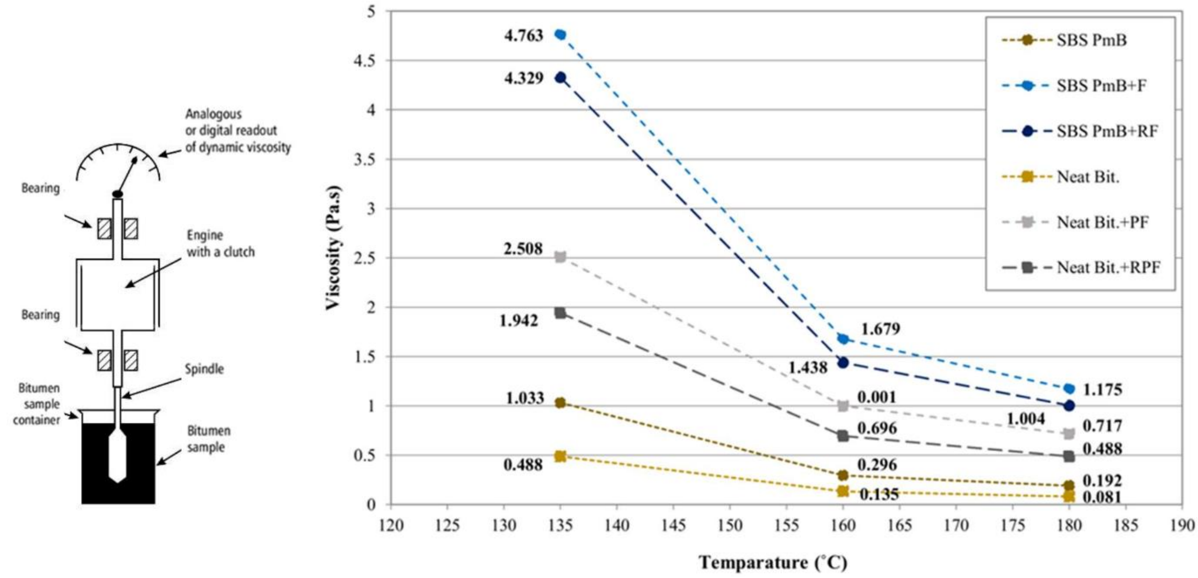

Fig. 8. Typical viscometer configuration and the dynamic viscosities.

Fraass breaking point

Fraass breaking point is one of the few tests introduced to examine the behaviour of bituminous binders in low-temperature levels. It is basically a research tool that determines the temperature at which bitumen becomes brittle and reaches to a critical stiffness and cracks. Shown in Fig. 9, in the Fraass test procedure, a 41 mm x 21 mm steel plaque is coated with 0.41 g of bitumen and slowly released. The test involves the determination of the temperature at which a 0.5 mm thick bitumen layer breaks when spread on a thin, steel plaque. The plaque sample is placed in the test set and subjected to cyclic, mechanical bending and relieving. The bending occurs every 1°C while the air temperature around the sample is constantly decreased at a rate of 1°C/minute. The bitumen layer is examined after each plate bending and any cracks are recorded. The tests ends when the first visible sample crack is observed. The result of the Fraass breaking point is expressed in (°C). The cracking temperature is called Fraass breaking point, which represents equi-stiffness temperature, which is the critical temperature and bitumen cracks [22].

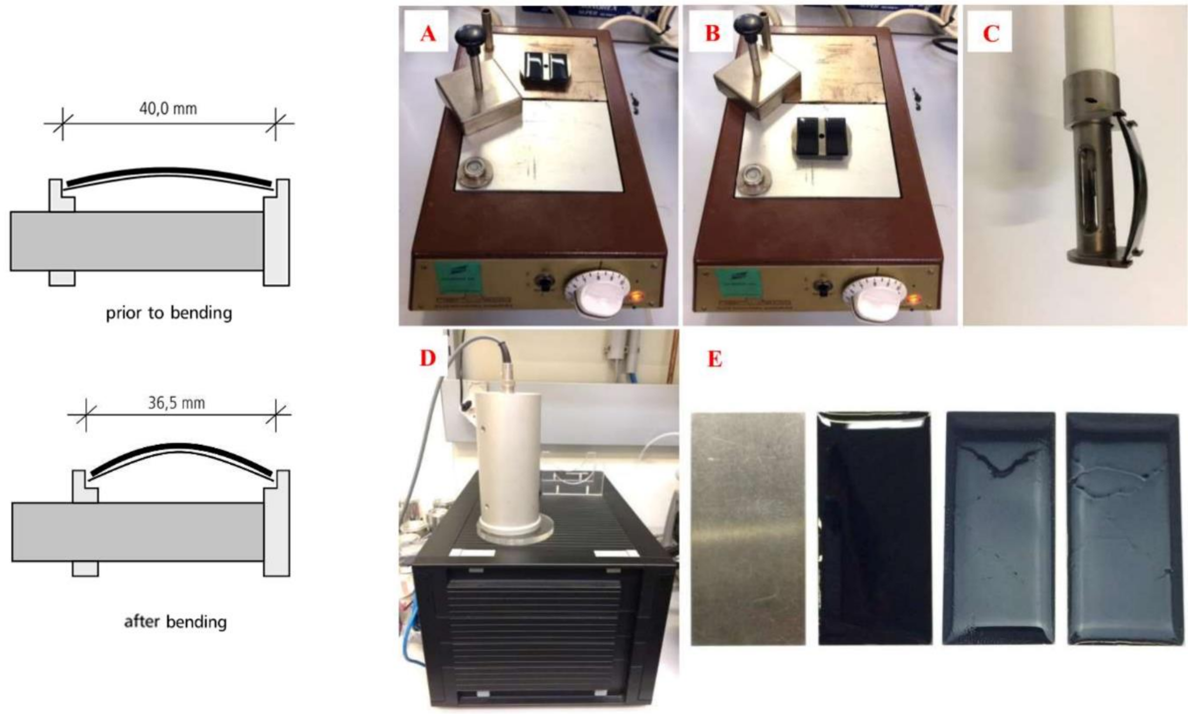

Fig. 9. Fraass breaking point test principle test's procedure: A) Spreading bitumen on the plaque by hot surface; B) Cooling down the plaques using cold surface; C) Installing the plaque; D) Test apparatus; and E) From left to right: test plaque, bitumen covered plaque before test, and two test plaques after test.

In terms of terms of low-temperature properties by means of Fraass breaking point, while the values of -9.4 and -10.5 recorded for the neat and SBS modified PmB respectively, no statistical results obtained for the samples containing fibre. The authors believe that this could be due the uneven surface of the samples, which results in the compound's accumulation on the test plaque. This unevenness could be expected when both cellulose fibre and CR of the rubberized fibres are of high potentials for absorbing the bitumen and the resulted in inflation. This phenomenon leads to a varied rough surface, which highly influences the accuracy of the test by impacting on the cracking development of thin bitumen film. While this tests were not applicable for the presented research work, because of the sample's limited small dimensions Bending Beam Rheometer (BBR) with bigger test specimens could be adopted understanding the influence of fibres on low-temperature characteristics of bitumen and bitumen compounds. BBR were considered for the further reaches.

4.3. Dynamic viscoelastic parameters

The most commonly used method of detailed rheological testing of bitumen is using oscillatory-type testing, using dynamic shear rheometers (DSRs) within the region of linear viscoelastic (LVE) response. Dynamic mechanical properties of a bitumen may be expressed in terms of a complex shear modulus G* that is composed of two components G′ and G″ representing the dynamic storage and loss modulus respectively and are either time or frequency and temperature dependent. Phase (or loss) angle (δ) is the phase, or time, lag between the applied shear stress and shear strain responses during a test.

$$G^* = \sqrt{G'^2 + G"^2} \quad (1)$$

$$\delta = tan^{-1} \frac{G"}{G'} \quad (2)$$

For the presented research work, according to EN 14770, 1.5 g of each material was placed in a disc-shaped silicon mould with diameters of 25mm and tested with the DSR. The Frequency Sweep (FS) tests were performed under the following test conditions:

- Mode of loading: controlled-strain;
- Temperatures: 22 to 82˚C with 6-degree steps;
- Frequencies: 0.01–40 Hz (eleven values);
- Parallel plate geometries: 25mm diameter with a 1mm gap;
- and strain amplitude: within LVE response 0.4 – 10.0%.

The rheological properties of the binders were measured in terms of complex (shear) modulus (stiffness), G*, and phase angle (viscoelastic balance of rheological behaviour), δ. The DSR rheological data were then presented in the form of isochronal plots at a loading frequency of 1.592 Hz and 10 Hz.

4.3.1. Rheological indices

Complex modulus

Isochronal plots of the complex modulus (G*) versus temperature at 1.592 and 10 Hz for both groups of compounds are shown in Figs 10 and 11. Bearing in mind that data at high frequencies represent the short-term behaviour of the sample whereas long-term effects influence the data at low frequencies, these figures are useful for studying the bitumens and the bitumen compounds' characteristics. The isochronal plots show that both the solely bitumen samples have a lower stiffness (G* value) over the entire temperature domain in comparison to those of compounds with fibre. It should be noted while for both the compared groups there are only minor increases in G* at low temperatures, there is considerable change at high temperature with the approach of plateau region indicative of dominant fibre effects. This indicates the improved temperature susceptibility of the modified fibres resulting particularly at high temperatures in terms of hardness. From another point of view, the fibre containing compounds for both groups highlight the reduced stiffness for the rubberized fibre compounds. This approach was also recorded within conventional tests, which represents the integrity of the obtained results. Comparing the PmB compounds, the response of cellulose/mineral fibre containing compound modified is nearly identical to that of rubberized, modulus levels being marginally greater across the medium level temperatures. From another perspective, considering the SEM images, the higher stiffness of PF containing compounds refers to the network construction, made by mineral fibres from one side and lower amount of cellulose in RPF fibres compared to PF. Bearing in mind that, rubber has lower absorption properties compared to cellulose.

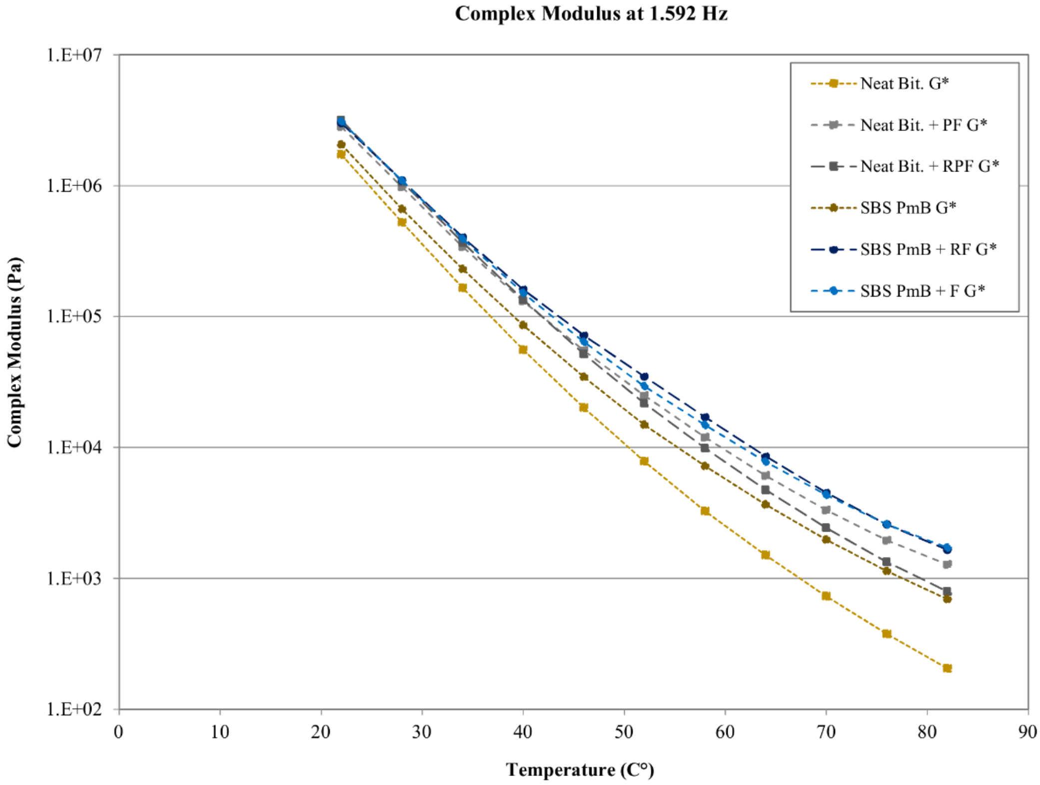

Fig. 10. Isochronal plots of complex modulus at 1.592 Hz.

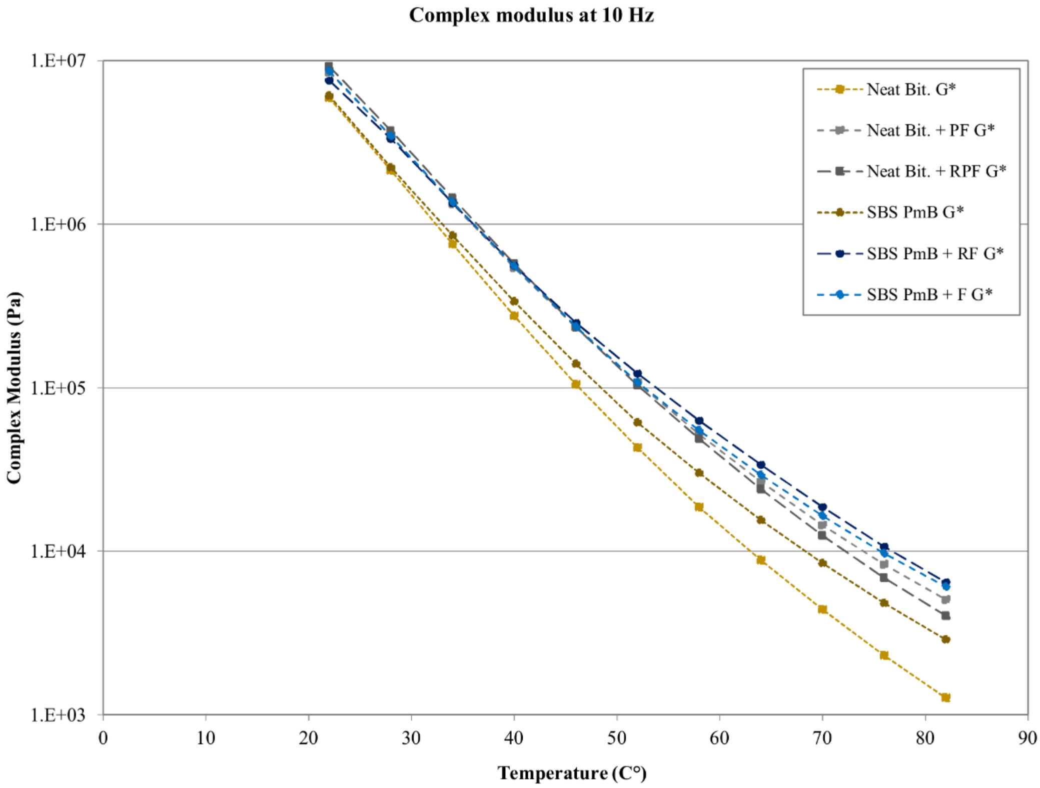

Fig. 11. Isochronal plots of complex modulus at 10 Hz.

Phase angle

In terms of viscoelastic behaviour, measurements of δ are generally considered to be more sensitive to the chemical structure and therefore the modification of bitumen than complex modulus [23]. The phase angle isochronal graphs shown in Figs. 12 and 13 clearly indicate not only the temperature but also the time dependency of the rheological behaviour of the two binders. The response of SBS PmB is dramatically different from that of unmodified bitumen. The δ is bell-shaped rather than the normal sigmoid curve for the neat bitumen, peaking at around 60˚ at an angular frequency of 1.592 and 10 rad/s. This decrease in phase angle is evident across the entire temperature domain of the plots, but is more significant at the higher temperatures were the unmodified binder becomes increasingly more viscous in nature. The phase angle curves of compounds containing fibre show the change in rheology with modification as a reduction in δ in comparison to those of reference compounds except for the compound containing cellulose/mineral fibre at high test temperatures.

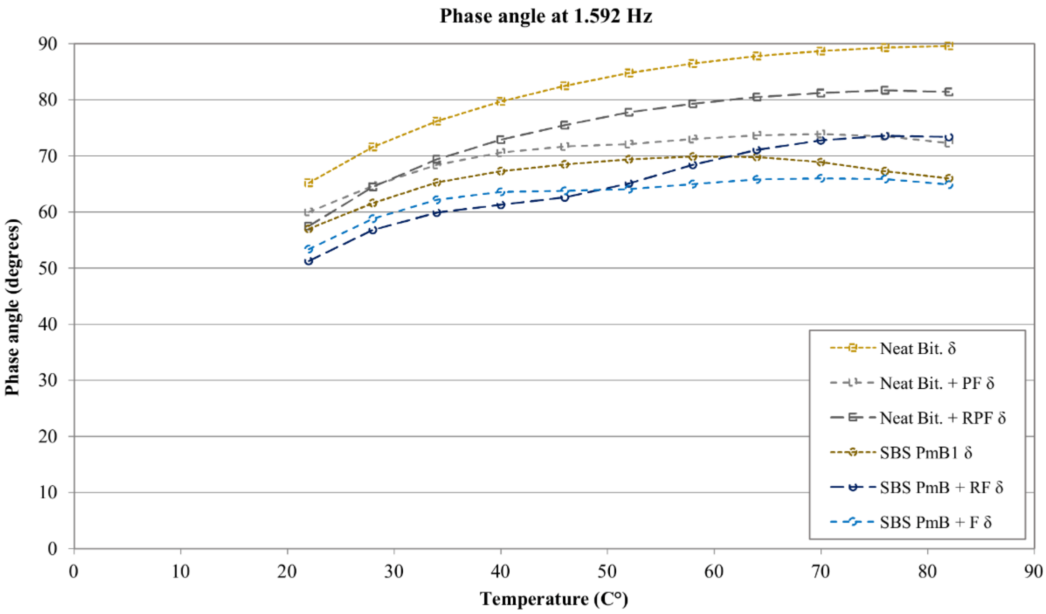

Fig. 12. Isochronal plots of phase angle at 1.592 Hz.

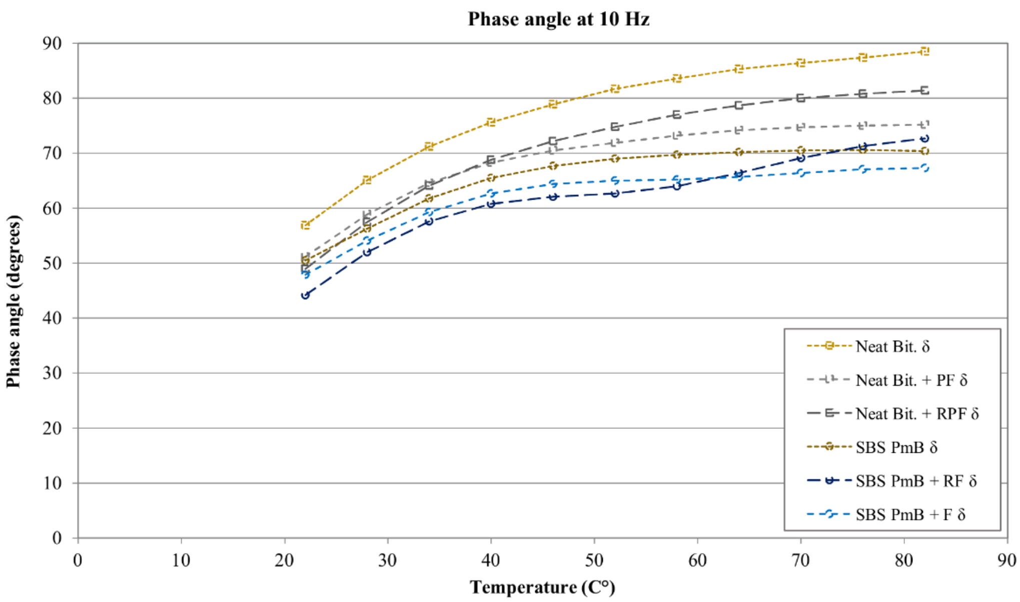

Fig. 13. Isochronal plots of phase angle at 10 Hz.

Superpave rutting binder parameter

According to the Superpave binder specifications, the parameter G*/sin δ measured at 1.592 Hz (10 rad/s) is used for the prediction of pavement rutting. The rutting parameters for the bitumen samples and the compounds are presented in Table 2. The parameters have been determined at a temperature of 58˚C to coincide with the temperature of the Multiple Stress Creep-Recovery test for permanent deformation analysis.

Table 2. Superpave rutting parameter at 58˚C.

Compound	G*/sin δ @ 1.592 Hz (KPa) 58˚C
Neat bit.	3.3
Neat bit. + PF	12.5
Neat bit. + RPF	10.1
SBS PmB	7.7
SBS PmB + F	16.4
SBS PmB + RF	18.3

In general, greater G*/sin δ values have been obtained for the PmBs compared to the neat binders. As expected the higher polymer and/or rubber content PMBs displayed the higher G*/sin δ values and were, therefore, ranked higher than the reference compound in terms of their potential rutting resistance. In another words, bearing in mind that PF is containing high mineral fibre and plastomeric polymer, it could act better than RPF compound with low amount of both plastomer polymer and rubber as an elastomer. This is why the RPF did not act properly as a modifier and reinforcing material. From another side, it can be seen that highly rubber containing RF could effectively improve the potential rutting resistance of the compound compared to SBS PmB and F compound.

4.3.2. Multiple-Stress Creep-Recovery (MSCR)

The MSCR test uses the well-established creep and recovery test concept to evaluate the binder's potential for permanent deformation. The MSCR tests were performed according to EN 16659. The bitumen samples and compounds were subjected to standardized loading–unloading conditions: 1-s creep time, 9-s recovery time, 10 creep–recovery cycles with stress levels of 0.1 and 3.2 kPa. In the MSCR test, two separate parameters can be determined: non-recoverable creep compliance (J_{nr}) and percentage of recovery (MSCR Recovery) during each loading cycle. Values are reported as the average of ten loading cycles at each shear stress level. The J_{nr} parameter has been shown through numerous field and laboratory studies to better correlate with rutting potential than G*/sin δ [24]. This is because firstly in G*/sin δ, the complex modulus is measured in the linear visco-elastic region while rutting is non-linear and secondly G*/sin δ is unable to adequately capture the elastomeric modification because of the relatively small impact of the phase angle on the overall value of G*/sin δ [25].

Fig. 14 represents the MSCR curves of the tested compounds at 3.2 kPa stress level. The result of the test provided in Table 3 shows the percentage of recoverable and non-recoverable creep compliance at 3.2 kPa shear stress level cycles (the results for the 0.1 kPa were no applicable). Based on the curves and the values in the Table 3, it can be obviously seen that how the neat bitumen behaves compared to the SBS PmB. From the stiffness point of view, the ranking of the compounds is in line with other tests and as expected the presence of rubber decreased the stiffness for both bitumens. The curves also exhibit the influence of fibres is more significant to the neat bitumen compounds, which is due to the low viscosity and higher absorption of the fibres. Hence the SBS PmB compounds showed less accumulating deformation at the end of the test cycles. Considering the recovery percentage, while for the neat bitumen compounds the presence of plastomeric polymer reduced the elastic properties, the presence of rubber improve the performance for the RPF compounds. On the other side, in contrary it can be seen that for the PmB compounds, the network matrix made by mineral fibres in F compounds performed better than RF materials, however, the difference was not significant.

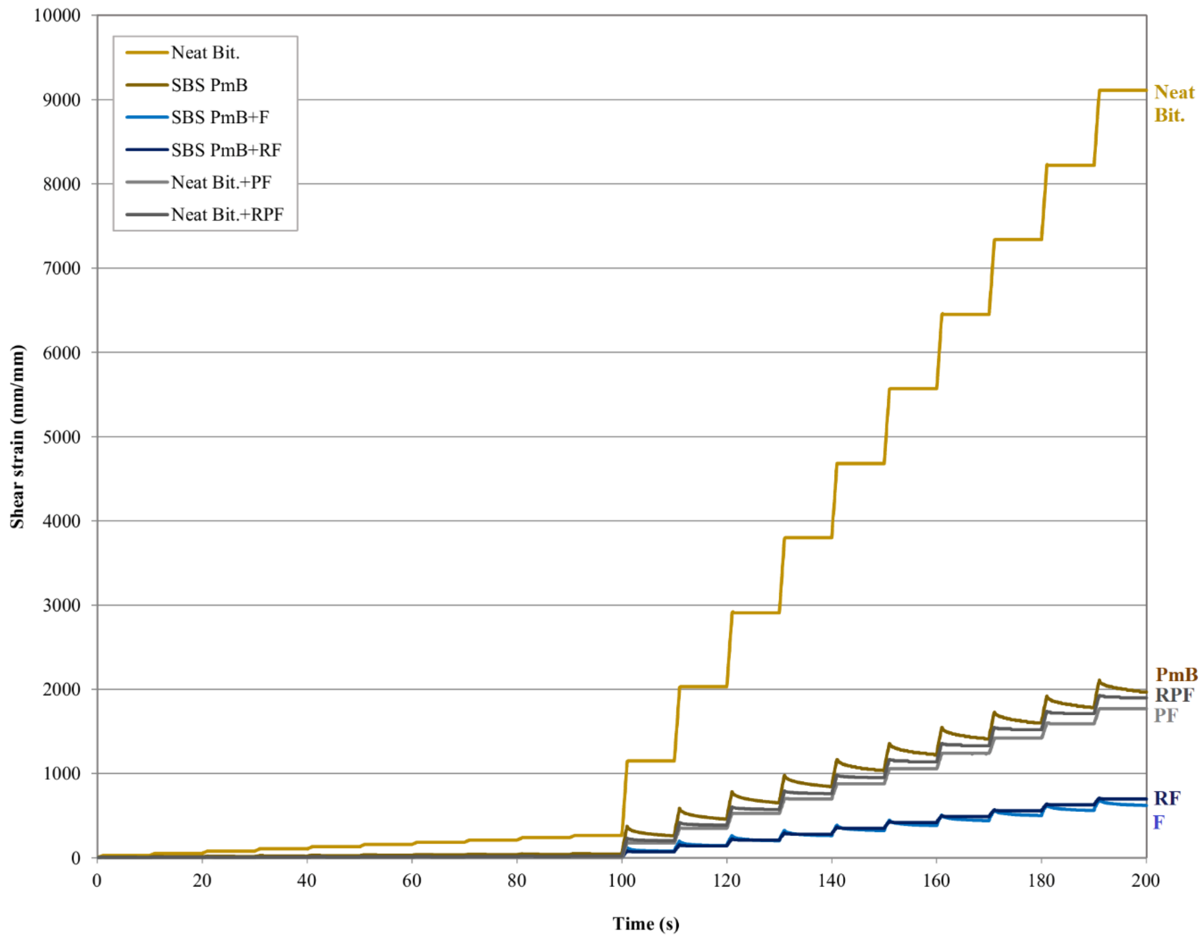

Fig. 14. Creep-recovery curves after 10 consecutive cycles at 3.2 kPa.

Table 3. MSCR test results at 58˚C and 3.2 kPa.

Compound	R (%)	Jnr (1/kPa)
Neat bit.	0.00	276.40
Neat bit. + PF	3.40	55.20
Neat bit. + RPF	14.30	58.70
SBS PmB	41.10	60.10
SBS PmB + F	50.60	19.40
SBS PmB + RF	16.20	21.80

5. Concluding Remarks

This study points out the effects of four different kinds of composite cellulose-based modified fibres on fundamental properties of a neat and SBS modified bitumen with same dose of fibre. Two approaches have been used in this paper to quantify the relative effects consisted of firstly, conventional binder tests and, secondly, fundamental rheological (DSR) binder tests. This may lead to a better understanding of the modified fibres and the relevant fibre-reinforced asphalt mixtures. On the basis of the presented research results, the following speculative conclusions can be drawn:

- Fibres can significantly improve bitumen penetration, softening point and viscosity values. Bitumen compound with cellulose+glass fibre showed the greatest increase in terms of viscosity and softening point and decrease in penetration. High viscosity and the softening point could lead to reduced draindown and permanent deformation of the asphalt mixture.
- While the addition of crumb rubber in fibres decreased the viscosity and softening point, the penetration increased.
- The Fraass test for the bituminous fibre-added compounds were not applicable. This inconvenience was mainly due to fibre very low amount of material on the steel plaque and the fibre accumulation, which did not let to provide smooth uniform bitumen coverage on the steel plaque.
- In terms of complex modulus, both neat bitumen and PmB showed increased stiffness in the entire test temperature domain; however, the difference was more evident for neat bitumen. From another perspective, while at intermediate temperatures all the fibre containing compounds showed identical stiffness, at low temperatures, lower stiffness was recorded for the rubberized fibre containing compounds.
- In terms of both complex modulus and phase angle, the response of PmB compounds was nearly identical even with different amount of rubber powder inside. It is considered that

this has resulted from the effective presence of glass fibre in one of the compounds and low amount of rubber in another.

- While the same trend was obtained by MSCR test results, the curves exhibited significant influence of fibres on bituminous binders, which was more crucial for neat bitumen compared to SBS PmB. From the stiffness point of view, noteworthy the MSCR curves were in line with viscosity and complex modulus isochronal curves.
- Considering the overall results, it can be deduced that while mineral fibres are not effective as a stabilizing additive, the three-dimensional network formation in binder matrix improves the binder's properties. This has been shown in few previous researches on the micro-suture of fibres. SEM images was efficient, getting knowledge on microstructure fibres' surface texture and structure.

In general, in the light of the obtained test results, it can be concluded that the composite modified fibres are of great potentials for enhancing the performance and mechanical properties of asphalt binders and respectively asphalt mixtures. In this respect, it was found that adding rubber via fibres is a possible alternative for producing rubberized mixtures with known benefits. However, it should be noted that simply adding composite modified fibres to asphalt mixtures does not guarantee to enhance the properties of asphalt concretes. Many aspects such as the dosage of the each components of composite modified fibres, the type of modifiers, and the fibres' origins, are of paramount importance, which should be studied in the further studies.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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5.4 Paper III

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Recycled and rubberized SMA modified mixtures: A comparison between polymer modified bitumen and modified fibres

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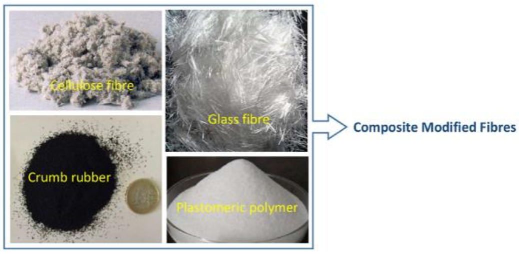
HIGHLIGHTS

- A series of SMA mixtures containing composite modified fibres were investigated.
- Overall, the results showed the possibility of enhancing asphalt mixtures properties by means of modified fibres.
- The addition of RAP into the asphalt mixtures, increased the stiffness recorded by means of ITS and ITSM.
- Crumb rubber-added fibres could be considered as a new effective approach for asphalt mixture modification.

GRAPHICAL ABSTRACT



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Plastomer polymer
Modified Fibres (MFs)

ABSTRACT

In the presented research a series of Stone Mastic Asphalt (SMA) mixtures with and without Reclaimed Asphalt Pavement (RAP) and rejuvenating agent modified with SBS Polymer modified Binder (PmB) or composite Modified Fibres (MF) were optimized and investigated. In addition, beyond the common wet and dry methods of using waste tire rubber for producing asphalt mixtures, the rubber was added to the fibres with and without containing a plastomer polymer as a modifier. A comprehensive experimental programme including mechanical and performance tests were considered for evaluating the properties of the mixtures modified with PmB or MF with and without rubber and RAP. According to the test results, the SMA mixtures modified with MF were comparable with those of modified with PmB in most of the cases, however, the superiority of PmB mixtures were apparent in some cases. In the case of RAP addition, while it increased the tensile properties of corresponding mixtures observed by ITS and ITSM tests, it intensified the low-temperature sensitivity and reduced the fatigue life of mixtures containing rubberized fibres. Finally, the performance tests, moisture susceptibility and bitumen/aggregate, showed no significant difference between the tested mixtures in terms of moisture susceptibility and effectiveness of rubberized-fibres in bitumen binder's adhesion properties.

1. Introduction

Significant developments in terms of both materials and mix design have resulted in higher performance and superior structural pavements. In terms of mix design and recipes, optimised Stone Mastic Asphalt (SMA), made with Polymer modified Binders (PmBs) and more recently, with different types of additives, are some of the successful approaches. Besides the SMA benefits, including improved mechanical properties, noise reduction, high skid resistance, and better wet visibility [1], higher producing costs (associated with the needed high-quality aggregates, higher binder

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Along with replacing conventional HMA with SMA for, the use of polymers carried by binders or additives are recommended alternatives for high-performance asphalt pavements, which experience heavy loads or slow-moving heavy-traffic flows [5]. In this respect, two major categories of polymers are used in the pavement industry: elastomers, including Styrene-butadiene rubber (SBR) and styrene-butadiene-styrene (SBS), which enhance strength at high temperature as well as elasticity at low temperature and Plastomers (plastics) to address the permanent deformation at high temperature but not elasticity [6]. PmBs in asphalt mixtures makes ticker binder coating on aggregates that leads to more durable pavements and reduced raveling potentials due to lessening the aging oxidation. In addition, higher viscosity provided by PmBs increases the rutting resistance while at the same time the elasticity improves fatigue properties. Comparing the significant benefits provided by PmBs, few limitations such as lower pumping in asphalt plants and reduced mix workability have been reported in the literature. However, looking deeper to the procedure of producing PmBs and the asphalt mixture's production containing PmBs, makes sustainability concern. This comes from the high amount of energy needed for mixing the polymer with bitumen and the higher heating and compaction temperatures for PmB containing asphalt mixtures compared to the neat bitumen containing asphalt mixtures.

Going back to SMA mixtures, It is also known that high bitumen content mastic of SMA mixtures necessitate the addition of fibre to control the bitumen draindown during the plant production, transport and laying. In addition to the mixture stabilizing properties of fibres, it has been shown that the addition of fibres to SMA mixtures could improve the high-temperature plastic deformation, decreased the binder aging and enhanced the tensile properties by many research works. It is worth mentioning that, although most of the technical specifications considered the fibres as an alternative when PmB is used, several research works have shown that the combined use of fibre and PmB could enhance both fatigue and rutting properties [7, 8 and 9.In this respect, the European Union EN 13108-5 standard allows the use of both neat and PmB binders in SMA in conjunction with fibre.

From another perspective the principles of sustainability made the road construction sector decision makers more focused on the waste materials such as Crumb Rubber (CR) derived from End of Life Tires (ELT's) and Reclaimed Asphalt Pavement (RAP). In case of RAP, bearing in mind the continuous aggregate grading of milled pavement and the high-quality aggregates needed for SMA, most of the up-to-date field practices with RAP have been made on conventional Dense Graded Asphalt (DGA). In addition, there are also scepticisms due to doubling the potentiality of reducing fatigue resistance imposed by SMA structure and enhanced stiffness resulted by aged RAP binder [10]. Nevertheless, while the use of RAP in SMA is not a common practice, there could be significant economic, environmental and engineering advantages using RAP in SMA mixtures if it is used without influence on the excellent performance of SMA mixtures [11]. Taking into account, the higher initial SMA production costs, the incorporation of waste materials like RAP and rubber can lessen the primary construction costs along with the environmental benefits. In addition to RAP, few studies on the inclusion of CR as fibre to control the bitumen draindown of SMA mixtures indicated some improved performance properties particularly in terms of indirect tensile strength (ITS) and water sensibility [12]. Whilst most of the previous researchers used CR stabilizer by means of the wet process (Rubber modified bitumen) [13], the authors' former study showed the effectiveness of adding CR by means of dry process in draindown control of Porous Asphalt (PA) mixtures [14].

Considering the mentioned issues, the main objective of this research is optimizing a sustainable high-performance SMA mixtures suitable for heavy-duty pavements. For this purpose series of SMA mixtures (shown in Fig. 1) containing either modified bitumen (PmB) and conventional fibres or neat bitumen and composite Modified Fibres (MFs) were produced and compared to investigate the feasibility of using MFs instead of PmBs. Besides this aim, the sustainability of mixtures were examined by producing and testing the corresponding mixtures containing RAP and CR. In fact, although the benefits of using RAP and CR as recycling materials have been discussed in paving technology individually, these materials together may work synergistically, contributing to the upgrade the final product in multiple ways. On the other hand, while the advantages of using CR in asphalt mixtures with both dry and wet method have been studied in many research works and practical experiences, the use of CR as a fibre and the addition of it to pre-rubberized composite fibres have not yet been studied.

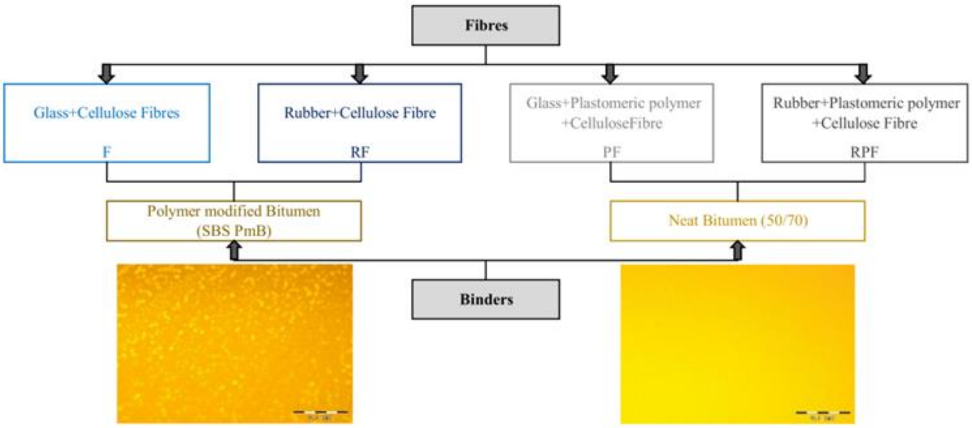


Fig. 1. Mix combinations of binders and MFs.

2. Materials and Methods

2.1. Virgin aggregates, RAP, and filler

Considering the SMA structure, the aggregates' properties become more important when compared to the other common bituminous mixtures. In this research, crushed Porphyry aggregates were used as virgin aggregates along with Limestone RAP (fractionated as fine and coarse). Porphyry is an extrusive igneous rock with the main chemical component of silica and an excellent characteristic such as High skid resistance, high compression strength, which remains constant at lower temperatures, dense matrix with low porosity, resistance to acids, and high resistance to freeze and thaw cycles. To assess the actual aggregates' grading of RAP (without binder) and estimate the level of aging of the bitumen and recoverable bitumen content, the binder extraction was carried out and the RAP aggregate grading was determined. Fig. 2 shows the used fine and coarse fractionated RAP and their grading curves before and after the binder extraction, referred to RAP black and white curves for fine and coarse RAPs.

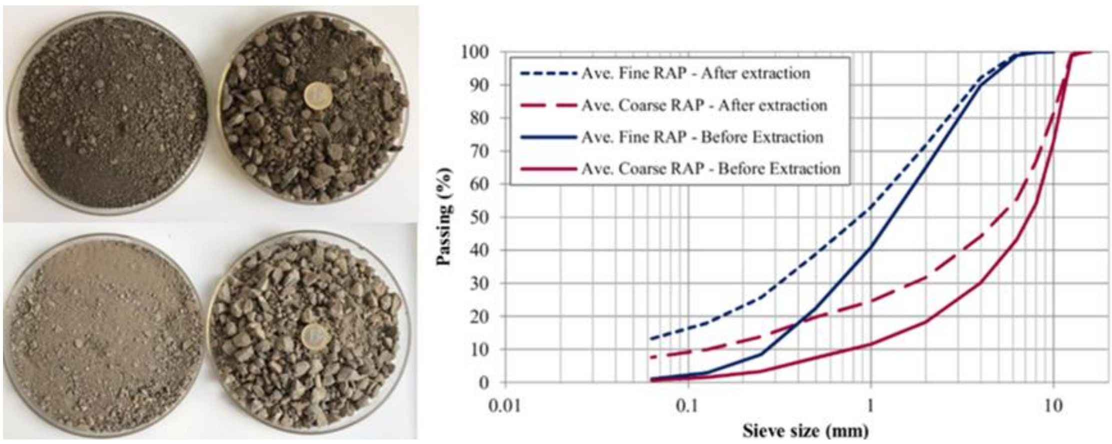
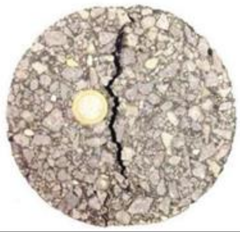


Fig. 2. Fine and coarse RAP before and after binder extraction: black and white grading curves. Scale coin: 1 Euro, 23.25 mm.

The SMA grading curve was selected among many studied grading bands proposed in the technical specifications. Considering the Nominal Maximum Aggregate Size (NMAS) as 12.5mm, the reference grading curve complied with the Italian specification, Autovie Venete [15] as shown in Table 1.

Table 1. Gradation limits.

Sieve size (mm)	Lower/Upper limit* (%)	Cut surface appearance**
12	100/100	
10	81/100	
8	60/80	
4	30/52	
2	22/34	
1	16/26	
0.5	11/21	
0.063	8/14	

* Italian specifications, Autovie Venete.

** RAP containing mixture sample after ITS test.

Given that the cohesion properties of SMA as a gap-graded mixture are highly dependent on the mastic characteristics, a high-quality mineral filler is needed to meet the desired mastic properties. Hence in this research, complying also the local Italian specifications the Limestone filler was selected.

2.2. Binders

PmBs are widely used for the pavement construction to improve the mechanical performance and durability of bituminous layers. Among the polymer modifiers for asphalt binders, Styrene-Butadiene-Styrene (SBS) polymers are commonly used in the production of SMA mixtures. Considering the research objectives, a commonly used 50/70 pen grade neat bitumen and a 10/40-70 SBS modified binder were adopted.

2.3. Fibres

Considering the main target of this study, 4 different fibres (Shown in Fig. 3) were used in this research including:

I. A cellulose-based mineral fibre (glass) added fibre. The mineral component (structural) supposed to form a three-dimensional network and play a role of micro-reinforcement in the binder matrix. In the present research called as (F).

II. A cellulose-based fibre containing mineral fibre (glass) and a plastomeric polymer. The compound was deemed to increase the viscosity and micro-structural reinforcement of the bitumen film. In the present research called as (PF).

III. A cellulose-based fibre mainly composed of cellulose and high amount of waste tire rubber. It contains also a minor portion of mineral (glass) fibres. In the present research called as (RF).

IV. A cellulose-based fibre composed of cellulose, minor portion of mineral fibre (glass), waste tire rubber, and also a minor portion of plastomeric polymer. In the present research called as (RPF). It is worth mentioning that the rubber percentage on the weight of fibre is less than RF fibre. It is worth mentioning that due to the small scale of lab work and for producing homogenous asphalt mixture specimens, the fibres were grinded before being used into the mixtures

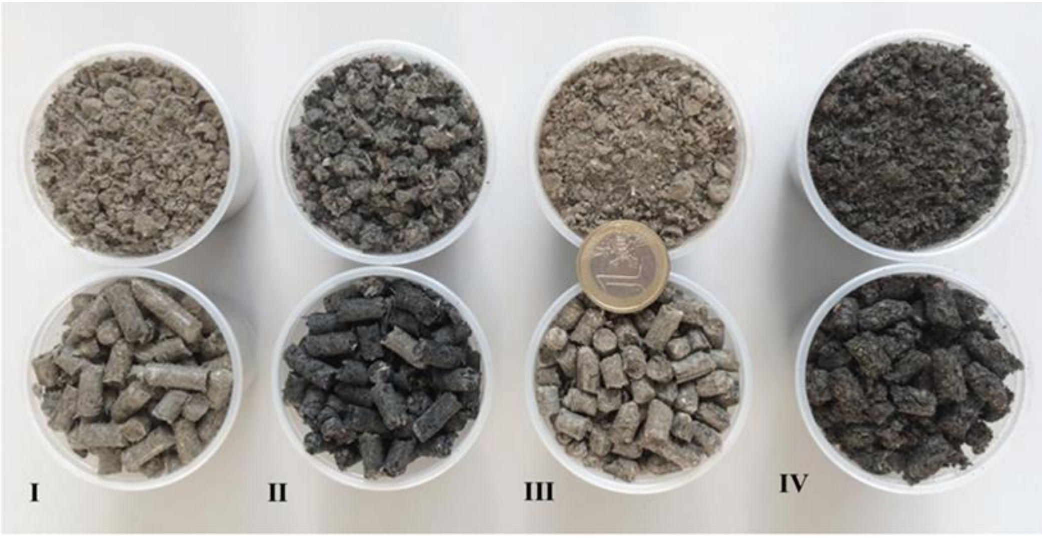


Fig. 3. Fibres before and after grinding. ; I: Cellulose+Glass Fibre (F), II: Rubberized Cellulose based Fibre (RF), III: Cellulose based Plastomer polymer added Fibre (PF), IV: Rubberized Cellulose based Plastomer polymer added Fibre (RPF). (Scale coin: 1 Euro, 23.25 mm).

2.4. Rejuvenating agent

Since half of the experimental mixtures contained 25% of RAP, in this study a vegetable oil-based rejuvenator was used to restore the rheological characteristics of the aged recoverable binder (approximately 4%) of RAP. The producer recommended dosage of rejuvenator was considered as an optimum dose, which was 0.15% by weight of RAP in the mixture. It is worth mentioning that, the quantity of rejuvenator was determined according to the producer recommendation and no tests were carried out for determining the direct effects of the rejuvenating agent on the properties of the aged binder in this research. In fact, the effectiveness of rejuvenator was as assessed by comparing the mixtures' performance and mechanical properties to those of totally virgin mixtures. The rejuvenator was added to the heated binder and mixed until getting a homogenous well-dispersed material.

2.5. Methodology and research scheme

The number of variables in this study resulted in eight different combinations earlier shown in Fig. 1. The components and mixtures definitions are stated in Table 2. As presented, the mixtures were divided into two major groups of mixtures with PmB and with a neat binder. Depending on the planned tests, a series of Marshall and gyratory compacted specimens were produced. The experimental work was divided into four parts including the mix design procedure, mechanical characterization, and performance properties. Fig. 4 represents the research framework and the adopted tests and methods.

Table 2. Mixtures' identification and dosages.

Mixture ID	Binder	Description
FPmB	**PmB**	Cellulose+Glass Fibre (0.3%) + Polymer modified Bitumen
FPmBRR		Cellulose+Glass Fibre (0.3%) + Polymer modified Bitumen + RAP (25%) + Rejuvenator
RFPmB		Cellulose +Rubber Fibre (0.3%) + Polymer modified Bitumen
RFPmBRR		Cellulose +Rubber Fibre (0.3%) + Polymer modified Bitumen + RAP (25%) + Rejuvenator
PFB	**Neat Binder**	Glass+Plastomeric polymer +CelluloseFibre (0.4%) + Bitumen
PFBRR		Glass+Plastomeric polymer +CelluloseFibre (0.4%) + Bitumen + RAP (25%) + Rejuvenator
RPFB		Rubber+Plastomeric polymer +Cellulose Fibre (0.5%) + Bitumen
RPFBRR		Rubber+Plastomeric polymer +Cellulose Fibre (0.5%) + Bitumen + RAP (25%) + Rejuvenator

Note: The percentages are calculated on the weight of mix aggregates.

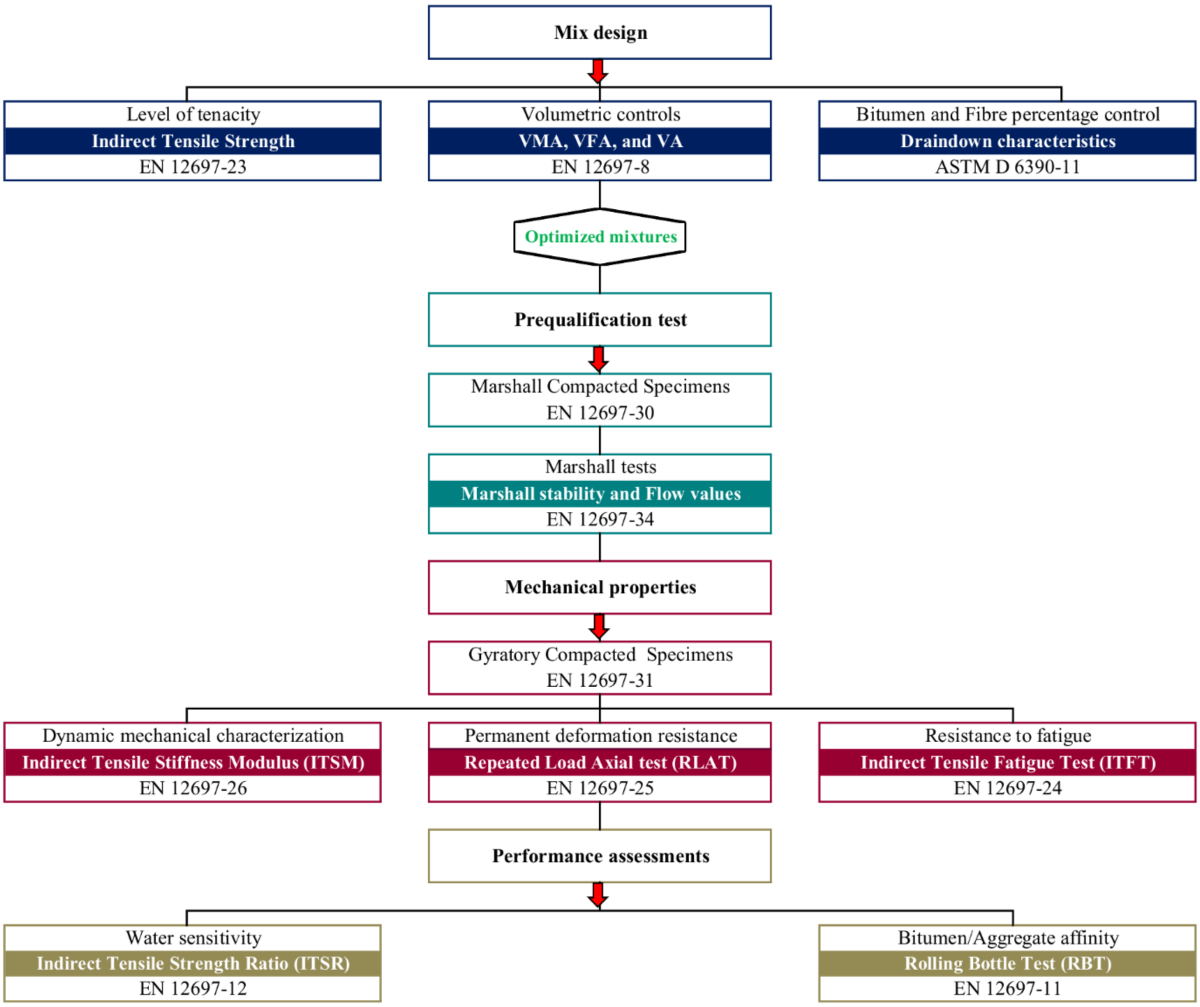


Fig. 4. Experimental plan.

3. Mix Design and Preliminary Tests

Regardless of the method applied for the mix design of SMA, the initial step is defining the NMAS and developing a correct aggregate composition based on the layer position, required thickness and design loads [16]. Given that the most important aspect of SMA mix design relies on volumetric criteria [17], the air void analysis was carried out in addition to the fundamental Indirect Tensile Strength (ITS) according to EN 12697-23 and to the bitumen draindown control. For this purpose, the designated aggregate grading curve was considered to produce a series of gyratory compacted specimens to optimize the binder content. In the literature, the recommended gyration number is relative to L.A. abrasion. In the presented work, 100 gyrations were chosen to comply with the local Italian specifications (Autovie Venete, 2005). Overall, bearing in mind the tripartite parameters of ITS values, bitumen draindown, and volumetric control (4-6% based on the considered specifications), the Optimum Bitumen Content (OBC) was considred 6% for all the mixtures. This led to provide comparable mixtures and fewer variables. The bitumen draindown test was conducted according to ASTM 6390-11 on uncompact samples considering the asphalt production temperature (160±5˚C). For the selected 6% bitumen (on the weight of aggregates) little draindown were recorded, which confirms the accuracy of the OBC.

Fig. 5. Compares the ITS of values of mixtures containing OBC. Regarding the SMA mixtures, considering the gap-graded skeleton relatively low cohesion was not unexpected.

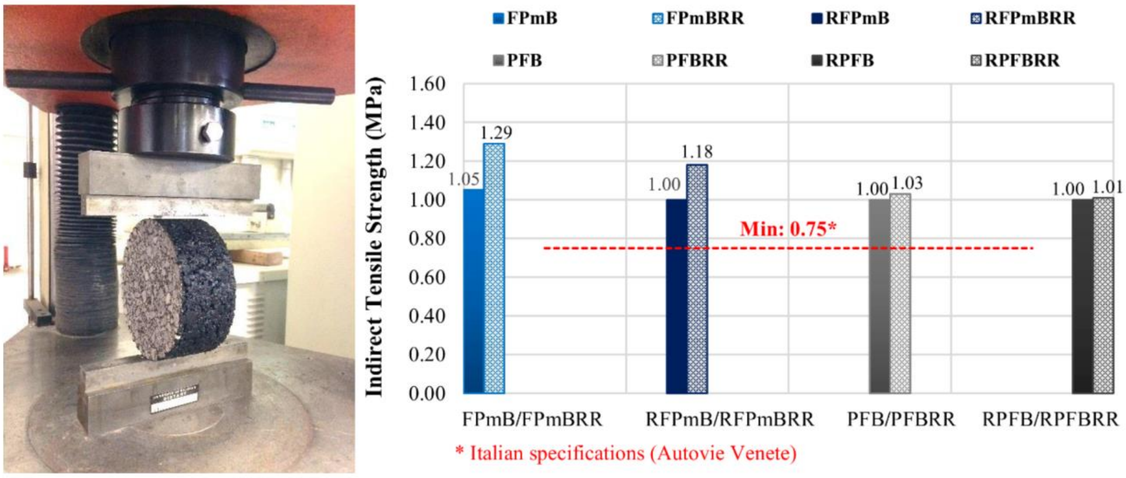


Fig. 5. ITS test configuration and average results of the optimized mixtures.

4. Prequalification Tests

Prequalification tests and controls in this study were done in terms of Marshall Stability and flow, controlling the optimized mixtures' fundamental characteristics and the Marshall compacted specimens air voids content. The test procedure followed the EN 12697-34 to measure the Marshall Stability and flow value of the optimized mixtures. In addition, Marshall Quotient (MQ), also known as rigidity ratio was determined.

Based on the results shown in Fig. 6, it can be inferred that although the mixtures (with or without RAP) containing rubberized cellulose fibres and PmB showed a higher Marshall Stability, in terms of rigidity values, the FPmB mixtures performed better than the rubberized set. This was also recorded in some research [18]. The lower values obtained for the mixtures with rubberized fibres can be due to the higher free binder content since the absorption properties of the rubberized fibres are generally lower when compared to cellulose fibres. It has also been shown that the ductility of the binder can be increased by adding rubber [19], which could result in higher flow values and lower rigidity. With reference to the modifications via the binder and fibre, it can be seen that the values for FPmB and PFB mixtures are comparable, which shows the effectiveness of MFs in Marshall Properties. From another perspective, the mixtures containing RAP always showed higher Marshall Stability and rigidity values. This was expected based on the voids analysis and the imposed stiffness due to the presence of the aged binder. It also shows the effectiveness of the used rejuvenator in favouring the needed virgin and RAP binder blending. It is worth mentioning that the results were in line with the primary air voids analysis on the gyratory compacted specimens.

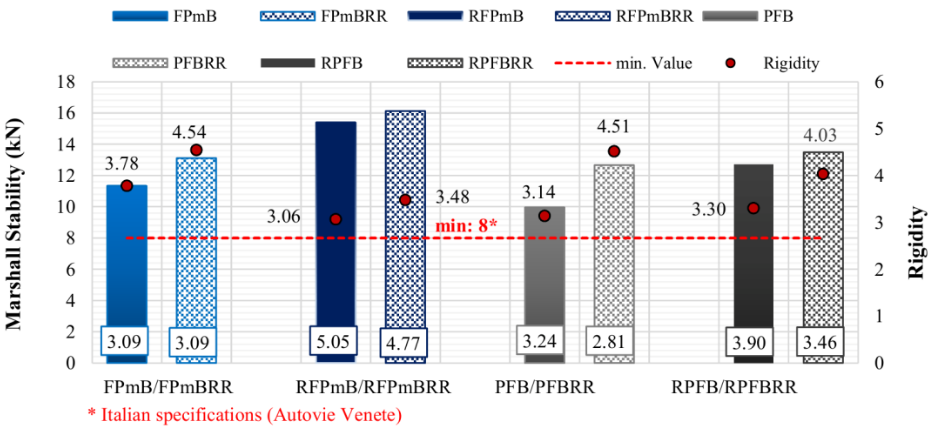


Fig. 6. Marshall Stability, Flow value (on the bottom of the bars), and Rigidity.

5. Dynamic Tests' Results and Analysis

5.1. Indirect Tensile Stiffness Modulus

The Indirect Tensile Stiffness Modulus (ITSM) was adopted to assess the mixtures thermal sensitivity as the test is usually conducted at a broad range of temperatures [20]. In this research, the test was carried out according to EN 12697-26 at 3 different temperature levels: 10, 20 and 30˚C. In literature, regarding the SMA mixtures, the stiffness is lower compared to the same source aggregate and NMAS dense-graded mixture [21 and 22]. This is due to the gap-graded nature of mixture and aggregate interlocking, which results in lower tensile strength resistance [23]. It has been also shown that while SBS modification increases the flexibility of the bitumen at low temperatures, the presence of reclaimed rubber increases the stiffness at high temperatures [19].

The results presented in Fig. 7 and Fig. 8 show the ITSM values for the mixtures with and without RAP. It can be clearly seen that the incorporation of RAP increased the stiffness at all the tested temperatures. Based on the values, SBS PmB decreased the stiffness at low temperature and increased the stiffness at high temperature, which indicates the superiority of the PmB mixtures (with and without RAP) in terms of Thermal sensitivity. From the results the lowest stiffness at high temperature was recorded for neat bitumen mixtures containing PF showing the deficiency of MF containing plastomeric polymer in thermal sensitivity. This could be due to the low amount of polymer inside the fibres. From another perspective, the mixtures containing rubberized fibre with neat bitumen showed increased stiffness almost at all the tested temperatures.

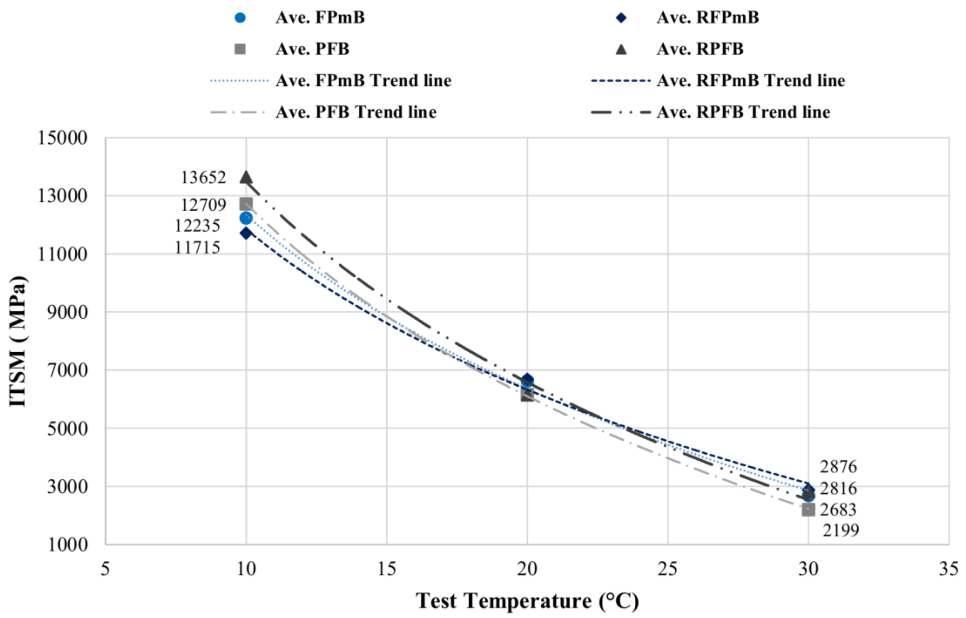


Fig. 7. Average ITSM values for the mixtures without RAP.

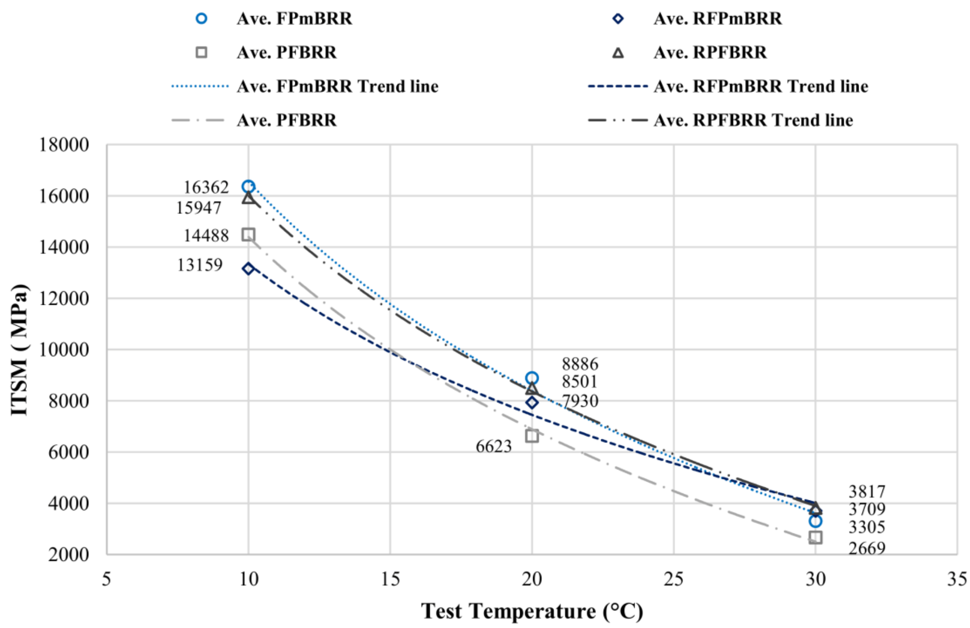


Fig. 8. Average ITSM values for the mixtures containing RAP.

5.2. Creep characteristics

With considering the high permanent deformation resistance properties of SMAs, the influence of different polymers added with bitumen or fibres were studied by means of Repeated Load Axial Test (RLAT). The test was carried out using the direct uniaxial compression configuration shown in Fig. 9 according to EN 12697-25 at 40˚C on 150 mm diameter sawed specimens. The test results can be presented as accumulated strain, creep stiffness, and strain rate (με/cycle). Listed in Table 3, the rutting performance parameters are divided into two groups: SMA mixtures with and without RAP. The results clearly show the superior rutting resistance of the mixtures containing PmB and conventional fibre (F) compared to the mixtures with neat bitumen and MFs. It is also evident that the presence of rubber in the mixtures increased their permanent deformation resistance, which could be expected due to the imposed higher viscosity by rubber. In addition, the Marshall Stability values confirm the validity of the obtained trends, as a basic method to predict the rutting resistance of asphalt mixtures [24].

Fig. 9. RLAT configuration and specimen setting.

Table 3. Creep characteristics average values.

Mix. ID	Mean RLAT parameters	
	Accumulated strain (%)	**Creep stiffness (MPa)**
FPmB	0.325	31.280
RFPmB	0.320	32.644
PFB	0.394	25.770
RPFB	0.344	29.299
FPmBRR	0.338	29.898
RFPmBRR	0.329	30.644
PFBRR	0.382	26.538
RPFBRR	0.353	29.156

5.3. Fatigue properties

Fatigue cracking has long been recognized as a complex failure mechanism of flexible pavements. Although the fatigue properties of SMA mixtures have been seen with some scepticism, many experimental pieces of research and field experiences showed that fibre reinforcement, CR addition and the use of PmBs could enhance the fatigue characteristics and are considered as a solution to combat this problem [25]. In particular, several experimental works and field practices have shown that rubberized asphalt mixes perform better than conventional dense graded HMA with respect to resisting fatigue cracking, reflective cracking, and thermal cracking [26]. In this research, fatigue resistance of the mixtures was investigated by means of the Indirect Tensile Fatigue Test (ITFT). The fatigue life is defined as the number of load cycles applied to reach 50% reduction in the initial stiffness measured at 100 cycles. The tests were carried out according to EN 12697-24 under three different level of stress at 20 °C. Fig. 9 represents the fatigue endurances for the SMA mixtures, divided into two groups of mixtures with and without RAP. Comparing the mixtures containing PmB and conventional fibres with those of containing neat bitumen and MF, the results are comparable at the 250 kPa level of stress and even higher performance at the low level of stress for SMA mixtures containing PmB, showing the effectiveness of elastomeric polymers of PmB in fatigue resistance. Overall these results were in line with the other tests confirming the superiority of elastomer polymer added by means of PmB compared to plastomer polymer added by means of MF to the mixtures. According to the results, it can be clearly seen that presence of rubber in the mixtures via fibres led to reduced fatigue performance. This reduction can be due to the absorption properties of CR, which led to imposed stiffness with lower tensile properties. Back to literature, while several studies showed the effectiveness of rubberized mixtures (in terms of both wet and dry process) in fatigue and reflective cracking resistance [27], a broad study at the University of Nevada, Reno, found no statistical difference in fatigue resistance between a gap-graded reference mix and the rubberized mixes [28].

From another point of view, comparing the RAP containing mixtures with those of totally virgin ones (Fig. 10 vs. Fig. 11) represents a similar fatigue performance trend. In addition, it is noteworthy that the mixtures containing

RAP showed better performance in comparison to the mixtures without RAP. However, in general, it is assumed that the fatigue performance of asphalt mixtures containing RAP decreases as the aged binder content increases. This is because of the imposed rigidity effects of the aged binder, increases the brittleness of mixture, and decreases the relaxation properties.

[29]. On the other hand, it has been shown that although the presence of RAP increased the stiffness of asphalt mixtures, the correct choice of rejuvenator is able to recover the flexibility in an effective way resulting in an improved fatigue performance of RAP containing mixtures. In these respect, several previous pieces of researches on fatigue life of mixtures containing RAP along with using different solutions, such as softening agents or suitable binder grades, recorded an increased fatigue life by increasing the level of RAP [30–32]

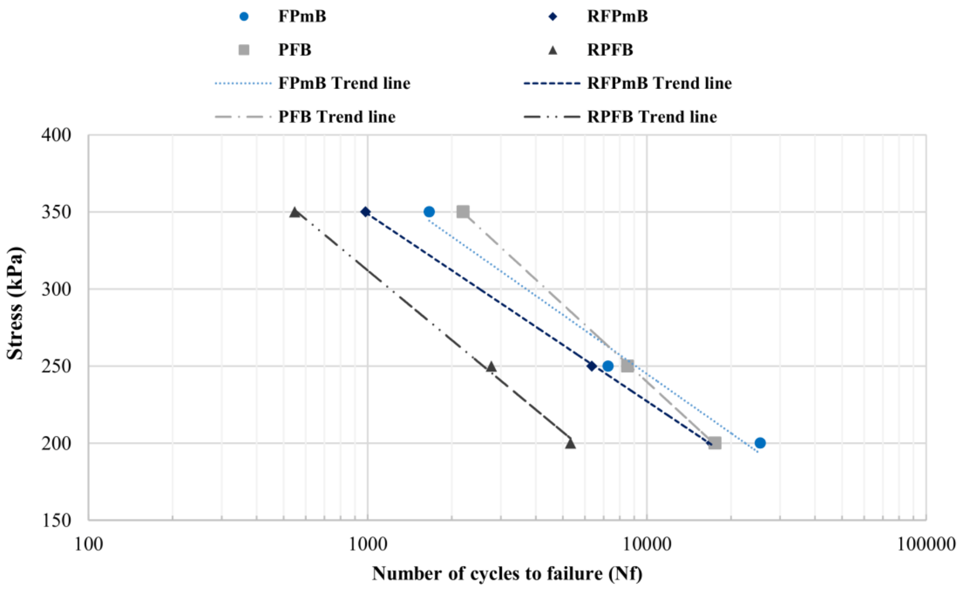


Fig.10. ITFT fatigue trends based on the average values for the mixtures without RAP.

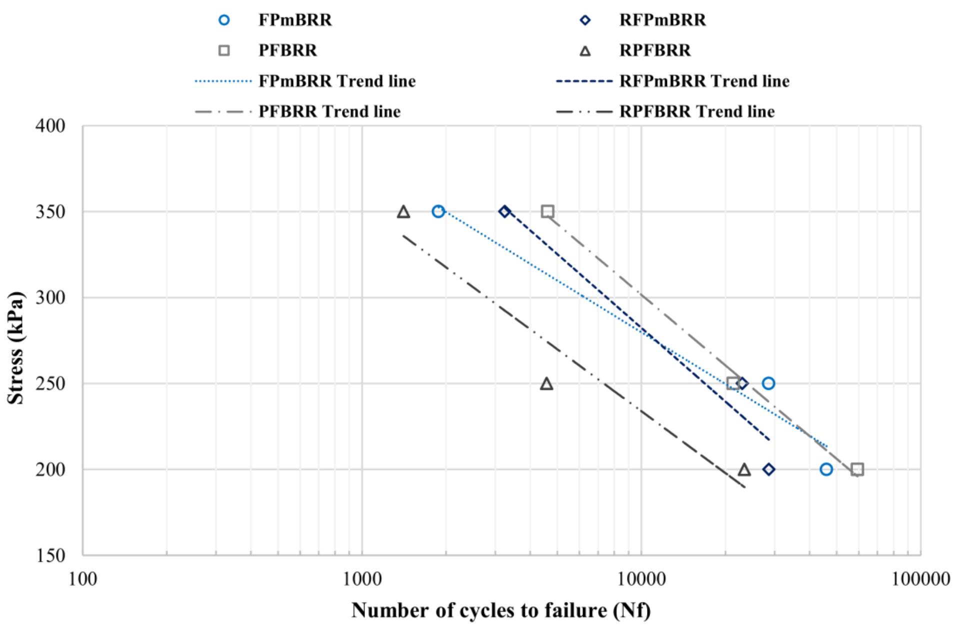


Figure 11. ITFT fatigue trends based on the average values for the mixtures containing RAP.

6. Performance Properties

6.1. Moisture susceptibility

For the asphalt pavement mixtures, moisture damage is defined as the functional decline resulted by the loss the adhesive bond between the bitumen and the aggregate surface and/or loss of the cohesive resistance within the bitumen, mostly due to the presence of water [33]. Low moisture resistance manifests itself through various failure mechanisms. In the literature several tests have been recommended for assessing the moisture susceptibility; here ITSR was adopted according to the EN 12697-12. ITSR is calculated as the ratio of the indirect tensile strength of wet subsets (3 days in water at 40˚C and two hours in water at 20˚C – Method A) to that of dry subsets tested at 25˚C, expressed in percent. Of the three major types of asphalt mixtures (Dense-graded, open-graded and gap-graded mixtures), moisture damage is expected to be less for the SMA due to the specific mix design characteristics. Higher binder and filler content make a thicker film on aggregates' surface, which reduces the possible moisture penetration [34]. Table 4 represents the ITSR values for the tested mixtures. Based on the test results it can be seen that in terms of moisture susceptibility, all mixtures behaved similarly recording high values that complied with the minimum values of 75% recommended in many technical specifications. Comparing the mixtures containing RAP with the ones without RAP, and rubberized fibres with the ones without rubber modification, no apparent difference can be distinguished and the results for PmB and MF modified mixtures are comparable. This is more likely due to the thick binder cover effectiveness in SMA mixtures, which is effective in tensile strength and higher the cohesion [35].

Table 4. Average ITSR values.

Mixtures with RAP	**FPmB**	**RFPmB**	**PFB**	**RPFB**
ITSR (%)	96	95	94	91
Mixtures without RAP	**FPmBRR**	**RFPmBRR**	**PFBRR**	**RPFBRR**
ITSR (%)	92	95	91	93

6.2. Bitumen/aggregate affinity

While low cohesion increases the ravelling and cracking tendency of asphalt mixtures, reduced adhesion properties may lead to early stripping [36]. Previous studies and field practice experiences indicated that several parameters such as bitumen, aggregates and filler type, physical and chemical characteristics are some of the effective parameters on bitumen/aggregate affinity [37& 38]. In contrast, there are just a few studies on the influence of polymers and CR (particularly dry process) on bitumen binder's adhesion properties. Authors' former research on porous asphalt containing fine CR showed that the affinity degree greatly depends on the mix temperature and the interaction time [14]. Notably, for the samples simulated based on the practical production dry method procedure, the results were equal or higher than those with two with different types of cellulose fibres. Several normalized procedures have been developed in order to assess the bitumen/aggregate affinity. For the presented research, Rolling Bottle Test-RBT (EN 12697-11) was carried out, which is a common European approach to quantify the bitumen/aggregate affinity. In order to simulate the practical mix production, the samples containing also filler and grinded fibres were prepared based on the recipe (material proportion) of optimized mixtures. It is worth mentioning that even the chronology of mixing the materials in the asphalt mixture production, was considered throughout the RBT sample production. Hence the fibres were added before the bitumen while the filler was added after adding the binder to the mixture. Fig. 12 shows the samples of the RBT after 72 h of rolling and the bitumen/aggregate affinity percentage after 6, 24, 48, and 72 h of rolling. According to the final values, the highest final bitumen coverage was recorded for the PmB mixtures and the lowest for the mixture with the plastomeric fibre without rubber. It can be deduced that, the PmBs are more viscous than neat binders that tend to improve the adhesion properties by making a thicker binder coating and finally resulting in a better resistance to striping and oxidation, which mentioned in many technical publications [6]. It should be noted that the addition of rubber to the fibres, could improve the bitumen affinity, which was experienced also in authors' former research [14]. However, it should be noted that the mixture's production temperature and conditioning time has a significant effect on the adhesion properties of bitumen binder.

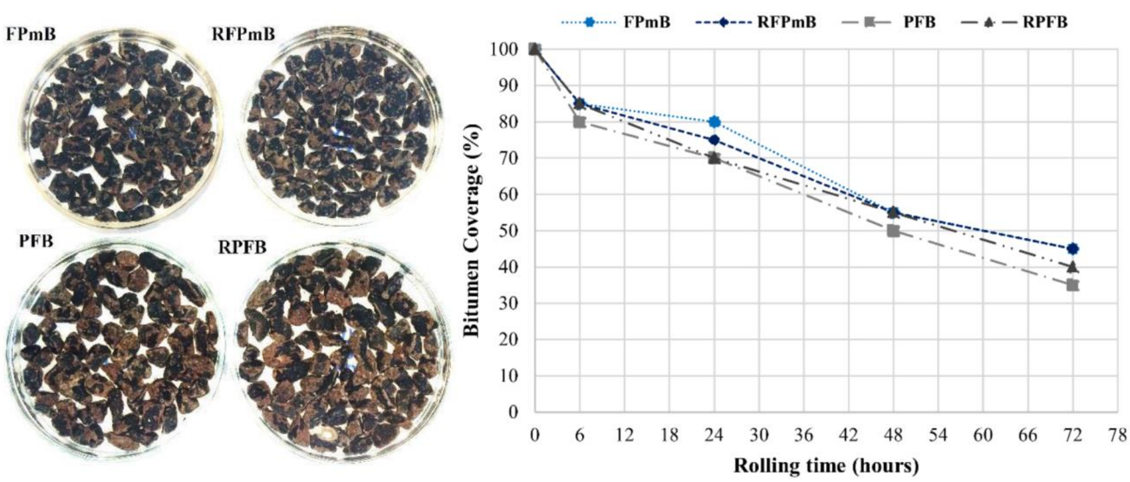


Fig. 12. RBT samples after 72 hours rolling and bitumen coverage vs. rolling time.

7. Conclusions and Remarks

Considering the approach of asphalt mixture modification by means of modified bitumen or modified fibres, in the presented research a number of SMA mixtures containing different a kind of composite modified fibres were optimized and investigated. In addition, the feasibility of adding CR into fibres as a new approach in using waste tire rubber into asphalt mixtures other than the commonly used dry and wet methods was studied. However, the authors believed that the composite modified fibres as a new approach for producing modified asphalt mixtures should be investigated more in order to be considered as a reliable sustainable alternative for available widely accepted modified binders. In this respect different composite fibres with different proportions are highly recommended. Considering the results obtained from the extensive experimental work on the different types of asphalt mixtures modifications, the following can be inferred.

- In terms of tenacity, the ITS values of the mixtures made with PmB were comparable to the mixtures made with modified fibres and neat bitumen and no significant differences were recorded. In addition, as expected, all the mixtures containing RAP showed higher values, which could be due to the interaction between the stiffened and the virgin binder through the rejuvenating agent.
- At the prequalification phase, higher Marshall Stability values were recorded for the mixtures containing PmB in comparison to the specimens made with neat bitumen and MFs. However, the differences between the mixtures were insignificant. It is noteworthy that the addition of rubber to the mixtures increased the flow values due to the increased ductility by rubberized fibres and their lower absorption properties of it when compared to the cellulose fibres. This phenomenon has been reported by several researches.
- In terms of thermal sensitivity by means of ITSM analysis, while no remarkable difference was recorded between the mixtures at medium temperature, the presence of rubber into the fibres increased the mixtures stiffness at high temperature. At this temperature, the highest values were obtained by mixtures containing PmB and rubberized fibres. This has been experienced in many pieces of researche by both dry and wet methods application of rubber into asphalt mixtures.
- The mixtures containing SBS modified binders showed better rutting resistance compared to the mixtures modified by composite modified fibres containing Plastomer polymer. Furthermore, from another perspective, the addition of rubber to the fibres could enhance the creep stiffness. The results were validated considering the similar trends throughout the ITSM and Marshall stability.
- Whereas similar fatigue endurance trends were recorded for the mixtures with and without RAP, the addition of rubber into the modified fibres reduced the fatigue life for the mixtures made with neat bitumen. This could be expected due to the imposed stiffness by rubber, while for the mixtures with SBS PmB, the presence of SBS could enhance the elastic

response of mixtures. From another point of view, this could be justified by the higher percentage of RPF when compared to the mixtures containing fibres with other content.

- In line with literature, the thick binder layer in SMA mixtures led to high and similar ITSR results for all tested mixtures.
- RBT results showed that the presence of rubber may enhance the bitumen/aggregate affinity with considering the importance of the controlled temperature and conditioning time of rubber interaction and digestion. By comparing the mixtures with different base binders, high viscosity PmB resulted in a better bitumen coverage when compared to samples made with neat bitumen.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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5.5 Paper IV

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A comparison study on low-temperature properties of Stone Mastic Asphalts modified with PmBs or modified fibres

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ABSTRACT

A research was conducted to assess the effectiveness of different kinds of Modified Fibres (MF) on the thermal cracking performance of a Stone Mastic Asphalt (SMA) compared to the conventional SMA mixtures modified with SBS Polymer modified Bitumen (PmB). In addition, the capability of rubberised fibres to alleviate the thermal cracking sensitivity was investigated. Besides the main scope, a series of the same SMAs were also produced containing 25% of Reclaimed Asphalt Pavement (RAP) to investigate the effects of RAP on the low-temperature performance of the mixtures, which were modified either with MF or PmB. The experimental plan included both binder and mixture characterisation by means of Bending Beam Rheometer (BBR) test and Thermal Stress Restrained Specimen Test (TSRST). Binder-scale test results showed that the stiffness of all bituminous compounds is increased by the addition of fibres and rubber improves the elasticity of both neat and PmB compounds. In the mixture scale, TSRST results showed no significant difference between the mixtures. However it is noteworthy that, in addition, better low-temperature performance was recorded for virgin mixtures compared to to RAP containing ones. The overall results may confirm the feasibility of modified fibres in the modification of mixtures at low temperatures.

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1. Introduction

While the use of different kinds of Stone Mastic Asphalts (SMA) have been considered as the primary alternative for highway pavements bearing high Equivalent Single Axle Load (ESAL), the use of Polymer modified Bitumen (PmB) showed many advantages alleviating the weak points of these mixtures (Pasetto and Baldo 2014). Besides the proven high rutting resistance and durability (due to the high binder content) of SMA mixtures, the conventional dense-graded mixtures showed higher tensile strength in comparison to the SMA in several research works (Brown 1991, Moghadas Nejad *et al.* 2010). In addition, along with experimental works in literature, field experiences also recorded the low tenacity of SMA. This is referred to the gap-graded nature of SMA, in which skeleton characteristics of the mixtures results in increased cracking sensitivity and decreased the durability. The problem becomes crucial since temperature decrease generates tensile contraction stresses. In the bituminous mixtures, this mechanism is known as the thermomechanical-coupling behaviour of which the severity depends on the thermal characteristics of the mixture (Pucci *et al.* 2004).

To this end, elastomer polymers and in particular Styrene Butadiene Styrene (SBS) modified binders could improve the lack of tenacity in SMA mixtures. Comparing these main groups of polymers, while plastomers are effective in stiffness properties, the elastomers are able to increase the stiffness of asphalt mixtures at high temperature beside elasticity at low temperature (IDOT 2005). From another perspective, a careful equilibrium of binder properties is always required to alleviate one type of asphalt mixture distress without aggravating other types, such as the use of harder bitumen to increase rutting resistance without aggravating fatigue and thermal cracking potentials (Airey 2004). Besides commonly used SBS modified bitumen, the advantages of rubberised binders and dry processed asphalt mixtures have been shown in many studies and experienced in field practices (Becker *et al.* 2001, Lo Presti 2013, Mashaan *et al.* 2013). Concerning the application methods, while the SBS modified bitumen is commonly used, rubber have been incorporated into the asphalt mixtures by means of both wet and dry methods as a bitumen modifier or as dry mixture additive, respectively. However, on the other hand, some technical limitations have been reported including decreased in strength and reduced penetration at high temperatures for SBS modified bitumen and high temperature and needed essential long digestion time for rubberised binders (Becker *et al.* 2001).

Back to the SMA mixtures, the considerable amount of bitumen in these mixtures necessitates the use of fibre as mixture stabiliser to inhibit the bitumen draindown. As a solution, besides commonly used cellulose and mineral fibres, many different alternatives have been introduced and investigated in the asphalt-mixture industry including coir, sisal, polypropylene, waste plastic and waste crumb tire rubber. Along with the effectiveness of different kinds of fibre on drainage control, the capability of fibres in improving the performance of asphalt mixtures was studied

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1. Introduction

While the use of different kinds of Stone Mastic Asphalts (SMA) have been considered as the primary alternative for highway pavements bearing high Equivalent Single Axle Load (ESAL), the use of Polymer modified Bitumen (PmB) showed many advantages alleviating the weak points of these mixtures (Pasetto & Baldo, 2014). Besides the proven high rutting resistance and durability (due to the high binder content) of SMA mixtures, the conventional dense-graded mixtures showed higher tensile strength in comparison to the SMA in several research works (Brown 1991, Moghadas Nejad et al. 2010). In addition, along with experimental works in literature, field experiences also recorded the low tenacity of SMA. This is referred to the gap-graded nature of SMA, in which skeleton characteristics of the mixtures results in increased cracking sensitivity and decreased the durability. The problem becomes crucial since temperature decrease generates tensile contraction stresses. In the bituminous mixtures, this mechanism is known as the thermomechanical-coupling behaviour of which the severity depends on the thermal characteristics of the mixture (Pucci et al. 2011).

To this end, elastomer polymers and in particular Styrene Butadiene Styrene (SBS) modified binders could improve the lack of tenacity in SMA mixtures. Comparing these main groups of polymers, while plastomers are effective in stiffness properties, the elastomers are able to increase the stiffness of asphalt mixtures at high temperature beside elasticity at low temperature (IDOT 2005). From another perspective, a careful equilibrium of binder properties is always required to alleviate one type of asphalt mixture distress without aggravating other types, such as the use of harder bitumen to increase rutting resistance without aggravating fatigue and thermal cracking potentials (Airey 2007). Besides commonly used SBS modified bitumen, the advantages of rubberized binders and dry processed asphalt mixtures have been shown in many studies and experienced in field practices (Lo Presti 2013, Mashaan et al. 2013, Becker et al. 2001). Concerning the application methods, while the SBS modified bitumen is commonly used, rubber have been incorporated into the asphalt mixtures by means of both wet and dry methods as a bitumen modifier or as dry mixture additive, respectively. However, on the other hand, some technical limitations have been reported including decreased in strength and reduced penetration at high temperatures for SBS modified bitumen and high temperature and needed essential long digestion time for rubberised binders (Becker et al. 2001).

Back to the SMA mixtures, the considerable amount of bitumen in these mixtures necessitates the use of fibre as mixture stabilizer to inhibit the bitumen draindown. As a solution, besides commonly used cellulose and mineral fibres, many different alternatives have been introduced and investigated in the asphalt-mixture industry including coir, sisal, polypropylene, waste plastic and waste crumb tire rubber. Along with the effectiveness of different kinds of fibre on drainage control, the capability of fibres in improving the performance of asphalt mixtures was studied by many researchers. While the insignificant effect of cellulose fibres on mechanical properties and in particular creep characteristics of SMAs were shown by several types of research works (Tayfur et al. 2007, Mohammadzadeh et al. 2014), new fibre resources (waste materials) and modified fibres by means of polymers, rubber, plastics, and etc. could be effective to surmount the shortcomings. For instance, considering rubber also as mixture stabilizer, shown that the incorporation of rubber into asphalt mixtures stiffens the mixture at high temperature and improves the rutting resistance as well as binder draindown control (Xiao et al. 2007). In this respect, authors' previous studies along with consistent literature have found the effectiveness of rubberized asphalt mixtures in thermal susceptibility, bitumen/aggregate affinity, moisture susceptibility, and binder drainage (Marco & Nicola 2013, Sangiorgi et al. 2017).

The presented paper describes an experimental research on the low-temperature performance of totally virgin and 25% RAP containing SMA mixtures produced with SBS PmB or modified Fibres (MFs) with and without the addition of rubber. The main goal of this research was comparing the low-temperature properties of SMA mixtures modified by either PmB or modified fibres. The idea of using modified fibres can be an economical and eco-friendly approach in asphalt technology since as a dry process method (adding directly to the mixture) can avoid a considerable amount of energy needed for producing the PmBs as well as using recycling materials. This served as the main objective of this research, which was the feasibility of MFs in the modification of asphalt mixtures.

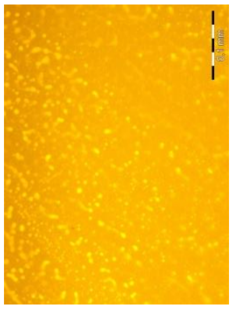
For this reason, half of the SMA mixtures and bituminous compounds made with PmB, while others made with neat bitumen and MFs. In parallel, in addition to the well-known methods of incorporating rubber into the asphalt mixtures, the capability of rubberized fibres as a new feasible approach, was one of the objectives of this research. The application of RAP into the mixtures aimed for two reasons, firstly considering the increasing trend of replacing virgin aggregates with recycled aggregates as sustainable eco-friendly material and secondly to study the feasibility of using RAP in SMA mixtures. However, these could reduce the primary higher costs of SMA production comparing to conventional dense-graded mixtures, which comes from the needed high quality aggregates and stabilizers for these mixtures. The paper concentrated on the low-temperature performance of SMA mixtures, investigated in terms of both rheological properties of binder samples and mixture cryogenic cracking potentials by means of Bending Beam Rheometer (BBR) analysis and Thermal Stress Restrained Specimen Test (TSRST).

2. Materials

2.1. Bituminous binders

Regarding the main objective of this research work, comparing the modification alternatives of asphalt mixture via modified fibres and rubber, a 50/70 bitumen and a 10/40-70 SBS modified bitumen according to EN 12591 and EN 14023 respectively, have been used to produce the modified SMA mixtures. The bitumens were chosen according to the local requirements and availability. Table 1 provides some of the physical properties of the used bitumens. It is worth mentioning that some of the binders' properties were not applicable like Fraass breaking point of SBS PmB that the obtained results were out of the bending repetition range in standard. The presented fluorescence microscopy images show the SBS dispersion into the binder and level of modification compared with the neat bitumen.

Table 1. Fundamental physical properties of neat bitumen compared with PmB.

Measured properties	Unit	Neat Bit.	SBS PmB	Standard	Microscopic image	
					Neat Bit.	SBS PmB
Penetration @25°C	0.1 mm	50-70	10-40	EN 1426		
Softening Point (R&B)	°C	46-54	≥70	EN 1427		
Flash Point	°C	≥250	≥250	EN 2592		
Dynamic Viscosity @60 °C	Pa.s	≥145	-	EN 12596		
Dynamic Viscosity @160 °C	Pa.s	-	≥0.4	EN 13702/2		
Fraass Breaking Point	°C	≤-8	-	EN 12593		

2.2.Fibres

Four cellulose-based fibres were used including the following:

5. A cellulose-based mineral fibre (glass) added fibre. The mineral component (structural) is supposed to form a three-dimensional network and play a role of micro-reinforcement in the binder matrix. In the present research called as (F).
6. A cellulose-based fibre containing mineral fibre (glass) and a plastomeric polymer. The compound were deemed to increase the viscosity and micro-structural reinforcement of the bitumen film. In the present research called as (PF).
7. A cellulose-based fibre mainly composed of cellulose and high amount of waste tire rubber (60-70%). It contains also a minor portion of mineral (glass) fibres. In the present research called as (RF).

8. A cellulose-based fibre composed of cellulose, minor portion of mineral fibre (glass), waste tire rubber, and also minor portion of plastomeric polymer. In the present research called as (RPF). It is worth mentioning that the rubber percentage on the weight of fibre is less than RF fibre (40-50%).

With regards to the research objectives, feasibility of asphalt mixture modification via fibres, fibres I and II were used for mixtures with SBS PmB, and fibres III and IV were used with neat bitumen to produce samples and mixtures modified with SBS bitumen or modified fibres, respectively. The added polymer in this research was a kind of plastomers, which are generally cheaper than block copolymers. As the main effect, these polymers could enhance the strength but not elastic response (IDOT 2005, Becker et al. 2001), which can be recovered by the presence of rubber. Fig. 1 shows the general appearance of the four adopted fibres before and after grinding for laboratory scale experimental works.

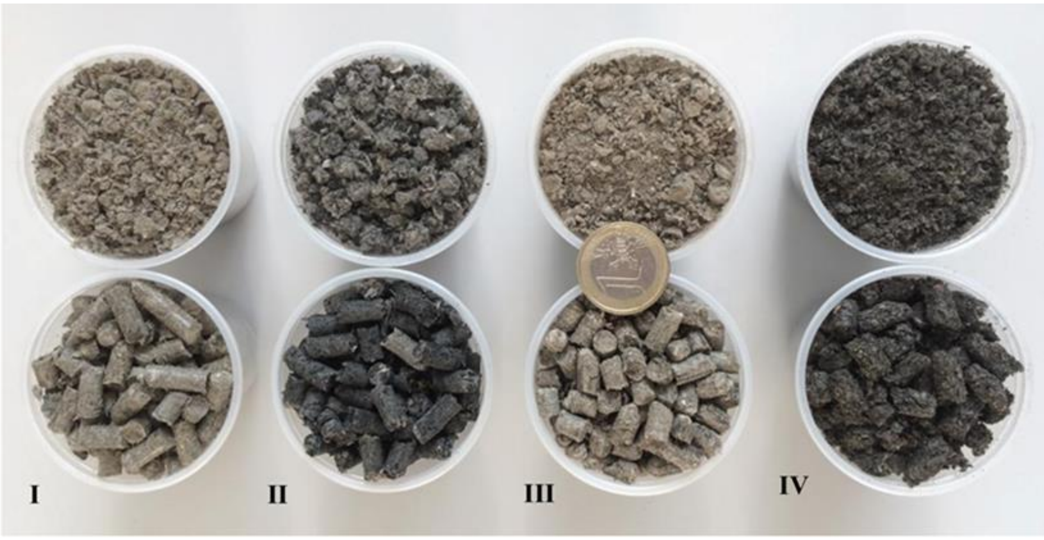


Fig. 1. I: Cellulose + Glass Fibre (F), II: Rubberized Cellulose-based Fibre (RF), III: Cellulose-based Plastomer polymer-added Fibre (PF), IV: Rubberized Cellulose-based Plastomer polymer added Fibre (RPF).

2.3. Virgin and RAP aggregates

The aggregates used in the present experimental work were 75% of virgin crushed porphyry and 25% (the maximum locally allowable use of RAP in asphalt mixtures) of limestone RAP. The aggregate properties are extremely important since the stone-on-stone contact is the vital backbone of SMA mixtures. Hence the characteristics of the aggregates should be controlled. Porphyry is a reddish-brown to purple igneous rock containing large phenocrysts of various minerals embedded in a fine-grained matrix. The main chemical component is silica, while other major components are iron, potassium and aluminium oxides.

The composition of the 12 mm (nominal maximum aggregate size) SMA consists of porphyry aggregate, limestone sand, and two RAPs shown in Fig. 2 and Table 2 , which complied with the gradation limits of an Italian specification (Autovie venete 2006). In order to avoid any further aging, the RAP was heated separately in another over under controlled temperature and was added to the mixture of virgin aggregates and fibre. For the mixtures containing RAP aggregates, the primary stage of mix design was dedicated to binder extraction which was needed for the further aged binder characterization as well as RAP aggregate properties. Within binder extraction, the recoverable amount of binder in RAP was determined 4% on the weight of RAP aggregates, which was considered through the mix design procedure. It is worth mentioning that for the mixtures containing RAP (25% on the total weight of aggregates) a vegetable oil-base rejuvenator (0.15% on the weight of RAP, mixed with the heated binder before adding to mix) was used through the mix design to restore the aged binder of RAP. In order to avoid any further aging, the RAP was heated separately in another over under controlled temperature and was added to the mixture of virgin aggregates and fibre.

Table 2. Mix design gradation limits.

Sieve Size (mm)	12	10	8	4	2	1	0.5	0.063
Specification limits (%)	100/100	81/100	60/80	30/52	22/34	16/26	11/21	8/14

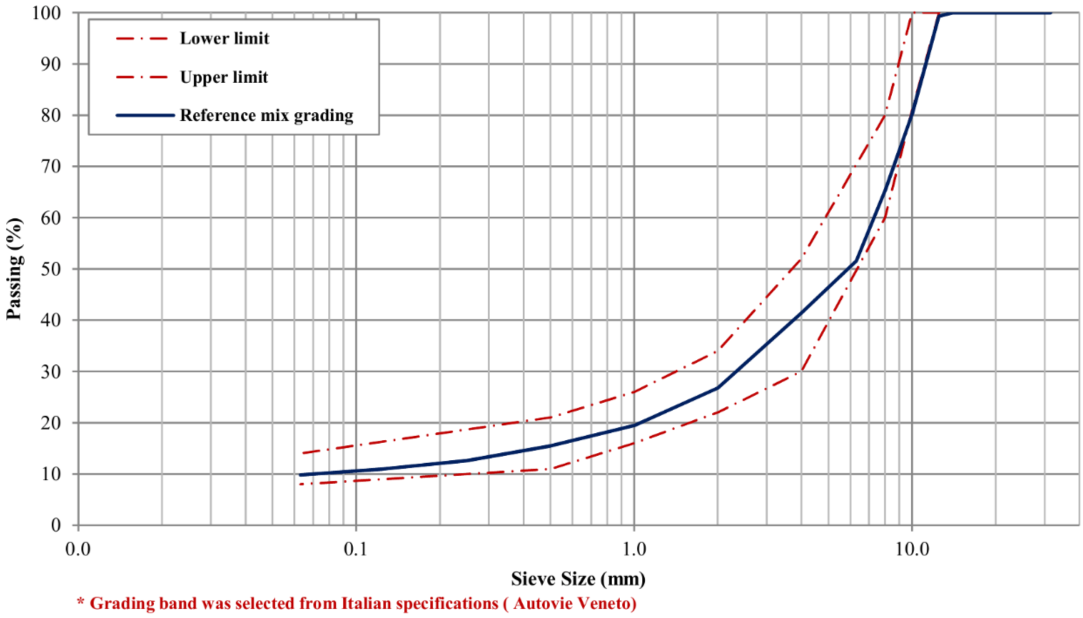


Fig. 2. Applied SMA grading curve and considered band.

3. Mix design and Methods

3.1. Mix design

The design of asphalt concrete mixture involves the selection and proportioning of materials to obtain the desired properties in the finished product. In particular, regarding the SMA mixtures, the mix design consists of two part. A coarse aggregate skeleton and binder rich mortar. The rationale in SMA mix design is first to develop an aggregate skeleton with a coarse aggregate-on-coarse-aggregate contact that is generally referred to as the stone-on-stone contact. The second part of the mix design rationale is to provide sufficient mortar of the desired consistency. Satisfactory mortar consistency and, thus, good SMA performance requires a relatively high asphalt cement content. For this reason, the voids in the mineral aggregate (VMA), or the design asphalt cement content, must exceed some minimum requirement (NAPA 2002). The adopted five-step mix design procedure required to obtain a satisfactory SMA mixture, are shown in Fig. 3.

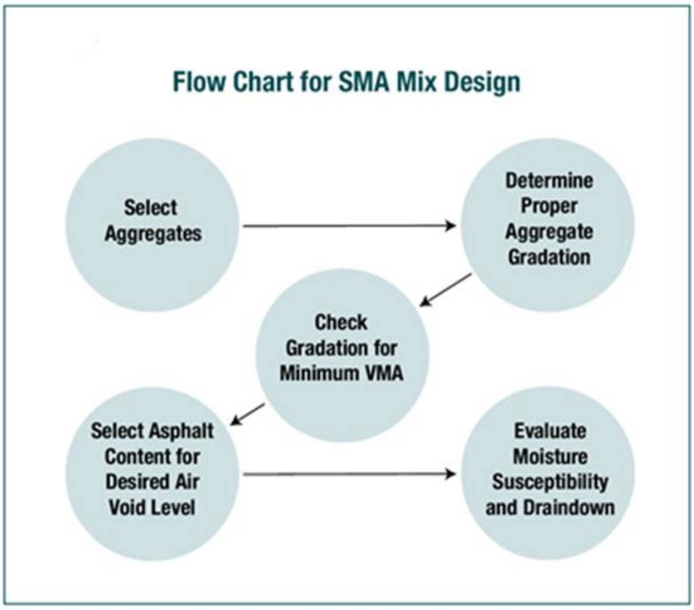


Fig. 3. NAPA recommended procedure for SMA mix design (NAPA 2002).

In order to provide a comprehensive understanding on the effects of different types of fibres on the low-temperature performance of SMAs and their binders, the experimental plan included two consecutive phases completed by means of BBR test (binder rheology) and TSRST (mixture behaviour). The two above mentioned neat and modified bitumen and the four fibres have been used to produce a series of modified SMAs to be compared with a reference control mixture (FPmB) made with SBS modified binder and commonly used cellulose fibre (cellulose + glass Fibre). The selection of the composition of the materials, was done according to the main goal of this research, which was comparing the asphalt mixture modification either with PMB or Modified fibres. Following the above mentioned procedure, the optimum bitumen mixtures were selected and tested. Table 3 provides the SMAs’ mix composition details and adopted nomenclature.

Table 3. Mix details and applied IDs.

Mixture ID	Mix details and materials proportion (on the weight of aggregates)
FPmB	[Cellulose + Glass Fibre] 0.3% + SBS PmB
RFPmB	[Rubberized Cellulose Fibre] 0.3% + SBS PmB
PFB	[Cellulose + Glass + Plastomeric polymer Fibre] 0.4% + Neat Bitumen
RPFB	[Rubberized Cellulose Fibre + Plastomeric polymer] 0.5% +Neat Bitumen
FPmBRR	[Cellulose + Glass Fibre] 0.3% + SBS PmB + RAP 25% + Rejuvenator
RFPmBRR	[Rubberized Cellulose Fibre] 0.3% + SBS PmB + RAP 25% + Rejuvenator
PFBRR	[Cellulose + Glass + Plastomeric polymer Fibre] 0.4% +Neat Bitumen + RAP 25% + Rejuvenator
RPFBRR	[Rubberized Cellulose Fibre + Plastomeric polymer] 0.5% + Neat Bitumen + RAP 25% + Rejuvenator

3.2. Methods

The research consisted of two main phases of tests on binder compounds and optimized mixtures' specimens shown in Fig. 4.

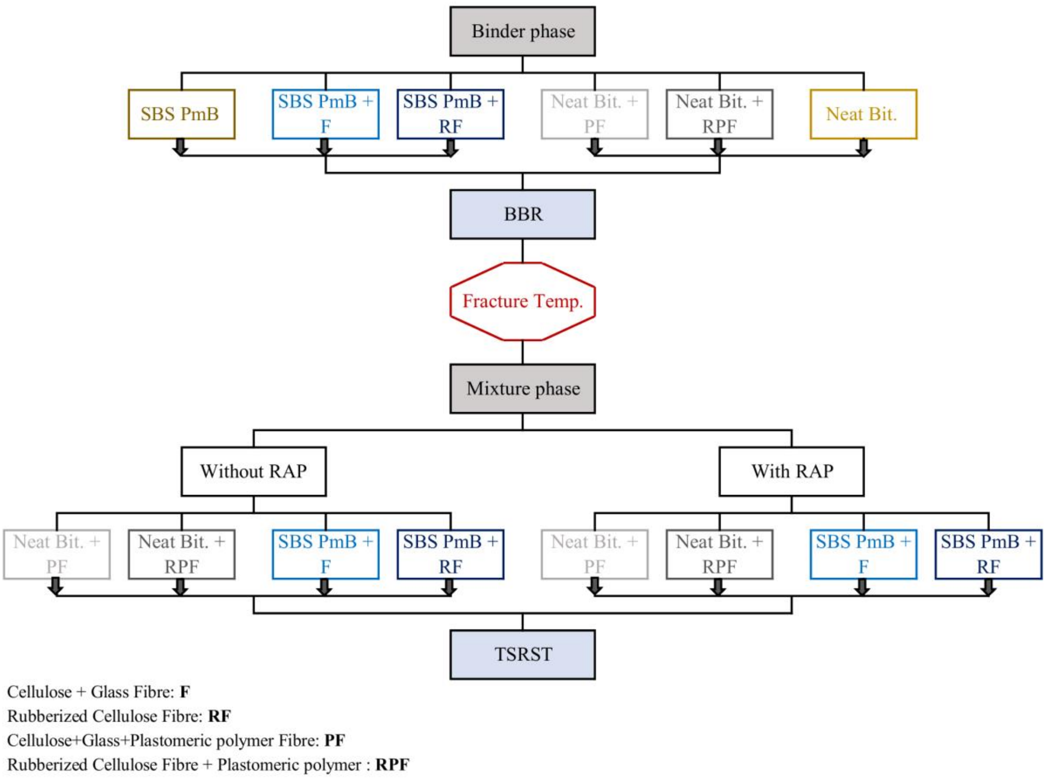


Fig. 4. Research scheme.

As for the rheological analysis by means of BBR the tests were performed following the EN 14771 standard both on bitumen samples and on fibre added samples. Considering the time needed for rubber digestion and simulating the practical conditioning time due to the mixture production and transportation, the sample preparation steps were:

I. Mixing manually the fibre proportion with the bitumen for 5 minutes at 170±5°C

II. 25 minutes conditioning and mixing at 160±5°C.

It is worth mentioning that the control samples (only bitumen) were also conditioned following the same procedure to avoid any additional variable. Hence it conditioned at 170°±5C for 5 min plus at 160±5°C for 25 min. The mixing and conditioning temperatures and duration were determined based on the estimated the filed practical values in field and the type of bitumens, however the homogeneity of the mixtures was controlled. The tests have been conducted at three different temperatures including the fracture temperature determined by TSRST.

In the mixture phase, the Thermal Stress Restrained Specimen Test has been carried out according to EN 12697-46 with 10°C/h constant temperature rate of cooling. TSRST is one of the laboratory tests adopted for the low-temperature characterization of asphalt mixtures. In principle, since the length of the specimen is kept constant, the specimen is subjected to a (cryogenic) tension stress. The cracking appears at the failure/fracture temperature T_{crack} by the induced failure/fracture stress σ_{cry} represented in Fig. 5 as a typical stress development with temperature decrease during the test.

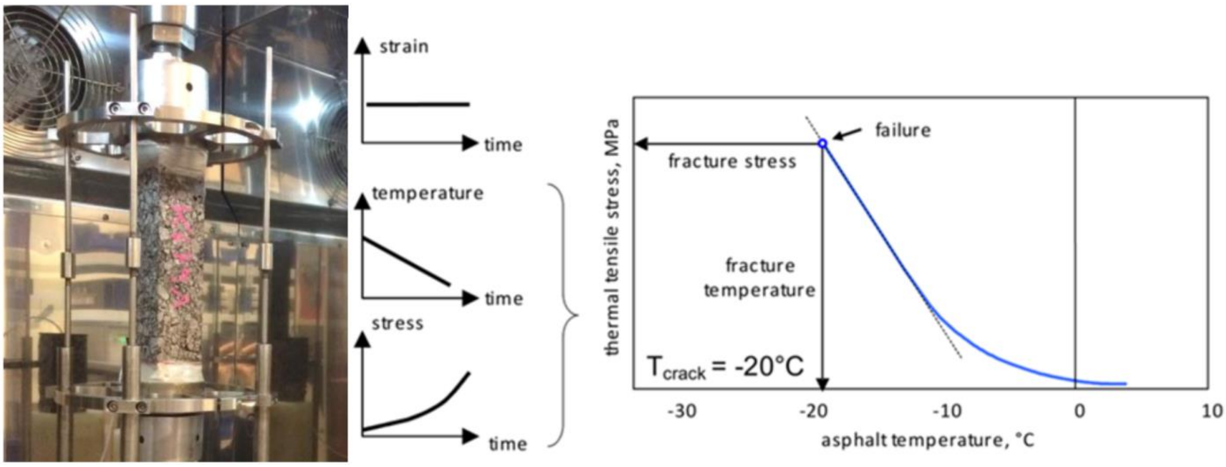


Fig. 5. Stress development with temperature variation and TSRST theoretical principles (Blab et al. 2009).

As for asphalt mixtures, the grinded fibres were added directly to the heated aggregates at the temperature of 170±5˚C, as a dry process. The TSRST specimens were sawn from roller compacted slabs. For this, the 32×26×7 cm size slabs were produced according to the EN 12697-33 standard providing 5×5×25 cm beams all surfaces cut specimens. The specimens were glued to two end platens with a two-component epoxy and cured for 2 days at room temperature until the glue get stiff enough. To record the core temperature, a dummy specimen was prepared for each mixture. The dummy specimen was a beam cut in half with a hole drilled in the centre of one plane end. The hole was then covered with an adhesive insulation foil and filled with glycerine. The temperature probe was inserted into the hole to record the core temperature. For the present study, the dummy specimen was placed into the thermal chamber next to the position, where the actual test specimen was mounted in the chamber. Fig. 6 represents the TSRST configuration and the dummy specimen positioning.

Fig. 6. A) Specimen gluing set up; B) Glued specimen before TSRST; and C) TSRST configuration with the dummy specimen.

4. Experimental Results and Analysis

4.1. Bending Beam Rheometer (BBR)

BBR has been shown as a consistent tool for the evaluation of binder's performance in terms of thermal cracking (Mouillet et al. 2004). The test consists of a constant force being applied to a beam-shaped specimen in a cooling bath, in order to derive specific rates of deformation at various temperatures. The resulting deflection is measured and the flexural stiffness is reported as a function of time providing indications of the low-temperature stiffness and cracking potential of the asphalt binder in terms of flexural-creep stiffness or compliance and *m*-value. The *m*-value is the absolute value of the slope of the logarithm of the estimated stiffness curves versus the logarithm of the time representing stress relaxation ability. It should be noted that the *m*-value calculation for any time during the test is based on the creep test results for the entire duration of the test. A higher *m*-value would indicate a faster relaxation of stresses, which is desirable for asphalt mixture performance at low-temperature (Al-Qadi et al. 2008). Therefore considering the thermal cracking resistance at low-temperature a binder with minimum creep stiffness and maximum *m*-value (creep rate) is desired.

In this study, the tests were performed at three different temperatures controlling the validity trend of the obtained values. As mentioned before, the bituminous compounds were subjected to the introduced conditioning protocol and not the Superpave aging method. This was decided to reduce any probable variability through the binder and mixture scale works. The results presented in Table 4 indicate the imposed stiffness and decreased *m*-value by all the tested fibres for both neat and modified binder. This has been recorded in the literature by few researches on the low-temperature analysis of bitumen samples containing cellulose fibres (Wu et al. 2015). Comparison of the values of neat bitumen with SBS modified one, shows the superiority of SBS modification as an elastomer to the plastomeric modification via fibres in decreasing the stiffness and increasing the *m*-value. This could be related to the genuine characteristics of elastomer copolymers comparing to plastomers by which elastomers enhance the strength at high temperatures, as well as elasticity at low-temperatures, while plastomers only enhance the strength but not elasticity. Considering the research conducted on low-temperature properties of modified bitumen via plastomers and elastomers, it was realized that elastomers, mainly SBS or rubber, are limited by *m*-value. In contrast, plastomer polymers such as EVA, increases the low-temperature stiffness (Mouillet et al. 2004, Keymanesh et al. 2017).

Table 4. Average BBR test results.

Bitumen Type	Stiffness (MPa)			*m*-Value		
	Temperature (˚C)			Temperature (˚C)		
	-12	-18	-24	-12	-18	-24
Neat Bitumen	86.46	209.89	445.43	0.483	0.393	0.301
Neat Bitumen+PF	97.81	244.13	494.07	0.472	0.373	0.281
Neat Bitumen+RPF	95.57	229.64	452.22	0.445	0.354	0.281
SBS PmB	74.40	179.92	329.17	0.424	0.370	0.296
SBS PmB+F	80.16	200.67	362.66	0.428	0.363	0.277
SBS PmB+RF	76.38	191.19	351.54	0.407	0.354	0.257

From another perspective, according to Fig. 7 it can be seen that cellulose fibre increased the stiffness of both the neat bitumen and the SBS modified bitumen. However, it is worth mentioning that the increased stiffness of fibre-containing compounds was expected, when fibres absorb the light aromatics of bitumen (play similar to the role of filler in bitumen compounds in general). Considering this principle, the aim of BBR tests was conducting a comparison study on the rate of stiffness imposed by adding fibres. Bearing in mind the main objective of this research; comparing the bitumen modification with added polymer or adding modified fibres, It can be stated that the bitumen compound of SBS PmB + cellulose-based fibre shows better low-temperature properties compared to bitumen compound of Not modified bitumen + Modified cellulose-based fibre.

These results were in line with the previous researches in the literature mentioned above.

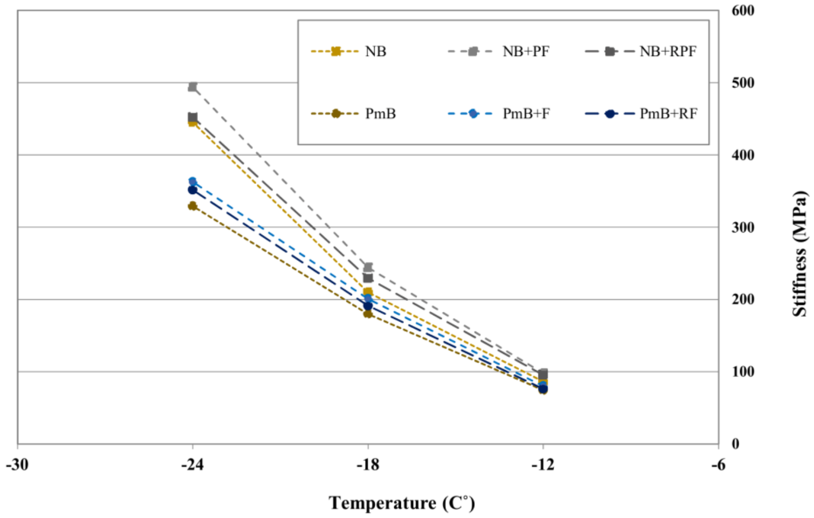


Fig. 7. Stiffness (S) vs. temperature.

4.2.Thermal Stress Restrained Specimen Test (TSRST)

In the literature, several factors were reported to have effects on the thermal cracking sensitivity of asphalt mixtures, which may broadly be categorized as pavement structure geometry (type), material properties (in particular bitumen), and additives. In addition, test setting in terms of temperature cooling rate was found to have a remarkable influence on the thermal cracking propagation. Specific factors recorded in previous researches under each of these categories are here described:

- A number of studies on the influence of mixture type on the low-temperature performance of asphalt mixtures reported a marginal difference between conventional dense graded and SMA mixtures. However, as it could be expected porous asphalt showed more susceptibility due to the high void content and low-tenacity of the mixture (Blazejowski 2011, Judycki & Pszczoła, 2002, Isacsson & Zeng, 1998).
- The effect of binder physical and rheological properties on thermo-mechanical performance of asphalt mixtures has been investigated by a number of researches. According to these studies, bitumen stiffness plays a key role regardless of the kind asphalt mixture (Isacsson & Zeng 1998). In this respect, several studies compared the low-temperature performance of a single type of standard mixture using different straight-run bitumens with or without polymer (SBS) by means of TSRST. It was found that, the softer the base bitumen at low-temperature or the higher the polymer content, the lower the cracking temperature (King et al. 1993, Aschenbrener 1995, Kallas 1982). In general, it can be concluded that increasing the content of polymer can improve the fracture temperature. From another perspective, regardless of the binder characteristics, the binder content has not got a significant effect on

low-temperature fracture strength since the binder content is optimized through mix design considering the air voids of the mixture

(Aschenbrener 1995, Kallas 1982). This is because increasing the binder content increases the coefficient of thermal contraction, but decreases the stiffness of the mixture (Vinson et al. 1990).

- A few research studies on the effects of fibres and reinforcement additives showed that although the cellulose fibres have no significant influence on the low-temperature cracking sensitivity of asphalt mixtures (Partl 1994, Stuart & Malmquist, 1994), modified fibres may improve it effectively (Serfass & Samanos, 1996). To this end, a more recent research showed the effectiveness of SBS modified binders on low-temperature cracking in comparison to mixtures reinforced with cellulose fibres (Tasdemir & Agar, 2007).
- The temperature rate and loading time have a great effect on the material's brittleness as well as ductility. Moreover, it is reported that the variation in testing conditions could affect the type of cracking (Steiner et al. 2016).

For this research, the results represented in Fig. 8 provided the cracking temperature (failure/fracture temperature) and cryogenic stress (maximum stress when cracking occurs) for the tested mixtures. The results are shown in two series of specimens: the totally virgin mixtures and those containing RAP. Bearing in mind requirements in the standard (Results of the failure temperature derived from the TSRST on three duplicates by the same operator shall be considered suspect if they differ by more than 2°C) at least 3 replicates have been considered for each mixture. Based on the presented average values of each mixture, it can be seen that no significant difference was recorded between the mixtures except for the mixtures containing RPF fibre (rubberized plastomer polymer-added fibre). In this respect, while considering the cracking temperature the maximum difference is less than 3.5 % for the FPmb, RFPmB, PFB mixtures, for the mixture RPFB is 11%. In addition, as it could be expected that the low-temperature properties of RAP containing mixtures were lower than those without RAP containing mixtures. One reason for this lower performance could be in sufficient amount of the used rejuvenator. The presence of cellulose-based fibres could also aggravate the problem, when it absorbs light aromatics of bitumen binder and makes the mixture stiffer. From another perspective, the cryogenic stress values showed the same trend of cracking temperatures. These results could be due to the high amount of fibre in it, which resulted in the low cohesion of materials. It is worth mentioning that this phenomenon can be seen in both the series of mixtures.

From another perspective, investigating the feasibility of using modified fibres if compared to modified bitumen, comparable results were recorded, which may confirm the effectiveness of the modified fibres in mixtures modification and against low-temperature distresses. However, the results could be validated within further binder studies.

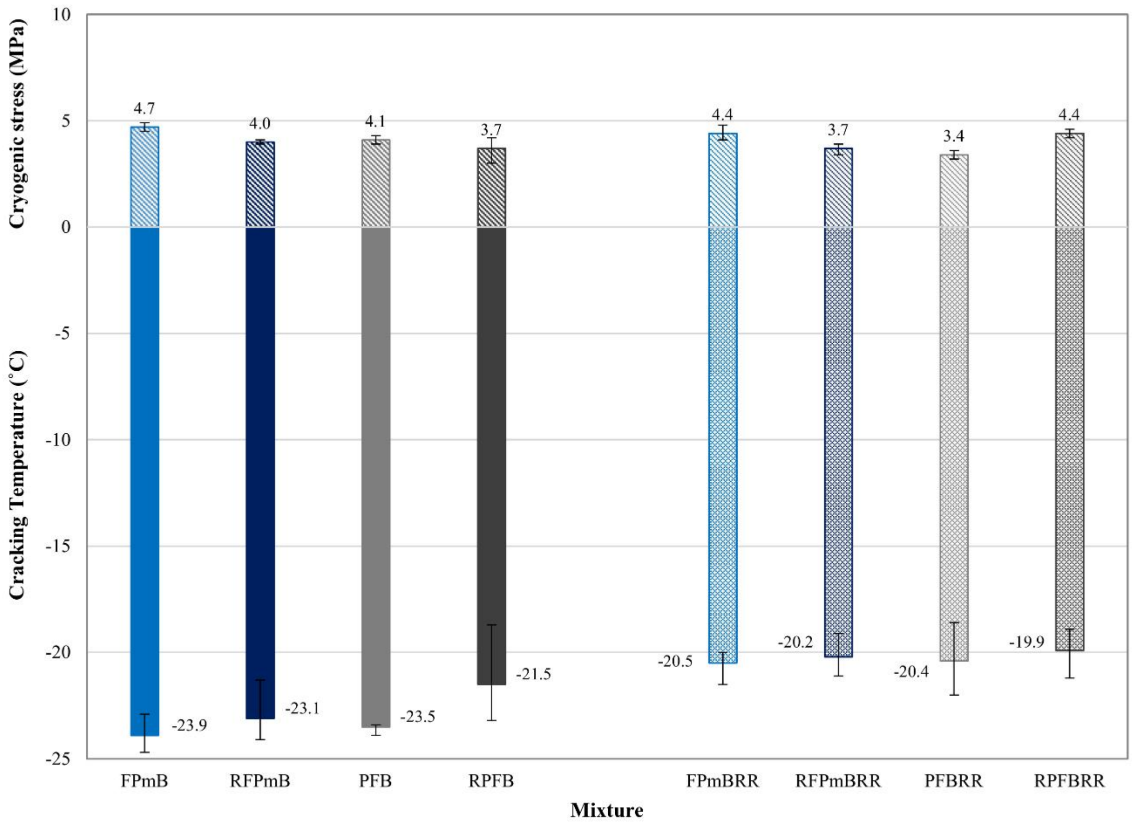


Fig. 8. Average TSRST results.

5. Concluding Remarks

Two approaches were used in this paper to examine the relative stiffness properties and cracking resistance of SMA mixtures containing modified fibres with and without rubber inside at low temperatures. The approaches have consisted on one hand of fundamental rheological binder testing by means of BBR, and on the other hand of performance properties of the mixtures tested with TSRST. The following conclusions can be drawn from the research reported in this paper:

- In line with the literature the addition of cellulose fibre increased the stiffness of both neat and modified bitumen binders at low temperatures.
- The analysis of the fundamental rheological parameters of stiffness modulus and *m*-value, indicated the improved low-temperature susceptibility (reduced stiffness) for the samples containing rubberized fibres for both the tested neat and SBS modified bitumen compounds.

- Considering the Fundamental thermo-mechanical characteristics of plastomers, the highest stiffness (via BBR) was recorded for the neat bitumen compounds containing plastomeric polymer fibre (PF). The stiffness was even higher than solely neat bitumen samples.
- Although the BBR test results showed the higher temperature sensitivity of the neat and fibre containing compounds in comparison to those made with PmB, no correlations were recorded with TSRST results. This may confirm the importance of the mixture's structure (aggregate grading, dense graded, open-graded, and etc.) on low-temperature performance properties of asphalt mixtures and in particular SMAs.
- No significant difference was recorded between the TSRST fracture temperatures of the mixtures produced with neat bitumen or SBS PmB in both series of mixtures (with and without RAP) except for the RFPmB and RPFB. It could confirm that the modification via fibres was effective for the low-temperature performance of SMA mixtures. The considerable difference between these two mixtures could be the result of high proportion of fibre (0.5%) in RPFB mixture. The authors believe that the high concentration of cellulose fibres decreases the tensile properties of SMA mixtures. In several research works it has been shown that while addition of fibres could increase the tensile properties of dense-graded mixtures, the same may not expected in SMA mixtures.
- Comparing the low-temperature performance of the mixtures containing 25% of RAP with the virgin mixtures, a lower performance was recorded for the RAP containing mixtures. In another words, the RAP containing mixtures were more susceptible to low-temperature cracking.

Disclosure statement

No potential conflict of interest was reported by the authors.

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5.6 Analysis Highlights

Considering the obtained test results and analysis, some highlights as following are notable:

Binder Scale;

- The addition of all kinds of fibres decreased the penetration, increased the softening point and viscosity values of the tested bitumens. However, the rubberized fibres showed higher penetration and lower softening point and viscosity compared to non-rubberized fibres.
- While adding the fibres increased the stiffness, the rubberized fibres showed lower stiffness compared to the bitumen compounds containing fibres without rubber.
- While the addition of Plastomeric polymer to the fibres improved the penetration and softening point, it also increased the stiffness at low temperatures.
- BBR test results showed the superiority of SBS modification as an elastomer compared to the Plastomeric modification via fibres by decreasing the stiffness and increasing the *m*-value.

Mixture scale;

- Almost all the obtained test results by different test methods were in line and a same trend was recorded.
- The addition of RAP enhanced the results in all the adopted test methods except for TSRST.
- Overall, the rubber-added fibres always performed better when compared to non-rubberized.
- In many test methods the obtained results for the mixtures containing composite fibres and neat bitumen were comparable to those of containing SBS PmB, including ITS, ITSM (intermediate temp.), Fatigue (intermediate stress level), TSRST, ITSR, and RBT showing the feasibility of the asphalt mixture modification by fibres. However, more research is needed for full optimization of such composite compounds.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

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6.1. Concluding Remarks

The experimental research work reported in thesis paper was implemented to determine whether the addition of different types of novel poly-functional cellulose-based fibres have any effect on the performance and mechanical properties of SMA mixtures. The research plan consisted of both binder and mixture scale, using a range of laboratory-based test methods. Based on the obtained results, it may be possible to reach the following conclusions:

- Reviewing a wide range of research works, filed experiences and scientific synthesis regarding the fibre containing SMA mixtures, two key points, which also were observed in this study were recognized:
    1. The main idea of developing SMA mixtures was introducing a durable pavement mixture under stud pressure of heavy duty load, which is provided with stone-on-stone contact of high-quality aggregates. However, the gap-graded nature of SMA generally results in the lower tenacity of a mixture when compared to dense-graded asphalt mixtures.
    2. On the contrary with tensile properties, SMA mixtures are basically durable under high compression usually regardless of binder characteristics and additives including fibres. In this respect, many research works showed that although fibres (mostly cellulose-based) has very low or no effect on rutting resistance, they have potentials to improve the tensile properties of SMA mixtures.
- The influence of fibres on the bitumen binders have been investigated by both fundamental conventional tests and dynamic rheological test methods. According to the results same trends have been obtained, which from one hand showed the validity of the results and from another hand indicated the feasibility of conventional tests on fibre/bitumen interaction analyse.
- While fibres have no effect on the rutting performance of gap-graded asphalt mixtures and OGFC's, they may increase the permanent deformation resistance by increasing the binders' viscosity. This phenomenon has been recorded in many previous researches and also in the present research. This behaviour mainly goes back to the fundamental properties of SMA and its compression resistance superiority due to stone on stone contact comparing to conventional dense-graded asphalt concretes.
- Regardless of the pavement type and also the fibres material, the addition of fibres would result in higher tensile properties and stiffness. However, the effectiveness of fibres on mixtures tenacity is highly depended on the fibres type, material, and form. The present

study, in line with the results recorded in context, showed the effectiveness of mineral fibres in enhancing the tensile properties.

- Implementing the research on cellulose-based fibre containing mixtures with the different percentage, showed that the larger amount of fibre than the commonly recommended portion by most of the specifications (0.3-0.4%) has a negative influence of final mixture's engineering properties. This is result could be due to the high saturate absorption properties of cellulose fibres, which may be the reason for later reduced adherent characteristics of the binder.
- The microscopic analysis revealed the influence of fibre's microstructure and surface texture on the capacity of asphalt stabilizing and further imposed mechanical/performance characteristics of mixtures containing the fibres. In this case, while cellulose fibres with rough porous texture have greater potentials for absorbing binder and binder drainage control, the mineral fibres with smooth texture and bar-shaped filament have greater potentials in asphalt mixture reinforcement.
- The extended results of this research indicated that polymer-added fibres and the idea of poly-functional composite fibres are effective alternatives for PMBs in asphalt mixture modification when the obtained test results were comparable in most the cases. However the research team believe that the efficiency of polymer added fibres in asphalt mixture modification is highly depended on the amount of polymer inside the fibres and application dosage of the fibres. In this respect, considering the previously proved effective amount of polymers in PmBs (more than 3% on the weight of bitumen) and the direct addition of polymer into asphalt mixture, the effective portion could be estimated.
- As an innovative approach, the presented comprehensive research indicated the possibility of the addition of rubber powder from ELT's in asphalt mixtures via fibres. The results showed successful achievements in elastic-recovery properties of rubberized fibre-containing mixtures as well as great potentials of draindown control. However, in line with many conducted researches, the level of rubber modification highly depends on the portion of rubber content of fibres and the overall percentage of rubberized fibre on the weight of the total mixture. This conclusion was achieved by comparing the fibres containing a different amount of rubber, observing almost no effectiveness for the mixtures containing fibres with less rubber portion. It is noteworthy that many pieces of research on rubberized binders and mixtures reached to 15% (on the weight of binder) as the optimum percentage of rubber content. The literature shows lower than this dosage, may not let to evident effects in particular on mixture's properties.

- Considering the influence of the fibres on bitumen/aggregate affinity, higher bitumen coverage was recorded for the mixture sample containing rubberized fibre (and neat bitumen). However, it is worth mentioning that in accordance with the authors' previous experience, the conditioning time and temperature (simulating the filed practice) for sample preparation is of prominent importance. Besides this achievement, the overall assessment showed the superior performance of fibres containing more rubber in comparison to that with a less rubber inside (RPF sample).
- Overall, the presented research data on the feasibility of mixture modification via composite fibres showed the possibility of the direct mixture modification via composite poly-functional fibres. This will lead to many functional and environmental benefits such as:

I. Easier implementation procedure in asphalt mixture plants.

II. Providing eco-friendly materials for modifying asphalt mixtures. This is possible from one hand by deleting the high energy consumption needed for producing the PmBs and asphalt mixtures containing PmB and from another hand by using of recycling materials such and glass and ELT's rubber in asphalt mixtures.

- The overall results of the research showed the improved test results for the mixtures containing 25% of RAP except for the TSRST results in which the inclusion of RAP led to higher low-temperature cracking sensitivity comparing to the totally virgin mixtures. The key point of the TSRST test results was that the lower performance for the RAP containing mixtures was independent of the type of the fibre inside the mixtures. This indicates the importance of imposed RAP stiffness, binder type and mixture types on low-temperature cracking potentials of the mixtures. In addition, the lowest performance was recorded for the mixture containing 0.5% RPF fibre (rubberize and plastomeric polymer containing fibre), which supports the idea of cellulose accumulation and reduced tensile properties of the mixture.
- Based on the TSRST results obtained in this study, it can be concluded that the type of mixture (aggregate grading) dominate the type of fibre due to the similar cracking temperature obtained for mixtures containing different types of fibres.
- Considering the low-temperature analysis, while the BBR test results showed the reduced binder stiffness for the compounds containing rubberized fibres compared to those without rubberized fibres, no significant difference was recorded from TSRST test results. Accordingly, it can be declared that no relevant correlation was recorded between BBR and TSRST in the presented research.

- The permanent deformation resistance parameters were studied by test methods at both binder scale and mixture scale by means of Superpave rutting binder parameter, MSCRT, and RLAT respectively. Based on the binder scale results, although the addition of all type of fibres increased the stiffness of the compounds, the rubberized ones decreased the stiffness, however, in the mixture scale no comparable difference was recorded within RLAT. This could be in agreement with the literature, in which the ineffectiveness of fibres on rutting performance of SMA mixtures was experienced and shown. This was related to the stone-on-stone structures of SMA mixture and its fundamental gap-graded nature, which has high compressive performance.

6.2. Future Scopes

Besides the information obtained from the former research works' conclusions and this investigation has revealed areas where further research could be undertaken to support and validate the findings of the present study. Therefore, the following recommendations for future studies are made to fulfil the gaps in the state of knowledge:

- The knowledge obtained from wide investigation through the former studies on bitumen modification, rubberized binders/mixture, and asphalt mixture fibre-modification/reinforcement shows that the optimum amount of modifier plays a key role on the effectiveness of any modification. Hence considering the new generation of fibres as modifier or reinforcing materials, enough inclusion of materials is necessary. The proven amount of 0.3-0.4% (on the weight of the mixture) is applicable just for controlling the binder drainage. Using this dosage in these study led to marginal results for mixtures containing the different kind of the testing fibres. Consequently, it is suggested that further researches on this topic continue on the fibres containing more polymer, glass fibre, and rubber inside to fulfil the minimum percentage needed for mixture modification.
- In the present study, different fibres were used for neat bitumen and SBS PmB mixtures. The research team highly suggest the further investigations on the effectiveness of the same fibres with both neat and SBS PmB and same mixture. This will let to remove all the possible variables and pure understanding of fibre's characteristics regardless of bitumen properties.
- Since the mixture type is of paramount importance in tensile properties of asphalt mixtures, and the grading curve used in this study was a close gap-graded mixture, other grading curves including open-graded mixtures be also investigated with this fibres.