Universidade do Minho
Escola de Engenharia

Carina Adelaide da Costa e Silva

Evaluation of sustainable technologies for the production of recycled asphalt mixtures

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Tese de Mestrado
Ciclo de Estudos Integrados Conducentes ao
Grau de Mestre em Engenharia Civil

Trabalho efetuado sob a orientação do
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Evaluation of sustainable technologies for the production of recycled asphalt mixtures

ABSTRACT

The concept of "Sustainable Development" has been on the agenda, acquiring an increasing importance on a global scale. This fact results from an environmental awareness among citizens in general, and particularly of entities able to enhance and contribute on a larger scale for their development.

The need for a more effective response to the topic of sustainability, namely in the Civil Engineering area, has stimulated the development of new constructive techniques that take into account the specifications necessary for construction and simultaneously obtaining acceptable values of sustainability. Thus, recycling of materials is currently gaining popularity, as one of the possible solutions for the rehabilitation of all types of constructions.

In particular, the techniques used for the rehabilitation of road pavements have increasingly been the target of innovative recycling processes. One of the latest goals is to develop recycling procedures that incorporate higher rates of RAP material, maintaining the quality and the performance of the mixtures, when compared with conventional new asphalt mixtures.

In the present work, a recycling rate of 50% was used in order to increase the sustainability of the resulting asphalt mixture. This led to the need of a rejuvenating agent that would recover part of the original properties of the aged binder. The selected additive also had the capability of reducing the production temperature of the mixture, improving the energy efficiency of the process.

Based on the results obtained in the present work, it was possible to confirm that recycled mixtures with 50% RAP incorporation can be produced with a performance similar to that of a conventional new mixture.

Key Words: Recycled asphalt mixtures; Rejuvenator; WMA additive; Performance.

Avaliação de tecnologias sustentáveis para produção de misturas betuminosas recicladas

RESUMO

A temática da sustentabilidade tem estado na ordem do dia, adquirindo cada vez uma maior importância à escala global. Este facto resulta de uma consciencialização ambiental por parte dos cidadãos em geral, e particularmente das entidades capazes de valorizar e contribuir em maior escala para o seu desenvolvimento.

A necessidade de dar uma resposta mais eficaz ao tema da sustentabilidade, nomeadamente na área da Engenharia Civil, tem vindo a estimular o desenvolvimento de novas técnicas construtivas que têm em conta as especificações necessárias à construção e simultaneamente a obtenção de valores de sustentabilidade aceitáveis. Assim, a reciclagem de materiais tem vindo a ganhar popularidade, assumindo-se como uma das soluções possíveis para a reabilitação de todos os tipos de construções.

No que se refere à reabilitação de pavimentos rodoviários, em particular, estes tem sido cada vez mais alvo de processos de reciclagens inovadores. Um dos objetivos é o desenvolvimento de processos de reciclagem que incorporem taxas de reciclagem elevadas, mantendo a qualidade e o desempenho das misturas, por comparação com misturas betuminosas novas.

No presente trabalho foi utilizada uma taxa de reciclagem de 50% de modo a aumentar a sustentabilidade da mistura betuminosa resultante, o que resultou na necessidade da utilização de um agente rejuvenescedor para recuperar parte das propriedades originais do betume envelhecido. O aditivo selecionado tem também a capacidade de reduzir a temperatura de produção da mistura, permitindo uma melhoria da eficiência energética do processo.

Com base nos resultados obtidos no presente trabalho conseguiu confirmar-se que é possível produzir misturas com 50% de material fresado, cujo desempenho se assemelha ao de uma mistura betuminosa nova convencional.

Palavras-chave: Misturas betuminosas recicladas; Rejuvenescedor; Aditivo redutor de temperatura; Desempenho.

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LIST OF ABBREVIATIONS

AASHTO – American Association of State Highway & Transportation Officials

AR – Asphalt rubber

ASTM – American Society for Testing and Materials

CIR – Cold in-place recycling

EN – European Standard

HIR – Hot in-place recycling

HMA – Hot Mixture Asphalt

ITSR – Indirect Tensile Strength Ratio

ITS_w – Average indirect tensile strength of the specimens conditioned in water

ITS_d – Average indirect tensile strength of the dry specimens

LVDT – Linear Variable Differential Transformer

MACOPAV – Manual de Concepção de Pavimentos (Portuguese Pavement Design Manual)

MORT&H – Ministry of Road Transport and Highways (India)

OBC – Optimum Bitumen Content

RTFOT – Rolling Thin-Film Oven Test

RAP – Reclaimed Asphalt Pavement

SHRP – Strategic Highway Research Program

TFOT – Thin-Film Oven Test

VMA – Voids in Mineral Aggregate

WMA – Warm Mix Asphalt

WTS_{AIR} – Wheel Tracking Slope in air

1. INTRODUCTION

1.1. Background

Due to increasing changes in the environment over the past few years there has been a great environmental awareness (Barbosa, 2012). It is therefore necessary to recognise the importance of the means of production used in construction nowadays, since this sector is one of the most responsible for the consumption of raw materials and energy worldwide. Thus, the production processes will have an increasing impact on the planet and its inhabitants.

According to what is to be addressed in this dissertation, it is important to point out the notion of sustainability, which can be seen as the capacity of Man interacting with the Earth, saving the environment in a manner as not to compromise the general resources for future generations.

Thus, the need to adapt the techniques required for the construction arises, in general, in order to respect the concept mentioned above. Relating this factor to the topic addressed in this master dissertation, recycling is assumed as one of the possible solutions for degraded pavement rehabilitation as well as the reuse of materials from the pavements in service, which are damaged, having lost most of their initial properties (Baptista, 2006).

Regarding road pavements, which will be the most important object of study of this thesis, their main function is to guarantee a free and levelled surface, which allows the circulation of vehicles in adequate safety, comfort and economic conditions (Gomes, 2005). To this end, the pavement surface must have certain characteristics that can be grouped into functional characteristics (related to the comfort and safety of the users) and structural characteristics (related to the structural behaviour of the entire pavement) (Branco *et al.*, 2005).

The loads that road pavements are subjected to due to traffic have increased in terms of volume and in terms of their wear factor. The requirements of the users have also grown over time. Thus, in parallel with the construction of new roads comes the need to rehabilitate an important part of the already built network (Gomes, 2005).

According to Nguyen (2009), recycling of pavements has been used for many years as a rehabilitation technique in the highway industry. The first recorded asphalt pavement recycling project was in 1915 (Epps *et al.*, 1980 apud, Nguyen, 2009). Since that moment, there has been a wide range of recycling methods regarding the equipment and procedures.

The recycling of road pavement materials arises in the 1970's in the United States, in the days of the oil crises. The prices of road paving materials were affected by crude oil at that time, as nowadays, and have led the road transport sector administrations to take into account the rising costs of asphaltic binder and fuel that directly influence the cost of manufacturing, transportation and application of mixtures (Batista and Antunes, 2012). When the recycling rate is high (over 30% of reclaimed asphalt pavement), it is essential to control the properties of the final binder, in order to guarantee the mechanical performances of the recycled asphalt concrete (Dony *et al.*, 2013).

The recycling of asphalt pavements is a production process with environmental and economic benefits that can be seen as a sustainable option for the paving industry. The use of high Reclaimed Asphalt Pavement (RAP) ratios in asphalt mixtures prevents the disposal of the RAP material in landfills, while reducing the amount of new resources used (aggregates and bitumen), thus being an effective technology at environmental and energy levels. In most countries, the total amount of reclaimed asphalt and the production of recycled asphalt continue to grow regularly, as well as the percentage of RAP used in recycled mixtures (Oliveira *et al.*, 2012b).

The asphalt mixtures may be comprised of many different materials, recycled or not. Since this thesis will be dealing with recycled materials this topic will be addressed in order to understand the process used in the application of these materials in asphalt mixtures. Therefore, the two main constituent materials are aggregates and binders. In relation to these aggregates, they make up about 90% to 100% of the pavement layers and may be natural, artificial, and recycled. This is definitely an important factor in the production of asphalt mixtures since they influence the physical properties of the layers.

As for the recycled aggregates, they are mostly construction and demolition waste, recycled crushed concrete aggregate, recycled asphalt pavement aggregates and other aggregates of urban solid waste, catalogued in the European waste list (Santos, 2010).

Regarding the binders (bituminous or hydraulic), it is known that they are products whose characteristics allow them to perform a mixing operation with other materials (generally stony), under specific conditions. When hardened, these binders stabilize the mixture, making it able to resist to traffic and weather actions.

In summary, the materials used in the construction of a road pavement are the key to its adequate performance (Santos, 2010). If these also contribute positively to the environment, it results in the perfect combination of those two objectives. Related to these, the sustainable asphalt mixtures production maximizes the reduction of costs, reduction of raw materials and energy, also positively contributing to the production.

1.2. The purpose of the dissertation

New road infrastructure projects are important and constitute of large investments that have to serve the society for a long time. The investments have to be durable at the lowest life cycle cost and the pavements have to withstand loads from increasing traffic intensity and heavy traffic loads (Söderqvist, 2006).

So, with the elaboration of this dissertation, it is intended to contribute towards the development of techniques that are able to give an answer to the topic of sustainability in the production of recycled asphalt mixtures. This should be achieved by using higher percentages of RAP incorporation and/or by using additives that improve the performance of the mixtures and reduce the production temperatures. Thus, various production techniques were reviewed, including cold, warm and hot recycling, in situ or in plant, in order to support the choices that were made for the production of the mixtures studied in this dissertation.

Taking the abovementioned into consideration, and based on the facilities available at the laboratory, it was decided to study the effect of a rejuvenating agent on the properties of an asphalt mixture produced with 50% reclaimed asphalt pavement.

The main objectives of this dissertation are the determination of the mechanical properties of a warm-recycled asphalt mixture, comparing them with those of a hot-recycled and a conventional asphalt mixture.

1.3. Organization of the dissertation

To organise the information gathered about of all the subjects covered in this thesis and present the results obtained from the laboratory study, the dissertation was divided in five chapters, according the order listed below.

Chapter one provides an introduction and purpose of the evaluation of sustainable technologies for the production of recycled asphalt mixtures as well as an overview of topic.

Chapter Two presents a synthesis of the knowledge gained during the research previously carried out by other researchers, which served as a first approach to the subject and to acquire the foundation for the development of this study. So in this chapter basic and technical concepts related to recycling of bituminous mixtures are included. Techniques are described for the production of asphalt pavements, including their advantages and disadvantages. Later in this chapter, materials used to improve the performance of bituminous mixtures are also mentioned.

Chapter Three describes the Materials and the Methodologies used specifically in each production process of conventional and recycled bituminous mixtures and their constituents. The testing methods used to characterise the mixtures are also described in this chapter.

In Chapter Four, the results obtained in this study are presented, which are separated by different phases of each test. Thus the analysis of the results is based on a comparison of recycled bituminous mixtures, produced with and without a specific rejuvenator agent, with a conventional bituminous mixture.

The Fifth Chapter presents the conclusions obtained with this dissertation, based on the results obtained in Chapter Four, and points towards specific points on which further work can be based.

2. LITERATURE REVIEW

With the concern of not depleting natural resources that still exist on the earth, and with the implementation of the idea of reusing and recycling materials, several sustainable techniques have been developed in the last few years, which add both economic and environmental benefits.

Recycling reduces the environmental impact associated with road maintenance operations, in particular, on the need for local storage of waste resulting from degraded pavements. Recycling is also advantageous because with the current shortage of material resources, it becomes an alternative technique to reduce the need for new materials (Oliveira *et al.*, 2013b, Silva, 2010).

Specifically, within the past twenty years, recycling asphalt has taken off - with highway construction leading the way (Herman, 2010). The pavement recycling is a technique which fundamental objective is to transform a degraded pavement in a homogeneous structure adapted to the traffic predicted to the future. More specifically, it consists in reusing the existing materials milled off from the pavement up to a certain depth, in the construction of a new layer, with the addition of a new binder (cement, bitumen or emulsion), water (if necessary, for hydration for pre-wetting and compaction) possibly aggregates (as correction of the particle size distribution or other purposes) and some additive, with a dosage obtained by previous tests (Fonseca, 2010).

In a global way the processes of reclaiming existing asphalt includes: scraping up the old asphalt, heating the material to a particular temperature (depending on the chosen process), adding aggregates or binders (if required) and then laying down the compacted material to create a new surface (Herman, 2010).

2.1. Structure of road pavements

Asphalt pavement is one of the most utilized highway surfaces. Most highway pavements are designed for a service life of about 20 to 25 years. However, many sections of highways never last that long without major pavement overhauls. Several damage mechanisms contribute to the shortening on pavement life (Boyes, 2011). The pavements can be classified into three types, which are flexible, semi-rigid and rigid, and further based on the association of various types of materials in their constituent layers (JAE, 1995).

According to JAE (1995), the construction of flexible road pavements comprise the overlay of distinct layers. These are generally divided into two types: the bituminous layers and the granular layers. These layers may have different thicknesses, which are based on their location, the proposed life period, road traffic, type of foundation and cost. Other characteristics may also be taken into account in the definition of their thicknesses.

Regarding the bituminous layers, the minimum and maximum thicknesses must be taken into account, as mentioned in the road construction specifications. This is related with the aggregate size and the position of the layer within the pavement structure (generally higher thicknesses are used for the lower layers and lower thicknesses are used for the surface courses).

The unbound layers essentially dependent on the characteristics of the granular materials, namely the nature, shape, physical properties of the aggregates, its particle size and amount applied in each layer, to contribute to the pavement bearing capacity.

According to Branco *et al.* (2005), the two criteria for the classification of road pavements into flexible, rigid and semi-rigid (Table 1), are the type of materials and the deformability.

Table 1 – Type of pavements depending on the materials and the deformability

Types of pavements	*Materials (binder)*	*Deformability*
Flexible	Hydrocarbon and granular	High
Semi-rigid	Hydrocarbon, hydraulic and granular	Very low
Rigid	Hydraulic and granular	Low

Flexible pavements have the upper layers formed by asphalt material that is stabilized by hydrocarbon binders, generally asphaltic bitumen, applied on top of one or two granular layers.

Rigid pavements have a top layer consisting of cement concrete (in other words, granular materials stabilized with a hydraulic binder, usually Portland cement), followed by one or two lower layers also comprising granular material stabilized with hydraulic binder and/or only granular material.

Semi-rigid pavements have characteristics common to both types of pavements mentioned above: with one or two top layers comprising bituminous mixtures, followed by a base layer of aggregate stabilized with hydraulic binder, and may also have a granular sub-base layer.

2.2. Production of bituminous mixtures

Bituminous mixtures have been the primary material used in the application of multiple layers of road pavements not only in Portugal, as elsewhere in the world. Generally these consist of stone aggregates and binder (Barbosa, 2012), so it is important to mention these main constituents, and specify some characteristics.

The aggregates constitute 90 to 95% by mass of asphalt and about 75 to 85% by volume. In this way, they represent the largest component of asphalt and their characteristics are of fundamental importance for the behaviour of bituminous mixtures to which they belong (Gomes, 2005).

The binders or also called by binding substance are the material present in the bituminous mixtures responsible for the agglutination function and the water proofing function. These are to provide an intimate connection between the aggregates, making the bituminous mixtures able of resisting the mechanical disintegration action produced by the traffic. When employed as bituminous binders, they also ensure effective sealing against penetration of water from precipitation, minimizing the harmful effect against this type of weather.

Regarding the production conditions of bituminous mixtures, they may be classified according to the temperature at which they are produced (Ferreira, 2009):

- Hot Mix Asphalts (HMA) - temperatures between 150 ºC and 180 ºC;
- Warm Mix Asphalts (WMA) - temperatures between 120 ºC and 140 ºC;
- Half-warm Mix Asphalts (HWMA) - temperatures below 120 ºC;
- Cold Asphalt Mixtures – ambient temperature, produced with foamed bitumen or bituminous emulsions.

2.3. Mix design process of recycled asphalt mixtures

The recycling of asphalt pavements is the process of re-using a deteriorated asphalt pavement material in a functionally new pavement. An existing asphalt pavement material usually contains a hardened asphaltic binder and a deteriorated aggregate, and has lost its desirable characteristics such as stability, flexibility and durability. The fundamental process of asphalt pavement recycling involves the addition of rejuvenating agents to soften the hardened old asphaltic binders, and the addition of virgin aggregates to upgrade the aggregates particle size distribution. Basically, it involves removing the old pavement material from the road, remixing it, when necessary with additional virgin aggregate, a virgin binder and/or a rejuvenating agent, and re-compacting it. The process can be carried out either hot or cold, i.e., with or without the application of heat. There are a wide variety of procedures by which asphalt pavements can be recycled. These procedures vary according to the type of equipment used, the type of pavement material to be recycled, the physical location where the process takes place, and the functional purpose of the end-product (Tia, 1982).

According to Sahu (2004) the proposed design procedure of recycled asphalt mixtures consists of two parts. The first part of the design procedure is to find out the optimum binder content for the recycled mix using the uncoated recovered aggregates obtained from the bitumen extraction test. The second part of the design procedure is to find out the percentage of RAP (old mix) which can be recycled without extracting the bitumen.

The proposed design processes are given in Figure 1 and Figure 2.

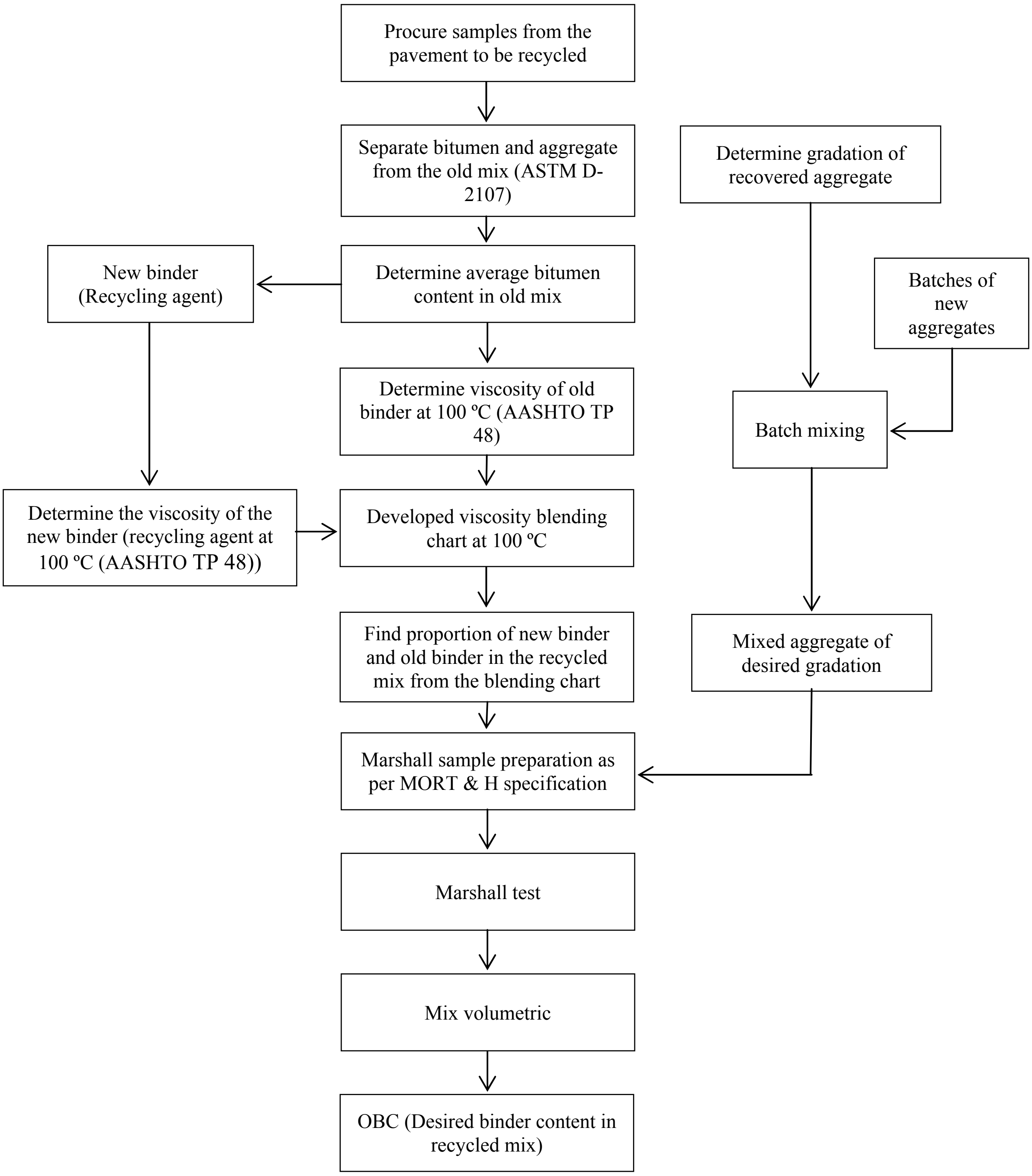


Figure 1 – First part of the mix design process of recycled asphalt mixtures

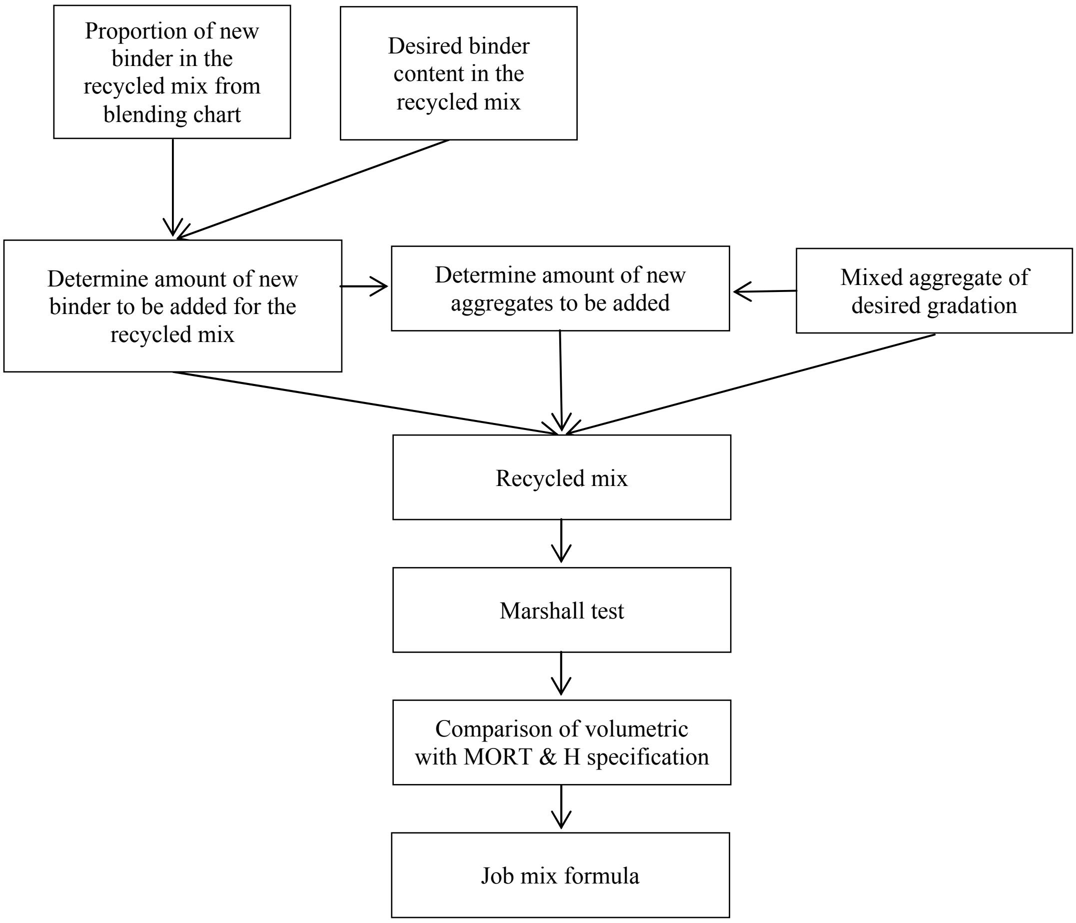


Figure 2 – Second part of the mix design process of recycled asphalt mixtures

2.4. Techniques for recycling of asphalt mixtures

Due to the steady increase in traffic, more and more roads are deteriorating. The proper strengthening and maintenance of the road network is urgently required. Effective, timely and speedy maintenance is the only way to protect the erosion of huge capital investments which are linked to the road system. Overlaying the distressed pavements with virgin courses had been adopted and continues to be the preferred method for restoration of aged pavements. The continuous application of overlays increases the pavement thickness and approaches the curb line. The conventional methods are responsible for 22 percent of the global energy consumption, 25 percent of fossil fuel burning across the world and 30 percent of global air pollution and greenhouse gases. Recycling, instead of overlaying of asphalt pavements has made a rapid advancement in the developed countries (Sathikumar and Nivedya, 2011).

One such contributor to asphalt pavement destruction is known as moisture damage. Moisture damage is caused by water infiltrating the pavement surface and weakening bonds that hold the mixtures together. Moisture damage provides the opportunity for other forms of pavement distresses as well, further weakening and destroying the pavement (Boyes, 2011).

The availability of proven and efficient recycling technology favoured the adoption of Reclaimed Asphalt Pavement (RAP) Technology in many countries. This method of strengthening and repairing roads was based on their durability rather than their initial cost.

The concept of RAP lies in restoring the physicochemical properties of the aged bitumen to its original conditions and at the same time to enhance the mechanical properties and strength of the aged binder. The various ecological and economic advantages which contributed to enhancement of recycling processes throughout the world are conservation of aggregates and binders, reduced cost of transportation, preservation of existing pavement geometrics, preservation of environment, conservation of energy and labour, decrease in pavement thickness/height (Sathikumar and Nivedya, 2011).

Aging of binders is a chemical process that is known to be source-specific; some binders are observed to age faster and become harder than others. Therefore, for proper reuse of the RAP material, there is a need to characterize aged properties and aging performance of binders so that the resistance to aging is taken into account in selecting the fresh binder, and in predicting performance of recycled asphalt pavements (Hussain and Yanjun, 2013).

The oxidized bitumen contained in RAP represents the most noticeable difficulty to overcome for the use of RAP in HMA. The bitumen oxidation is linked to a double aging process: “Short Term Aging” and “Long Term Aging”. The first takes place during paving while the second is caused by the oxidative components of the atmosphere. The reduction in viscosity, caused by the oxidation, leads to a worsening in workability at high temperatures. In addition, the bitumen contained in RAP is particularly stiff, therefore at low temperature it could show brittle behaviour as Thermal Cracking (Leandri *et al.*, 2012).

Recycling of asphalt mixtures is increasing due to higher costs of bitumen, scarcity of quality aggregates and environmental issues related to the disposal of aged asphalt mixtures. Nevertheless, the amount of RAP used is usually limited, due to the reduction on the asphalt plant productivity and on the performance of the mixture (Oliveira *et al.*, 2012a).

Thus, according to Fonseca (2005), based on the various characteristics mentioned above, the following production techniques of recycled asphalt may be used:

- Total recycling of bituminous mixtures and eventually part of the granular layers (Full Depth Reclamation): such a strategy is usually performed in situ using a large recycling equipment, including the addition of a binder which may be foamed bitumen or hydraulic binder, depending on the total thickness of the recycled layer;
- Cold In-Place recycling: such a strategy essentially involves recycling of the surface layer in order to rejuvenate their properties. In this process, the material is disaggregated and mixed with bitumen emulsion, cement or other rejuvenating agents in order to obtain a mixture having the desired properties. Typically this operation is performed continuously (disaggregation, addition of binder and compaction in a single phase) although there is also the chance to do it in two phases (first joining the binder and later disaggregating, spreading and compacting the recycled material) depending on the equipment used;
- Hot Recycling in-situ or in plant: this strategy is also essentially applied to surface layers. When carried out in-situ, it involves heating the material to be removed, the eventual reprocessing of this material (milling and particle size separation), and the mixture of aggregate and new bitumen or rejuvenating agents. Then the recycled material is spread and compacted.

The majority of old asphalt pavements are recycled at central processing plants, asphalt pavements may be pulverized in place and incorporated into granular or stabilized base courses using a self-propelled pulverizing machine. Hot in-place and cold in-place recycling processes have evolved into continuous train operations that include partial depth removal of the pavement surface, mixing the reclaimed material with additives (such as virgin aggregate, binder and softening or rejuvenating agents to improve binder properties), and placing and compacting the resultant mix in a single pass (Sathikumar and Nivedya, 2011).

2.4.1. Cold in-situ recycling

Recycling "in situ" was the first recycling technique to be used in Portugal with the objective of simultaneously rejuvenating and strengthening the distressed road surface. The implementation process consists of milling the existing pavement in a predetermined thickness, in order to, in the same place, mix and homogenize the resulting material with one or more unheated binders, followed by its laying down and compaction, ensuring the desired layer thickness (Azevedo, 2009).

The cold in-situ recycling (CIR) of asphalt pavements is a technique for pavement rehabilitation that uses 100% of the milled or reclaimed asphalt pavement (RAP) from a deteriorated road surface at ambient temperature, and which does not heat any of the mix components. Consequently, CIR has the advantage of reducing gas emissions into the atmosphere. It also cuts fuel consumption since there is no need to transport RAP to an asphalt plant or to convey the mix from the plant to the paving site for spreading and compaction. Nevertheless, one of the weaknesses of this technique is the design of the job mix formula since the densities of laboratory test specimens are generally higher than the densities of the samples obtained at the worksite (Martínez-Echevarría *et al.*, 2012).

According Santos (2010), in-situ recycling is more favourable when it occurs in pavements with thick granular layers and very distressed bituminous layer, where it is possible to:

- Use the existing materials;
- Reduce or eliminate the use of new aggregates and bituminous binders;
- Lower energy consumption;
- Increased speed of execution;
- Avoid changing the RAP or new materials;
- Lower the impact on traffic and surrounding pavements.

From the environmental point of view, one of the disadvantages is the pollution produced especially in the hot in-situ recycling. At the technical level there are limitations on the quality of RAP material (aggregate and binder), on the thickness of the cold recycled layers, on the mechanical characteristics of the final recycled layers and on the need for standardization of the production and quality control of the recycled mixtures (Santos, 2010).

The cold recycling can be performed "in situ" or in plant, and it can be applied in two ways, with the use of asphaltic binders or with the application of cement.

Cold in-situ recycling with foamed bitumen

About the foamed bitumen, this is a colloidal system, and this recycling technique combines, in general, the advantages of any in-situ recycling process and any cold recycling process, presenting other advantages (Lewis and Collings, 2008):

- Easy application - the foamed bitumen is sprayed directly into the recycler's mixing chamber;
- It is resistant to the ingress of water;

- Foamed bitumen treated material forms a flexible layer with good fatigue properties that is not prone to shrinkage cracking.
- Usually less expensive than bitumen emulsion or a combination of emulsion and cement;
- Additional water is not added to the recycled material, as is the case when emulsion is used;
- Rapid strength gain - the road can be trafficked immediately after compaction is complete.

According to Lewis and Collings (2008) this technique has the following disadvantages:

- Requires a supply of hot (180ºC) bitumen. For foamed bitumen treatment, the material should have between 5% and 15% passing the 75 micron sieve size;
- If this is not the case, the grading should be rectified by importing and spreading a layer of suitably graded aggregate over the layer to be recycled.

The production control of this kind of recycling technique is presented in Figure 3.

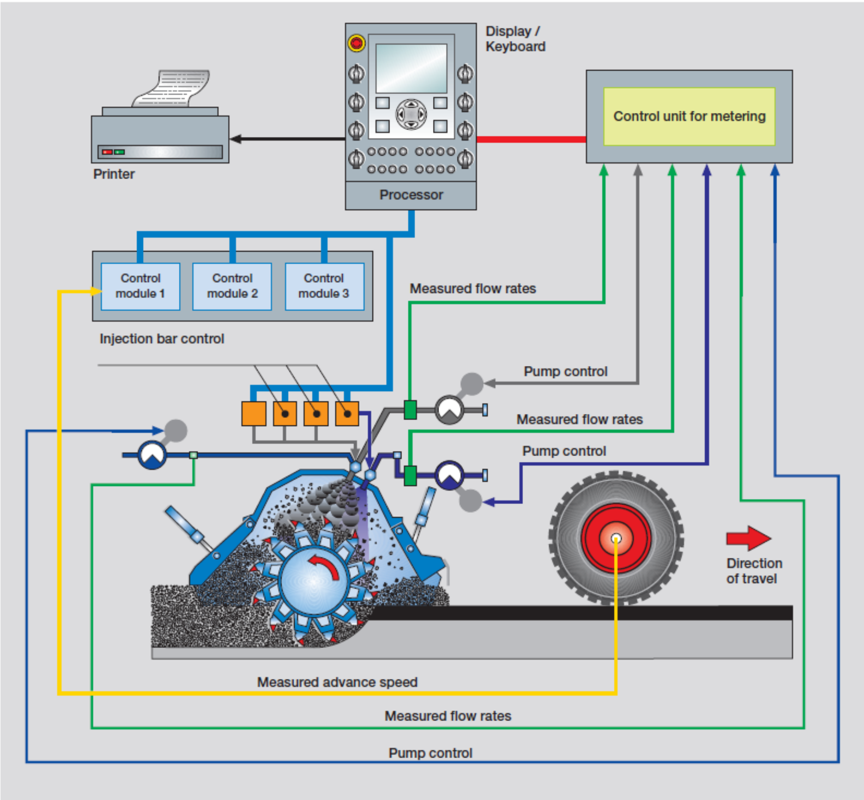


Figure 3 – Control of in-situ pavement recycling with foamed bitumen (adapted from Wirtgen (2013))

Cold in-situ recycling with cement

In distressed pavements with high granular layer thickness, recycling with cement may be, in most cases, an economical and technically feasible rehabilitation solution. The recycled layer turns out to be a cement stabilized material and presents much higher resistance than the previous, turning the final structure to be similar to a semi-rigid pavement (Baptista, 2006, Branco *et al.*, 2005, Silva, 2011).

The cold in-situ recycling with cement allows the use of higher depths than when the recycling is carried out with bituminous emulsion. In this way, it is a suitable technique for those situations in which a substantial increase in bearing capacity of the pavement is to be obtained, with a low addition of new layers (Silva, 2010).

Another advantage of recycling with cement compared with recycling with bitumen emulsion is that the mixtures recycled with cement are characterized by a much greater stiffness than that of the mixtures with emulsion. That will be reflected in a very significant increase in the pavement bearing capacity in relation to the initial situation, and also an important decrease of deflections and stresses transmitted to the foundation (Jofré, 2003 apud, Silva, 2010).

2.4.2. Cold recycling with bitumen emulsion

Cold recycling with bitumen emulsion, like recycling with foamed bitumen, can be done in two different ways, in-situ or in-plant. Emulsions are colloidal systems, namely two immiscible liquids, water and bitumen, which coexists by dispersing small droplets of water in the bitumen, which is aided by the introduction of an acidic or basic emulsifier that ensures that dispersion (Baptista, 2006).

According Batista and Antunes (2012), the works of in-situ pavement recycling with cold bitumen emulsion (Figure 4) involve, in a general way, the following constructive stages:

- Spreading of correction material (cement, aggregates and/or lime), based on a previously established mix design; currently, modern equipment can be used to the addition of lime or cement immediately before the recycling machine passes on the pavement;
- Passage of the recycling machine in the existing:
  - Breakdown of the existing pavement by milling to a depth established;
  - Continuous addition of bituminous binder, and optionally, water;
  - Mixing disaggregated material with additional materials;

— Spreading the final mixture;

- Compaction of the mixture.

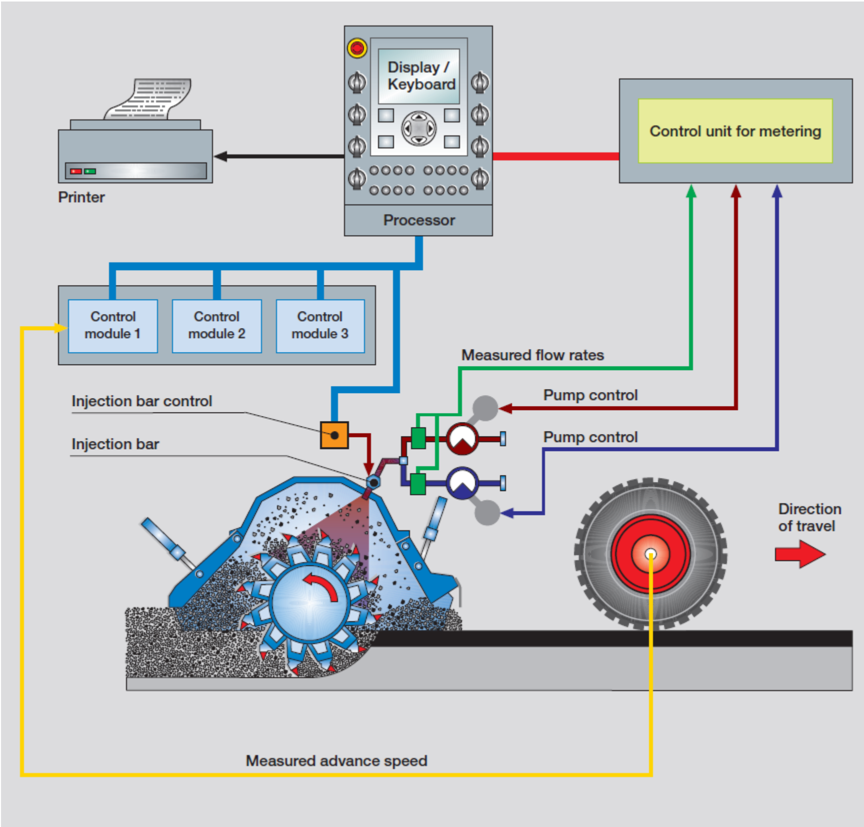


Figure 4 – Control of in-situ pavement recycling with bitumen emulsion (adapted from (Wirtgen, 2013))

2.4.3. Warm recycled bituminous mixtures

In order to reduce the production temperature and, consequently, the energy consumption in the manufacture of asphalt mixtures, a new concept was developed and has been tested and implemented in the last few years. This is the WMA technology which intends to lower the production temperature, but keeping the mechanical and rheological properties of warm asphalt mixtures as close as possible to those of conventional mixtures (Oliveira *et al.*, 2013b).

Nowadays, WMA is a very important technology for the reduction of energy consumption and gas emissions during the production stage of asphalt mixtures, but it becomes significantly more important, when applied to recycled asphalt mixtures. In the road pavement industry, sustainability is often associated to pavement recycling, where part of the demolition waste (also known as reclaimed asphalt pavement – RAP) is reused and incorporated in the production of new asphalt mixtures (Oliveira *et al.*, 2012a).

WMA technology can significantly reduce the temperatures of mixing and application of the mixture comparatively to the traditional hot mix asphalt (HMA), by 20–30ºC. This reduction of temperature is translated into a reduction on the consumption of energy on the manufacturing process. Moreover, the use of this technology leads to a decrease on the emissions of gases and odours from plants, and an improvement on the personnel working conditions. With respect to gas emissions, there are studies that report reductions of about 30–40% in emissions of CO2; 35% in emissions of SO2; 50% in emissions of VOC; 10–30% in emissions of CO; 60–70% in emissions of NO_x and 20–25% in emissions of dust. Another benefit associated to this technology is the possibility of extending the construction season and the time available for the application of the asphalt mixture during a certain day (Prowell, 2007).

Two technologies have been primarily used for the production of WMA. The first technology is the use of a proprietary mineral or additive blended with asphalt binder which helps in lowering its viscosity value or in improving the workability of the mixture at lower temperatures, such as *Sasobit*, *Rediset WMX*, *Cecabase*, *Evotherm*, among others. This process can be considered a non-foaming WMA technology. The second technology consists of a physical production process known as foamed bitumen or by using foaming material like *Asphamin*. By adding it to the mixture at the same time as the binder, a very fine water spray is created as all the crystalline water is released, which causes a volume expansion in the binder, thereby increasing the workability and compatibility of the mixture at lower temperatures (Xiao *et al.*, 2012).

2.4.4. Hot in-place recycling

Recycling processes of hot bituminous materials can be performed in plant, making small adaptations to conventional asphalt plant or in-situ using developed equipment for this purpose (Oliveira *et al.*, 2013b, Silva, 2010).

The hot in-place recycling (HIR) consists of heating the existing pavement, facilitating their dissolution, and mixing with a binder or soft rejuvenating bitumen. The binders to use are specific bituminous emulsions or polymer modified bitumen able to regenerate oxidized bitumen aged.

The equipment used in the HIR is extremely large and difficult to move, so the selection depends not only on existing availability, but also the method of transporting them to the construction site. This is one of the disadvantages of hot in-situ recycling, together with the high cost of equipment, and the fact that the technique also causes high energy consumption and pollution (Santos, 2010). Some of that equipment is presented in Figure 5.

Figure 5 – Example of a hot in-situ recycling operation (adapted from adapted from Wirtgen (2013))

Comparing hot in plant recycling with hot in-situ recycling, the latter has some advantages, since there is no need to transport the milled materials to the plant and the recycled material back to the working site, thus making it more economical, and also has the advantage of causing less disturbance to the traffic, making it a less time-consuming operation. As inconvenience is difficult to control the quality control of the final mixture (Oliveira *et al.*, 2013b).

2.4.5. Hot in-plant recycling

Amongst the several techniques available to recycle asphalt mixtures, hot in-plant recycling is one of the solutions most adopted in Europe, especially in countries like the Netherlands, Germany and Denmark, which currently recycle over 75% of the total asphalt mixtures produced. Despite having recognized advantages of an economic and environmental nature, to be used in a significant and standard way in many countries, this technique has been relatively little used in Portugal. This delay was due largely to a certain resistance to change resulting from some fear felt by the road sector (project owners, builders and designers) with respect to both the manufacturing process, and the performance of mixtures when in service (Baptista, 2006).

The in plant recycling, by conventional methods, always involves milling, transportation of the milled material, storage and production and bituminous mixtures and can thus be used as a pavement regeneration process or a recovery of milled materials obtained in other road sections. In these cases the percentage of recycled materials used in the composition of the recycled mixtures do not exceed 40 to 50% and the bitumens used are generally less stiff. Currently, the major development in the field of asphalt plant technology is the appearance of new drum mixers, which allow the use of higher percentages of recycled material (Azevedo, 2009).

The execution of a hot recycled bituminous mixture in plant includes the following operations (Azevedo and Cardoso, 2003 apud, Silva, 2010):

- Storage of the material coming from old pavement;
- Processing of raw bituminous material to be recycled;
- Characterization and storage of treated bituminous material to recycle;
- Study of the mixture and obtain the working formula;
- Manufacture of the mixture according to the working formula;
- Transport of the mixture to the application site;
- Preparation of the surface on which the mixture will be spread;
- Spreading and compacting the mixture.

Figure 6 shows a classification system used to incorporate recycled material in a hot-mix asphalt plant.

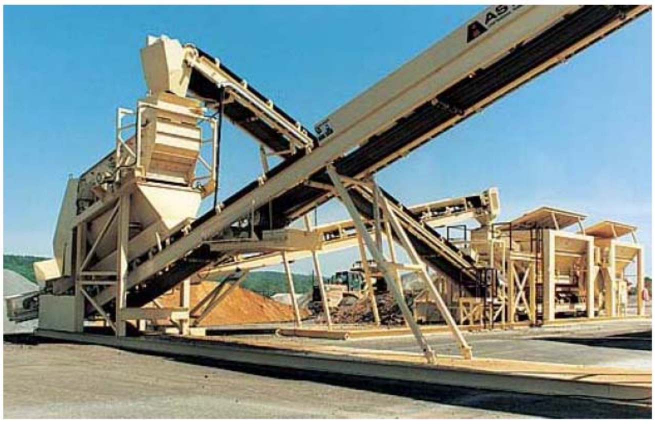


Figure 6 – Classification system for incorporation of recycled material in continuous plant (adapted from Fonseca (2005))

The hot recycling presents clear advantages of an economic nature and environmental compared to the production of conventional new asphalt mixtures, due to the economy with the aggregate and bitumen. This last one is more pronounced with the increase that has been observed in recent years in the price of crude oil. At the environmental level, the lower consumption of natural resources (bitumen and aggregate) and a better application of milled materials can be highlighted (Branco *et al.*, 2005).

The disadvantages normally associated with the production are related to the reduction in the production capacity of the plant and the higher heating of aggregates and, therefore, higher energy costs. However, it should be noted that, although the heating temperature is higher than normal, the amount of new aggregates is also smaller, so in terms of energy costs, since the final temperature of the mixture is equal to the hot bituminous mixtures, consumption is identical (Branco *et al.*, 2005).

2.5. Behaviour of recycled asphalt mixtures

A recycled asphalt mixture generally consists of a blend of old and virgin aggregates, and a blend of old and virgin binders. In a hot recycled mix, the blending of the old binder and the virgin binder (or rejuvenating agent) is relatively more homogeneous. In a cold recycled mix, the virgin binder or rejuvenating agent tends to adhere to the old material (old aggregate coated with old binder), and to form a thin film around it. The diffusion of the virgin binder or rejuvenating agent into the old binder is a function of time, temperature and additional traffic compaction. This diffusion process can greatly influence the behaviour of a recycled material, and thus knowledge of its long-term behaviour is very important in designing a recycled mix (Tia, 1982).

About hot central plant recycling, in this process RAP is combined with required quantity of bituminous binder, and fresh aggregates in a hot mix plant. The resultant mix is heated to an elevated temperature and mixed thoroughly. The hot mix is transported to paving site, placed, and compacted to the required compaction level. The main advantage of this process is that the mix properties and performance is comparable to that of virgin mixtures (Aravind and Das, 2005).

Epps *et al.* (1980) have noted that the quality control in this process is better when compared to hot in-place recycling. As RAP is susceptible to moisture, care needs to be taken while storing it. Less workspace is required for laying the recycled mixture; hence this is suitable for the roads where the right-of-way is somewhat restricted. The RAP should not be exposed to extremely high temperature as it causes pollution due to smoke emission (Aravind and Das, 2005).

2.6. Materials used to improve the performance of recycled asphalt mixtures

Recycling asphalt pavements has the advantages of decreasing the demand for natural resources, decreasing the production of waste material and reducing costs. Desirably the amount of the asphalt pavement that is recycled should be maximized and the amount of new material that is added to the recovered asphalt should be minimized (Nigen-Chaidron and Porot, 2009).

In order to improve the performance of recycled bituminous mixtures, some additives can be used, which may ultimately confer characteristics similar to those of new bituminous mixtures to the recycled mixtures. Thus, it is important to recover some lost properties of the aged bitumen. The additives used in this kind of process are mostly rejuvenating agents that are one of the recycling agents, suitable for either highly oxidized or for mixtures containing a large percentage of RAP (Shen *et al.*, 2007).

2.6.1. Anti-stripping and temperature reduction additives

The techniques more used for the Warm Mix Asphalts are: the organic additives, chemical additives, foamed bitumen with water injection and foamed bitumen with synthetic or natural minerals. This technology aims to reduce the temperature of production and compaction of bituminous mixtures, maintaining an adequate workability of the mixture, in comparison with the hot asphalt mixtures. This improvement comes from additives which increase the characteristics of the blends, such as workability and reduction in volume of voids (Silva, 2011).

According to Boyes (2011), perhaps the most commonly used ant-stripping additives are hydrated lime and liquid amine-based chemicals. More recently however, improving pavement performance through the use of recycled waste materials such as fly ash, cement kiln dust, glass, and used tires has gained interest.

The additives are divided into two types: organic additives and chemical additives.

Organic additives

Several processes are available to reduce the mixing and compaction temperature of hot mix asphalt, one of these processes uses waxes to reduce the viscosity of the bituminous binder in the high temperature range. In order to be efficient, this wax should be solid at the highest service temperature, but at temperatures above the highest service temperature the wax should melt, become liquid, lower the viscosity of the mixture and in this way should allow production and compaction of asphalt mixes at reduced temperatures. Literature shows that waxes with a melting point in the range between 100°C and 145°C have been used as viscosity reducers. According to the producers of these waxes, a temperature reduction of 30°C can be achieved compared to standard hot mix applications. Apart from their ability to reduce the production temperature, these waxes are also promoted as performance improvers for rutting (Soenen *et al.*, 2008).

Chemical additives

This type of additive is added directly to the binder, facilitating the coating of aggregates at lower temperatures. The properties of the bitumen are not significantly changed with the use of such additives, since its use does not reduce the viscosity of the bitumen. These additives allow substantially improvements in the workability of the mixture, thus enabling the production of bituminous mixtures at lower temperatures. The improvement in workability of the mixtures is also positive in the case of using RAP material (Silva, 2010).

2.6.2. Crumb rubber recycled from used tires

The rubber-modified binders are obtained by the incorporation of crumb rubber to the conventional asphalt binder under certain temperature and agitation conditions. The resulting asphalt rubber (AR) has both the mechanical properties of the asphaltic matrix and the elasticity of rubber (Huang and Yan, 2000 apud, Neto *et al.*, 2003).

AR binder can be used with asphalt mixtures incorporating new material and recycled material. The use of AR or the use of a conventional binder will depend on the expected performance of the new bituminous mixture and on a cost/benefit analysis. The binders (conventional bitumen) of asphalt incorporating recycled material generally have a penetration in the range of 100 to 150 mm. The use of such bitumen allows obtaining less rigid mixtures, since the binder existing in the RAP tends to become harder in service with time. Considering the high resistance to aging (due to manufacturing, application, and the action of ultra-violet rays when in service) of AR binders and mixtures, it is expected that this binder is not as oxidized as a conventional binder and still presents good elastic properties and adhesiveness after a longer service life (Fonseca, 2005).

2.6.3. Rejuvenating agents

A rejuvenating agent that is commonly used is a low viscosity product obtained from crude oil distillation. Other alternative products have also been used as rejuvenating agents by different authors, including waste materials from other industries (Oliveira *et al.*, 2013a, Oliveira *et al.*, 2013b) or natural products of plant origin (Nigen-Chaidron and Porot, 2009). Incorporating a plant product instead of a petroleum product offers a potentially more sustainable product, and may lead to price and supply advantages. The natural-product based rejuvenating agent must have the required technical properties and in use should be safe and easy to handle.

These kinds of additives have, as their name indicates, the purpose of rejuvenating the aged bitumens, recovering their properties by reconstituting the chemical composition of bitumen. Bitumens are constituted by asphaltenes and maltenes, and the hard component (asphaltenes) is insoluble and is not affected by oxidation. The maltenes instead are highly reactive and disappear over time, with the aging of the bitumen, which occurs during the production of the mixtures and throughout the life of the pavement. The rejuvenator is a product having the ability to restore part of the maltenes that disappeared due to oxidation of the bitumen. The use of rejuvenating agents is therefore ideal for recycled mixtures, because the bitumen in the milled material is aged. The use of rejuvenating agents allows reducing the viscosity of bitumen and also decreases the stiffness of the asphalt mixture, thereby making it possible to increase the pavement lifetime (Silva, 2010).

The rejuvenator percentage may be crucial to the properties of the blended aged asphalt. The rejuvenator should be properly added so that the binder properties under low temperature are improved while the properties under high temperature are not adversely affected. Traditional methods to determine the percentage of the rejuvenator are predominantly based on blending charts of either a penetration or a viscosity criterion. In addition, a more integrated approach for the determination of the rejuvenator percentage was proposed by considering not only the penetration or viscosity criterion. However, some of these methods do not consider the performance-based properties of the rejuvenated aged asphalt binders using a rejuvenator as required by SHRP specifications (Shen *et al.*, 2007).

In most mix design methods of hot recycled bituminous mixtures, the selection of the type of a new bitumen and/or rejuvenating depends on the recycling rate of the mixture, the characteristics of the aged binder and the desired properties of the final binder (Bento, 2010).

2.6.4. Foamed bitumen

Despite being a technology developed for over 40 years, the use of foamed bitumen just turned massive in 1991, the year in which the rights to the patent belonging to the company MOBIL Australia expired (Seixas, 2008).

The paving processes always incorporate some variability that comes generally from the diversity of materials used and foamed bitumen are a good example. The properties of the foam varies with various factors such as the properties of the bitumen or features of the device which produces the foam (Teixeira, 2006).

Foamed bitumen is a stabilizing agent that may be used with full depth reclamation. Full depth reclamation involves milling the existing bituminous pavement plus a portion of the base material. The milled material is then graded and compacted. Traffic can use the roadway until a bituminous base and surface course is applied (Marquis *et al.*, 2003).

Foamed bitumen, also referred to as expanded bitumen, is a hot bituminous binder which has been temporarily converted from a liquid to a foam state by the addition of a small percentage of water (typically 2 per cent). The foamed bitumen is characterized in terms of expansion ratio and half-life. The expansion ratio of the foam is defined as the ratio between the maximum volume achieved in the foam state and the final volume of the binder once the foam has dissipated. The half-life is the time, in seconds, between the moment the foam achieves the maximum volume and the time it dissipates to half of the maximum volume (Muthen, 1999). This process of foamed bitumen production is illustrated in Figure 7.

The foamed function is the binder component of the mixture. Initially, it is necessary to consider the presence of water in the form of initial moisture in the aggregates since this affects how the foam disperses in the aggregates. In a second phase the water needed for the production of the foam has to be considered. And in a third phase, the moisture content of the mixture should be within certain limits in order to allow a good compaction (Teixeira, 2006).

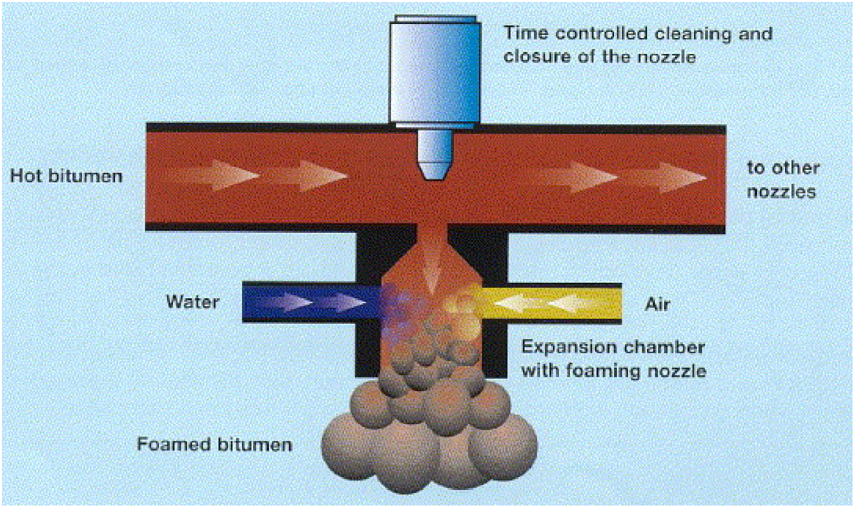


Figure 7 – Production of foamed bitumen on the expansion chamber (adapted from Wirtgen (2013))

The optimum mixing temperature of the aggregates for foamed asphalt mixes lies in the range of 13° C to 23° C, depending on the type of aggregate. Temperatures below this range result in poor quality mixes (Bowering and Martin, 1976). Foamed asphalt mixes may also be prepared with heated aggregates which will increase the binder dispersion within the mix and aid in the coating of the larger aggregates (Muthen, 1999).

Brennen *et al.* (1983) found that the half-life and expansion ratio of the foam produced from any particular bitumen was affected by the volume of foam produced, the quantity of water used and the temperature at which the foam was produced. Higher foaming temperatures and increased quantities of water both resulted in increased expansion ratios, but resulted in decreased half-lives.

Thus, the expansion and the half-life are related to the percentage of water used in the production of the foam, as shown in Figure 8. The higher the value of the percentage of water used in the production of the foam, the higher the expansion and smaller the half-life of the foam. Once the parameters expansion and half-life are inversely related, it is concluded that the optimization of both is not an easy process (Muthen, 1999).

According Muthen (1999), the following advantages can be mentioned in the use of foamed bitumen in asphalt mixtures:

- The foamed binder increases the shear strength and reduces the moisture susceptibility of granular materials. The strength characteristics of foamed asphalt approach those of cemented materials, but foamed asphalt is flexible and fatigue resistant;

— Foam treatment can be used with a wider range of aggregate types than other cold mix processes;
— Reduced binder and transportation costs, as foamed asphalt requires less binder and water than other types of cold mixing;
— Saving in time, because foamed asphalt can be compacted immediately and can carry traffic almost immediately after compaction is completed;
— Energy conservation, because only the bitumen needs to be heated while the aggregates are mixed in while cold and damp (no need for drying);
— Environmental side-effects resulting from the evaporation of volatiles from the mix are avoided since curing does not result in the release of volatiles;
— Foamed asphalt can be stockpiled with no risk of binder runoff or leeching. Since foamed asphalt remains workable for very extended periods, the usual time constraints for achieving compaction, shaping and finishing of the layer are avoided;
— Foamed asphalt layers can be constructed in adverse weather conditions, such as in cold weather or light rain, without affecting the workability or the quality of the finished layer.

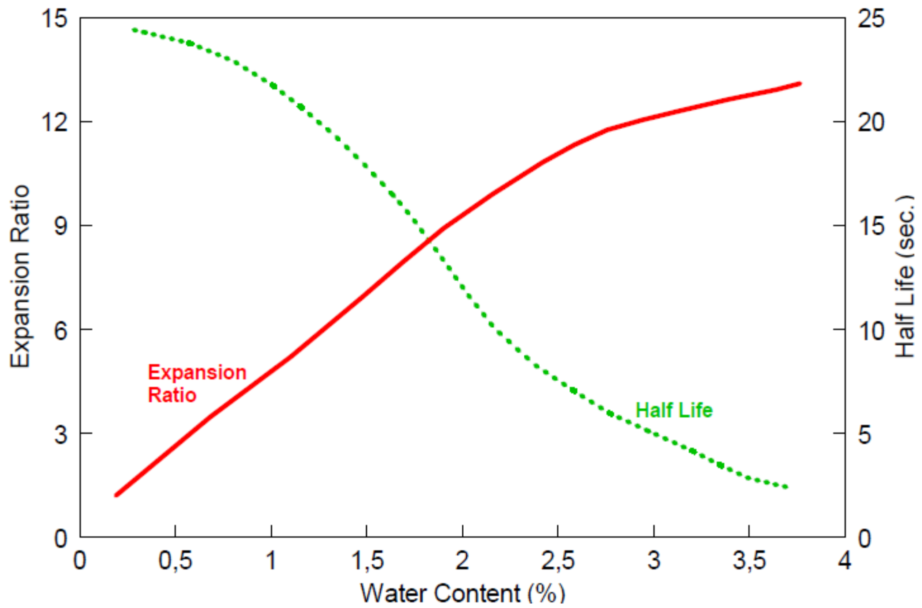


Figure 8 – Optimizing foam properties (Muthen, 1999)

3. MATERIALS AND METHODS

To comply with initial objectives of the present study, a laboratory work on the physical characteristics and mechanical properties of various binders, aggregate materials and finally the bituminous mixtures was established.

The study is divided into three stages; the first stage is the production of a conventional bituminous mixture, the second stage comprises the production of recycled bituminous mixtures, with 50% of new aggregates and bitumen and 50% reclaimed asphalt pavement, and the third and last stage, includes the production of a recycled bituminous mixture with 50% of new materials and 50% RAP, but with a rejuvenating and WMA additive in its composition.

3.1. Materials

The first stage of this study involves the characterization and study of a conventional AC14 surf asphalt mixture, usually used in surface courses. Thus a conventional 50/70 bitumen and new granite aggregates were used. The study started by the definition of the percentage of each aggregate fraction that would result in a particle size distribution that would fulfil the Specifications for a conventional surface course bituminous mixture. The production of this bituminous mixture will aim at serving as a basis of comparison for the analysis of the performance of the recycled bituminous mixtures that were also studied in the present work.

In the second stage, a recycled bituminous mixture was produced with 50% of RAP material and 50% of new materials (granite aggregates and a 70/100 bitumen), without any rejuvenating agent.

In order to assess the influence of a rejuvenating agent in the performance of a recycled mixture with 50% RAP incorporation, a third stage was established, where two newly developed additives (from *Korea Institute of Construction Technology,* named additive A and B and for this dissertation) were studied; the additive showing the most promising results in terms of binder modification and cost was selected for the remainder of the investigation carried out in this dissertation. Subsequently, the laboratory tests were carried out to determine the optimum additive content, in order to obtain a final binder with properties similar to those of a conventional 35/50 bitumen (since the hard binder present in the RAP makes it difficult to obtain softer final binders, like a 50/70 binder).

3.1.1. Characterization of new aggregates

The new aggregates used in conventional mixture, are granite aggregates, except the filler, which is a limestone. The aggregates used in particle size distribution study belonged to the 6/14, 4/8, 4/6, 0/4 and filler fractions, showed in Figure 9.

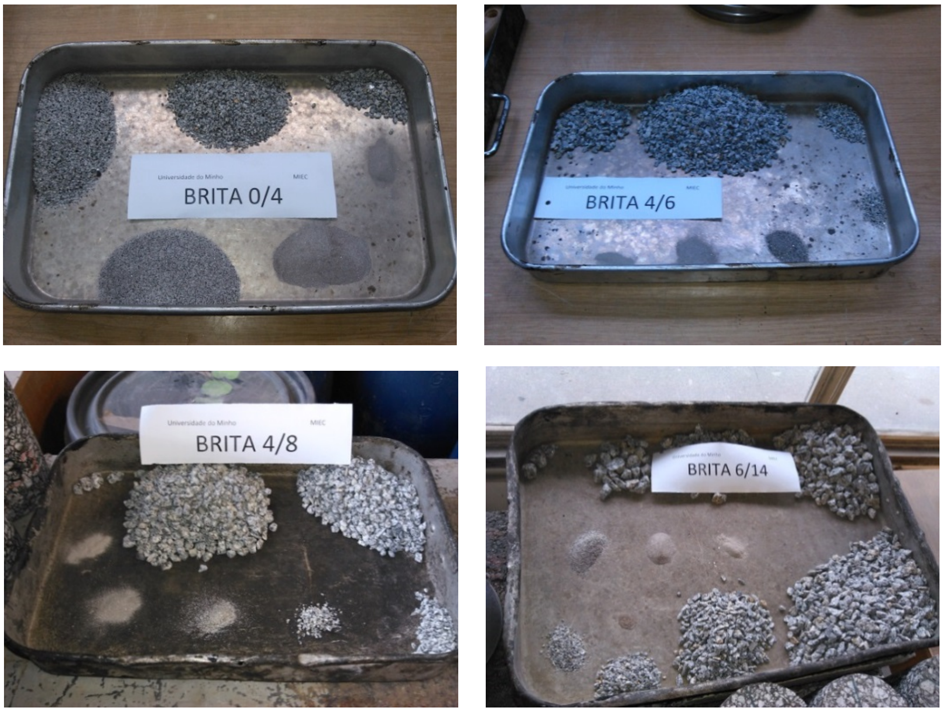


Figure 9 – Aggregates used for the conventional bituminous mixture

The particle size distribution of each fraction was carried out according to EN 933-1. Table 2 summarizes the results obtained for each aggregate fraction.

Table 2 – Gradation of aggregates for use in conventional bituminous mixtures

Sieves ASTM	Cumulative percentage of material passing				
Opening the sieve (mm)	Gravel 6/14	Gravel 4/8	Gravel 4/6	Powder 0/4	Fillers
40.000	100	100	100	100	100
31.500	100	100	100	100	100
20.000	100	100	100	100	100
16.000	99	100	100	100	100
14.000	94	100	100	100	100
12.500	80	100	100	100	100
10.000	53	99	100	100	100
6.300	10	40	87	100	100
4.000	2	3	6	94	100
2.000	1	1	3	71	100
0.500	1	1	2	39	100
0.125	1	0	2	17	100
0.063	0	0	1	11	99
Rest	0	0	0	0.8	0

According the material specifications of Estradas de Portugal (2009) the grading envelope of this type of mixture, the limits of which are shown in Figure 10.

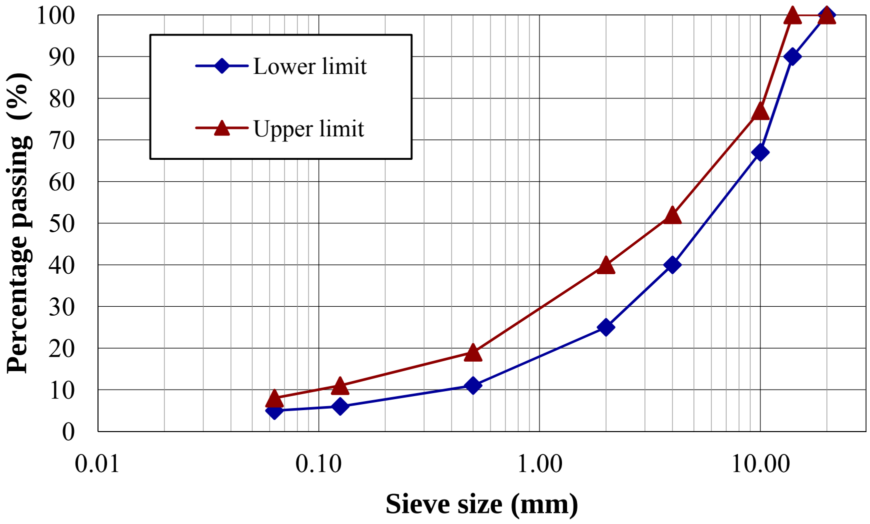


Figure 10 – Limits of the aggregates grading envelope for a conventional AC14 Surf mixture

3.1.2. Characterization of the new binders

Penetration and Softening temperature

The asphaltic bitumen is classified according to the limits penetration at 25°C (EN 1426). The Table 3 indicates compliance requirements for bitumen provided for in this specification. Other tests are also used to better characterize the bitumen, for example, the softening point temperature by the Ring and Ball method (EN 1427), the dynamic viscosity with rotational (“Brookfield”) viscometer, and also rheological tests by the dynamic shear rheometer.

Table 3 – Types of paving bitumen, properties and compliance requirements

Properties			10/20	20/30	35/50	50/70	70/100	100/150	160/220	220/330
Penetration at 25°C		Min	10	20	35	50	70	100	160	220
		Max	20	30	50	70	100	150	220	330
Softening temperature (°C)		Min	63	55	50	46	43	39	35	30
		Max	76	63	58	54	51	47	43	38
Kinematic viscosity at 135°C (cSt)		Min	1000	530	370	295	230	175	135	100
Solubility in toluene or xylene (%)		Min	99	99	99	99	99	99	99	99
Inflammation’s temperature (°C)		Min	250	240	240	230	230	230	220	220
Resistance to hardening (RTFOT or TFOT)	Weight variation (%)	Max	0.5	0.5	0.5	0.5	0.8	0.8	1.0	1.0
	Residual penetration (%)	Min	60	55	53	50	46	43	37	35
	Softening temperature (°C)	Min	65	57	52	48	45	41	37	32
	Increased softening temp. (°C)	Max	8	10	11	11	11	12	12	12

The bitumen used in the production of the conventional bituminous mixture was a 50/70 pen bitumen. For the recycled bituminous mixture a new 70/100 pen bitumen was used. The results of the penetration test at 25°C and the ring and ball test obtained for both types of bitumen are shown in Table 4.

Table 4 – Test results of characterization of bitumen

Type of bitumen	Average penetration (0.1 mm)	Softening temperature (º C)
Bitumen 50/70	57.0	50.7
Bitumen 70/100	45.7	84.80

Dynamic viscosity

To characterize the bitumen, its dynamic viscosity decrease associated to an increase of temperature was also determined, using the rotational viscometer from Brookfield, as shown in Figure 11.

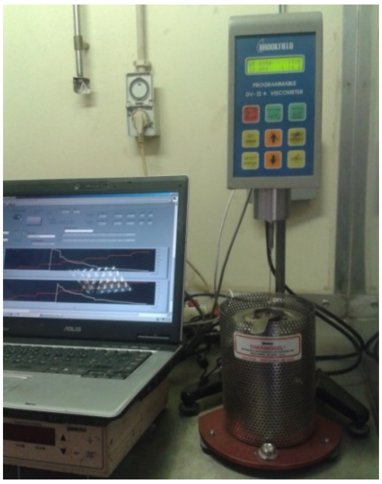


Figure 11 – Rotational ("Brookfield") viscometer

The viscosity of an asphalt binder is used to determine the flow characteristics of the binder to provide some assurance that it can be pumped and handled at the hot mixing facility; also to determine the mixing and compacting temperatures of asphalt mixtures (Xiao *et al.*, 2012).

In order to evaluate the properties of the several binders at higher temperatures (100 to 170°C) in which the bituminous mixtures are mixed and applied, their dynamic viscosity was accessed using a rotating spindle apparatus (according to the EN 13302 standard). The typical temperature of a coaxial viscometer using a rotating spindle apparatus is ranged from 50 to 250°C. During the test, the torque (relative resistance of the spindle to rotation) applied to a spindle rotating in a special sample container enclosing the binder measured its dynamic viscosity. According to EN 13302, after setting the test temperature and lowering the spindle into the binder, the system temperature should equilibrate after 15 to 30 min (lab practice showed that the usual equilibrium time is 18 min). Then, at least three readings were taken during the next 3 min for each evaluated temperature. The dynamic viscosity at each temperature is the arithmetic mean of the three readings taken between the 18th and 21st min of the test (Silva *et al.*, 2009).

The viscosity of the new 50/70 and 70/100 bitumens at different temperatures is presented in Figure 12.

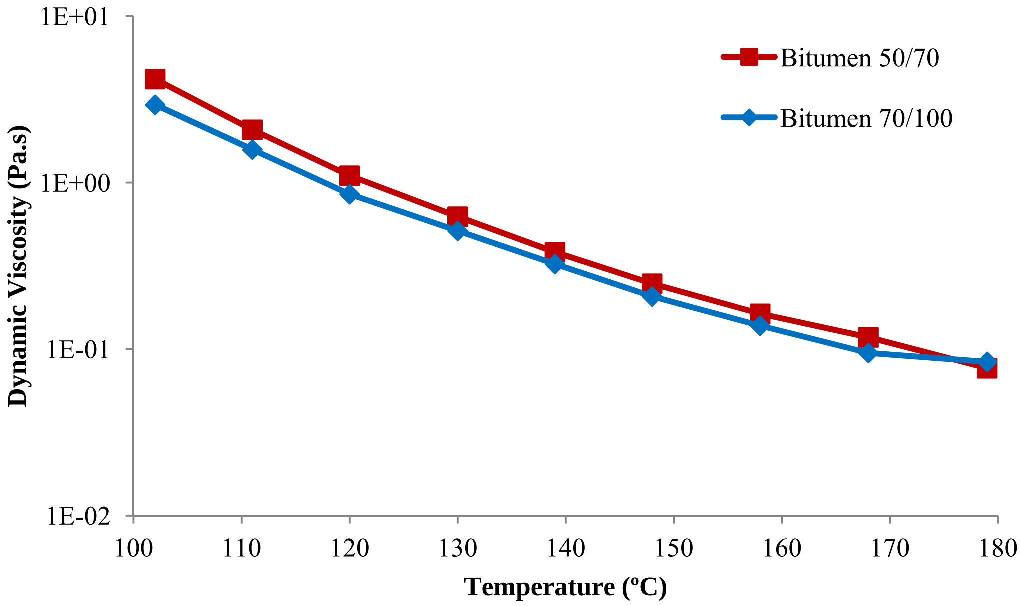


Figure 12 – Dynamic viscosity (Pa.s) of 50/70 and 70/100 bitumens

Rheology

The rheological tests were carried out in two different types of samples (one sample of 25 mm diameter, with a gap of 1 mm between plates, and another sample of 8 mm, with a 2 mm gap). Figure 13 shows the equipment used in this test. The temperatures for the 25 mm plate are: 46ºC, 52ºC, 58ºC, 64ºC, 70ºC 76ºC and 82ºC. For the 8 mm plate the temperatures are: 40ºC, 37ºC, 31ºC, 25ºC and 19ºC.

Figure 13 – Dynamic shear rheometer

Figure 14 shows the results (complex modulus and phase angle) of rheological tests carried out on the 50/70 and 70/100 bitumen.

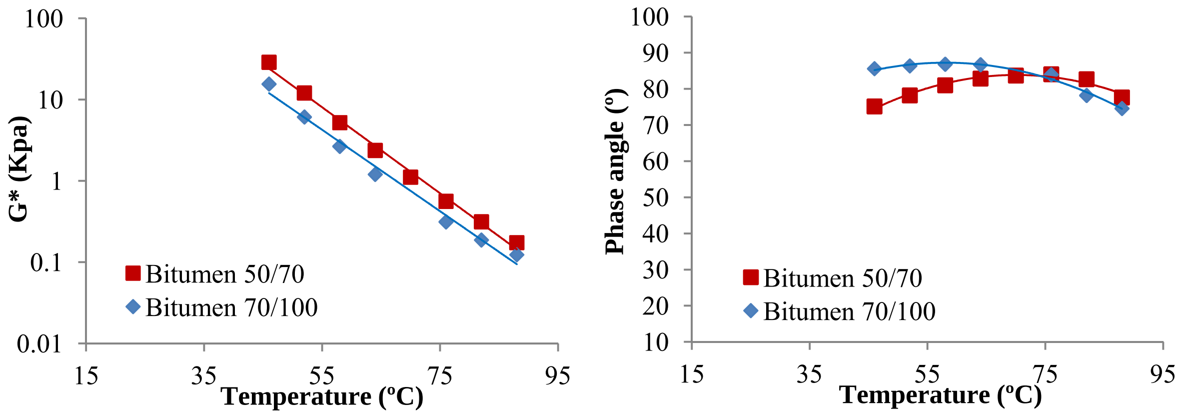
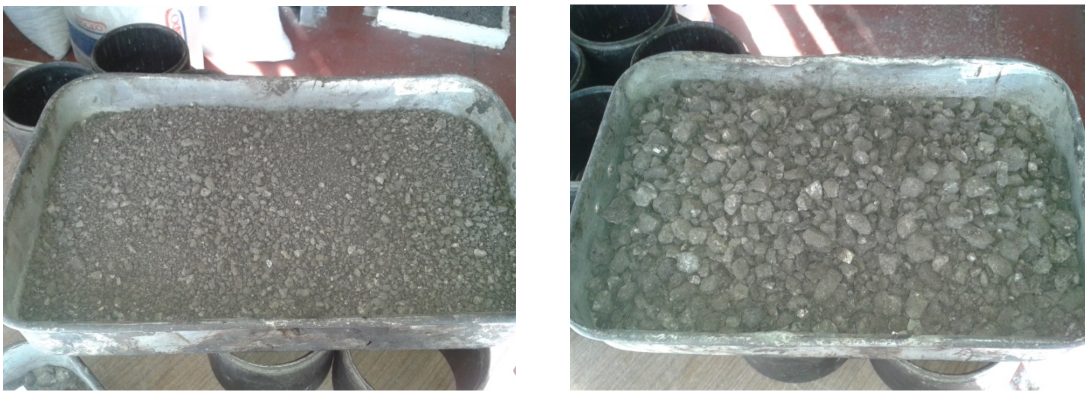


Figure 14 – The rheological analysis of 50/70 and 70/100 bitumen

As expected, the 50/70 pen bitumen is slightly harder (higher complex modulus) than the 70/100 pen binder.

3.1.3. Characterization of reclaimed asphalt pavement

As already mentioned, the recycled bituminous mixture is composed by 50% new materials and 50% RAP material, which was removed from a highway surface course. The visual aspect of the RAP material is illustrated on Figure 15, separated in two different fractions.



(a) (b)

Figure 15 – Visual aspect of RAP material: (a) – RAP 0/6; (b) –RAP 6/12

The RAP materials were derived from a milling process of bituminous pavement surface and binder layers. Fonseca *et al.* (2013), who have used the same RAP material, has determined its particle size distribution, as presented in Figure 16, for each RAP fraction.

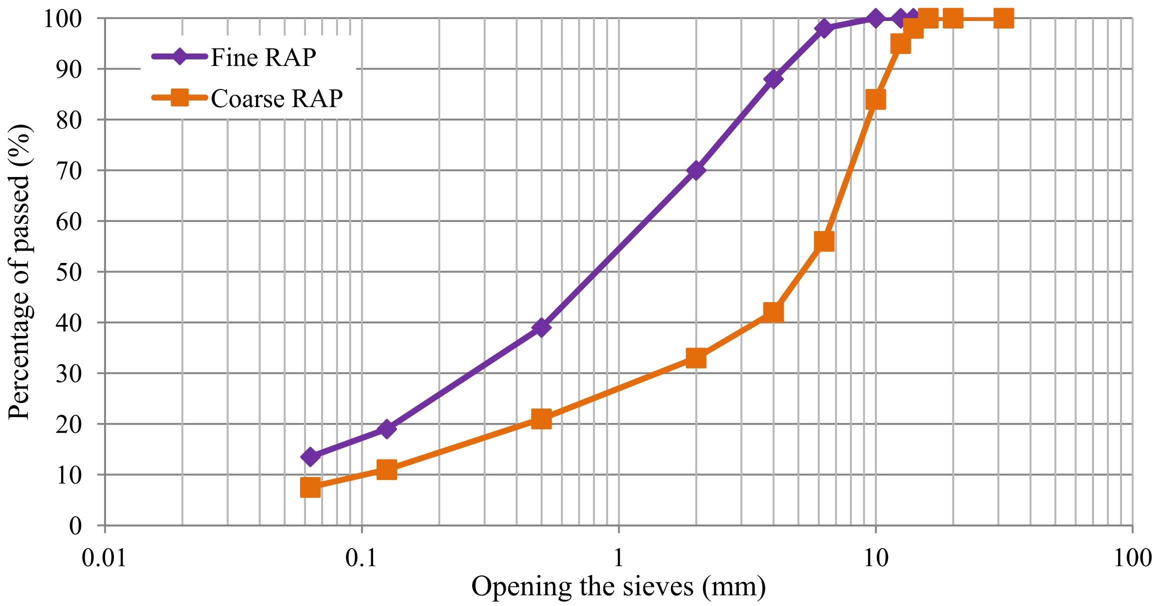


Figure 16 – Particle size distribution of fine and coarse RAP fractions

After the process of recovering the bitumen from the RAP, which contains about 5% bitumen, some tests were performed to make the characterization of the recovered bitumen. With that it was possible to define the average penetration and the softening point temperature, as shown in Table 5, the dynamic viscosity shown in Figure 17 and for last, the rheological test results presented in Figure 18.

Table 5 – Characterization of penetration and softening temperature of recovered bitumen

Type of bitumen	Average penetration (0.1 mm)		Softening temperature (º C)	
Recovered bitumen	Fine RAP	Coarse RAP	Fine RAP	Coarse RAP
	9.3	8.2	73.4	74.2

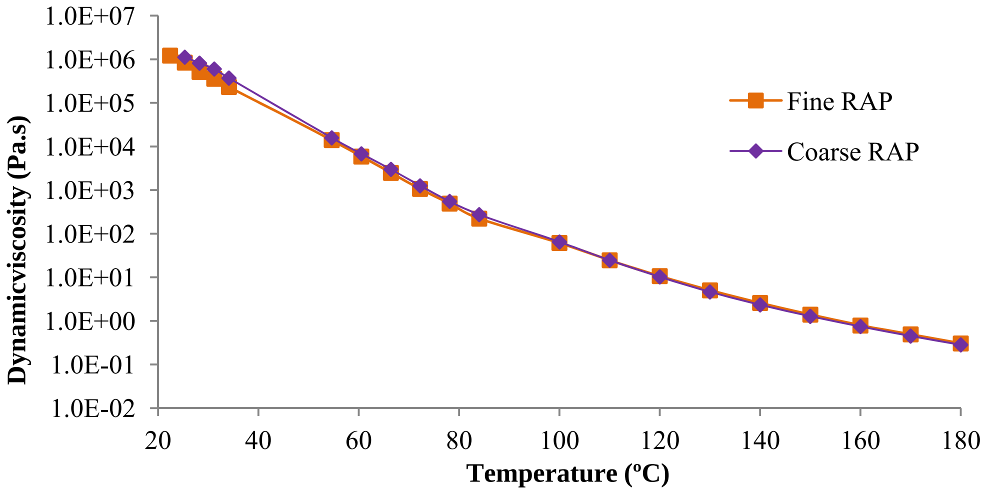


Figure 17 – Dynamic viscosity of the recovered bitumen

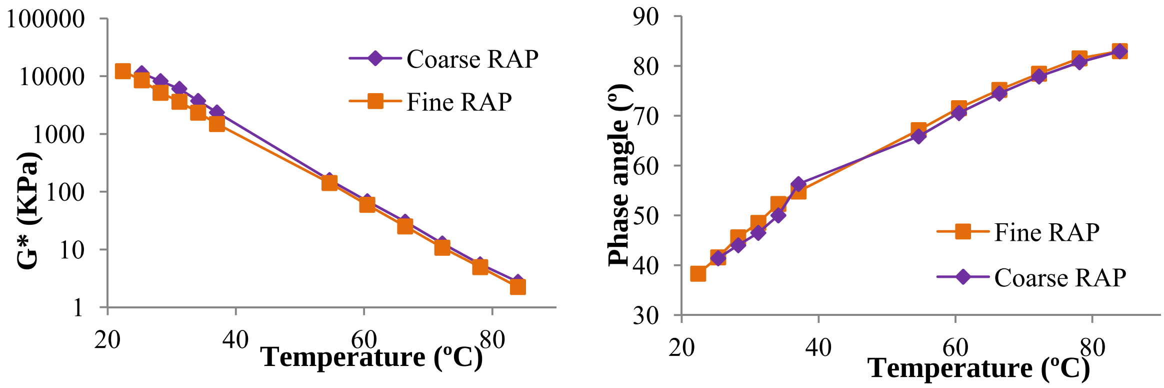


Figure 18 – Complex modulus and phase angle of the recovered bitumen

Aging is mainly due to oxidation can thus conclude that this bitumen is quite exposed to air oxidation, as it is possible to observe the reduced average penetration in the bitumen means that it's quite aged, also with the viscosity can verify this characteristic.

3.1.4. Characterization of the additives

In the present work two newly developed additives (A and B) were tested. They were produced by a South Korean company, with the objectives of rejuvenating the aged binder present in the RAP and reducing the production temperatures of the recycled mixtures. These additives have got a brownish colour; their visual appearance is presented in Figure 19.

Figure 19 – Samples of A and B additives, respectively

The additive A was also characterised in terms of dynamic viscosity (Figure 20). This test was performed only for this additive because it was the only additive used in bituminous mixture as it will be shown later.

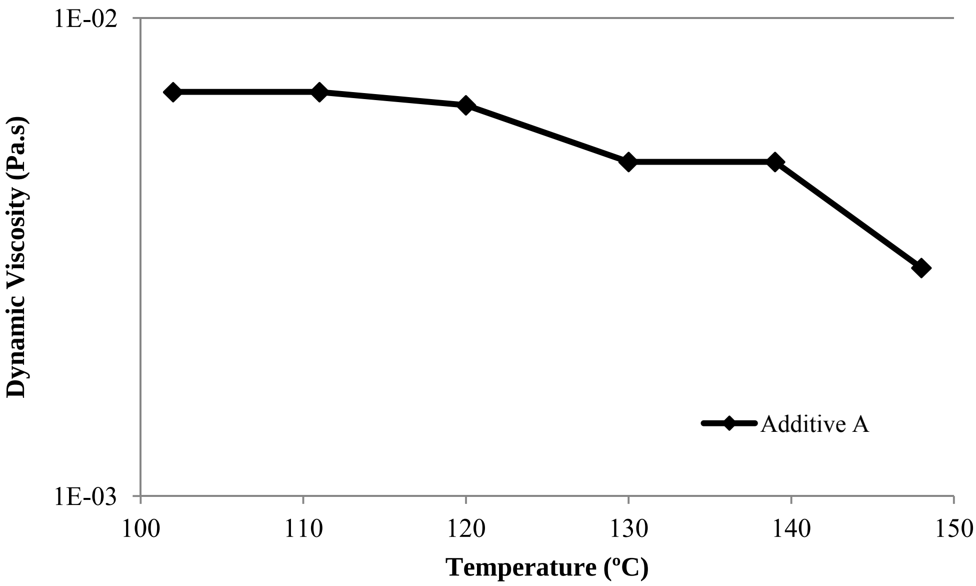


Figure 20 – Dynamic viscosity of additive A

Even though, this additive shows a very low dynamic viscosity at room temperature, it is possible to observe from Figure 20 that its viscosity slightly decreases at temperatures above 120 ºC, which helps improving the workability of the mixture produced with high rates of RAP incorporation.

3.2. Methods

3.2.1. Production of the bituminous mixture

In the mixtures manufacturing process, the reference temperature for the production of the mixture was taken into account, according to the class of penetration of the bitumen used therein, based on the EN 12697-35 standard.

When producing recycled mixtures it is important to understand how the temperature of the mixture evolves according to the temperature of aggregates and the temperature of the RAP. In the present work 30% of RAP fine material and 20% of RAP coarse material were used. Since the first is introduced at room temperature and the second is heated up, the temperature of the recycled bituminous mixture is obtained from Equation 1, adapted from Abreu (2012), which corresponds to a weighted average of all temperatures.

$$T_{bm} = (\%C_{RAP} + \%NA) \times T_{CRAP+NA} + \%F_{RAP} \times TF_{RAP} \quad (1)$$

Where:

T_{bm}	production temperature of bituminous mixture;
$\%C_{RAP}$	percentage of coarse RAP;
$\%NA$	percentage of new aggregates;
$T_{CRAP+NA}$	heating temperature of the coarse RAP and new aggregates;
$\%F_{RAP}$	percentage of fine RAP;
TF_{RAP}	temperature of fine RAP.

Using Equation 1 and knowing the temperature of the fine RAP (at room temperature, it is about 25ºC) it is possible to obtain a relationship between the mixture production temperature and the heating temperature of the remaining material, as presented in Figure 21.

Thus, based on the production temperature, the aggregates are heated up to the defined temperature after which the production process is initiated, comprising the following steps:

- Placement of new aggregates and coarse RAP fraction in the mixer, at maximum speed for 1 minute. This process allows homogenization of the material;
- Addition of fine RAP material to the mixer, mixing for 1 minute at maximum speed; this material will drop the temperature of the mixture;

— Finally, addition of the new bitumen and mixing for 2 minutes at maximum speed.

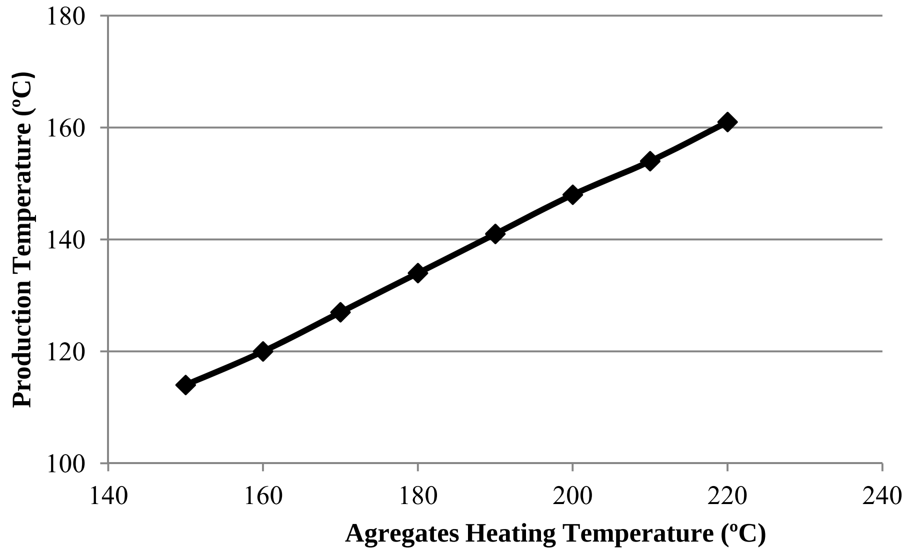


Figure 21 – Relationship between the mixture production temperature and the aggregates heating temperature

Immediately before producing the mixture, it is necessary to add the rejuvenating agent to the new bitumen. This includes the following the steps:

— Heating up the bitumen up to 150ºC;
— Add the additive to the bitumen and mix it using an agitator until the binder becomes homogeneous (in this study, a speed of 230 rpm was used and the binder was agitated for 10 minutes).

3.2.2. Optimum additive content

In order to select the correct amount of rejuvenating agent, it was necessary to perform a characterization of the binders modified with different percentages of rejuvenator. Thus, some blends of rejuvenating agent with the recovered bitumen and the new 70/100 pen bitumen were produced, after which Penetration and Ring and Ball tests were carried out.

The combination of these three components (rejuvenating agent, recovered bitumen and bitumen 70/100) is very important to turn the binder into a bitumen equivalent to a conventional new binder used in the production of new asphalt mixtures. In the present work, the objective of this modification was to obtain binder properties similar to those of a normal 35/50 pen bitumen conventionally used in AC14 surf mixtures.

Based on the recommendations of the company that provided the additive, the percentage of additive should be between 1.5% and 2%. Thus, blends of new 70/100 pen and recovered binders were prepared with the mentioned additive contents and their characteristics were determine in order to confirm if the final binder could be considered as a 35/50 pen binder. If the properties did not fulfil the requirements, the additive content should be increased up to a necessary amount.

3.2.3. Marshall mix design method

Aggregates particle size distribution study

The mix design method that was chosen is the empirical method of Marshall, according to EN 12697-34, which is the standard method used in Portugal. For the Marshall test, samples were produced according the EN 12697-30 standard, using an impact compactor with the compaction energy of 75 blows.

In order to fulfill the envelope requirements of the type of mixture used in this work (Figure 22), the percentage of each aggregate fraction was calculated, as described in the Portuguese asphalt mixtures specifications of Estradas de Portugal (2009).

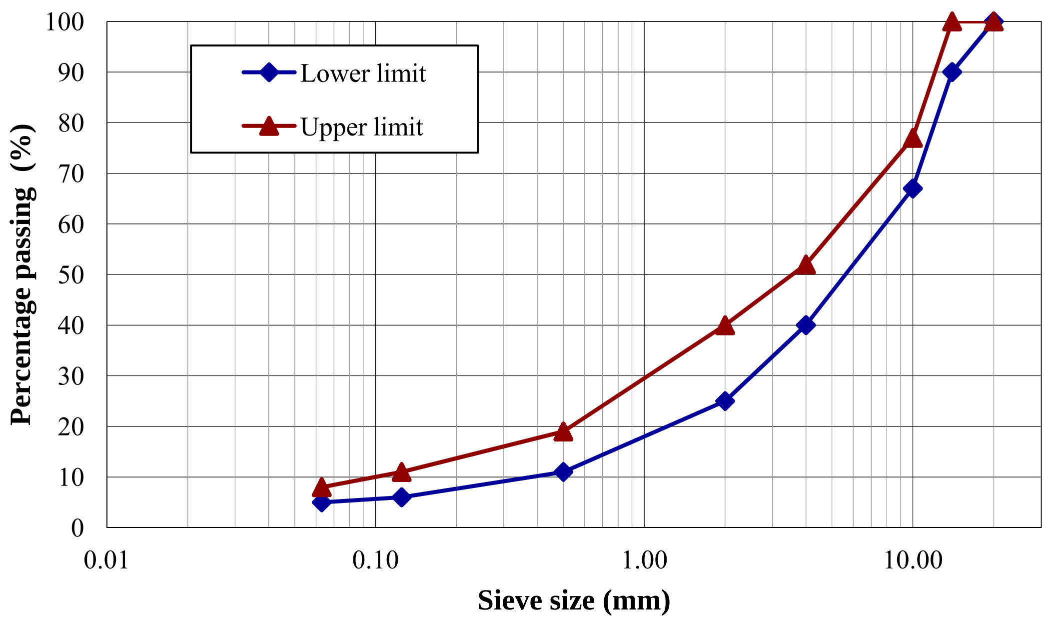


Figure 22 – Envelope of the aggregates particle size distribution used in studied surface course mixtures

Compacting test specimens of Marshall

The compaction of the specimens is undertaken with a normalized impact compactor, applying 75 blows on each specimen according to the EN 13108-1 standard. The temperature was measured during compaction of each specimen in order to understand its influence in the volumetric properties of the specimens.

Marshall Test

For the analysis of the Marshall test results, five sets of three specimens must be prepared (Figure 23) with different bitumen contents (the percentage of binder, by mass of mixture should vary half unit among each group of specimens). It should be noted, however, that two groups should have a binder content above and below the "optimal theoretical" binder content, which is calculated from the specific surface area of aggregates.

Figure 23 – Five groups of specimens used in the Marshall test to determine the optimum binder content

An optimum binder content is determined based on the Marshall test results (maximum strength and deformation) and the volumetric properties of each group of specimens (bulk density, air voids content, V_v, and volume of voids in mineral aggregate, VMA).

3.2.4. Volumetric properties of the mixtures

Bulk density

After compaction the specimens go through a process of characterization, where its physical properties (dimensions, weight and voids content) are determined.

For the bulk density, different methods can be used to obtain the values, namely method A, C and D according to the EN 12697-6 standard). These methods use some of the following steps: weighing the specimens dry and immersed in water, with and without a sealant (“Parafilm”), as represented in Figure 24, and measuring of the specimens. With these methods, it is possible to determine the bulk density of each bituminous mixture.

Figure 24 – Processes of measuring and weighing the specimens

Maximum theoretical density

The maximum theoretical density is determined according the EN 12697-5 standard. A sample of the bituminous mixture is placed into the pycnometer and weighed; water is added, and then goes through a process of vacuum for about 15 minutes. During this time vibration is applied on the pycnometer, which facilitates the process for releasing any air present in the sample (Figure 25). After filling the pycnometer with water up to the top, it is then placed in a water bath at 25°C for 30 minutes; finally it is weighed (to indirectly determine the volume of mixture), and then it is possible to obtain the value of the maximum theoretical density.

Figure 25 – Pycnometer used in the determination of the maximum theoretical density

Air voids content in the bituminous mixture

For the calculation of the air voids content, it is necessary to know the bulk density and maximum theoretical density, and this is calculated by using Equation 2.

$$V_v = \frac{MTD - BD}{MTD} \tag{2}$$

Where:

V_v air voids content;

MTD maximum theoretical density;

BD bulk density.

To calculate the VMA it is necessary to know the specific weight of the bitumen (which was assumed to be 1030 kg/m^3) and it is calculated by Equation 3.

$$VMA = V_v \frac{BD \times BC}{\gamma_b} \tag{3}$$

Where:

VMA voids in mineral aggregate;

V_v air voids content;

BD bulk density;

BC binder content of the sample;

γ_b specific weight of bitumen.

3.2.5. Optimum bitumen content

Before performing the Marshall Stability tests, all specimens must be characterised, because this test is destructive.

For the analysis of Marshall test results, it is important to retain information about the maximum strength that the specimen resists (stability) and the deformation of the specimen at the point of this maximum strength. Before being tested, it is necessary to ensure that it is at a temperature of 60 °C, by placing the samples in a water bath for one hour.

The optimum binder content of a bituminous mixture is calculated as the average of the percentages corresponding to the maximum stability, the maximum bulk density, and the average of the air voids content limits. The binder content found should correspond to a deformation and a VMA value within the limits imposed by the applicable specifications (Branco *et al.*, 2005).

According to the National Annex of the EN 13108-1 standard, the air voids content of a bituminous AC 0/14 surf mixture should be between 3% and 5%. This value must be validated at 150 blows of Marshall Compaction (75 blows on each side of the specimen).

3.2.6. Affinity between aggregates and bitumen

The performance of asphalt mixtures is closely related to the chemical affinity of the aggregate with bitumen. A good bond between these components will make it harder to separate them which will increase the durability of the mixtures, namely in the presence of water. To measure this property, a test was developed in the last few years were a sample of aggregates covered by bitumen are placed in contact with water in controlled conditions (according the EN 12697-11 standard). This test aims to understand the affinity that each aggregate has with the bitumen, even subjected to the most demanding conditions. Is it expected that aggregates with worse adhesion to bitumen will result in a less durable pavement (more sensitive to the presence of water).

For the test, it was necessary to select at least 600 g of each aggregate and choose the material that was retained between 10 and 6.3 mm sieves. After that, the material was dried in the oven and mixed with 3% of the 50/70 pen bitumen used in the conventional mixture.

Figure 26 shows an example of the procedure used to mix the aggregates with bitumen. This mixture was taken for 2 minutes in a vessel heated to 190 ° C. The material was then spread on a tile in order to let the bitumen stiffen, and to evaluate the initial percentage of the aggregates surface covered by bitumen.

Figure 26 – Preparation of the aggregates covered with bitumen for the affinity test

Then the material was divided into three flasks with 150g of material in each and water is added until almost to the top of the flasks, as it is possible to see in Figure 27.

Figure 27 – Flasks with samples for the affinity test

They are then placed in a specific apparatus that rotates the flasks at 60 rpm for 6 hours (Figure 28). At the end of that period, the material is removed, washed and visually analyzed to determine the percentage of bitumen which remained on the surface of the aggregates.

Figure 28 – Flasks in rotation for 6 hours

3.2.7. Compactability

One of the main objectives of this dissertation is to evaluate the possibility of reducing the production temperature of recycled bituminous mixtures. Thus, compactability tests were carried out, according to the EN 12697-10 standard. This test evaluates the volumetric parameters obtained on specimens produced and compacted at specific temperatures in order to determine the best production/compaction temperature for a given additive content. If a target temperature reduction is to be obtained, this test also allows determining the percentage of additive needed to achieve that goal.

In this test for, each bituminous mixture studied, three specimens were produced. The compaction of the specimens was carried out with a conventional impact compactor (Marshall Compactor) using the procedures described in EN 12697-30 standard.

In order to determine the evolution of the air voids content throughout the test, compaction of the specimens was performed with 200 blows only on one side of the specimens. To determine the evolution of the air voids content of the specimens, it is necessary to determine the maximum theoretical density the mixtures according to EN 12697-5, and bulk density from each of the specimens according to EN 12697-6. It is also necessary to determine the variation of the thickness of samples during the application of the 200 blows. This was obtained by using an LVDT device, as shown in Figure 29.

Figure 29 – Marshall Compactor with LVDT device

After all characterization processes, the specimens' properties (namely air voids content after 150 blows) are compared with those of the reference mixture to confirm if the production/compaction temperature used results in an adequate workability of the mixture.

3.2.8. Indirect Tensile Strength Test

The indirect tensile test was performed according to EN 12697-23. This test evaluates the indirect tensile strength (ITS) of the specimens when they are diametrically compressed. Specimens used in this test are usually compacted in the Marshall Compactor. Figure 30 shows the equipment used in this test, which can be performed on specimens stored in different conditions (dry, as the specimens compacted with 200 blows of the compactability study, or wet, as some of the specimens used in water sensitivity tests).

Figure 30 – Equipment used for the indirect tensile test

3.2.9. Water Sensitivity Test

The study of water sensitivity is important to ensure adequate performance of bituminous mixtures in a road pavement. The resistance to the action of water is critical since it is directly related to the performance and durability of such materials during the useful life of road pavements (Jesus, 2010 apud, Silva, 2011).

For this study two testing procedures were carried out: the European test, according to the EN 12697-12 standard, and the American test, according to the AASHTO T 283-89 test.

European standard

The water sensitivity is a property determined by the EN 12697-12 standard. This test consists of preparing 6 cylindrical test specimens, which are divided into two groups. These two groups are defined in a way that an equivalent volumetric properties is obtained for both groups, based on the air voids content determination, according to the standard EN 12697-5 and EN 12697-6. Then, one of the groups is immersed in water and the other is kept dry. The specimens immersed in water are subjected to a previous preparation, where they are placed in a pycnometer under action of vacuum for 30 minutes, at the end of which they are placed in a water bucket with a new period of 30 minutes. The test specimens are then placed in water at constant temperature (40 °C) for 72 hours. At the end of this time the samples are placed in water for 2 hours at 15 °C and the group of samples that throughout this process were left at room temperature are conditioned at 15°C for 2 hours.

The specimens are tested to determine the ITSR - Indirect Tensile Strength Ratio, which is the ratio of the average indirect tensile strength for the group of specimens conditioned in water ITSw and the group of dry specimens ITSd. The indirect tensile tests were performed as indicated in standard EN 12697-23.

American standard

As for the European standard, when using the AASHTO T 283-89 standard, it is necessary determine the bulk density, the maximum theoretical density, and the air voids content in order to divide the specimens into two groups with similar bulk density.

One group of specimens is left at room temperature until the time of testing, the other group goes through several different stages, according to the following steps:

- Weighing the sample within and outside water, in order to calculate the bulk density, the degree of saturation by comparing the volume of water absorbed with the voids volume, the volume of water absorbed should be between 55 and 80% by voids volume;

- Placing the specimens immersed in distilled water, to which vacuum (13-75kPa) will be applied for 5 to 10 minutes;
- Removing the vacuum and leaving the samples immersed for 5 to 10 minutes;
- Placing specimens in a water bath of distilled water at 60 ºC for 24 hours;
- Subjecting the specimens to a freeze-thaw cycle. In this phase the test specimens are wrapped in adherent film and are placed in sealed plastic bags with about 10 ml of water, and are placed at -18 °C for 16 hours;
- The plastic bags and the adherent film are removed and the specimens are placed in a water bath at 25 °C for 2 hours;
- The first group of specimens (kept dry at room temperature) is conditioned at a temperature of 25 ºC for the same period of time;
- After the 2 hours all the specimens are tested, using the indirect tensile strength test.

Some of these steps are showed in Figure 31.

Figure 31 – Phases of the water sensitivity test according to the American Standard

3.2.10. Wheel Tracking Test

The evaluation of the asphalt mixtures permanent deformation is carried out by the Wheel Tracking Test (WTT), during which the depth of rut formed under the wheel passing repeatedly over the samples is measured.

The permanent deformation that takes place on the surface of flexible pavements may have its origin in the bituminous layers and/or in the subgrade. The ruts that develop in the wheel path under the passage of vehicles, can arise in flexible pavements subject to heavy traffic and high bearing capacity subgrade, consisting of thin granular layers and thick asphalt layers (Baptista, 2006).

For this test, 2 samples were cut from each of the slabs manufactured. The procedure adopted for manufacturing a slab with dimensions 75 cm × 39 cm × 4 cm, was performed according to the procedure presented in Section 3.2.2. The slabs were then compacted with a roller compactor, as shown in Figure 32.

Figure 32 – Procedures use to produce an asphalt mixture and to compact a slab

The wheel tracking test was performed according to the EN 12697-22 standard. The temperature of the test was selected to be representative of the climate conditions observed in the pavement on hot Summer days in this region of the Country (50 ºC) and the force applied on the wheel was 700N. The equipment used is presented in Figure 33.

Figure 33 – Equipment used in the wheel tracking test

For this test, procedure B was adopted (chosen from 6 different procedures presented in the mentioned European Standard). For this procedure two samples are used, to which 10 000 loading cycles are applied. The main results of this test are the wheel tracking slope in air (WTSAIR), the mean proportional rut depth in air (PRDAIR), and the mean rut depth in air (RDAIR). According to these parameters a classification of the mixtures can be issued according to EN 13108-1 standard.

3.2.11. Stiffness Modulus Test

For the stiffness modulus test, a thicker slab with dimensions 75×49×4 cm was produced for each asphalt mixture, following the same procedures presented in Section 3.2.11.

The procedure carried out to obtain the stiffness modulus of each bituminous mixture was performed by four-point bending tests, according to EN 12697-26. Prior to that, it was necessary to cut the slab in 9 beams as is showed in Figure 34.

In this study, all beams were tested for the standard temperature of 20 ºC (EN 13108-20). Following the recommendations of the EN 12697-26 standard, a frequency sweep test protocol was used. Thus the specimens were tested for the following sequence of frequencies: 0.1, 0.2, 0.5, 1, 2, 5, 8, 10, and 0.1 Hz again. This allows obtaining a material characterization for different loading and temperature conditions.

Figure 34 – Beams used in the stiffness modulus test

3.2.12. Fatigue Resistance Test

The fatigue criterion is the far most important factor in the design of asphalt pavements. The criterion is used to predict failure and is normally investigated through material testing of small specimens (cubes, cylinders, or beams) in laboratories or full scale field test sections. Small scale testing is more convenient but include various estimations on how the actual behaviour in the field changes (Söderqvist, 2006).

Laboratory compacted asphalt specimens are required to have homogeneous distributions of air voids and aggregate. Air void content is controlled by the compaction effort and is one of the most important variables affecting the fatigue resistance of compacted bituminous mixtures (Hartman *et al.*, 2001).

Fatigue of asphalt pavements is the phenomenon of emergence of cracking due to repeated traffic loads. The fatigue resistance of asphalt mixtures is seen as their ability to withstand repeated bending loads without reaching failure. It is usually expressed by a relation between the tensile strain (ε_t) and the number of load applications (N) (Gomes, 2005).

The fatigue tests were performed according to AASTHO TP 8-94 standard. The fatigue resistance of bituminous mixtures was obtained using the four-point bending test with repeated sinusoidal load at a temperature of 20 °C and the load frequency of 10 Hz. In the fatigue tests performed, the initial stiffness modulus was considered as the value corresponding to the 100th cycle. The fatigue resistance ("life") of each beam tested is assumed to correspond to the number of load applications after which the stiffness modulus reduces to 50% of its initial value. This test takes place in a complex testing piece of equipment shown in Figure 35.

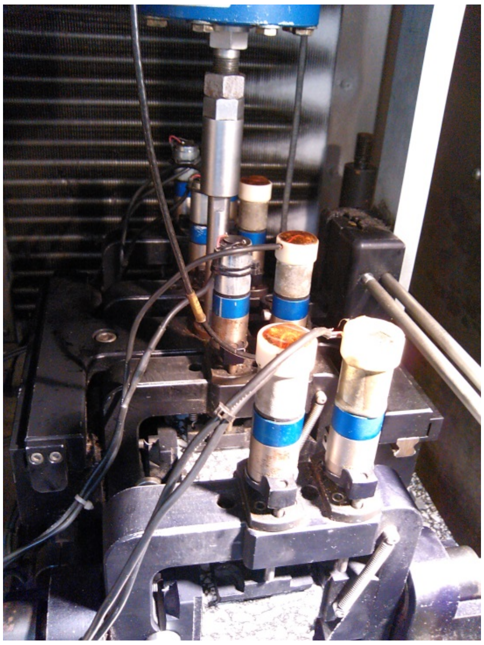


Figure 35 – Four-point bending equipment used in the fatigue resistance test

With the results obtained from each individual specimen tested it is possible to define a fatigue life equation that represents the fatigue performance of a certain mixture, according to Equation 4.

$$N = a \times \left(\frac{1}{\varepsilon_t}\right)^b \quad (4)$$

Where:

N no. cycles corresponding to the failure of the mixture for a strain ε_t;

V_v tensile strain applied to the mixture;

a, b laboratory determined coefficients.

4. RESULTS AND DISCUSSION

4.1. Determination of the optimum additive content

As previously mentioned, different amounts of rejuvenating agent were used in order to determine the optimum additive content that would result in a binder equivalent to a conventional 35/50 pen bitumen. Table 6 shows the results of penetration and softening point tests obtained for the blends of new 70/100 pen bitumen with recovered binder and different additive contents. In a first stage, two different additives (A and B) were tested with the objective of assessing their influence on the rejuvenation of the aged binder.

Table 6 – Test results of the rejuvenation study

Additive	Additive content (%)	Average penetration (0.1 mm)	Softening point temperature (º C)
A	1.5	32.7	57.3
	2.0	33.5	55.8
	3.0	44.0	54.5
B	1.5	29.0	57.6
	2.0	33.1	56.3
	3.0	40.1	54.6

For a better visualization of the results, Figure 36 and Figure 37 show the average penetration and softening temperature test results, together with the limits of a generic 35/50 pen bitumen, to better understand what would be the most appropriate additive percentages to get a bitumen with characteristics as close as possible to those of a conventional 35/50 pen bitumen.

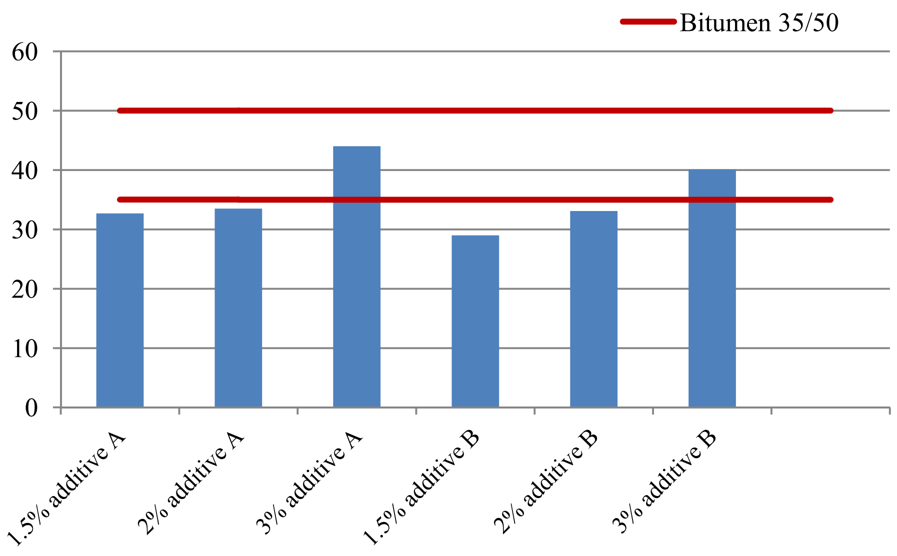


Figure 36 – Average Penetration of the different blends of bitumen and rejuvenator

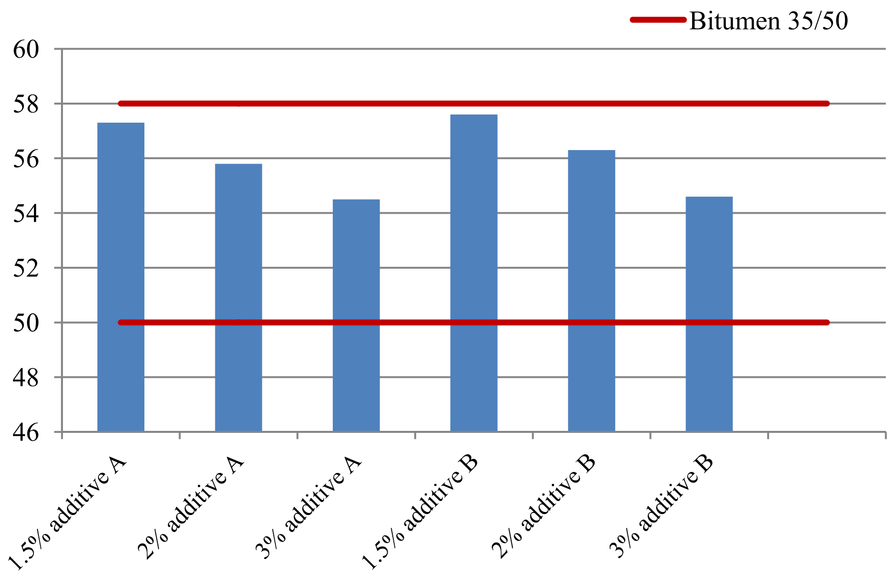


Figure 37 – Average Softening point temperature of the different blends of bitumen and rejuvenator

Taking into account the limits of the penetration and softening point values of a conventional 35/50 pen bitumen it was found that the bitumen with 3% additive A presents the closest results to the average of the limit values. Although the bitumen with 3% additive B also shows acceptable values, it is still better to opt for an additive that provides a higher rejuvenation effect (higher increase on the penetration value). It is also important to mention that between these two additives, and based on information provided by the additive supplier, additive A is less expensive than additive B, which is another advantage for its selection.

The dynamic viscosity and the rheological (phase angle and complex modulus) test results obtained for the binders modified with additive A are presented in Figures 38 and 39.

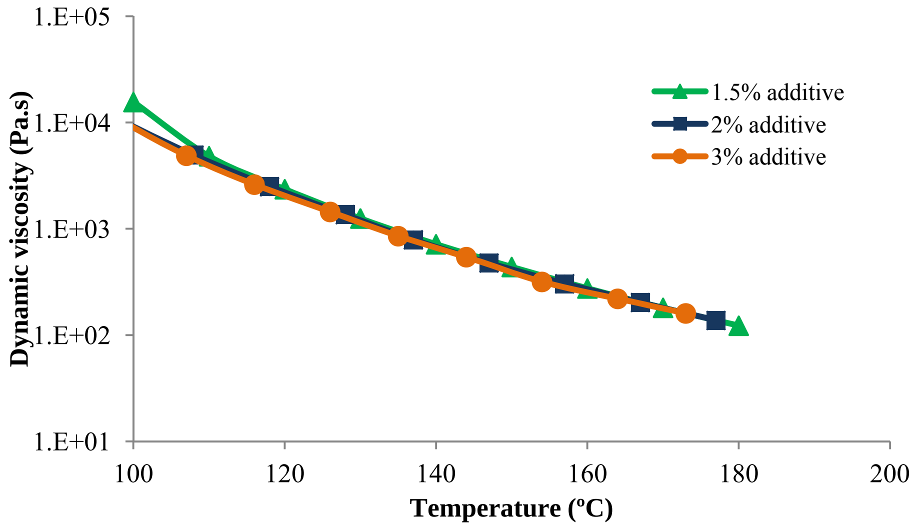


Figure 38 – Dynamic Viscosity (Pa.s) of binders with additive A

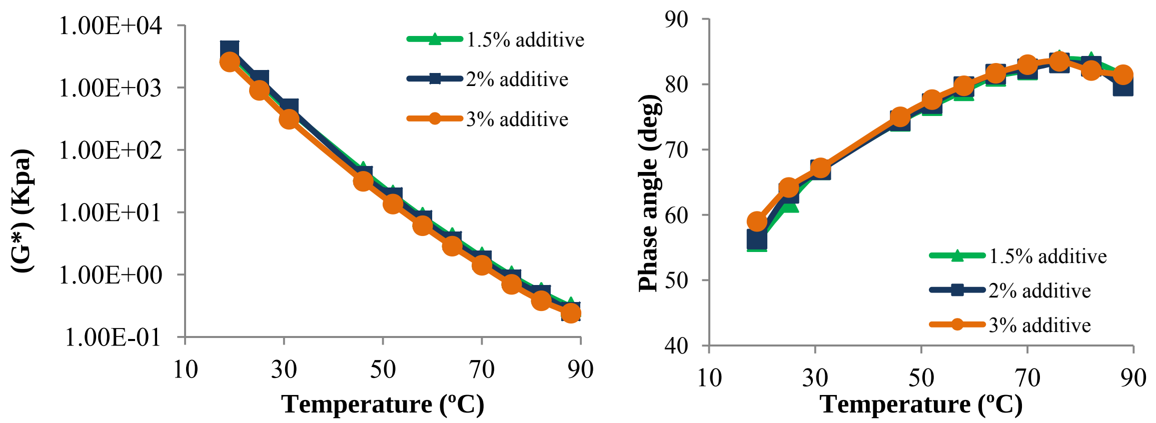


Figure 39 – Complex modulus and phase angle of binders with additive A

As can be observed from the previous figures, the rheological properties of the binders produced with different percentages of additive did not show significant differences between them, although the results obtained for the binder with 3% additive show a slightly softer binder (lower complex modulus and higher phase angle for the same temperature) in comparison with the other binders.

4.2. Marshall Mix Design Study

4.2.1. Study of the aggregates particle size distribution

Conventional bituminous mixture

Based on the particle size distribution of each aggregate fraction used in the production of conventional bituminous mixture, it was concluded that the percentages of aggregates and filler that would fulfil the requirements for a surface course type mixture are those presented in Table 7.

Table 7 – Percentage of each aggregate fraction and filler used in the production of the conventional bituminous mixture

	Aggregate 6/14	Aggregate 4/6	Aggregate 0/4	Filler
Percentage	50%	8%	40%	2%

Figure 40 illustrates the particle size distribution obtained with the percentages of each aggregate mentioned in the previous table. It is possible to observe that the proposed mix design generally fulfils the envelope defined in the specifications (in terms of the percentage passing in each sieve) of Estradas de Portugal (2009).

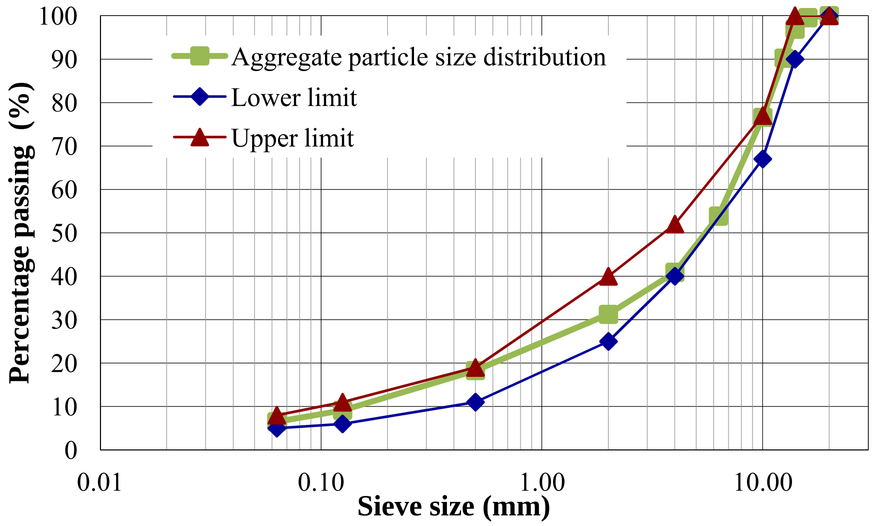


Figure 40 – Particle size distribution of the aggregates used in the conventional bituminous mixture

Recycled bituminous mixture

The particle size distribution of the recycled mixtures studied in the present dissertation was defined taking into account the specifications mentioned for the conventional asphalt mixture. The results obtained for this type of mixture are presented in Table 8.

Table 8 – Percentage of aggregates, filler and RAP for the recycled asphalt mixtures

	Aggregate 8/14	Aggregate 4/10	Aggregate 0/4	Filler	RAP 0/6	RAP 6/12
Percentage	38.8%	5.5%	4.8%	1.0%	29.7%	20.2%

Figure 41 shows the results of the particle size distribution of the recycled asphalt mixtures, fulfilling the envelope limits.

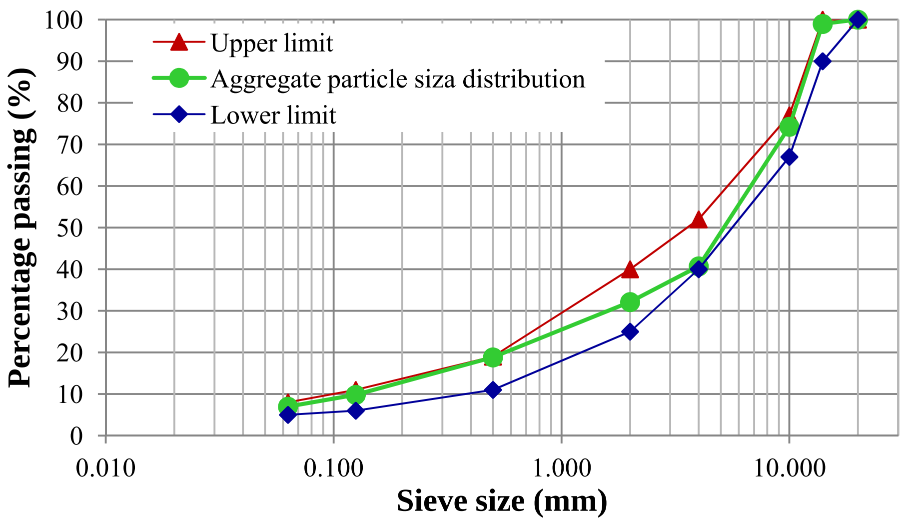


Figure 41 – Particle size distribution of the aggregates used in the recycled bituminous mixture

4.2.2. Temperatures of the bituminous mixtures

During production and compaction of the studied mixtures, the temperature of the aggregates, bitumen and mixture were measured in order to confirm if the standards/requirements were being met. The results of this temperature control study are presented in Table 9.

Table 9 – Temperature of different production stages of the studied bituminous mixtures

Bituminous mixtures	Bitumen (ºC)	Fine RAP (ºC)	Aggregate Temperature (in the oven) (ºC)	Production Temperature (ºC)	Expected production Temperature (ºC)	Compaction Temperature (ºC)
Conventional bituminous mixture	160	-	180	155	-	129
Hot-recycled Bituminous Mixture	150	22	240	165	175	119
Warm-recycled Bituminous Mixture (with additive)		21	240	160	175	138
		22	210	150	154	136
		28	180	135	134	126

Analysing the temperature obtained in each bituminous mixture it is possible to conclude that the recycled bituminous mixtures produced at lower temperatures (with the incorporation of the WMA and rejuvenating additive) achieved the expected production temperature more easily than that of the mixture produced at higher temperatures. This highlights the effect of the additive in maintaining the workability of the mixture at lower temperatures.

4.2.3. Marshall Test – Optimum bitumen content

As previously mentioned, before performing the Marshall stability test, which is a destructive test, it is important to determine certain volumetric and composition parameters. These results are important to obtain the optimum binder content of the mixture.

The bulk density results of all Marshall specimens of the conventional mixture, obtained by three methods, A, C and D are shown in Table 10.

Analyzing the methods used to determine the bulk density it is possible see that the results are not very different. Thus, based on the ease of implementation, method A has been chosen as the best method for determining the bulk density of the specimens. In Table 11, the results of bulk density, maximum theoretical density, air voids content and VMA of the specimens are presented.

Table 10 – Bulk density for each sample of conventional bituminous mixture

			Methods		
	% of bitumen	**Specimens**	**A**	**C**	**D**
Bulk density (kg/m³)	4	A	2374	2250	2242
		B	2374	2254	2248
		C	2350	2230	2213
	4.5	A	2379	2284	2258
		B	2378	2283	2279
		C	2374	2276	2254
	5	A	2392	2325	2324
		B	2399	2331	2328
		C	2402	2331	2310
	5.5	A	2407	2343	2348
		B	2412	2324	2332
		C	2418	2349	2361
	6	A	2416	2353	2351
		B	2421	2366	2335
		C	2415	2351	2423

Table 11 – Summary of non-destructive testing results of initial characterization of Marshall specimens

Binder content (%)	**Specimens**	**MTD (kg/m³)**	**Bulk density (kg/m³)**	**Average of bulk density (kg/m³)**	**V_v (%)**	**Average of V_v (%)**	**VMA (%)**	**Average of VMA (%)**
4	A	2513.2	2374	2366	5.5%	5.9%	14.7%	15.0%
	B		2374		5.6%		14.7%	
	C		2350		6.5%		15.6%	
4.5	A	2500.0	2379	2377	4.8%	4.9%	15.2%	15.3%
	B		2378		4.9%		15.2%	
	C		2374		5.1%		15.4%	
5	A	2478.8	2392	2398	3.5%	3.3%	15.1%	14.8%
	B		2399		3.2%		14.8%	
	C		2402		3.1%		14.7%	
5.5	A	2462.0	2407	2412	2.2%	2.0%	15.0%	14.8%
	B		2412		2.0%		14.9%	
	C		2418		1.8%		14.6%	
6	A	2435.2	2416	2417	0.8%	0.7%	14.8%	14.7%
	B		2421		0.6%		14.6%	
	C		2415		0.8%		14.8%	

In the stability test it is necessary to make a correction in the values obtained. In this case the maximum force has to be corrected by a factor c, which depends on the height of the specimen. The corrected results of this test are presented in Table 12.

The results obtained for each binder content allowed the preparation of the graphs of bulk density, porosity, deformation, VMA and stability, present in Figure 42 up to Figure 46. In each graph, the allowed limits are displayed by the red line for each feature according to the specification of Estradas de Portugal (2009).

Table 12 – Summary of Marshall Stability test results

Binder content (%)	Specimens	Stability (kN)	Average Stability (kN)	Deformation (mm)	Average deformation (mm)
4	A	12.31	11.42	3.36	3.51
	B	11.28		3.14	
	C	10.67		4.04	
4.5	A	12.37	12.54	4.24	3.90
	B	12.77		3.42	
	C	12.49		4.05	
5	A	13.78	14.13	4.07	3.87
	B	14.05		3.61	
	C	14.55		3.93	
5.5	A	13.24	13.35	4.08	3.95
	B	12.96		4.13	
	C	13.84		3.63	
6	A	13.55	13.55	4.02	4.05
	B	14.03		3.77	
	C	13.06		4.37	

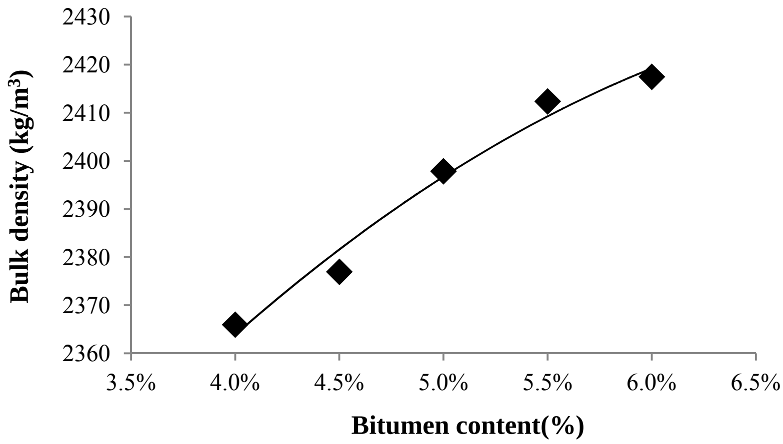


Figure 42 – Influence of the binder content on the bulk density of the conventional mixture

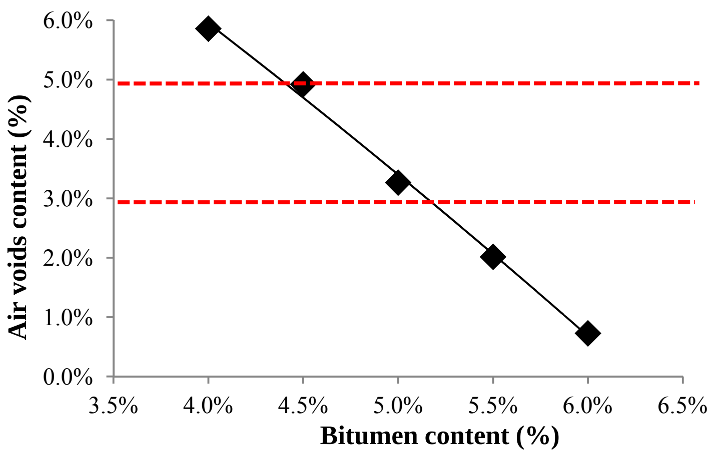


Figure 43 – Influence of the binder content on the air voids content of the conventional mixture

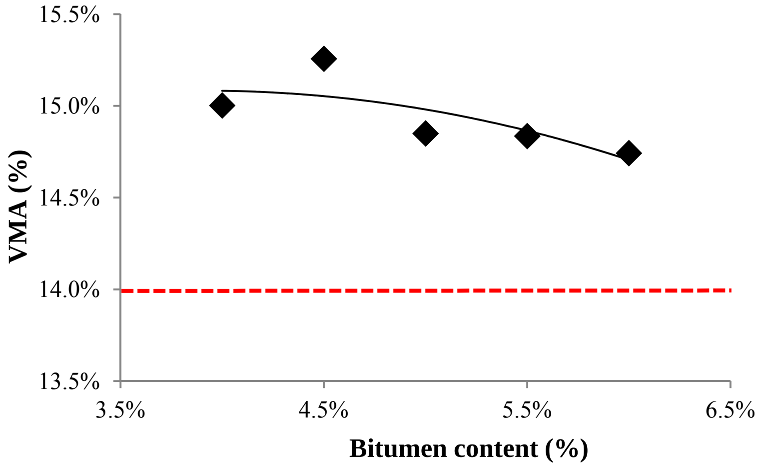


Figure 44 – Influence of the binder content on the VMA of the conventional mixture

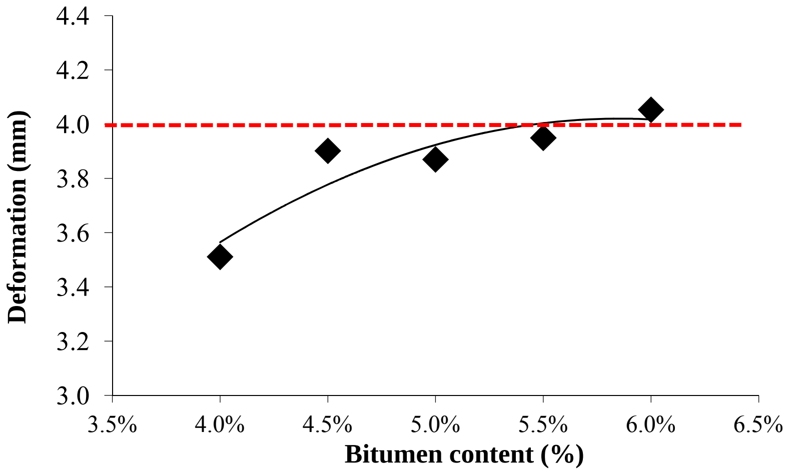


Figure 45 – Influence of the binder content on the deformation of the conventional mixture

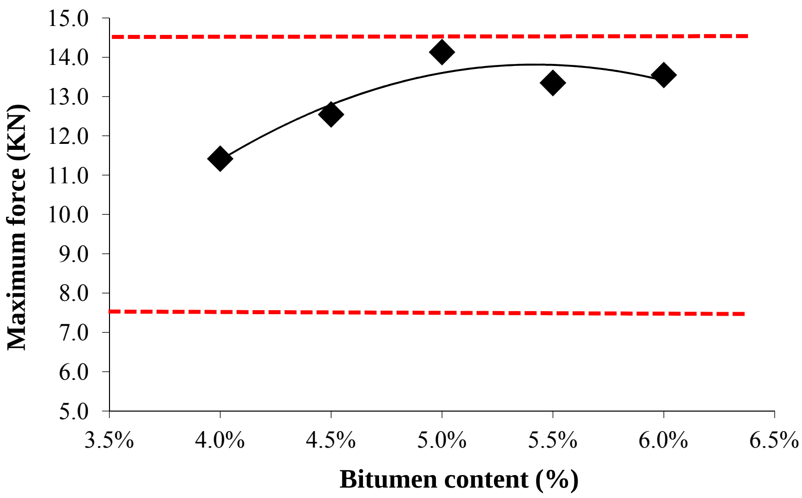


Figure 46 – Influence of the binder content on the stability of the conventional mixture

Analyzing the previous graphs, and to determine the optimum binder content to produce the mixture, it can be seen that the bulk density reaches its highest value for binder contents exceeding 5%. It is also possible to verify that the air voids content of the mixtures produced with 4%, 5,5% and 6% are completely out of the limits. In terms of VMA, all mixtures fulfilled the minimum permissible value of 14%. Regarding the deformation, the samples with 6% of bitumen present value out the limit, and in what concerns the stability the maximum value was achieved for a binder content above 5%. After this analysis the optimum binder content of the conventional bituminous mixture is 5%.

For the production of the recycled bituminous mixtures, an optimum binder content of 5.1% was used, based on a study published by Palha *et al.* (2013) which a RAP material from the same source and with a similar recycling rate (ratio of RAP incorporation on the final mixture); the main results are summarized in Table 13.

Table 13 – Results of the Marshal Test for optimum binder content for the recycled bituminous mixture from Palha *et al.* (2013)

Optimum Binder content (%)	MTD (kg/m^3)	Bulk density (kg/m^3)	Air voids content (%)	VMA (%)	Stability (kN)	Flow (mm)
5.1	2456	2362	3.8	15.40	19.70	3.5

4.3. Affinity between aggregates and bitumen

For a good affinity between aggregates and bitumen it is necessary to have a molecular contact between both of them. The affinity is reduced considerably if there is powder on the surface of the aggregates and can be canceled if the aggregates are wet. In addition, water may repel the bitumen, compromising the affinity and decreasing the durability of the pavement.

In the present work, all aggregates were covered by bitumen, thus having an initial analysis of 100% aggregates surface area covered by bitumen (Figure 47). This figure also shows the results obtained at the end of the testing period.

The analysis of this test should be done by a specialist, since it is a visual analysis, and it takes some experience to assure that the evaluation is as close as possible to reality.

It is possible to observe from Figure 47 that there is significant loss of bitumen from the aggregate surface, which was estimated to be of about 75% (the amount of bitumen that remains attached to the aggregates is about 25%).

Figure 47 – Surface of the aggregates covered by bitumen before and after the affinity test

Based on the previous results it can be concluded that the aggregates used in the conventional asphalt mixture may not be the best choice to use with the conventional 50/70 pen bitumen used. Alternatively, a different binder could be studied or an adhesion promoter additive could be suggested to improve this property.

4.4. Compactability

Besides the composition of the bituminous mixtures, previously described, it is important to define their production/compaction temperature. This can be studied by the compactability test. Alternatively, this test can also be used to confirm the optimum additive content (if the objective is to obtain a certain temperature reduction).

The main parameter that can be analysed from the compactability test is the specimens air voids content. The results obtained for each bituminous mixture studied, corresponding to the standard compaction energy (150 blows using the impact compactor), are presented in Table 14, together with the temperatures used to heat the aggregates and the coarse RAP (fine RAP was introduced at room temperature), and to compact the mixtures.

The evolution of the air voids content of each specimen may be monitored to determine the influence of temperature on the compactability of the mixtures or to observe whether different mixture compositions compact differently. Figure 48 shows the curves of the recycled bituminous mixture produced with the rejuvenating additive at different temperatures.

Table 14 – Air voids content of the mixtures after compactability tests

Bituminous mixtures	Aggregates Temperature (ºC)	Compaction Temperature (ºC)	Air voids content	
			Specimen air voids content (%)	Average (%)
Conventional bituminous mixture	180	129	5.84	5.55
			5.96	
			4.87	
Recycled Bituminous Mixture without additive	240	119	5.15	5.38
			5.72	
			5.27	
Recycled bituminous Mixture with additive	240	138	4.67	4.72
			4.77	
			--	
	210	136	4.82	4.92
			5.01	
			5.07	
	180	126	5.37	5.11
			4.85	
			5.50	

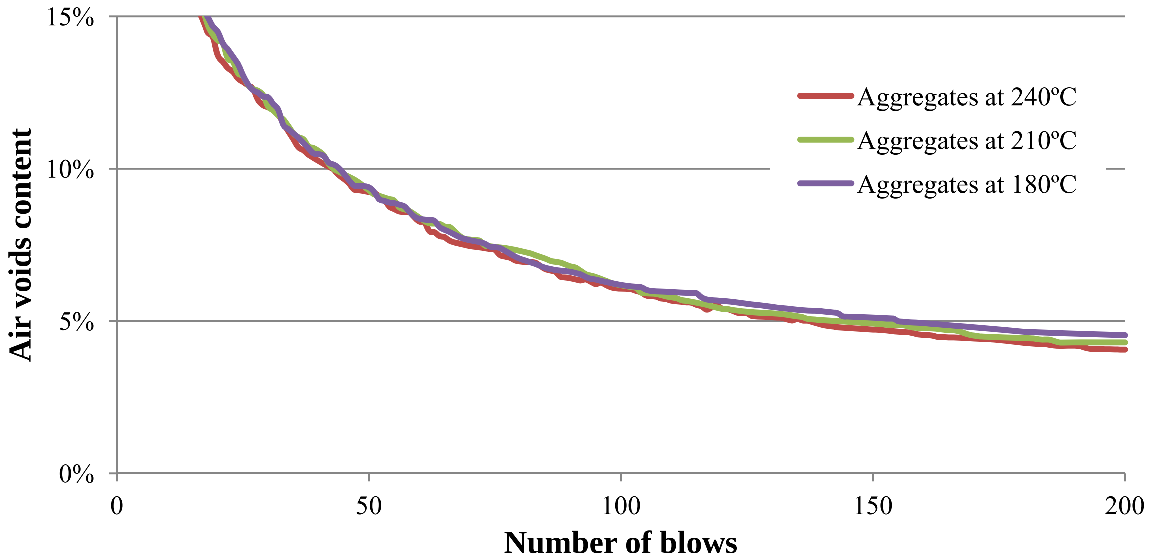


Figure 48 – Evolution of the air voids content of the mixture with rejuvenator during compactability tests

As can be observed from Figure 48, the recycled mixture produced with the aggregates heated up to 210ºC has air voids content very similar to that of the recycled bituminous mixture with the aggregates at 240°C. This is a consequence of the use of the additive, which made it possible to maintain the workability of the mixture even though the temperature was 30 ºC lower. Regarding the recycled bituminous mixture produced with aggregates at 180ºC, this starts to show slightly higher values of air voids content, which are also slightly above the maximum value of the specification (5.0% after 150 blows), as can be confirmed from Table

14. Thus, it can be concluded that this temperature reduction may be too high to assure an adequate performance of the mixture.

Based on the abovementioned, it was decided to select the temperature of 210 °C to heat the aggregates, resulting in a compaction temperature of 136°C. In Figure 49 it is possible to observe the evolution of the air voids content of this mixture, in comparison with the other two studied mixtures.

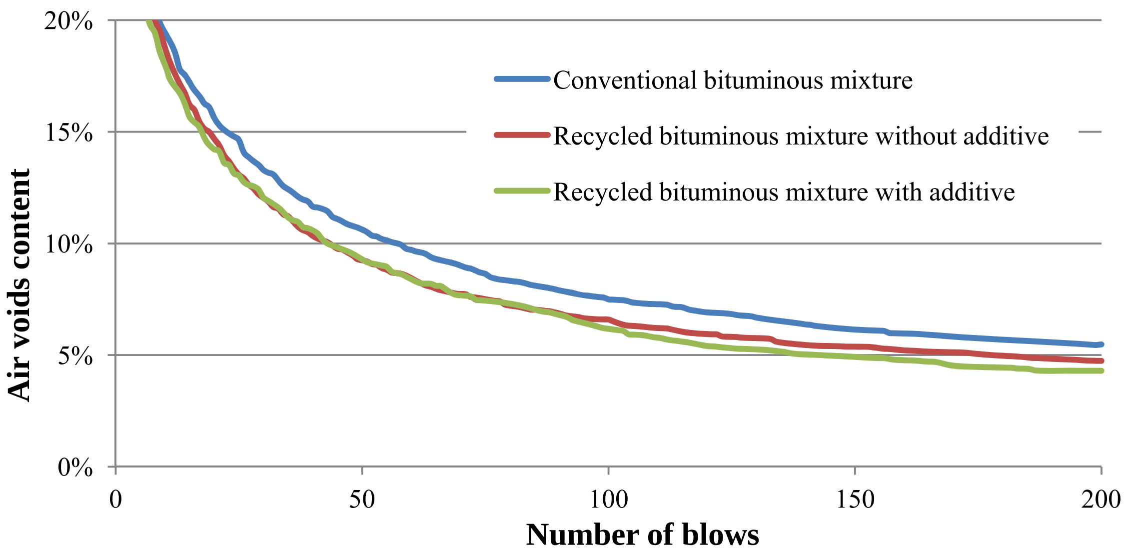


Figure 49 – Evolution of the air voids content of different bituminous mixtures during compactability tests

The results presented in Figure 49 clearly show that the recycled bituminous mixture with additive A, produced with the aggregates at 210°C, present the best volumetric properties among the three studied mixtures, probably due to the effect of the additive in promoting the workability of the mixture.

4.5. Indirect Tensile Strength Test

The specimens that were compacted with 200 blows during the compactability study were used in the Indirect Tensile Strength test; the results obtained are presented in Table 15.

Due to the presence of a very hard (aged) binder in its constitution, the recycled bituminous mixture without additive showed the highest values of ITS. The rejuvenator reduced the strength of the recycled mixture, increasing the average deformation of the specimens at failure, which should represent an improvement on the fatigue resistance of the mixture. The results of that mixture are also higher than those of the conventional mixture, which is a result of the harder type of binder that resulted from the rejuvenation process (35/50 pen in comparison to the 50/70 pen bitumen used in the conventional mixture).

Table 15 – Results of indirect tensile strength test

Bituminous mixtures	Specimen	ITS (kPa)	Average ITS	Average deformation (mm)
Conventional bituminous mixture	C1	1973.0	2076.7	3.3
	C2	2073.6		
	C3	2183.6		
Recycled bituminous mixture without additive	R_NA1	3251.4	3201.7	2.68
	R_NA2	3106.2		
	R_NA3	3247.4		
Recycled bituminous mixture with additive	R_WA1	2654.5	2633.7	2.78
	R_WA2	2633.1		
	R_WA3	2613.5		

4.6. Water Sensitivity Test

Table 16 presented the results obtained for all the specimens of the conventional and the recycled bituminous mixture with and without additive tested the indirect tensile test, after different conditioning periods, according to the EN 12697-12 standard.

Table 16 – Results of the water sensitivity test according to the EN 12697-12

Bituminous mixtures	Group	Specimen	Maximum Load (kN)	Average Maximum Load (kN)	ITS (kPa)	Average ITS	ITSR (%)
Conventional bituminous mixture	ITS_d	WS_4	19.82	19.43	1963.4	1953.5	59 %
		WS_5	18.59		1914.5		
		WS_6	19.89		1982.6		
	ITS_w	WS_1	11.14	11.60	1138.3	1160.6	
		WS_2	12.25		1226.9		
		WS_3	11.41		1116.7		
Recycled Bituminous mixture without additive	ITS_d	R_WS7	32.75	32.71	4844.4	4794.4	79%
		R_WS8	32.75		4666.6		
		R_WS9	32.63		4872.3		
	ITS_w	R_WS4	27.81	26.02	4103.8	3786.3	
		R_WS5	23.58		3438.4		
		R_WS6	26.66		3816.6		
Recycled bituminous mixture with additive	ITS_d	RA_WS2	26.84	26.16	2702.2	2633.0	91%
		RA_WS4	26.18		2623.17		
		RA_WS6	25.44		2573.8		
	ITS_w	RA_WS1	22.90	23.70	2308.6	2394.8	
		RA_WS3	24.31		2451.2		
		RA_WS5	23.89		2424.8		

From the Average ITSR values it is possible to observe that the conventional mixture presented a value well below 80% (value taken as a reference), which is in line with the low value obtained in the affinity test. Thus it is possible to conclude that the reference mixture would need an adhesion promoter additive if the same aggregates and bitumen were to be used in mass production. The ITSR value of the recycled mixture without additive is just below 80% and, therefore, it could be said that this mixture presents satisfactory water sensitivity properties. The mixture produced with the rejuvenating agent is the one with the best performance regarding the water sensitivity. The average ITSR value (above 90%) shows the efficiency of the additive in improving the workability of the mixture which resulted in a better bond between the aggregates and the rejuvenated binder.

Another type of test for moisture susceptibility, carried out according to the American standard - AASHTO T 283-89, was also performed for the recycled bituminous mixture with additive and the results of this test are presented in Table 17.

Table 17 – Results of the test moisture susceptibility according to the AASHTO T 283-89

Bituminous mixtures	Group	Specimens	Maximum Load (kN)	Average Maximum Load (kN)	ITS (kPa)	Average ITS	ITSR (%)
Recycled bituminous mixture with additive	ITS_d	RA_WS10	12.53	13.09	1241.017	1314.89	87%
		RA_WS11	13.68		1352.824		
		RA_WS12	13.06		1350.803		
	ITS_w	RA_WS7	11.35	11.68	1108.973	1149.56	
		RA_WS8	12.11		1201.286		
		RA_WS9	11.58		1138.426		

The test carried out according to the AASHTO T 283 standard represents a more severe testing condition, since the specimens are subjected to a freeze-thaw cycle. Another important aspect that shall be highlighted is that the test is carried out at 25 ºC, resulting in lower ITS values when comparing to the ITS values obtained according to the EN 12697-12 standard (which is performed at 15 ºC). Nevertheless, it was possible to observe that the overall performance of the mixture was not significantly affected by the freeze-thaw cycle, since the ITSR obtained (87%) is well above the reference value.

4.7. Wheel Tracking Test

To make sure bituminous mixtures show an adequate performance in the hot summer days, especially in countries with warm weather, it is important to assess the mixtures permanent deformation resistance. Figure 50 shows the final rut depth obtained for the different mixtures studied in the present work in the wheel tracking test.

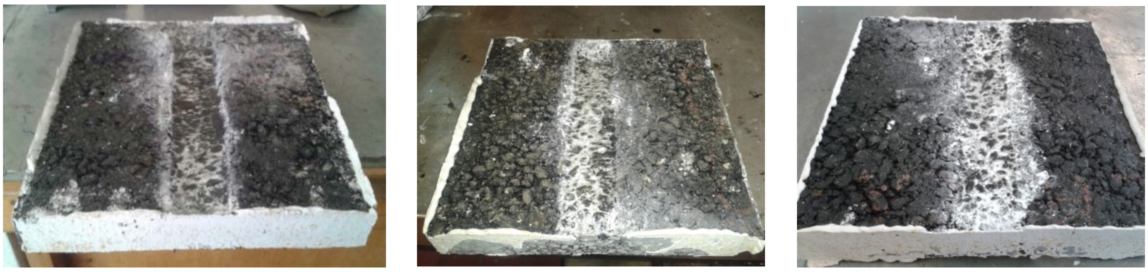


Figure 50 – Images from the samples after the wheel tracking test: (a) Conventional bituminous mixture; (b) Recycled bituminous mixture without additive; (c) Recycled bituminous mixture with additive

Table 18 shows the results obtained for the three parameters already mentioned (WTS_{AIR}, PRD_{AIR} and RD_{AIR}), while Figure 51 shows the evolution of the rut depth of each mixture during the WTT test. These results are the average results of two samples from each of the mixtures studied.

Table 18 – Average results of the wheel tracking test

Bituminous mixture	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	RD_{AIR} (mm)
Conventional bituminous mixture	0.18	12.92	5.22
Recycled without additive	0.10	8.00	3.28
Recycled with additive	0.15	9.34	3.82

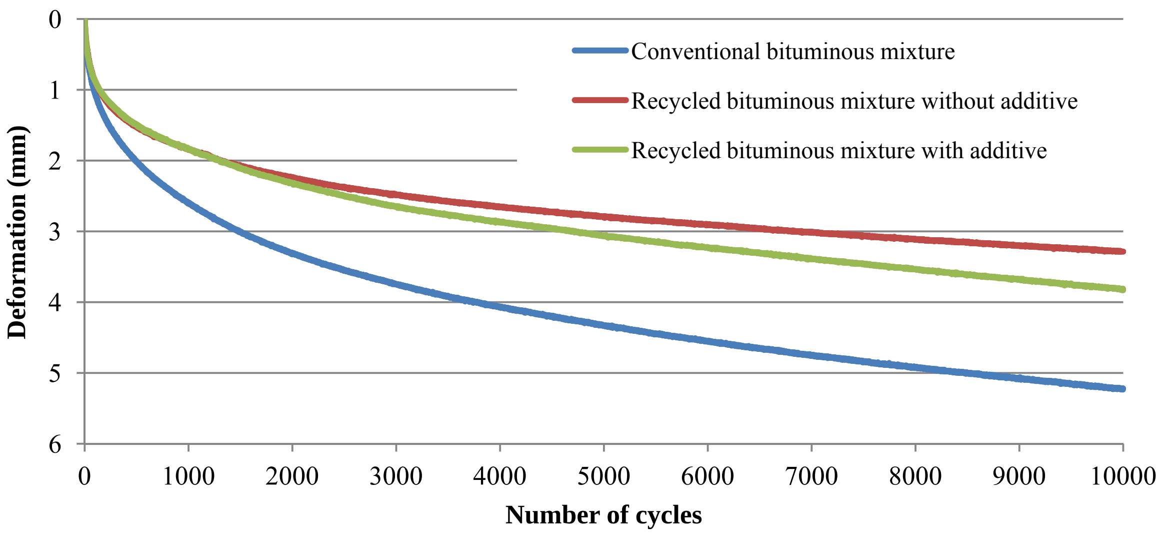


Figure 51 – Variation of rut depth of all bituminous mixtures during the WTT

Through the analysis of Table 18 and Figure 51 it is possible to see that, as expected, the recycled bituminous mixture has a better behaviour than the conventional mixture. The use of RAP material (50%) leads the final bitumen in the bituminous mixture will to be harder, since it includes a very aged binder, improving the permanent deformation performance of the mixture. The incorporation of the rejuvenator in the recycled bituminous mixture slightly reduced the rut resistance of the mixture (in comparison to the recycled bituminous mixture without additive), but did not compromised its permanent deformation performance, since the values obtained in the WTT are still better than those of the conventional mixture.

4.8. Stiffness Modulus Test

Through the four-point bending tests carried out on each individual specimen, the average stiffness modulus and phase angle results were determined for each frequency, as presented in the Table 19 and Table 20 for the testing temperature of 20 ºC.

Table 19 – Average Stiffness Modulus of the studied mixtures (MPa)

Frequency (Hz)	Conventional mixture	Recycled mixture without additive	Recycled mixture with additive
0.1	794	2878	1310
0.2	1099	3723	1838
0.5	1672	5013	2758
1	2243	6056	3606
2	2897	7078	4513
5	3966	8422	5849
8	4562	9087	6514
10	4849	9370	6826

Table 20 – Average phase angle values of the studied mixtures (º)

Frequency (Hz)	Conventional mixture	Recycled mixture without additive	Recycled mixture with additive
0.1	47.1	38.2	47.0
0.2	45.6	34.0	44.0
0.5	41.9	28.3	38.7
1	38.7	24.3	34.3
2	35.1	20.7	30.0
5	30.1	16.4	24.1
8	27.3	14.3	21.3
10	26.0	13.3	19.9

Figure 52 and Figure 53 show the variation of stiffness and phase angle with frequency, at 20ºC, obtained for all bituminous mixtures.

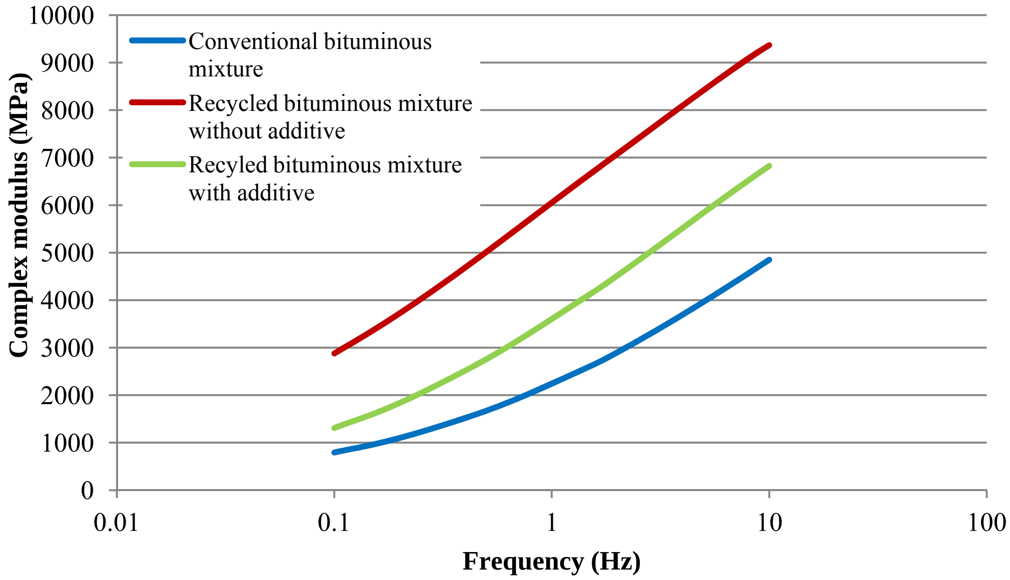


Figure 52 – Stiffness modulus of the studied bituminous mixtures at 20ºC

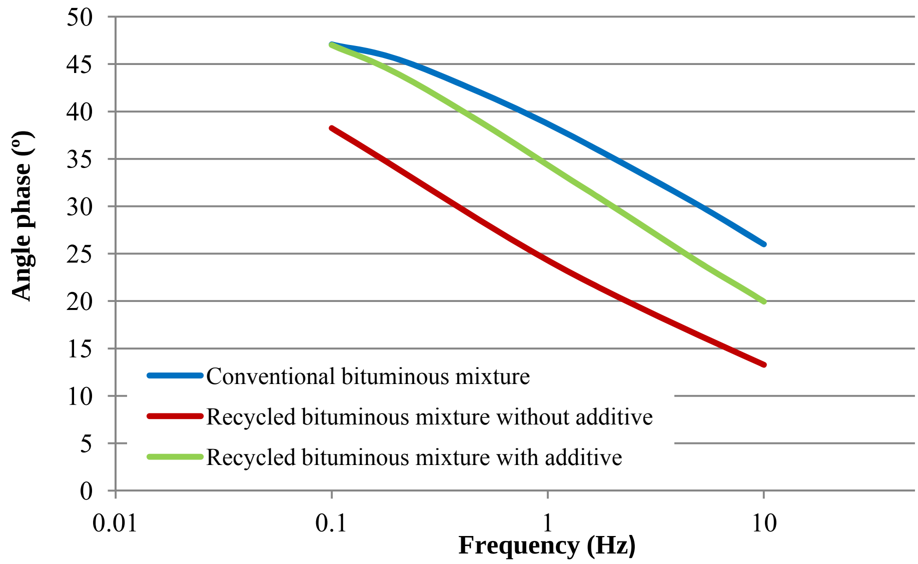


Figure 53 – Phase angle of the studied bituminous mixtures at 20ºC

By analysing the graphs above it is possible to conclude that the recycled bituminous mixture without additive presents values of phase angle significantly lower than the conventional bituminous mixture. This results from the more elastic behaviour of recycled mixture due to its harder (aged) binder. The mixture produced with the rejuvenating additive show a behaviour that is closer to the conventional mixture, especially at lower frequencies, which highlights the role of the additive in rejuvenating the aged binder present in the RAP material. For the stiffness modulus, it is possible to observe that both recycled mixtures show higher values for all frequencies, in comparison with the conventional mixture, although the rejuvenated mixture (which has a final binder equivalent to a 35/50 pen binder) showed a behaviour closer to the conventional mixture.

4.9. Fatigue Resistance Test

The fatigue life of a bituminous specimen in the four-point bending test is determined by the number of cycles for which stiffness modulus reduces to half of its initial value. The results obtained for the studied mixtures for a frequency of 10Hz and a temperature of 20 ºC are presented in Table 21.

Table 21 – Results of the fatigue test (according to standard AASTHO TP8-34)

Bituminous mixtures	Specimens	Initial modulus	Strain (10^{-6})	No. cycles to failure
Conventional bituminous mixture	C_1	3703.4	411	6,94E+03
	C_2	4027.5	137	2,18E+05
	C_3	4623.17	223	1,38E+05
	C_4	4546.92	131	1,11E+06
	C_5	4424.17	237	9,95E+04
	C_6	4146.21	255	4,88E+04
	C_7	4699.49	144	6,54E+05
	C_8	3568.83	419	8,23E+03
	C_9	3393.21	413	7,60E+03
Recycled bituminous mixture without additive	R_1	8521.95	356	6.97E+03
	R_2	8242.1	409	3.87E+03
	R_3	8425.93	359	1.37E+04
	R_4	8916.84	232	1.19E+05
	R_5	8732.27	230	4.59E+04
	R_6	8948.82	221	4.54E+04
	R_7	9175.67	112	1.29E+06
	R_8	9339.12	112	2.09E+06
	R_9	3393.21	413	7.60E+03
Recycled bituminous mixture with additive	R_WA1	6081.83	352	2.54E+04
	R_WA2	5723.7	256	7.94E+04
	R_WA3	6227.71	362	1.96E+04
	R_WA4	5625.73	374	2.59E+04
	R_WA5	6375.16	262	6.95E+04
	R_WA6	6622.61	141	1.29E+06
	R_WA7	6265.55	248	9.52E+04
	R_WA8	6152.64	156	9.74E+05
	R_WA9	6072.54	155	6.68E+05

From the results presented in Table 21 it is possible to determine the fatigue life equations that represent the mixture resistance to repeated load applications that induce a certain strain level in the material. Figure 54 graphically represents the fatigue life equations of each studied mixture.

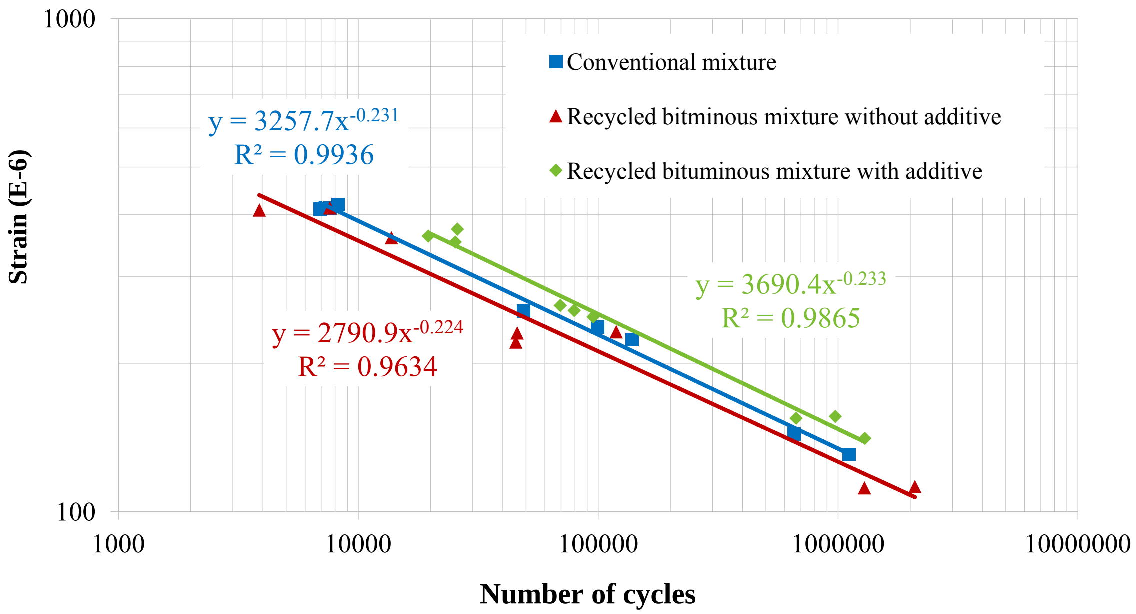


Figure 54 – Fatigue resistance of all studied mixtures, at 20 ºC and 10Hz

Analysing the results, it is found that the recycled bituminous mixture without additive presents a fatigue resistance slightly worse than the conventional mixture. This is due to the presence of the aged binder in the recycled mixture, which makes the mixture more brittle and less fatigue resistant. However, when a rejuvenating agent is incorporated, the fatigue life of the recycled mixture significantly improves (in this case it is even higher than the conventional mixture, but the results may have been influenced by the insufficient affinity between the aggregates and the bitumen of that mixture). The good performance of the recycled mixture with the rejuvenator may be explained by the effect of the additive that recovered some of the original properties of the aged binder, softening it and improving the workability of the mixture during the mixing stage. This would result in an improvement of the bond between the RAP and the new materials (aggregates and binder) which may have contributed to a better fatigue performance of this mixture.

Table 22 summarises the parameters of the fatigue life equations of each mixture and the two essential variables for the evaluation of fatigue cracking resistance (N_{100} – number of cycles that the mixture can withstand before failure at a tensile strain level of 100×10^{-6}; ε_6 – tensile strain that causes a fatigue cracking resistance of 1×10^{6} cycles). In general, the higher the values of those two characteristics, the higher the fatigue cracking resistance of the tested mixture.

Table 22 – Fatigue characteristics of the studied mixtures

Bituminous mixtures	Parameters of fatigue life equation			N_{100}	ε_6
	a	b	R^2		
Conventional bituminous mixture	1.419E+15	4.305	0.994	3.49E+06	134
Recycled Bituminous mixture without additive	9.78E+14	4.299	0.963	2.46E+06	123
Recycled bituminous mixture with additive	1.430E+15	4.229	0.987	4.97E+06	146

The results presented in Table 22 confirm the best fatigue performance of the recycled mixture produced with the additive (higher values of N_{100} and ε_6). It is also possible to observe that all mixtures present a very significant coefficient of determination (R^2), with values above 96%. The worse result was that obtained for the recycled mixture produced without additive, which can be explained by the difficulty in obtaining a very homogeneous mixture without softening the aged (hard) binder of the RAP, thus resulting in more variability in the data.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

According to the objectives initially proposed, it can be concluded that they were generally achieved. It was possible to produce a recycled mixture with mechanical properties equivalent to those of a conventional mixture, using temperatures lower than what is usually necessary for the production of a mixture with a very hard binder.

The mix design of bituminous mixtures is based on an iterative process in order to find the most appropriate particle size distribution of the aggregates to meet the limits imposed by the specifications, according to the type of mixture under study. However, the mix design of recycled bituminous mixtures is a far more complex process, as one of its components (the RAP) already has its characteristics defined (aggregate gradation and binder type and content). Furthermore, the use of rejuvenating agents or temperature reduction additives introduce more complexity to the process, since the determination of optimum binder content depends on the additive content, which is determined based on the binder content. Thus a few iterations may have to be carried out to achieve the final composition of the mixtures. In this work, a simplified procedure was used, where the optimum binder was determined (according to a previous study) for the hot-recycled mixture and the same value was used for the warm-recycled mixture (produced with the additive).

The first stage of the experimental work carried out was to select the additive that would be used on the determination of the mechanical properties of the warm-recycled mixture. Using the two additives supplied by an international research partner (Korea Institute for Construction Technology), different blends of aged binder (recovered from the RAP) new binder and additives were produced and their characteristics were determined. Based on the results, it was possible to observe that additive A (which was less expensive, according to the supplier) showed similar results to those of additive B. Thus the first was selected for the remainder of the investigation.

One of the principal goals of this study was to lower the temperature of the recycled bituminous mixture production incorporating additive, taking into account a maximum possible approximation to the air voids content of a conventional asphalt mixture. This was studied by compactability tests, where it was possible to conclude that the heating temperature of the new aggregates (and the coarse RAP) could be lowered by 30 ºC without compromising the air voids content of the final mixture. The results obtained for a 60 ºC reduction showed also encouraging results (with voids content similar to those of the conventional mixture), but the more conservative value of 30 ºC was selected for the production of the final mixture. During the production and compaction of the studied mixtures, an effort was made to control the temperatures, although in some parts of the work the lost of temperature was slightly higher than expected due to the small quantities of mixture produced (which lost temperature very quickly).

In the rejuvenation process of an aged binder, the ideal situation would be to add the rejuvenator directly to the RAP. However, due to the very small amounts of additive used in the present work (3% by mass of total binder) and the introduction of the RAP in two different stages (first the coarse RAP and later the fine RAP), it was not possible to mix the RAP directly with the additive. It was introduced in the new binder and mixed for a short period of time before introducing it in the mixture. Thus, the homogeneity of the final mixtures may be compromised due to the difficulty in spreading the additive to all aged binder.

Regarding the mechanical properties of the final bituminous mixtures, it is possible to conclude that both recycled bituminous mixtures showed an adequate performance in the presence of water, with ITSR values close to or even higher than 80%. The conventional mixture showed lower values that may be related to problems of affinity between the aggregates and the bitumen. Similarly, both recycled mixtures showed improved permanent deformation performances, when compared with the conventional mixture, although the mixture produced with additive has shown a lower rut resistance due to the effect of the additive (it has soften the final binder).

The stiffness modulus obtained for the recycled mixtures was also higher than that of the conventional mixture, with the hot-recycled mixture showing the highest values due to the harder binder present in the mixture. The fact that this mixture has a harder binder turns it into a more brittle material and this could be observed in the fatigue resistance obtained. The hot-recycled mixture was the worst performing mixture and the recycled mixture produced with the rejuvenating agent was the best performing mixture in terms of fatigue cracking resistance (even higher than the conventional mixture). This highlights the rejuvenating effect of the additive used, which was able to recover some of the flexibility of the aged binder.

Considering the whole study around the introduction of high rates of recycled material and the use of rejuvenating/temperature reduction additive in the production of bituminous mixtures it was observed that it is possible to produce recycled mixtures with properties equivalent or even higher than those of conventional mixtures.

5.2. Recommendations for future work

After the conclusion of this project, and taking into account all the processes carried out, based on some information of relevant articles, theses, and other references, it is important to mention some essential recommendations for a possible continuation of this work, with the intent of further contributing to the general knowledge on this filed.

In order to assess the sustainability of the studied mixtures, besides their mechanical properties, which are related to the durability of the material, it is also important to determine the costs of the final mixtures (this was not possible to estimate in the current work because the additive cost is still not defined, since it is still in a pre-production stage). Additionally, the environmental aspects related to the production of these mixtures should also be considered. Thus the savings in the consumption of new materials and energy together with the assessment of the greenhouse gas emissions obtained in the production of recycled mixtures should be determined and compared with those resulting from the production of new conventional mixtures.

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