Laboratory assessment of recycled bituminous mixtures with high RAP content

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Goods Practices of the Universidade de Lisboa.

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Resumo

Devido ao envelhecimento da infraestrutura rodoviária e para assegurar a segurança dos seus utilizadores, são necessárias operações de manutenção aos pavimentos que geram uma quantidade considerável de resíduos. Entre eles encontra-se o material fresado das camadas constituídas por misturas betuminosas, denominado por “Reclaimed Asphalt Pavement” (RAP) em inglês, e composto por agregado e betume.

Apesar de ambos os componentes do RAP serem materiais 100% recicláveis, o RAP tem sido reutilizado apenas como agregado, depreciando o seu uso e ignorando o valor do betume. De facto, o betume encontra-se envelhecido após a vida útil do pavimento, mas algumas das suas propriedades podem ser recuperadas com a adição de um rejuvenescedor na mistura reciclada.

Esta dissertação teve como objetivo a avaliação do desempenho de uma mistura betuminosa densa para camada de desgaste com incorporação de alta percentagem de RAP (75%), tratado com rejuvenescedor. Foi também avaliada a capacidade desta mistura betuminosa ser re-reciclada, após a sua vida útil, numa outra mistura com 75% de material fresado.

Foi realizado um estudo experimental em laboratório que envolveu: a formulação de uma mistura betuminosa reciclada; o seu envelhecimento em estufa; a produção de RAP em laboratório; a produção de uma nova mistura com esse RAP; e a avaliação do desempenho mecânico e caraterísticas superficiais de ambas as misturas.

Os resultados obtidos revelaram que o desempenho mecânico das misturas recicladas foi melhor ou esteve a par com o da mistura de referência, embora as suas características superficiais ficaram ligeiramente abaixo dos limites estipulados nas especificações portuguesas.

Palavras-chave: Material fresado, misturas betuminosas, economia circular, reciclagem, envelhecimento

Abstract

Due to the ageing of the road infrastructure and to ensure the safety of its users, the required maintenance operations generate a considerable amount of by-products. Among those, one can find the milled material from the bituminous layers, known as Reclaimed Asphalt Pavement (RAP), which is composed of aggregates and bitumen.

Even though both components of RAP are 100% recyclable materials, RAP has been recycled only as aggregate, downgrading its use and disregarding the bitumen's value. Indeed, the bitumen is aged after a pavement's service life, yet some of its properties can be recovered with the addition of a rejuvenator in the recycled mixture.

This dissertation aimed to evaluate the performance of a surface dense graded hot bituminous mixture that incorporated a high percentage of RAP (75%), treated with a rejuvenator. Its capacity of being re-recycled into another 75% RAP content mixture after enduring a service life was also evaluated.

An experimental laboratory study was carried out, encompassing the formulation of a recycled bituminous mixture, subjecting it to an oven-ageing procedure, the laboratory production of RAP, the production of a new mixture with that RAP and the assessment of both mixtures' mechanical and surface characteristics performance.

The results have shown that the mechanical performance of the recycled mixtures was better or on par with the reference mixture, while the superficial characteristics were slightly below the limits set in the Portuguese specifications.

Keywords: Reclaimed asphalt pavement, bituminous mixtures, circular economy, recycling, ageing

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Abbreviations

AASHTO – American Association of State Highway and Transportation Officials

AC – Asphalt Concrete

ACPA – American Concrete Pavement Association

CDW – Construction and Demolition Waste

EAPA – European Asphalt Pavement Association

EP – Estradas de Portugal

EU – European Union

ITSR – Indirect Tensile Strength Ratio

MTD – Mean Texture Depth

PTV – Pendulum Test Value

RAP – Reclaimed Asphalt Pavement

SMA – Stone Mastic Asphalt

VMA - Voids in the mineral aggregate

Symbols

E_1 – Real component of the complex modulus

E_2 – Imaginary component of the complex modulus

ITS_d – Indirect Tensile Strength of the dry group

ITS_w - Indirect Tensile Strength of the wet group

PRD_{AIR} – Mean proportional rut depth

R^2 – Coefficient of determination

RD_{AIR} – Mean rut depth at 10.000 cycles

V_m – Air voids content

WTS_{AIR} – Mean wheel-tracking slope

σ – Standard deviation

1. INTRODUCTION

1.1. Problem statement

The road infrastructure is indispensable for society, enabling the functioning and development of a country by providing mobility and accessibility of people and goods. The maintenance required to be kept in such conditions that ensure the safety and comfort of its users generates a considerable amount of by-products.

Growing environmental concerns push for the transition to a circular economy, whose aim is to decrease waste production and natural resource depletion by reintroducing products at their end-of-life stage in the cycle, rather than disposing of them. In fact, in 2015, the EU has implemented the Action Plan for the Circular Economy, which advocates for a more efficient use of resources and for turning waste into secondary raw materials (European Commission, 2015).

In Europe, bituminous mixtures are the predominant construction material of the bound layers of a pavement and are 100% recyclable (EAPA, 2014). However, the reclaimed bituminous mixtures - or reclaimed asphalt pavement (RAP) as it is widely known - are recycled mostly in unbound layers as aggregates or in small percentages (5-20%) in new bituminous mixtures, which is not an efficient use of this resource, as the bitumen's properties are not being taken advantage of, thus downgrading the RAP's use (Zaumanis et al., 2016).

This downgrading of the RAP's use can be attributed to the lack of confidence in the recycled pavement's performance, the increased complexity of the recycling operation, the variability of the material and the unknown degree of mobilization of the aged binder (EAPA, 2014; Karlsson and Isacsson, 2006; Lo Presti et al., 2016; Zaumanis et al., 2016; Zaumanis and Mallick, 2015).

Additionally, the exposure of the binder to the climate during its service life has an ageing effect that changes the binder's properties. This is an important aspect to be considered in recycling bituminous mixtures, especially when the RAP incorporation rate is high (>25%), as the ageing process makes the binder stiffer and influences the mixture's performance. Therefore, when producing recycled mixtures with a high RAP content, it is recommended to use a softer binder or rejuvenator which improve the aged binder's properties (EAPA, 2018).

In essence, it is fundamental to deepen the knowledge on recycled bituminous mixtures in order to overcome the previously listed challenges and maximize the utility of RAP, bringing a contribution to the transition to a circular economy.

1.2. Objectives and methodology

The main objectives of this thesis are to analyse the performance of a recycled bituminous mixture incorporating high RAP content after going through an ageing process, as well as the re-recycling capacity of RAP in new bituminous mixtures. Through this analysis, it is expected to obtain insight into:

- how production temperature and rejuvenator use affect the mobilization of RAP’s aged binder on a recycled mixture;
- the effects of the incorporation of rejuvenated RAP in a hot bituminous mixture in terms of long-term performance;
- the viability of using the RAP from a recycled mixture that has been rejuvenated before in a new recycled mixture.

To that end, a laboratory study involving a surface dense bituminous mixture, incorporating 75% RAP and treated with a commercial rejuvenator, was performed.

The mobilization of RAP’s aged binder was addressed through the production of several Marshall specimens in varied conditions and respective visual inspection. The virgin binder used to produce these specimens was pigmented blue bitumen, so it contrasted with the black, aged bitumen from the RAP.

The long-term performance of a recycled bituminous mixture was addressed through the design of a mixture using the Marshall method and its performance evaluation before and after ageing. The ageing process that the bituminous mixtures undergo during the mixing, storage, transportation and compaction of the mixture until it cools down was simulated through short-term oven conditioning, and the ageing process that the bituminous mixtures undergo during their service lives was simulated through long-term oven conditioning.

Finally, the viability of re-recycling a bituminous mixture was addressed through the production and performance evaluation of a mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle. That RAP was produced in the laboratory from aged slabs of the recycled mixture.

As mentioned before, the performance evaluation was carried out on the laboratory-produced mixtures and consisted on stiffness, fatigue resistance, water sensitivity and permanent deformation tests, for the mechanical behaviour, as well as macro and micro-texture tests, for the surface characteristics.

1.3. Thesis organization

This thesis is divided into five chapters:

In Chapter 1, the problem is introduced, the objectives for this thesis are set and the methodology to approach the problem is outlined.

In Chapter 2, important concepts of pavement technology, circular economy in the context of the pavement industry and bituminous mixtures are introduced; and a literature review on RAP is presented: it defines the material and its recovery, describes various recycling methods, presents the rejuvenators and their usage, as well as the properties and mechanical performance of recycled mixtures. Then, the multi-recycling capacity of bituminous mixtures is also reviewed, ending this chapter with a highlight of the benefits and the identification of the challenges that the recycling practice faces.

In Chapter 3, the materials used to produce the studied bituminous mixtures and respective characterisation process are described, followed by the evaluation of the aged binder's mobilization and the descriptions of the bituminous mixture design, the performance evaluation tests, the ageing procedure and the re-recycling process.

In Chapter 4, the results from the performance evaluation tests are analysed and the performance between the mixtures is compared.

In Chapter 5, the conclusions that were drawn from the previous analysis and comparisons are presented, followed by recommendations for future research that could improve the knowledge and, therefore, improve the confidence in the use of recycled mixtures.

Finally, the included annexes contain the syntheses of the collected data on each performance test.

2. LITERATURE REVIEW

2.1. Pavement technology

The road infrastructure is essential for the functioning and development of any country since it provides mobility and accessibility of people and goods. That traffic is carried by the pavement and it should ensure the safety and comfort of its users during its service life, through the traffic and environment loads.

Over a pavement's service life, it is required to maintain functional and structural characteristics. The first are mainly related to the users' requirements of safety and comfort, conveyed by the pavement's texture, colour, surface friction and noise produced by the rolling of the tire over it. The structural characteristics refer to the ability of the pavement to withstand loads without sustaining permanent damage beyond certain limits (Branco et al., 2016).

A pavement is composed of the foundation, which usually is the natural soil; followed by granular layers, made up of unbound aggregates; and bound layers at the top, made up of aggregates bound by a binder. From the bottom layer to the top one, the material's quality and resistance increases. Moreover, depending on the type of binder and, consequently, on the way a pavement responds to traffic loads, they can be classified as flexible, rigid or semi-rigid (Branco et al., 2016).

A flexible pavement consists of several granular layers, followed by bitumen bound layers, generally called bituminous mixtures. These bend under an axle load and distribute the load throughout the layers, decreasing it as the depth increases (Mohod and Kadam, 2016). On the contrary, a rigid pavement consists of several granular layers that support a concrete slab. Due to the concrete's strength, these almost do not bend as the load is distributed over the large area of the slab. These different load distributions are shown in Figure 2.1. Subsequently, a semi-rigid pavement has elements of both flexible and rigid pavements, consisting of a granular layer, followed by a granular layer stabilized by hydraulic binders and a bituminous mixture as the surface layer. In this case, as the previous one, most of the strains are absorbed by the hydraulic bound layer.

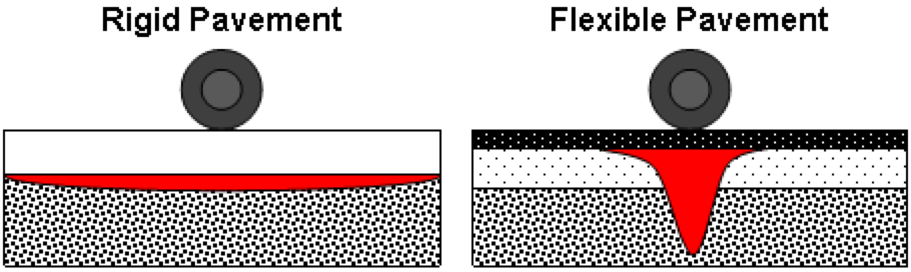

Figure 2.1: Rigid and flexible pavement load distribution (adapted from ACPA, 2013)

2.2. Circular economy and recycling

A circular economy aims at minimizing waste and resource consumption during the entire life of a product, hence when a product is at the end-of-life phase, its materials are reintroduced in the cycle as a resource instead of being disposed of.

In an effort to encourage sustainability and competitiveness for businesses, in 2015, the EU has implemented the Action Plan for the Circular Economy (European Commission, 2015), whose general measures address product design, production process, consumption, turning waste into resources and innovation, investment and other issues. Additionally, it outlined actions for specific materials and sectors, as those present some particularities and, thus, specific challenges.

The general measures advocate (i) a more careful product design which considers its maintenance and durability; (ii) providing more reliable information to consumers and stimulating the emergence of new forms of consumption; (iii) a more efficient use of resources as well as the production of less waste in the manufacturing processes and turning by-products into input for other industries; (iv) upgrading the waste collection, sorting and characterization systems in order for it to be reused as secondary raw materials, and (v) research and investment to enable transitioning to a circular economy.

One of the sectors which have been targeted with specific actions is the construction and demolition sector, as it was the largest contributor to the total waste generation in Europe (in 2016, it was responsible for the production of 36.4% of the total waste (Figure 2.2) (Eurostat, 2019)). Those actions are mostly focused on improving waste management in the sector in order to recover and recycle valuable resources, as well as increasing the confidence in recycled construction materials.

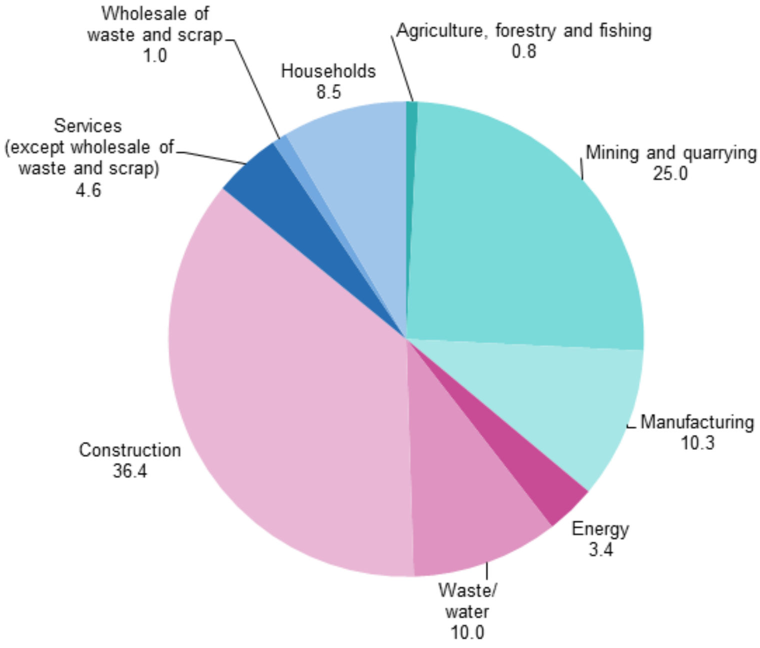

Figure 2.2: Waste generation by economic activities and households (%), EU-28, 2016 (Eurostat, 2019)

Essentially, it is becoming increasingly important to consider the whole life cycle of a construction project: from the origin of its materials and construction process, through its maintenance during service life, to its disposal at the end-of-life, including not only the total cost but also energy consumption, greenhouse gas emissions, and waste production.

Since both the aggregates and the binder which are traditionally used in the paving industry come from non-renewable sources, several technologies and innovative materials are being investigated and put into practice: those include, among others, the incorporation of construction waste and other industries’ by-products in the pavements or the extension of their service life by designing long-life pavements.

Construction waste and other industries’ by-products are being introduced in every layer of a pavement: some of the materials that can replace mineral aggregates include reclaimed asphalt pavement (RAP), construction and demolition waste (CDW) (recycled concrete aggregates, recovered roof membranes and shingles), residues from the metal and power industries (steel slag and fly ash), and recycled waste (glass, plastic, tyre rubber, etc.) (Balaguera et al., 2018; EAPA, 2017; Kowalski et al., 2016; Martinho et al., 2018). As for the binder, there has been some research into materials that can replace, totally or partially, or modify the properties of crude-oil bitumen, such as waste cooking oil, vegetable oils (e.g. soybean oil), wood and paper industries’ by-products (e.g. lignin) and swine manure (Fini et al., 2012; Ingrassia et al., 2019a, 2019b; Li et al., 2019; Pérez et al., 2019; Portugal et al., 2018; Sun et al., 2016; Wen et al., 2012).

On the other hand, the concept of a long-life pavement (perpetual pavement, in the USA) implies that it is designed and constructed in such a way that its structural life surpasses 50 years (as opposed to the 20 years of a traditional design), independently of the traffic load, and only requires surface maintenance. This is achieved by eliminating the most common distress mechanisms of the unbound layers and constraining cracking and rutting to the surface layer (EAPA, 2007; Ferne, 2006; Timm and Newcomb, 2006).

The main advantages of such a structure are a decrease in the consumption of non-renewable materials, a decrease in the time required for rehabilitation activities and the exclusion of the costs associated with structural reconstruction, hence, a decrease in the life-cycle cost of a pavement (Timm and Newcomb, 2006). However, the costs associated with thicker layers and better materials might constitute a financial constraint to the implementation of this concept (EAPA, 2007).

2.3. Bituminous Mixtures

The main focus of this study is the surface layer of the flexible pavements, materialized by a bituminous mixture, which is, essentially, composed by aggregates bound by bitumen and its performance can be enhanced with the incorporation of additives.

2.3.1. Types and production

There are several types of bituminous mixtures with different characteristics, suitable for different applications, locations and traffic volumes. They can be divided in three types, based on their particle size distribution: dense-graded, open-graded and Stone Mastic Asphalt (SMA) (Asphalt Pavement Alliance, 2019).

A dense graded bituminous mixture is characterised by a continuous aggregate gradation and low air-voids content, while an open graded bituminous mixture is comprised mostly of coarse aggregates (with low proportion of fines and filler) and high air voids content. Regarding the SMA, it is characterised by a gap-graded aggregate gradation and a low air voids content, as the voids are filled by a mastic of binder, filler and fine aggregate (Austroads, 2014).

Bituminous mixtures can be produced at cold, hot or warm temperatures. The temperature range for each method is represented in Figure 2.3. The hot and warm mixtures can be produced in batch or continuous mixing plants, while the cold are produced in continuous mixing plants.

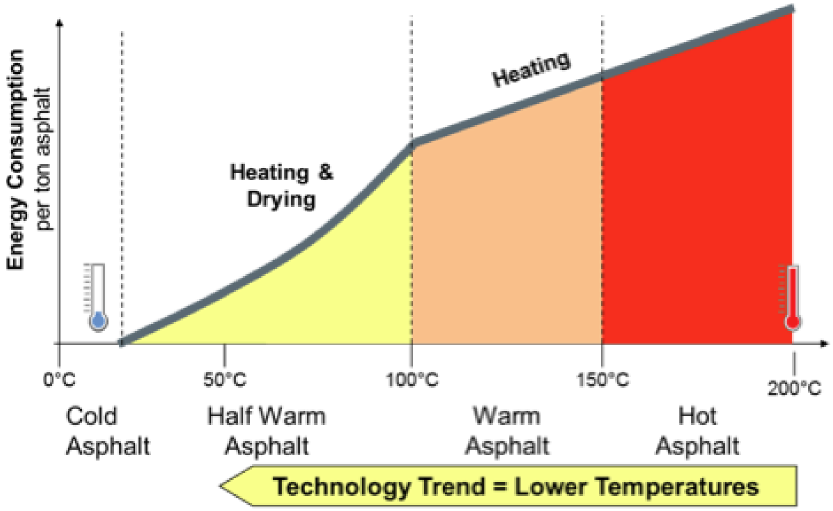

Figure 2.3: Mixture production temperatures (EAPA, 2019)

In a batch plant, the aggregates are heated in a dryer drum, weighted and fed to a mixer, where they are blended with the previously heated binder; the mixture is then discharged to a truck or a storage silo. In a continuous plant, the process is the same, except that the materials are fed continuously to the mixer. This type of plant, instead of having a separate dryer drum and mixer can have those equipments combined in a dryer/drum mixer (Branco et al., 2016).

In a continuous mixing plant, the cold mixtures are produced in a similar manner but dismiss the heating of the materials (Branco et al., 2016). For warm mixtures, the process is similar to that of the hot mixtures but it is included an additive and/or or used a technology that lowers the production temperature (Austroads, 2014).

2.3.2. Components

The aggregates usually are a particulate mineral material, obtained either in their natural state, extracted near riverbeds or by extracting and crushing rock. However, they can also be recycled material from other construction uses, such as concrete or bituminous mixtures, or even be industrial by-products, such as iron or steel slag.

The main purpose of using aggregates in bituminous mixtures is to create an aggregate skeleton that withstands the traffic loads, so they must be thoroughly characterized when it comes to particle size distribution and shape, toughness, cleanliness and affinity between aggregate and bitumen, among others.

Bitumen is a binder obtained from the distillation of crude oil. Depending on the temperature, its consistency is variable: at lower temperatures, it is stiffer and at higher temperatures, it is softer. It is characterized, mostly, by its softening temperature and penetration, from which it gets its grade designation according to the European standards.

The choice of a bitumen grade to use is dictated by the climatic conditions, mainly the operating temperature, and the desired type of mixture (whose production can be carried out either in hot, cold or warm temperatures).

Lastly, the additives can take the form of various substances such as polymers, chemical modifiers, extenders, antioxidant, hydrocarbons or anti-stripping additives. Their main purpose is enhancing a mixture’s performance and the benefits for their use can include, among others, increased rutting, fatigue and thermal cracking resistance, extended service life of a pavement, enabling the production of a mixture at lower temperatures or rejuvenating an aged bitumen (Daly, 2017; King G., 1999).

2.3.3. Properties

Depending on what layer a bituminous mixture is used, it must ensure the functional characteristics of the pavement, in the case of a surface course, or ensure the structural ones, in case of a binder or base course (Austroads, 2014; Branco et al., 2016).

In general, the desired bituminous mixture properties are (Hicks et al., 2003):

- The ability to withstand the service loads with minimal deformation (resistance to permanent deformation).
- The resistance to the induced tensile strain caused by the repeated passing of wheel loads (fatigue resistance).
- The resistance to the contraction of the pavement caused by low temperatures (resistance to low-temperature cracking).
- The resistance to disintegration inflicted by the vehicles and the climate (durability).
- The resistance to moisture induced damage (water susceptibility).

- Adherence to the vehicle’s tires (skid resistance).
- Ease to place and compact (workability).

These properties are heavily influenced by the mixture’s density and voids content, the aggregate gradation, shape and surface texture, and the grade and quantity of bitumen. These parameters must be balanced to obtain a suitable mixture for each different pavement application, as there is no proportion that will optimize all of the desirable mixture properties (Lavin, 2003). For example, a higher percentage of bitumen would be beneficial to the durability of the mixture, as the aggregates would be coated with a thicker binder film (delaying binder ageing and minimizing the ravelling of the mixture), yet it would hinder the mixture’s resistance to permanent deformation, as too much binder reduces the aggregate inter-particle friction (Branco et al., 2016).

2.3.4. Performance

A bituminous mixture’s performance can be assessed by its fatigue and cracking resistance, permanent deformation, stiffness, workability and water susceptibility.

Fatigue is caused by applying a cyclic load on a pavement, which builds up irreversible extensions leading to the development and propagation of cracks. Cracking can also be caused by low temperatures (thermal cracking), which cause the pavement to contract, being more significant on extreme cold conditions.

On the contrary, permanent deformation, usually manifested by rutting, is mainly influenced by higher temperatures, being more significant in warm climates.

Stiffness is a measure of deformation endurance behaviour, dependent on temperature and loading conditions. It can influence the performance on the previous parameters, as a pavement that presents high stiffness at higher temperatures is less susceptible to rutting while one that presents low stiffness at low temperatures is less susceptible to thermal cracking and a pavement that presents high stiffness is more susceptible to fatigue cracking and vice-versa (Zaumanis et al., 2018).

Workability defines the ease with which a mixture is placed and compacted and is mostly dependent on the binder’s viscosity. In fact, taking into account how parameters affect workability is fundamental, as it influences a compacted mixture’s final air voids content.

Water susceptibility is related to how liable a bituminous mixture is to be damaged by the presence of water since it can weaken the bond between the bitumen and the aggregates, resulting in stripping and ultimately affecting the mixtures’ stiffness and structural strength (Diab and Pais, 2017).

2.4. RAP bituminous mixtures

According to EN 13108-8, RAP is defined as “asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements or lumps from asphalt slabs and asphalt from reject and surplus production”. Considering that, in developed countries, the paving industry is dominated by road maintenance activities rather than the construction of new ones, RAP is a material that is widely available (Zaumanis et al., 2014). Figure 2.4 shows a pavement after being milled and Figure 2.5 shows the resulting pile of RAP.

Figure 2.4: Milled pavement

Figure 2.5: RAP pile

Even though there were earlier attempts at recycling RAP, the first main driver of research on this topic was the 1970’s oil crisis, in which there was an increase in the bitumen’s price. Until then, because the milling machinery was not as advanced, the cost of removing and processing old pavements outweighed the cost of virgin materials (Al-Qadi et al., 2012).

More recently, aside from the still increasing bitumen prices, the paving industry is facing shrinking budgets, rising traffic and a growing concern for sustainability, when it comes to both the nature of its materials and its energy consumption (Dony et al., 2013; Zaumanis et al., 2016).

In spite of these concerns, RAP is being mostly incorporated in the unbound layers or in small percentages (5-20%) in new bituminous mixtures. These uses, however, do not take advantage of the full potential of RAP, as it is being employed solely as an aggregate while it could also provide a part of the bitumen needed for a bituminous mixture (Zaumanis et al., 2016). Since the incorporation of small percentages of RAP has little to no influence on the resulting product, there is no need to test these materials’ performance on either use while higher RAP incorporation in a mixture implies thorough testing of the materials themselves as well as the mixture’s performance (Hussain and Qiu, 2013).

2.4.1. Production

There are several methods to recycle RAP, differing in place and temperature in which it is carried out. It can be done in-place - *in situ* - or in-plant and at cold, warm or hot temperatures (below 70°C, between 70 to 120°C and above 120°C, respectively (Karlsson and Isacsson, 2006)).

In-place recycling consists of milling or scarifying the pavement’s surface, mixing the RAP (optionally, adding new aggregates or binder) and laying and compacting it. When cold or warm recycling, milling is performed at cold temperatures and a bituminous emulsion, foamed bitumen or soft bitumen is added into the mixture (cold remixing can also use concrete as a binder). Even though milling can be performed at hot or cold temperature, hot milling carries the advantage of minimal crushing of the aggregates, allowing for the needed adjustments to be based on that pavement’s original grading curve (Batista, 2006; Karlsson and Isacsson, 2006).

On the other hand, in-plant recycling requires the transportation of milled materials to a plant and of the new mixture to the place where it is to be laid. Depending on the type of plant and mixture, the RAP is introduced in different stages.

In cold recycling, in a cold mixing plant, RAP is introduced directly in the mixer, where it is mixed with a bituminous emulsion or foamed bitumen (Branco et al., 2016).

Warm recycling is performed in a hot mixing plant: in a batch plant, RAP is introduced in the dryer drum and goes on to the mixer, where a bituminous emulsion is added; in a continuous plant, it is introduced in the dryer/drum mixer (Batista, 2006).

In hot recycling, RAP can be introduced directly in the mixer, where it is heated indirectly by superheated aggregates (for it not be exposed to direct flame); along with the aggregates in the dryer drum or by itself in a parallel dryer drum (Batista, 2006).

The main factors which limit the incorporation rate in a conventional hot mixing plant are that RAP’s contact with the dryer’s flame generates blue smoke and that RAP’s contact with superheated aggregates, can cause the aged bitumen to catch fire if the aggregate’s temperature is high enough (Batista, 2006; Zaumanis et al., 2014). However, Zaumanis et al. (2014) describe several 100% RAP production technologies which consist mostly of adaptations to the conventional plants: either (i) adding blue smoke filtration systems to prevent the release of combustion gases from the direct contact of RAP with the flame in the dryer, or (ii) adapted dryer drums to prevent direct contact of RAP with the flame. It is also recommended to have bins for separate RAP fractions or to screen the fractions before adding RAP to the mixer since it provides better control over the mixture’s particle size distribution, as well as additional tanks for a softer bitumen or a rejuvenator (Zaumanis and Mallick, 2015).

The decision on which recycling method to use must take into account, among other factors, that pavement’s traffic level, type of binder, climatic conditions and equipment, material and personnel availability.

In the cases of cold and warm recycling the bituminous emulsions take some time to set, leaving the pavement prone to deformation for a short period after construction, and its construction is more affected by weather conditions. When comparing both methods, cold recycling has lower energy demands, but warm recycling improves the mixtures' workability (easier laying and compaction), reduces the setting time (in some cases, traffic can be resumed immediately) and is less susceptible to weather conditions (Karlsson and Isacsson, 2006).

Regarding where the recycling takes place, in-place recycling minimizes the need for RAP transportation and storage, reduces the stresses caused on the roads adjacent to the construction site, the construction time and the investment in equipment, yet in-plant recycling has better control over the material's properties and the quality of the mixture, as well as easier access to binder, corrective materials, and equipment maintenance (Branco et al., 2016; Karlsson and Isacsson, 2006).

Furthermore, it is important to mention that, for higher RAP content bituminous mixtures, the traditional mix design methodology has to be adapted to include RAP and a rejuvenator. Essentially, the RAP has to be processed and characterized before combining it with the new aggregates to define the mixture gradation and the rejuvenator has to be tested to determine the correct dose and ensure that it does not excessively soften the mix. After determining the mixture's volumetric and performance-related properties, it is assessed whether or not it complies with the requirements, being altered if not (Zaumanis et al., 2016).

2.4.2. Rejuvenators

Being exposed to the climate for a prolonged amount of time, the binder that is included in the RAP is aged. Binder ageing is an important aspect to be considered in recycling bituminous mixtures, especially when the RAP incorporation rate is high, as that process makes the binder stiffer and influences the mixture's performance.

To address that matter, softer binder or rejuvenators can be added to the mixture. In general, the rejuvenator's purpose is lowering the aged bitumen's viscosity, improving its workability, and restoring its chemical properties, making it able to endure another life cycle (Karlsson and Isacsson, 2006).

However, it is important to point out that there is not an official definition for the word "rejuvenator", as stated by the European Asphalt Pavement Association (EAPA, 2018), and there is pressing need to classify the products that are used as such. Throughout the literature, that type of products is referred to by different terms, including softening, rejuvenating, modifying or recycling agent, recycling modifier, etc. Besides different names, they can also come from different origins whether engineered products or plant/waste-derived or refinery base oils (Karlsson and Isacsson, 2006; Mazzoni et al., 2018; Ongel and Hugener, 2015; Zaumanis et al., 2016).

The main issues related to rejuvenator usage concern the possibility of overly softening the mixture (leading the pavement to premature failure) and the lack of knowledge regarding the rejuvenator's effects and diffusion rate (Tran et al., 2012; Zaumanis and Mallick, 2015). In light of such concerns, the choice of rejuvenator and its dosage should be based on testing and consider its short and long term properties.

Firstly, it is recommended that the choice of rejuvenator and its dosage be based on the penetration value and softening point temperature of the aged binder combined with it, having to meet the values for the intended binder category. Then, the final bituminous mixtures should be tested regarding their stiffness, resistance to permanent deformation, fatigue resistance, low-temperature properties, and water sensitivity, which have to meet the values defined in each country's specifications (EAPA, 2018). In fact, a couple of studies (Nie et al., 2018; Zaumanis et al., 2015) concluded that the penetration test was a good method to determine the optimum dose of rejuvenator.

Moreover, in the short term, it is desirable that a rejuvenator diffuses quickly into the RAP binder, mobilizes and softens the aged binder and produces a workable mixture; while, in the long term, a rejuvenator should restore the aged binder's properties, so that it is able to endure another service period, addressing the potential for low fatigue and low temperature cracking (associated with a stiff mixture), yet not resulting in rutting problems from over softening the binder (Zaumanis et al., 2014).

2.4.3. Properties

Being resultant of milling or crushing bituminous pavements, RAP is constituted by the same components as a bituminous mixture (aggregates and bitumen). As it is often a material at the end-of-life stage, it is fundamental to determine not only its properties but also those of both constituents.

In Europe, even though there is a European Standard (EN 13108-8) in which the classification and description requirements of RAP for bituminous mixtures are defined, the requirements on RAP for the use in hot bituminous mixtures differ from country to country. The European Standard indicates the RAP's maximum grain size, binder content, content of foreign matter and homogeneity, as well as the aggregate's grading and binder's type, softening temperature and penetration as the required characteristics to determine, yet some countries require additional ones (mostly related to the aggregates themselves) (Mollenhauer and Gaspar, 2012). Moreover, several sources emphasize the importance of applying the same requirements for RAP aggregates as those for virgin aggregates, especially if it is to be incorporated in a surface layer (Copeland, 2011; EAPA, 2014; Hajj et al., 2012).

The RAP's binder content can be assessed either via solvent extraction or the ignition method, though the ignition method is more accurate than the solvent extraction ones, as they often underestimate the value due to binder residue being left on the aggregates (Hajj et al., 2012).

Determining the individual properties of the RAP's components implies their recovery. The bitumen is recovered via a solvent extraction method and the aggregates can be recovered either via solvent extraction or the ignition method. However, when assessing the aggregates' properties, it is advisable to use a solvent extraction method as the ignition one may cause aggregate degradation (Hajj et al., 2012).

Lastly, there are a few measures that can be taken both in RAP processing and stockpile management so that it is used more efficiently (Zhou et al., 2010):

Firstly, RAP should not be over-processed, as the crushing process generates a considerable amount of fines, and, to guarantee more uniformity in gradation and bitumen content, the material should be fractionated into two or three sizes, giving more control over those properties in the mixture.

Regarding stockpile management, ideally, RAP from different sources and layers should be kept in separate piles; however, if there are space limitations, it can be kept on the same pile as long as it is thoroughly blended before processing or fractionating. Furthermore, by piling the material on paved, sloped areas, as well as in conical shapes, rather than horizontal, the piles keep less moisture, saving energy and, therefore, costs in the drying process.

2.4.4. Mechanical Performance

In order to be viewed as a viable alternative to a traditional mixture, a recycled one and its materials should perform as well as the first, or better. Up to the present time, the performance of recycled mixtures has been evaluated in different conditions: with different percentages of RAP incorporation (up to 100%), with or without rejuvenator and different types of it, with or without fractionation of the RAP and before and after short/long term ageing.

In general, those evaluations verify that increasing RAP content on recycled bituminous mixtures results in increasing stiffness, thus lowering cracking resistance and workability but increasing resistance to permanent deformation. The addition of a rejuvenator or a softer binder can enhance the workability, as they reduce the bitumen's/mixture's viscosity and stiffness, and, in the case of the rejuvenated mixtures, still keeping a high permanent deformation resistance (Mogawer et al., 2012; Zaumanis et al., 2015). Furthermore, different types of rejuvenator can affect different properties: for example, in a study about the effects of various types of recycling agents (Zaumanis et al., 2015) the organic products improved the aged binder's fatigue behaviour, while the petroleum ones did not have a significant effect.

It was also verified that the RAP incorporation rate could be limited because of its gradation, as its extraction process produces a high amount of fine aggregates, decreasing the mixture's air voids content as the RAP content increased (Bańkowski et al., 2018). However, RAP fractioning provides more control over the mixture's gradation and, therefore, of its volumetric properties, making it possible to produce 100% RAP recycled mixtures (Al-Qadi et al., 2012; Zhou et al., 2010).

Finally, it is important to mention that the recycled mixture’s performance can be impacted by the production process (especially the mixing of the materials), the handling of the material after the production and its storage practices (Mogawer et al., 2012; Tran et al., 2012).

2.5. Multi-recycling capacity

In a circular economy, the end of life stage of a product that was made from recycled materials does not mean that its constituents should be disposed of; therefore, as a 100% recyclable material, RAP from a pavement that was already produced with RAP should be able to be introduced back in the cycle.

Provided that ageing has little to no influence in the aggregate’s properties, they are still suitable for re-use in the same value applications. On the contrary, the binder’s behaviour is influenced by the ageing processes and its suitability for repeated use should be considered (EAPA, 2014).

Petho and Denneman (2016) and Nie et al. (2018) have simulated the use of RAP binders in several ageing and recycling cycles using the Rolling Thin Film Oven procedure. Petho and Denneman (2016) concluded that, even though there was an increase in the RAP binder’s viscosity, it could be subjected to multiple recycling, as long as it was properly characterized and treated in the mix design and production process, especially after the second and third cycle. Nie et al. (2018) found that through the selection of an appropriate rejuvenator and the adjustment of its content, the repeated use and recycling of the binder was feasible, as it could be restored to similar rheological indices to a virgin binder.

Regarding the impact of the multiple recycling on the bituminous mixtures themselves, Mollenhauer et al. (2013) subjected bituminous mixtures containing 50% RAP to three recycling cycles, adding a softer bitumen to manage the increase in the binder’s viscosity, and obtained a performance comparable to a virgin mixture. Heneash (2013) subjected bituminous mixtures with different RAP content to different ageing levels repeatedly and found that repeated recycling did not have a significant effect on the degradation of the mixtures’ stiffness and fatigue, and that those properties remained acceptable even in high RAP mixtures (>50% RAP content), given that it was properly pre-heated before mixing.

The majority of the studies involving RAP are focused on its effects in the bituminous mixture’s performance but do not take into consideration the possibility of incorporating material that was subjected to more than one life cycle (Nie et al., 2018). Therefore, the repeated recycling of bituminous mixtures is a subject matter that requires further investigation.

In the long run, this practice carries the potential to multiply the environmental and economic benefits of onetime recycling and is the next step towards achieving a circular economy.

2.6. Benefits and challenges

Since there is a rising demand for more sustainability and cost-effectiveness, RAP recycling can be a viable answer for the paving industry.

When it comes to sustainability, it avoids the disposal of such materials in landfills while reducing the need for the extraction, processing, and transportation of raw materials and its respective carbon emissions (Balaguera et al., 2018; EAPA, 2014). However, comparing these savings to the emissions generated by the vehicles throughout the whole life of a pavement, they are not significant and, therefore, not the main incentive for this practice (Antunes et al., 2019).

When it comes to cost-effectiveness, the costs of RAP disposal and of virgin materials can be reduced or even eliminated (in the case of 100% RAP mixtures), as shown in Figure 2.6. There is also the possibility that around urban areas, given its abundance, RAP can be acquired without charge. Nonetheless, increasing RAP incorporation involves additional costs with processing, testing, pollution control and rejuvenators (Zaumanis et al., 2016).

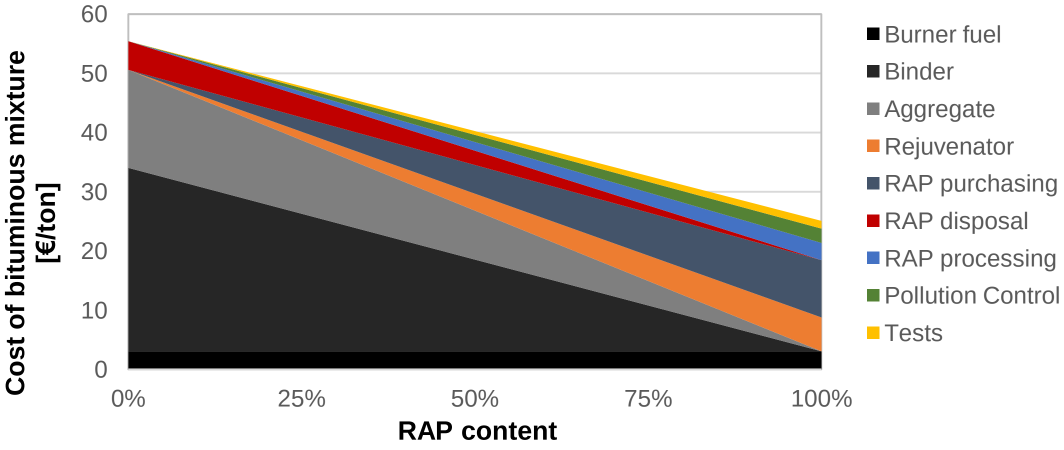

Figure 2.6: Material related costs of hot mix recycling (adapted from Zaumanis et al., 2016)

On the other hand, the RAP recycling practice has been limited mostly due to the lack of confidence in the recycled pavement's performance, the increased complexity of the operation, the variability of the material and the unknown degree of mobilization of the aged binder (EAPA, 2014; Karlsson and Isacsson, 2006; Lo Presti et al., 2016; Zaumanis et al., 2016; Zaumanis and Mallick, 2015).

The lack of confidence in the recycled pavement's performance is tied to earlier unsuccessful projects with high RAP content, as well as concerns about the unknown durability of such pavements and the possibility that they demand maintenance operations more often (Aurangzeb et al., 2014; Zaumanis et al., 2016, 2014).

This practice entails additional requirements when compared to the traditional maintenance operations, thus the increased complexity argument. It requires an experienced pavement engineer and adapted plants, in the case of hot bituminous mixtures, as well as the added effort to mill, characterize and manage the RAP properly (Zaumanis and Mallick, 2015).

The variability of RAP can be addressed by handling heterogeneities existent in the old pavement, such as road markings, soil and patches, or by the thorough homogenization of the material (EAPA, 2014; Karlsson and Isacsson, 2006).

Finally, the actual degree of mobilization of the aged binder is currently unknown and is situated between full mobilization and no mobilization at all, the latter meaning that the RAP acts solely as aggregate (called “black rock”). This variable has an impact on the characteristics of the mixtures, therefore, on the mix design process, yet, it has been verified that the mixing temperature and shape and size of the aggregates have an influence on it (Cavalli et al., 2017; EAPA, 2014).

3. MATERIALS AND METHODS

3.1. Introduction

The experimental study has concerned a dense graded asphalt concrete with a maximum aggregate dimension of 14 mm and a bitumen with a nominal penetration grade 35/50: AC 14 surf 35/50. Two mixtures of this type were analysed and compared in laboratory: a reference mixture with virgin materials and a mixture that included 75 % of RAP and a rejuvenator in its composition, both produced and compacted in the laboratory.

Preceding the mixture production and analysis, a set of blue Marshall specimens were produced in different conditions to visually assess the extent to which the aged bitumen in the RAP is mobilized and the effect that the rejuvenator has on the mixture.

The first phase of this study consisted of the bituminous mixture design, through the Marshall method, and its performance evaluation before and after ageing. This phase represented the first life cycle in which there was RAP incorporation.

The second phase's focal point was a mixture incorporating RAP whose aggregates and bitumen had already completed their second life cycle. Such RAP was produced in the laboratory and that bituminous mixture was characterised and its performance was evaluated.

This chapter describes the materials used in the mixture's production, the procedure to formulate it and produce samples, the laboratory tests used to evaluate the mixture's performance as well as the procedures carried out to age it and to produce RAP in the laboratory.

3.2. Materials

The recycled mixtures were designed and produced in the laboratory. They included the following components (represented in Figure 3.1):

- RAP: milled from a Portuguese high trafficked road, whose aggregates and bitumen are of unknown origin and nature.
- Virgin aggregates: basalt in the 10/16 mm, 4/12 mm and 0/4 mm fractions and limestone in the 0/4 mm fraction (each fraction's properties were determined by the supplier and are discriminated in Table 3.1.
- Virgin binder: bitumen with a penetration grade of 35/50.
- Rejuvenator: commercial rejuvenator derived from crude tall oil (a by-product of the paper industry).

Figure 3.1: Components used to produce the recycled mixture (from left to right: RAP fractions, virgin aggregates, virgin bitumen and rejuvenator)

Table 3.1: Determined properties for each aggregate fraction

			Fraction			
Properties			Basalt 10/16	Basalt 4/12	Limestone 0/4	Basalt 0/4
Mechanical and physical	Resistance to fragmentation - LA	EN 1097-2	✓			
	Polishment resistance - PSV	EN 1097-8		✓		
	Resistance to wear - micro-Deval	EN 1097-1		✓		
	Particle density and water absorption	EN 1097-6	✓	✓	✓	✓
Geometrical	Particle size distribution	EN 933-1	✓	✓	✓	✓
	Elongation and Flakiness Index	EN 933-4	✓	✓		
	Flakiness Index	EN 933-3	✓	✓		
	Sand Equivalent test (0/2 mm fraction)	EN 933-8			✓	✓
	Methylene blue test 0,125mm 0/2 mm	EN 933-9			✓	✓
Thermal and weathering	Resistance to thermal shock	EN 1367-5		✓		
	Sonnenbrand Basalt	EN 1367-3		✓		

3.2.1. RAP

Since the mixture incorporated a high percentage of RAP, an adequate characterization of its components (bitumen and aggregates) was essential. The tests used for the characterisation are identified in Table 3.5, along with applying standards, purpose and several aspects of the procedure.

The RAP was characterised through the particle size distribution (EN 933-1), and was divided into four fractions: 19/25 mm; 12.5/19 mm; 4.75/12,5 mm; 0/4.75 mm. However, it was set that the 19/25 mm fraction would not be used in the mixtures, as its collection implied large quantities of RAP to be sieved.

The four fractions were also individually characterized by their bitumen content and particle size distribution. The first property was determined by the Soluble binder content (EN 12697-1) and the particle size distribution characterization was carried out on the aggregates left from the binder extraction procedure (EN 933-1). The bitumen content in each fraction is shown in Table 3.2, whereas Figure 3.2 and Table 3.3 show the particle size distribution of the aggregates for each fraction.

Table 3.2: Bitumen content in the RAP

RAP Fraction [mm]	12.5/19	4.75/12.5	0/4.75
Bitumen Content [%]	3.40	3.30	6.40

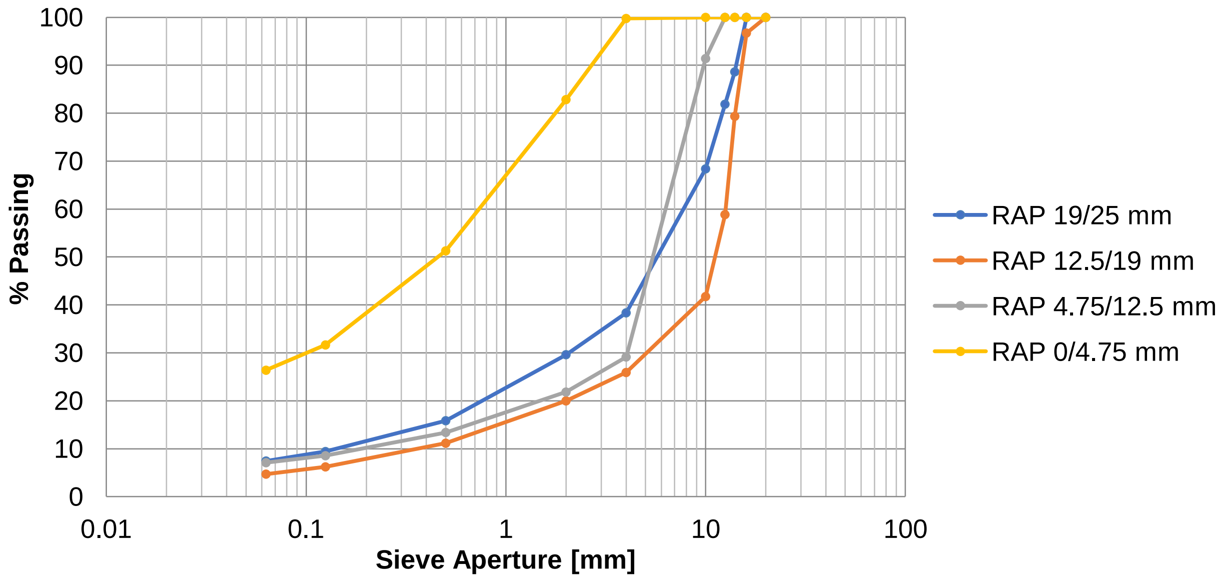

Figure 3.2: RAP aggregates particle size distribution

Table 3.3: RAP's aggregates particle size distribution

	Sieve Aperture [mm]									
	20	16	14	12.5	10	4	2	0.5	0.125	0.063
RAP Fraction [mm]	**% Passing**									
19/25	100.0	100.0	88.6	81.9	68.4	38.4	29.6	15.9	9.4	7.4
12.5/19	100.0	96.7	79.4	58.9	41.8	25.9	20.0	11.2	6.2	4.7
4.75/12.5	100.0	100.0	100.0	100.0	91.4	29.2	21.8	13.4	8.6	7.1
0/4.75	100.0	100.0	100.0	100.0	100.0	99.8	82.8	51.3	31.7	26.4

In order to characterise the RAP binder, it was first recovered from each fraction using the rotary evaporator method (EN 12697-3). Then, the consistency and softening point (shown in Table 3.4) were assessed by needle penetration (EN 1426) and the ring and ball method (EN 1427).

Table 3.4: RAP binder's characteristics

Aged bitumen [by fraction]	**Penetration (at 25°C) [$\times10^{-1}$ mm]**	**Softening point [°C]**
4.75/12.5 mm	18	67.6
12.5/19 mm	21	67.0
19/25 mm	20	66.7
Mean	20	67.1

Table 3.5: Tests performed to characterise the RAP and its components

Standard	Apparatus	Scope	Procedure
Particle size distribution (EN 933-1)	 Sieving column in sieving machine	Characterisation of the aggregates	• Aggregate or RAP sample • Sieve aperture sizes: 20, 16, 14, 12.5, 10, 4, 2, 0.5, 0.125 and 0.063 mm (base series + 2) • Washing and dry sieving method • Mechanical and manual sieving • Weighing the retained material in each sieve
Soluble binder content (EN 12697-1)	 Crucible in the sand bath	Determination of each fraction’s bitumen content	• Loose bituminous mixture sample • Solvent extraction method: 1. binder extraction by dissolution in toluene 2. separation of mineral matter from the binder solution, through the centrifuge extractor method (Annex B.1.5) 3. determination of residual mineral matter in the binder extract by incineration (Annex C.2)
Rotary Evaporator Method (EN 12697-3)	 Rotary Evaporator	Recovery of the RAP binder	• Loose bituminous mixture sample; • Binder extraction: 1. binder extraction by dissolution in toluene 2. separation of mineral matter from the binder solution, by centrifuging • Binder recovery in a rotary evaporator (vacuum distillation)
Determination of needle penetration (EN 1426)	 Penetrometer stand (with sample)	Characterisation of the binder (consistency)	• Conditioned binder sample at 25 °C • Penetration at 25 °C • Performed in a conditioned room, rather than in a water bath • 3 determinations at points 10 mm distant from each other and the sides of the container.

Table 3.5 (continued): Tests performed to characterise the RAP and its components

Standard	Apparatus	Scope	Procedure
Determination of the softening point (EN 1427)	 Ring and ball apparatus (end of the test)	Characterisation of the binder	• Ring and ball method • Two binder samples contained in brass rings • Automatic apparatus • Starting temperature: 5 °C • Heating rate: 5 °C/min

3.2.2. Rejuvenator

The percentage of rejuvenator to mix with the aged bitumen was defined following the manufacturer's guidelines. It was recommended that two samples of recovered bitumen be mixed with 3 % and 7 % dosage (per weight of aged binder) and their penetrations and softening temperatures be assessed. After comparing those results to the desired properties of a 35/50 grade bitumen, defined in EN 12591, the procedure was repeated with 4.5 % of rejuvenator. The results are presented in Table 3.6.

Table 3.6: Bitumen's properties for rejuvenator dosage definition

	Penetration (at 25°C) [×10^{-1} mm]	**Softening point [°C]**
Desired properties (EN 12591)	35-50	50-58
Aged bitumen (mean)	20	67.1
3 % rejuvenator	30	62.6
7 % rejuvenator	61	53.4
4.5 % rejuvenator	38	58.6

With cost minimization in mind and an acceptable value for the penetration; despite the softening point being above the required values, but close to the upper limit, it was set that the percentage of rejuvenator to use was 4.5 %.

3.3. Evaluation of aged binder mobilization

The unknown extent to which the aged binder is mobilized when producing a recycled mixture has been presented as an obstacle to the recycling practice. It is known, however, that it lies between total and no mobilization and also that it is dependent on the mixture production conditions (mixing temperature, efficiency of the mixer, presence of aggregates and prior RAP processing) (Nguyen, 2009).

Therefore, a set of blue Marshall specimens were produced to visually assess the extent to which the bitumen in the RAP is mobilized, the effect of the rejuvenator in the mixture as well as that of the heating temperatures of the various materials. The specimen components and respective production conditions are presented in Table 3.7.

Table 3.7: Production conditions for each blue specimen

	Components					
Specimens	**Virgin Aggregates**		**RAP**		**Bitumen**	**Rejuvenator**
	Percentage [%] per total weight of aggregates	Heating Temp. [°C]	Percentage [%] per total weight of aggregates	Heating Temp. [°C]	Percentage [%] per weight of specimen	Percentage [%] per weight of aged binder
0 RAP H	100	165	0	-	4	0
75 RAP H	25	165	75	165	4	0
75 RAP L	25	195	75	120	4	0
75 RAP LR	25	205	75	130	4	4.5

H stands for Higher temperature, L stands for Lower temperature and LR stands for Lower temperature plus rejuvenator. This temperature refers to that used for heating the RAP. Both samples whose name contains an H were prepared following the same procedure, which is not the case for those whose name contains an L or LR.

The blue colour is achieved by using blue pigment to dye the colourless bitumen (Figure 3.3 and Figure 3.4, respectively). This coloured bitumen was chosen because there would be a contrast between the black from the RAP bitumen and the blue from the virgin one, allowing easy identification of the aged binder film coating the aggregates.


Figure 3.3: Blue pigment


Figure 3.4: Colourless bitumen

3.3.1. Sample preparation

The samples were prepared in the laboratory using a mixer (Figure 3.5) and a heating mantle, to maintain the mixing temperature, and were compacted using an impact compactor (Figure 3.6). As indicated by the bitumen's supplier, the mixing temperature for all the samples was 165 °C.

Figure 3.5: Mixer with a heating mantle

Figure 3.6: Impact compactor

According to Nunes et al. (2016), for virgin pigmented mixtures, the recommended dosage for the pigment was between 0.75 % to 2 % relative to the mass of the aggregates and for the bitumen was of 5 % to 6 %. The pigment dosage was set at 2 %, so that the colour would appear stronger, and the virgin bitumen dosage was set at 4 %, as it was assumed that not all the aged binder would be mobilized. It was also recommended that, in the mixing procedure, the pigment and the bitumen pellets were added cold to the mixture.

The H samples followed the mixing procedure described in EN 12697-35. The L sample differed in the heating temperatures of the virgin aggregates and the RAP; as such temperature could further age the RAP's binder. The LR sample was prepared following the rejuvenator's manufacturer guidelines (which are based on EN 12697-35). They were the following:

High temperature (H):

Step 1. The virgin aggregates were heated at 165 °C for 4 h (for the 75 RAP H sample, the RAP was heated alongside the virgin aggregates).

Step 2. The virgin aggregates (and the RAP, for the 75 RAP H sample), the bitumen and the blue pigment were added to the mixer and mixed for 3 min.

Step 3. The mixture was poured into the mould and compacted by applying 50 blows to each side of the specimen.

Low temperature (L):

Step 1. All the materials were heated:

- The RAP was heated at 120 °C for 2h30.
- The virgin aggregates were heated at 195 °C for 4 h.

Step 2. The RAP and the virgin aggregates were added to the mixer and mixed for 30 s.

Step 3. The bitumen and the blue pigment were added and mixed for 2min30s.

Step 4. The mixture was poured into the mould and compacted by applying 50 blows to each side of the specimen.

Low temperature + rejuvenator (LR):

Step 1. All the materials were heated:

- The RAP was heated at 130 °C for 2h30.
- The virgin aggregates were heated at 205 °C for 4 h.

Step 2. The RAP and the rejuvenator were added to the mixer and mixed for 30 s.

Step 3. The virgin aggregates were added and mixed for 60 s.

Step 4. The bitumen and the blue pigment were added and mixed for 90 s.

Step 5. The mixture was poured into the mould and compacted by applying 50 blows to each side of the specimen.

3.3.2. Resulting samples

A specimen still in its mould is shown in Figure 3.7. Its surface was smooth and there was excess bitumen in the rim of the mould, indicating that there was indeed excess bitumen in the mixture, thus more aged binder was mobilized than expected.

Figure 3.7: Moulded 75 RAP specimen (after compaction)

These specimens were then sliced and cut in half. The slices of each of the specimens are shown in Figure 3.8 and Figure 3.9.

It is visible that, in every case, there is no aged binder film surrounding the aggregates and that the aged binder has darkened the mixture, evidencing that most of the aged binder was mobilized. Additionally, to the naked eye, the mixture seems homogeneous independently of the mixing procedure used.

Given these points, in the recycled bituminous mixture design it was considered that there is total mobilization of the aged binder and, when mixing the following samples, the mixing procedure followed the rejuvenator's guidelines.

3.4. Bituminous mixture design

3.4.1. General concerns

The bituminous mixture design was based on the Marshall method, using a dense graded asphalt concrete with a maximum aggregate dimension of 14 mm and a bitumen with a nominal penetration grade 35/50 (AC 14 surf 35/50) as a reference mixture, incorporating 75 % of RAP in its composition.

The Marshall method is an empirical method that requires the definition of the aggregate gradation, the production of samples with varying bitumen content and the determination of their properties. The comparison between the limits set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014a) (Table 3.10) and the plots relating the percentage of bitumen to those properties provides the optimum bitumen content.

3.4.2. Aggregate gradation

The mix design aggregate gradation was obtained through a trial and error process, in which the gradation curve was fit between the upper and lower limits for the aggregate gradation of an AC 14 surf mixture, defined in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014a). It was set that the mixture would be composed of 25 % of virgin aggregates and 75 % of RAP and the amount of each fraction was determined accordingly.

The gradation of the reference and recycled mixtures, along with the upper and lower limits, are shown in Figure 3.10 and Table 3.8.

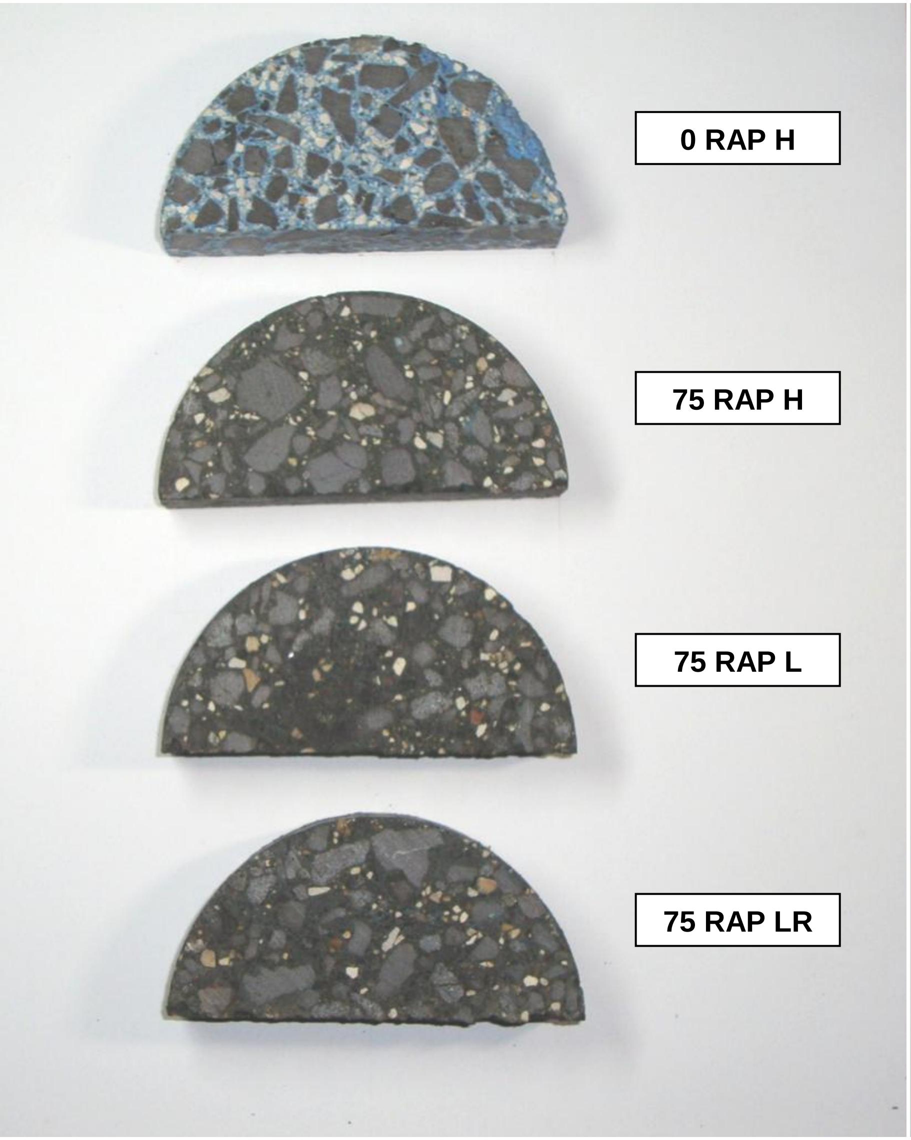

Figure 3.8: Blue specimens - top view

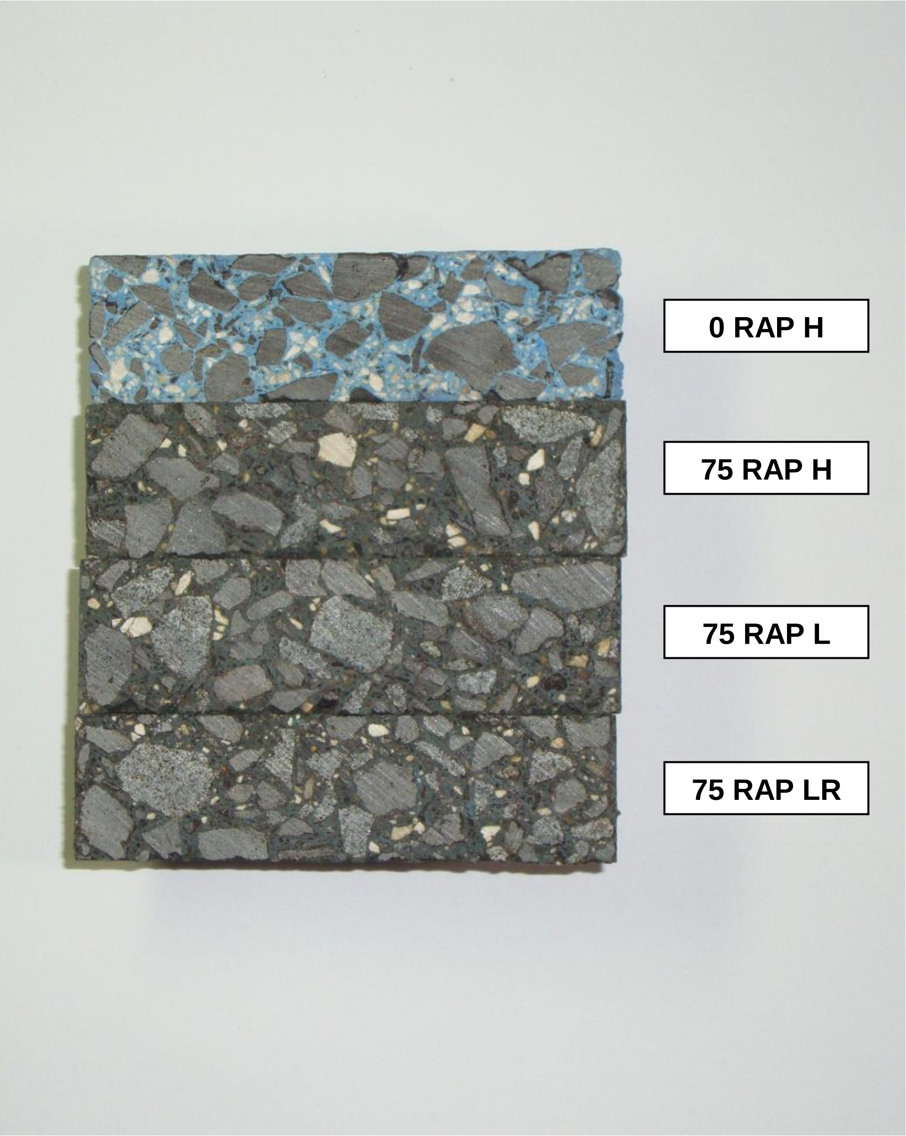

Figure 3.9: Blue specimens – half-cut view

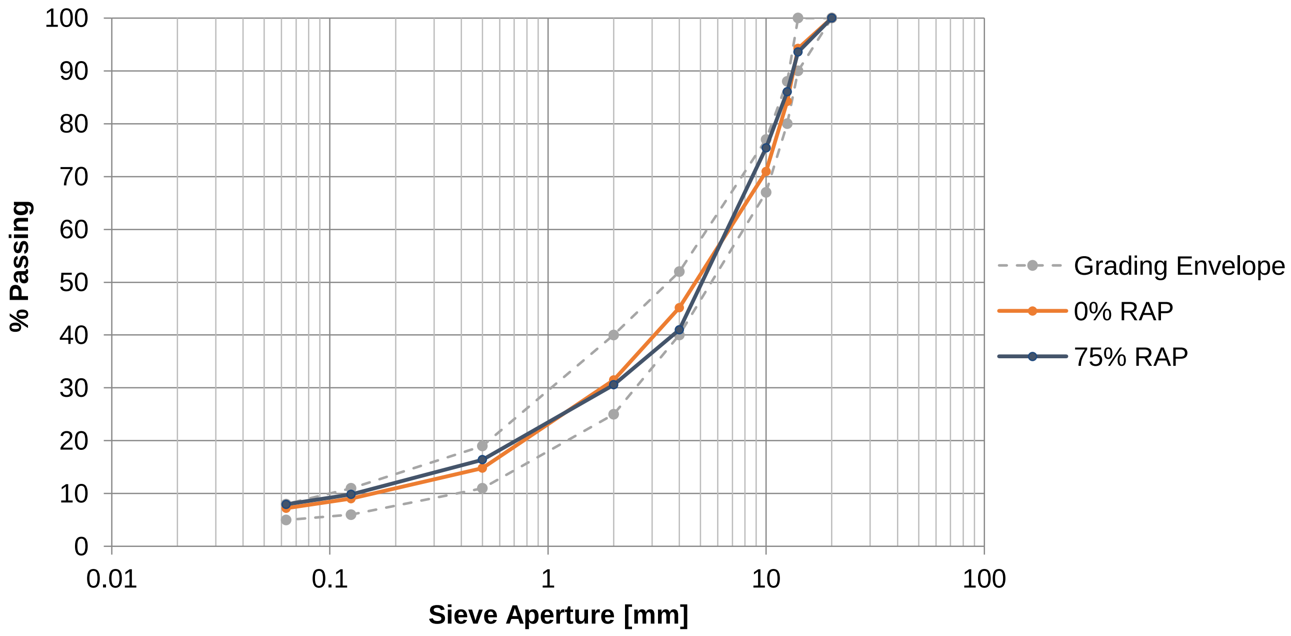

Figure 3.10: Reference and recycled mixtures' gradation curve

Table 3.8: Reference and recycled mixtures’ gradation

Sieve Aperture [mm]			20	14	12.5	10	4	2	0.5	0.125	0.063
Passing [%]	Portuguese specifications (EP - Estradas de Portugal, 2014a)	Upper Limit	100.0	100.0	88.0	77.0	52.0	40.0	19.0	11.0	8.0
		Lower Limit	100.0	90.0	80.0	67.0	40.0	25.0	11.0	6.0	5.0
	0% RAP		100.0	94.2	84.2	71.0	45.2	31.5	14.8	9.0	7.2
	75% RAP		100.0	93.6	86.0	75.4	41.0	30.6	16.4	9.8	7.9

3.4.3. Sample preparation

After establishing the gradation curve for this mixture, five sets of Marshall specimens were produced, varying the bitumen percentage between 4 % and 5.5 % (relative to the total mass) in increments of 0.5 %.

From the visual inspection of the blue specimens in 3.3.2, it was hypothesised that all of the aged bitumen contained in the RAP would be mobilized and that was taken into account when preparing the samples: the total aged bitumen contained in the RAP for each sample was calculated and the difference between it and the total bitumen needed was the amount of virgin bitumen to be added.

The mixture for the specimens was prepared following the rejuvenator’s manufacturer guidelines and compacted according to EN 12697-30 with a target temperature for compaction of 165 °C (specified in EN 12697-35 for a 35/50pen paving grade bitumen). The mixing procedure was the following:

Marshall specimens

Step 1. All the materials were heated:

- The RAP was heated at 130 °C for 2h30.
- The virgin aggregates were heated at 205 °C for 4 h.
- The virgin bitumen was heated at 165 °C for 3 h.

Step 2. The RAP and the rejuvenator were added to the mixer and mixed for 30 s.

Step 3. The virgin aggregates were added and mixed for 60 s.

Step 4. The virgin binder was added and mixed for 90 s.

Step 5. The mixture was poured into the mould and compacted by applying 75 blows to each side of the specimen using an impact compactor.

Further in this study, the mixture's performance evaluation tests were performed either in slabs, beams sawed from them or cylindrical specimens cored from the slabs. The greater homogeneity between specimens brought about from producing a slab, which has a larger area and more material, and coring it, rather than producing and compacting cylindrical specimens individually; makes the specimens cored from the slabs the preferable cylindrical specimens for the performance evaluation of the mixtures.

The slabs were produced in a higher capacity mixer (Figure 3.11) and compacted in a steel roller compactor (Figure 3.12), according to EN 12697-33 with a temperature for compaction of 165 °C, until the sample height reached 50 mm. The slab moulds had an area of 305×400 mm^2, except for the ones intended for the wheel tracking test, which measured 305×305 mm^2. Moreover, due to equipment restrictions, the slab mixing procedure was an adaptation of the previously described Marshall specimen mixing procedure and it included the following steps:

Slabs

Step 1. All the materials were heated:

- The RAP was heated at 130 °C for 2h30.
- The virgin aggregates were heated at 205 °C for 4 h.
- The virgin bitumen was heated at 165 °C for 3 h.

Step 2. The RAP and the rejuvenator were added to the mixer and mixed for 30 s.

Step 3. The mixing bowl was dismounted from the mixer and half of the RAP was set aside in a pre-heated tray.

Step 4. The virgin binder was added to the mixing bowl.

Step 5. The mixing bowl was mounted on the mixer and the RAP that was set aside as well as the virgin aggregates were added and mixed for 2min30s.

Step 6. The mixture was poured into the mould and compacted.

Figure 3.11: High capacity mixer

Figure 3.12: Steel roller compactor, with a loose bituminous mixture

3.4.4. Sample testing

Determining the optimum binder content required the specimens' voids in the mineral aggregate (VMA), air voids content (V_m), stability and flow to be known. The VMA and V_m were calculated from the maximum and bulk density, determined according to EN 12697-5 and EN 12697-6, respectively. The stability and flow were determined by the Marshall test, performed according to EN 12697-34. These tests are identified in Table 3.9, along with applying standards, purpose and several aspects of the procedure.

Table 3.9: Tests performed for the mix design

Standard	Apparatus	Scope	Procedure
Maximum density (EN 12697-5)	 Pyknometer in vibrating table	Determination of the volumetric properties	• Loose bituminous mixture sample • Volumetric Procedure (Procedure A): 1. Mass of the empty pyknometer 2. Mass of the pyknometer with the dry sample 3. Mass of the pyknometer with the sample and filled with water • Pyknometer w/ known volume • Measuring the water temperature to determine its density

Table 3.9 (continued): Tests performed for the mix design

Standard	Apparatus	Scope	Procedure
Bulk density (EN 12697-6)	 Immersed slab mounted on balance	Determination of the volumetric properties	• Compacted bituminous sample (cylindrical specimen, slabs or beams) • Saturated surface dry (SSD) (Procedure B): 1. Mass of the dry specimen 2. Mass of the immersed and saturated specimen 3. Mass of the specimen after its surface is dried with a damp towel • Measuring the water temperature to determine its density
Marshall test (EN 12697-34)	 Sample in the compression machine	Determination of the Marshall properties (Stability, Flow and Marshall Quotient)	• Cylindrical specimens compacted by applying 75 blows to each side using an impact compactor • Specimens conditioned for 50 min in a water bath at 60 °C • Compression machine applies a load resulting in a constant deformation rate of 50 mm/min until the maximum load is achieved • Performed on 4 specimens

3.4.5. Optimum bitumen content

In order to obtain the optimum bitumen content, each property was plotted in a graph, in which the binder percentage was the independent variable (Figure 3.13 to Figure 3.16), and compared with the required range of each property (shown in Table 3.10 and represented in the graphs as red dashed lines).

Table 3.10: Requirements for AC 14 surf mixture (adapted from the Portuguese specifications (EP - Estradas de Portugal, 2014a))

Property		Standard	Requirement
Marshall Properties	Stability [kN]	EN 12697-34	7.5 – 15 (21)
	Flow [mm]		2 - 4
	Minimum Marshall quotient [kN/mm]		3
Minimum voids in the mineral aggregate (VMA) [%]		EN 12697-8	14
Air voids content (V_m) [%]			3 - 5

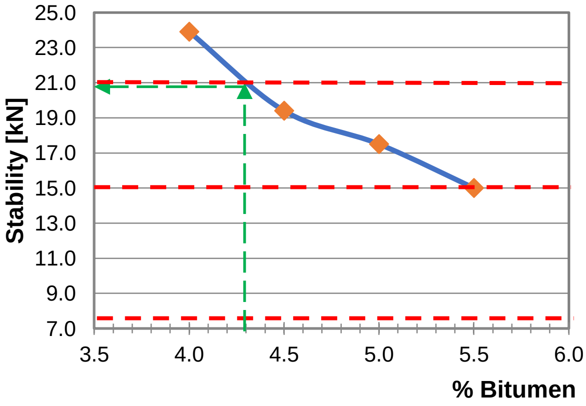

Figure 3.13: Stability vs. Bitumen content

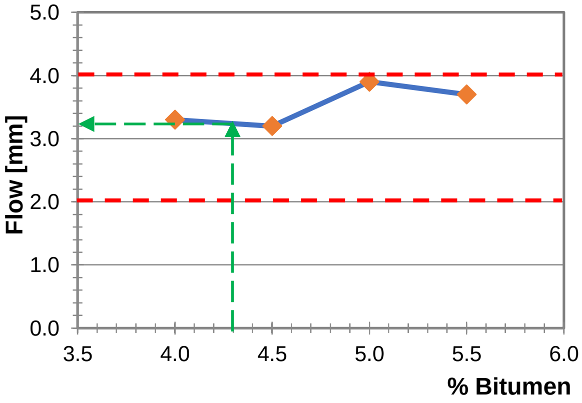

Figure 3.14: Flow vs. Bitumen content

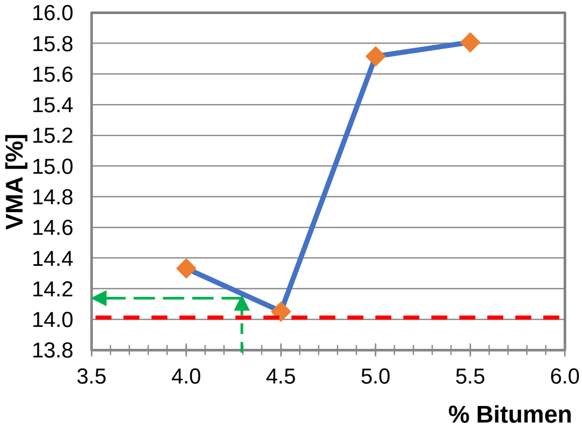

Figure 3.15: Voids in the mineral aggregate vs. Bitumen content

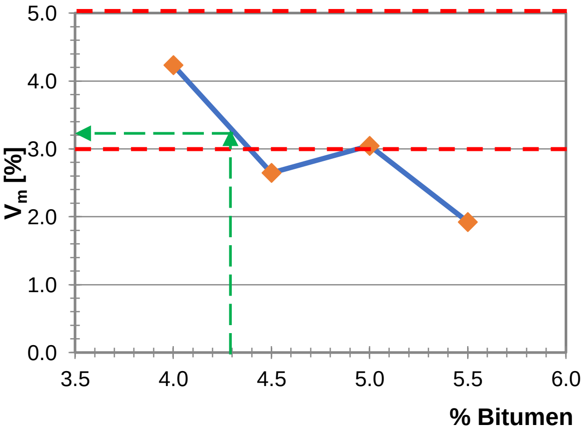

Figure 3.16: Air voids content vs. Bitumen content

In the specifications (EP - Estradas de Portugal, 2014a), there is a note stating that the maximum value for the stability is 21 kN if the mixture contains granitoids or aggregates sourced from rocks predominantly composed of silica. As the RAP aggregates' nature is unknown and the stability values obtained were mostly over the 15 kN mark, the 21 kN was deemed an acceptable upper limit. Therefore, taking the graphs and the requirements into consideration, the determined optimum binder content was 4.3 %, with a 6.2 kN/mm Marshall quotient.

3.5. Performance evaluation

The mixtures' performance was evaluated through stiffness, fatigue resistance, permanent deformation, water sensitivity and surface characteristics (macro and micro-texture). The tests used for the evaluation are identified in Table 3.11, along with applying standard, purpose and several aspects of the procedure.

Table 3.11: Tests performed to evaluate the mixtures' performance

Standard	Test	Scope	Procedure
Stiffness (EN 12697-26)	 Beam in the bending bed	Characterisation of the stiffness	• Beam sawed from a slab • Four point bending test • Test temperature: 20 °C • Constant strain: 50 μm/m • Set of frequencies: 0.1, 0.2, 0.3, 0.4 , 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 1 and 0.1 Hz • Last measurements (1 and 0.1 Hz) reflect if the beam was damaged during the test
Resistance to fatigue (EN 12697-24)		Characterisation of the fatigue behaviour	• Beam sawed from a slab • Four-point bending test • Test temperature: 20 °C • Strain-controlled mode • Frequency of sinusoidal load: 10 Hz • Tested strain levels: 200, 300, 400 μm • Failure criteria: complex stiffness modulus reaching half its initial value
Water sensitivity (EN 12697-12)	 Specimen in the testing head	Determination of the effect of moisture	• Cylindrical specimens: moulded or cored from a slab • Method A: Indirect tensile strength (EN 12697-23) • Specimens conditioned for 72h: ○ One set maintained at dry conditions (stored in a room at 20 °C) ○ One set maintained at wet conditions (water bath at 40 °C) • Test temperature: 15 °C • Compression machine applies a diametrical load
Wheel tracking (EN 12697-22)	 Slab in the wheel tracking device	Determination of the resistance to permanent deformation	• Two slabs • Small size device (Procedure B in air) • Specimens are conditioned for 6h at the test temperature • Test temperature: 60 °C • Loaded wheel passes over a slab • Monitoring the developed rut

Table 3.11 (continued): Tests performed to evaluate the mixtures' performance

Volumetric patch technique (EN 13036-1)	 Volumetric patch	Determination of the average macro-texture depth	- Slabs - Spreading a known volume of glass spheres on a dry pavement surface - Measuring the patch's diameter in four equidistant places
Pendulum test (EN 13036-4)	 Pendulum tester	Determination of the skid resistance (micro-texture)	- Slabs - Adjusting the height of the arm so that the sliding length is 126 mm - Wetting the surface of the slab and the slider rubber - Releasing the pendulum arm - At least five repetitions for each slab (dependent on the results)

3.6. Ageing procedure

In order to measure the performance of the recycled mixture at a later stage in its service life, the ageing process was simulated in the laboratory. The laboratory ageing procedure was based on the AASHTO R30 Standard, which consists of two ageing moments: the short and long term mixture conditioning.

The short term conditioning accounts for the ageing that occurs during the mixing, storage, transportation and compaction of the mixture until it cools down; while the long term conditioning aims to simulate the ageing that occurs during the bituminous mixture's service life.

Firstly, the mixture to produce the slabs was mixed as described in 3.4.3 and, prior to compaction, was spread in a pan and placed in an oven for 2 h at 155 °C, which corresponds to the short term conditioning. Then, the mixture was compacted as described in 3.4.3 and, after demoulding, the slabs were placed in an oven for 5 days at 85 °C, for the long term conditioning. After turning off the oven, they were left there to cool down for 16 h.

These specimens were either used for testing (wheel tracking test and surface characteristics), sawed into prismatic specimens (to test fatigue resistance and stiffness) or to produce RAP for the second phase of this thesis.

3.7. Re-recycling

3.7.1. General procedure

In the second phase of this thesis, a new mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle (denoted as RAP 0A) was studied. This material was produced in the laboratory so that its origin and characteristics were the same as the RAP used until this point.

Due to time constraints, some hypotheses about the materials and optimum bitumen and rejuvenator content were assumed in the characterisation of this mixture.

This mixture's performance was evaluated through its stiffness, fatigue resistance, permanent deformation, water sensitivity and surface characteristics (macro and micro-texture). These tests were identified in 3.5 in Table 3.11.

3.7.2. Laboratory RAP production

The laboratory RAP production process consisted of preparing slabs through the procedure described in 3.6, and reheating them at 90 °C to be separated manually into aggregates in a similar way as the sample separation for the determination of a mixture's maximum density (EN 12697-5). The final product is shown and compared to the original RAP in Figure 3.17.

Figure 3.17: RAP comparison: RAP 0A (left) and original RAP – 4.75/12.5 mm fraction (right)

Given that RAP 0A was not fractionated, when weighing the material to produce the test specimens it had to be ensured that the mass of RAP 0A included in them was homogenous in terms of gradation. That was achieved through a quartering method.

This method consisted in thoroughly mixing the totality of the produced material using a trowel and dividing it in half, then storing one half and diving the other one in two, repeating this step until the desired sample mass was obtained. Some steps of this process are shown in Figure 3.18.

Figure 3.18: Quartering method

3.7.3. Bituminous mixture characterisation

In the characterisation of the bituminous mixture several hypotheses were assumed, being considered that this approach would provide insight to the behaviour and viability of a mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle in a feasible time frame. Those hypotheses were the following:

- The particle size distribution of RAP 0A was the same as the mix design aggregate gradation obtained for the first phase's mixture – it was assumed that the laboratory RAP production process did not affect it as no aggregates were crushed.
- The optimum bitumen content was the same as the first phase's mixture (4.3 %).
- The optimum rejuvenator content was the same as the first phase's mixture (4.5 %).
- The mixture's maximum density was the same as the first phase's mixture.

For this mixture, the aggregate gradation was also obtained through a trial and error process, much the same as the previous one, and included 25 % of virgin aggregates and 75 % of RAP 0A. The gradation of the reference and both recycled mixtures, along with the upper and lower limits for the aggregate gradation of an AC 14 surf mixture, defined in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014a), are shown in Figure 3.19 and Table 3.12.

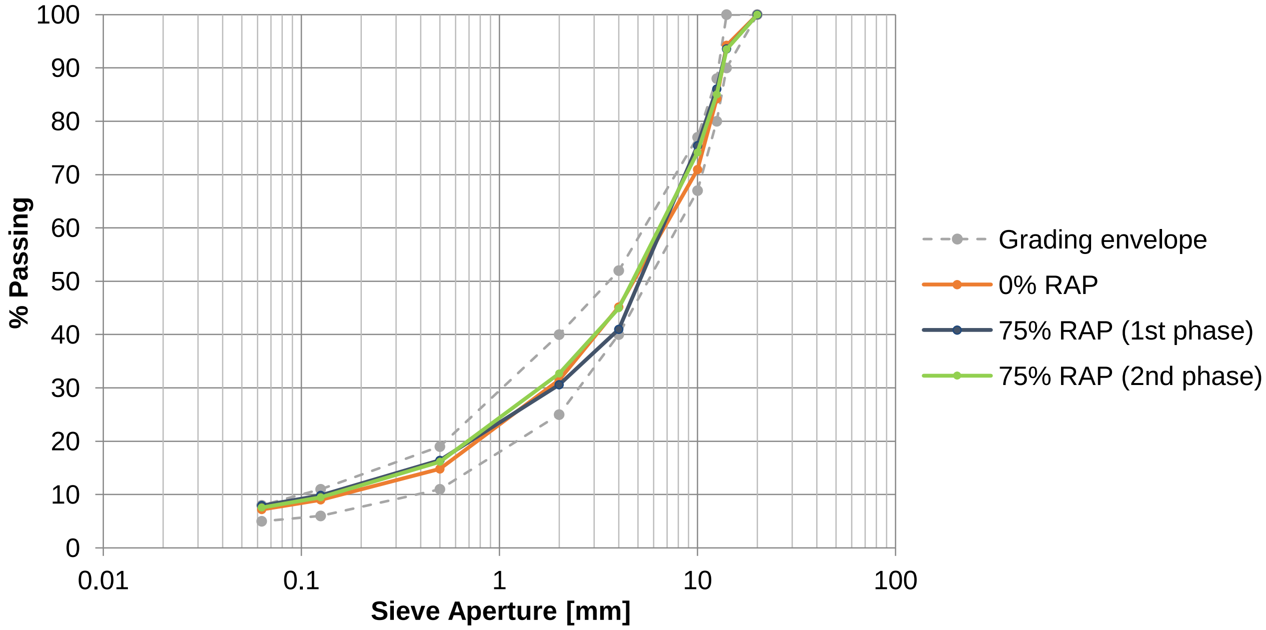

Figure 3.19: Reference and recycled mixtures' (1st and 2nd phase) gradation curve

Table 3.12: Reference and recycled mixtures' (1st and 2nd phase) gradation

Sieve Aperture [mm]			20	14	12.5	10	4	2	0.5	0.125	0.063
Passing [%]	Portuguese specifications (EP - Estradas de Portugal, 2014a)	Upper Limit	100.0	100.0	88.0	77.0	52.0	40.0	19.0	11.0	8.0
		Lower Limit	100.0	90.0	80.0	67.0	40.0	25.0	11.0	6.0	5.0
	0% RAP		100.0	94.2	84.2	71.0	45.2	31.5	14.8	9.0	7.2
	75% RAP (1st phase)		100.0	93.6	86.0	75.4	41.0	30.6	16.4	9.8	7.9
	75% RAP (2nd phase)		100.0	93.5	85.0	74.2	45.0	32.7	16.2	9.5	7.6

In order to calculate the right amount of new bitumen content to add when producing the specimens, the RAP 0A's bitumen content was determined to be 4.4 % by the Soluble binder content, according to EN 12697-1 (described in 3.2.1 in Table 3.5).

Finally, the slabs to carry out the performance evaluation produced following the same procedure as described in 3.4.3.

4. RESULTS AND DISCUSSION

4.1. Performance parameters

This chapter presents the results from the tests described in 3.5, which were carried out on specimens from the following mixtures:

0% RAP:	Virgin mixture.
75% RAP:	Recycled mixture.
75% RAP (Aged):	Recycled mixture after going through the ageing procedure described in 3.6.
75% RAP (2nd phase):	Recycled mixture that incorporated RAP whose aggregates and bitumen had already completed their second life cycle.

In order to position the performance test results with those used on the current practice, the requirements set in Brisa's special technical clauses (Brisa, 2019) – Brisa is one of the biggest highway concession company in Portugal - and the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014b) for an AC 14 surf mixture are presented in Table 4.1 and Table 4.2.

Table 4.1: Brisa's performance requirements for an AC 14 surf mixture (Brisa, 2019)

Test	Standard	Parameter	Value
Resistance to permanent deformation ("Wheel-tracking")	EN 12697-22	Wheel-tracking slope (WTS_{AIR}), max [mm/10^3 cycles]	0.15
Water sensitivity	EN 12697-12 (50 blows)	Indirect tensile strength ratio (ITSR), min [%]	85

Table 4.2: Portuguese authority's performance requirements for an AC 14 surf mixture (EP - Estradas de Portugal, 2014b)

Test	Standard	Parameter	Value
Macro-texture	ISO 10844:1994	Mean texture depth (MTD), min [mm]	1.0
Skid Resistance	EN 13036-4	Pendulum test value (PTV), min	60

4.2. Stiffness

The stiffness tests were carried out in beams sawed from slabs for every studied mixture (Figure 4.1). They measured approximately 50×50×400 mm^3 ($h \times w \times l$). In this test, the stiffness (complex modulus), the phase angle and the real and imaginary components of the complex modulus (E_1 and E_2, respectively) were determined for 10 beams tested at 20 °C, each subjected to the following set of frequencies: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 1 and 0.1 Hz. A synthesis of the collected data is presented in Annex A.1.

Figure 4.1: Beams in which were carried out the stiffness and fatigue resistance tests (from upper to lower: 0% RAP, 75% RAP, 75% RAP (Aged) and 75% RAP (2nd phase))

The phase angle expresses the degree of elasticity of visco-elastic materials: a 0 ° phase angle represents a pure elastic material and a 90° phase angle represents a pure viscous material. The phase angle and stiffness (or complex modulus) can be used to determine the real component of the complex modulus, E_1, which expresses the elastic properties of a mixture, and the imaginary component, E_2, which expresses the viscous properties.

Figure 4.2 to Figure 4.5 show the resulting stiffness, phase angle, E_1 and E_2 relative to the frequency and Figure 4.6 and Figure 4.7 show the Black and Cole-Cole diagrams, respectively.

In every parameter all the mixture’s curves have similar development with the increase in frequency. The 0% RAP mixture exhibited the lowest stiffness and elastic behaviour, as it had the highest phase angle and E_2 and lowest E_1; and the 75% RAP (Aged) mixture was the opposite, exhibiting the highest stiffness and E_1, and consequently, a predominantly elastic behaviour, having the lowest phase angle and E_2. This difference in elastic behaviour is quite noticeable in the Cole-Cole diagram (Figure 4.7).

The 75% RAP mixture’s performance was situated above the 0% RAP mixture, but below the 75% RAP (Aged) one, evidencing that the recycled mixture was stiffer than the virgin one and showing that the ageing process also had a stiffening effect in the mixture (also visible in the Black diagram (Figure 4.6)).

The 75% RAP (2nd phase) mixture had a close performance to the 75% RAP one and it is possible to observe the effects of the rejuvenator: the mixture was softened, and its elastic properties were restored to the 75% RAP mixture level. However, when comparing the E_2 parameter, it presents a more viscous behaviour than both the 75% RAP mixtures (non-aged and aged).

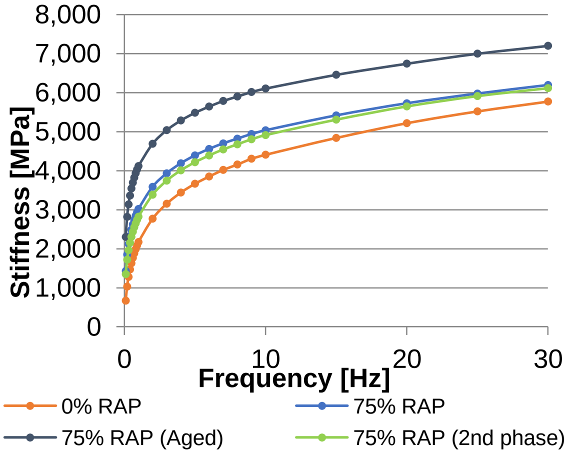

Figure 4.2: Stiffness vs. Frequency

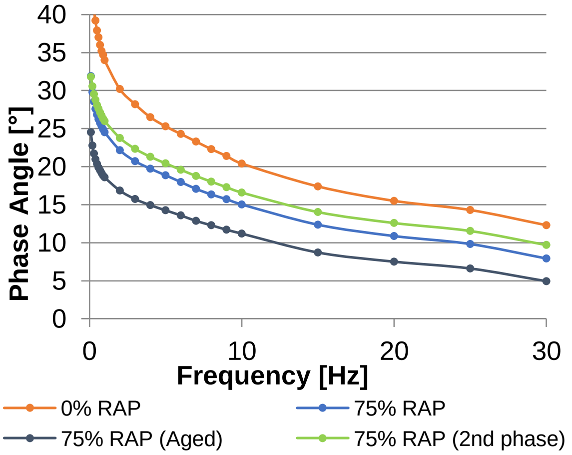

Figure 4.3: Phase angle vs. Frequency

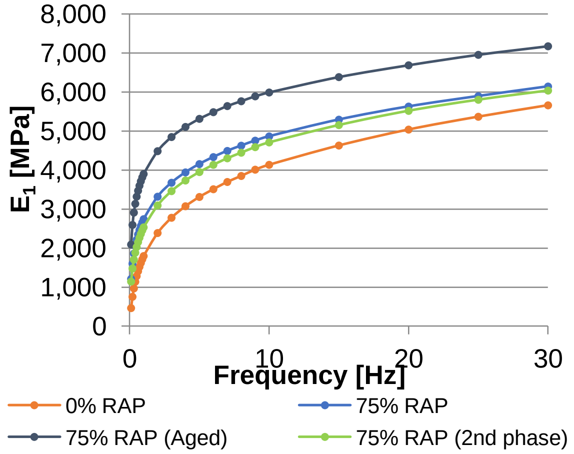

Figure 4.4: E_1 vs. Frequency

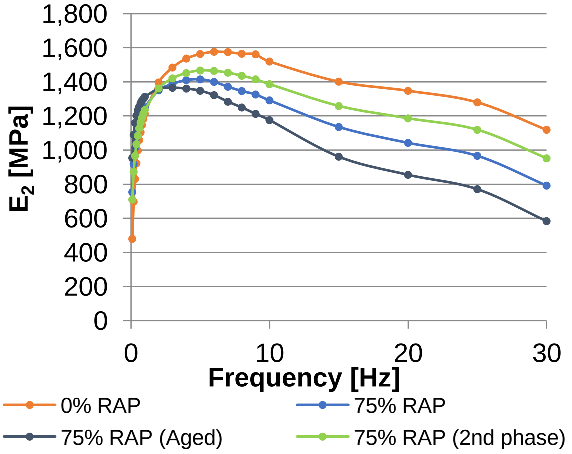

Figure 4.5: E_2 vs. Frequency

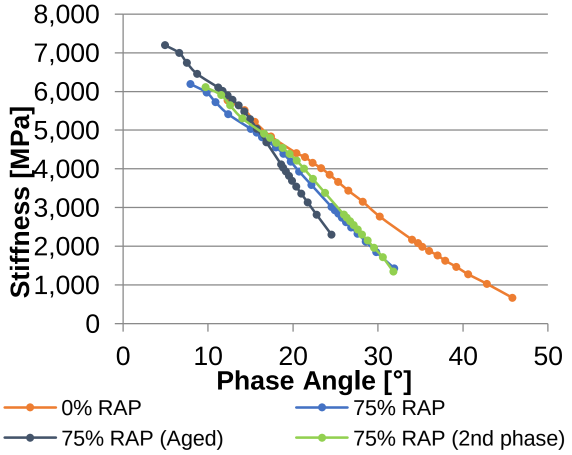

Figure 4.6: Black diagram

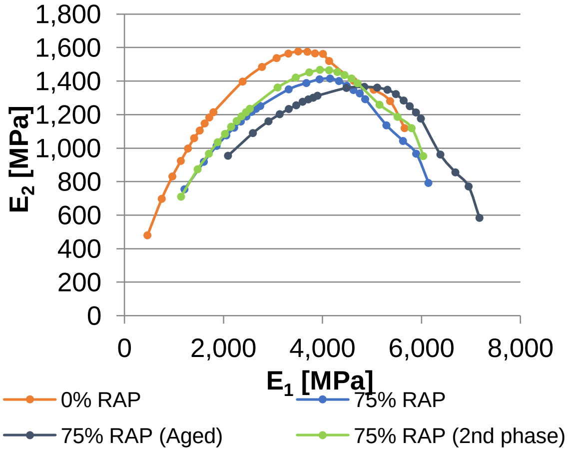

Figure 4.7: Cole-Cole diagram

4.3. Fatigue resistance

The fatigue tests were carried out in beams sawed from slabs for every studied mixture (Figure 4.1). They measured approximately 50×50×400 mm^3 (*h*×*w*×*l*). In this test, for every mixture that incorporated RAP, 4 beams were subjected to 200 µm strain, 3 were subjected to 300 µm and 3 were subjected to 400 µm, determining the number of cycles to reach the failure criteria at 20 °C. For the 0% RAP mixture, 3 beams were subjected to 200 µm strain, 3 were subjected to 300 µm and 3 were subjected to 400 µm. A synthesis of the collected data is presented in Annex 0.

The number of cycles endured by each mixture in each strain level and the respective fatigue lines are represented in Figure 4.8.

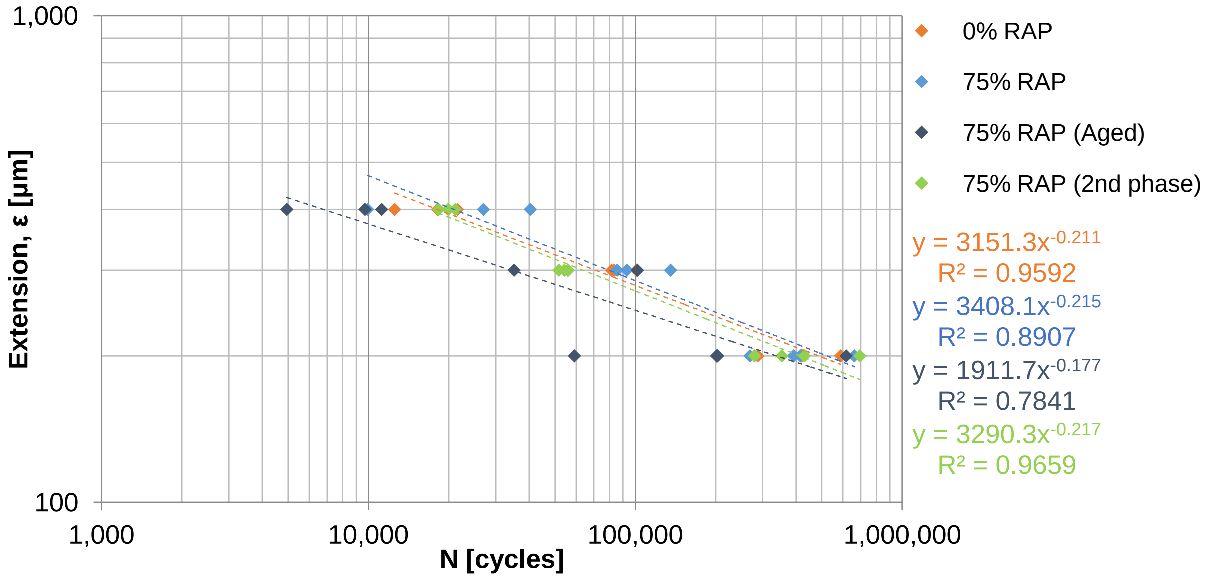

Figure 4.8: Fatigue lines

The fatigue lines of the mixtures that did not go through the ageing process (0% RAP, 75% RAP and 75% RAP (Aged)) have a very similar slope, thus very similar fatigue behaviour. The 75% RAP (Aged) mixture has a slightly lower slope, exhibiting worse fatigue behaviour (as was expected from a mixture with a stiffened binder). The latter mixture was also the one with the worst coefficient of determination (R^2), displaying higher variability between the values obtained for each specimen.

The 75% RAP (2nd phase) mixture, in terms of fatigue behaviour, is almost identical to the virgin one and presents the lowest coefficient of determination. On this test, the effect of the rejuvenator is also evident, as this mixture's fatigue line was situated between the 75% RAP mixtures (non-aged and aged).

The fatigue performance of a mixture can also be analysed by the strain values that induce specimens' failure after 10,000, 100,000 and 1,000,000 loading cycles (ε_4, ε_5 and ε_6 respectively), calculated from a mixture's fatigue law ($\varepsilon = a \times N^b$, where A and B are constants (Table 4.3)). The ε_4, ε_5 and ε_6 values are represented in Figure 4.9.

Table 4.3: Fatigue law constants

Mixture	a	b
0% RAP	3151.3	-0.211
75% RAP	3408.1	-0.215
75% RAP (Aged)	1911.7	-0.177
75% RAP (2^{nd} phase)	3290.3	-0.217

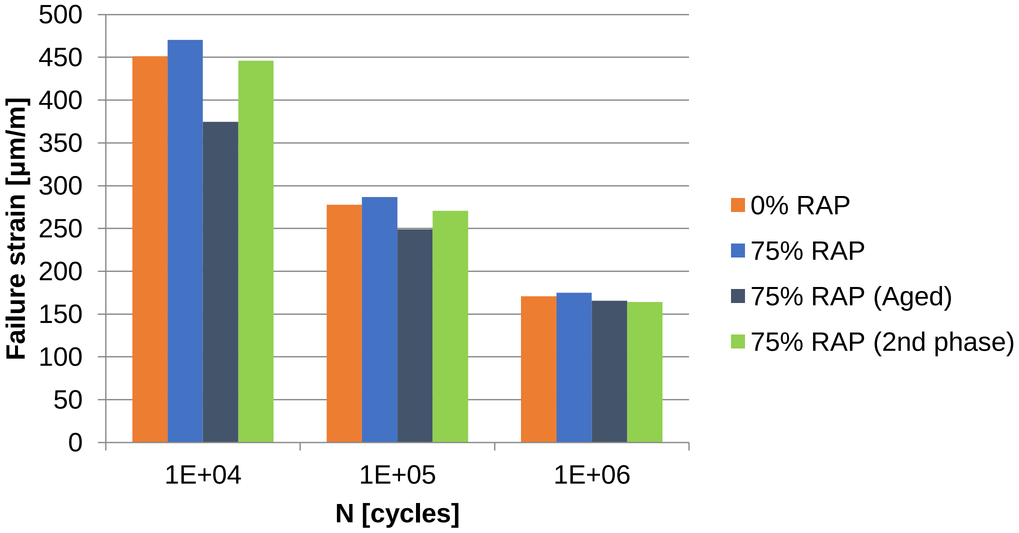

Figure 4.9: Strain needed for fatigue failure

Overall, the best fatigue behaviour is observed for the 75% RAP mixture. Also, for the 10,000 and 100,000 loading cycles, the previous analysis is correct: the 75% RAP (Aged) mixture has a worse fatigue behaviour than the other mixtures. However, for the 1,000,000 cycles, the difference in failure strain between the mixtures is minimal. This is significant because it is more relevant to evaluate the fatigue performance of the mixtures for a high number of loading cycles.

4.4. Permanent deformation

The wheel tracking tests were carried out in slabs that measured 50×305×305 mm^3 (h×w×l). In this test, the rut depth was measured on 2 slabs (tested simultaneously) for every studied mixture. The mean rut depth at 10,000 cycles (RD_{AIR}), wheel-tracking slope (WTS_{AIR}), proportional rut depth (PRD_{AIR}), and air voids content (V_m) are presented in Table 4.4, Figure 4.10 shows the progression of the rut depth with the number of cycles for each tested sample, and a synthesis of the collected data is presented in Annex A.3.

To analyse this data, it is relevant to have in mind that the maximum value for the WTS_{AIR} parameter set in Brisa's special technical clauses (Brisa, 2019) for an AC 14 surf mixture is of 0.150 mm/10^3 cycles.

Table 4.4: Mean values of the mixtures' permanent deformation

Mixture	**RD_{AIR} [mm]**	**WTS_{AIR} [mm/10^3 cycles]**	**PRD_{AIR} [%]**	**V_m [%]**
0% RAP	5.91	0.282	11.7	1.4
75% RAP	2.01	0.027	4.0	2.5
75% RAP (Aged)	1.62	0.026	3.2	2.3
75% RAP (2^{nd} phase)	2.68	0.048	5.3	1.6

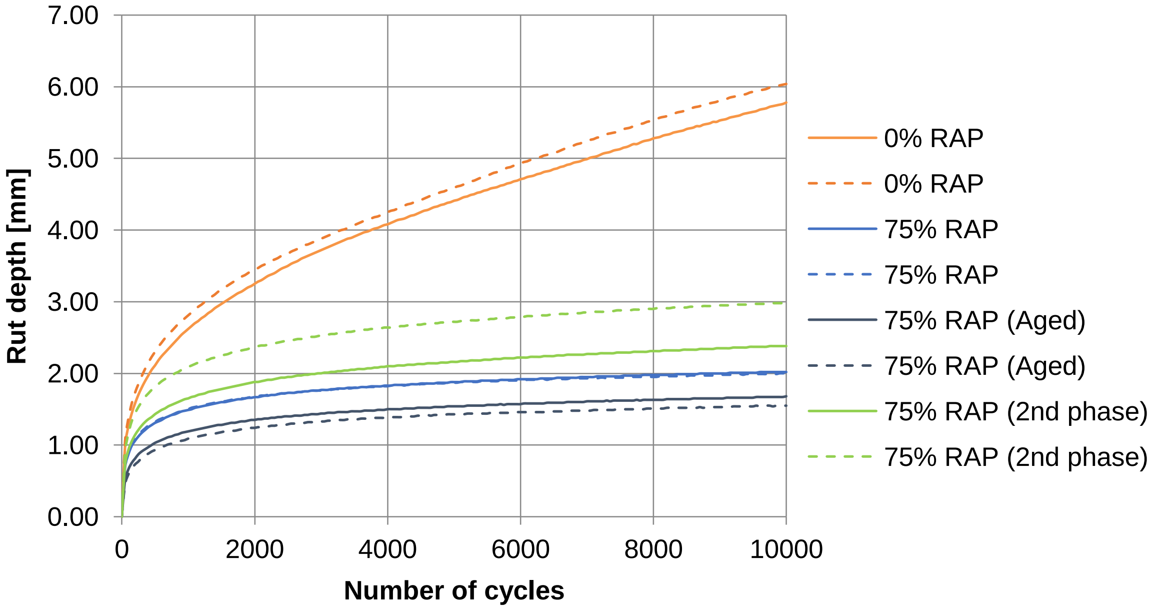

Figure 4.10: Progression of the rut depth

The mean rut depth for the recycled mixtures varied between 1.6 to 2.7 mm, the mean wheel-tracking slope varied between 0.027 to 0.048 mm/10^3 cycles and the proportional rut depth varied between 3.2 to 5.3 %. For the virgin mixture, though, all those values were higher, with a mean rut depth of 5.9 mm, a mean wheel-tracking slope of 0.282 mm/10^3 cycles and a proportional rut depth of 11.7 %; being the only mixture that did not comply with Brisa's requirements for the wheel tracking slope.

Despite having higher air voids content than the virgin mixture, which would render the mixtures more susceptible to rutting by consolidation, the recycled ones had lower values on every parameter. These results clearly demonstrate that the recycled mixture is stiffer than the virgin one, making it less susceptible to rutting: an expected behaviour due to the presence of aged binder in the recycled mixtures. The further lowering of all the permanent deformation parameters from the 75% RAP mixture to the 75% RAP (Aged) also demonstrates the stiffening effect of the ageing process.

Regarding the 75% RAP (2^{nd} phase) mixture, it had worse behaviour when compared to the other mixtures, which could be attributed to excess bitumen and/or overly softening of the mixture caused by excess rejuvenator.

4.5. Water sensitivity

The water sensitivity tests were carried out in cylindrical specimens cored from slabs for every studied mixture (Figure 4.11). For the 75% RAP mixture, an additional test was carried out in impact compacted specimens (Marshall specimens, denoted as 75% RAP – M). The specimens measured approximately 50 mm in height and 102 mm in diameter.

Figure 4.11: Cylindrical specimens used for the water sensitivity (from left to right: 75% RAP - M, 75% RAP, 75% RAP (Aged) and 75% RAP (2^{nd} phase))

In this test, the indirect tensile strength was determined for 6 specimens for each mixture: 3 at dry conditions (ITS_d) and 3 at wet conditions (ITS_w). Those values, along with the Indirect Tensile Strength Ratio (ITSR) and the mean air voids content (V_m) of each mixture, are presented in Table 4.5 and Figure 4.12. The values for the virgin mixture produced and analysed by the aggregates and RAP supplier's laboratory, from impact compacted specimens (denoted as 0% RAP – M (AR)), are also included in the table and figure.

To analyse this data, it is relevant to have in mind that the minimum value for the ITSR parameter set in Brisa's special technical clauses (Brisa, 2019) for an AC 14 surf mixture is of 85 %.

Table 4.5: Mean values for the mixtures' water sensitivity

Mixture	Type of Specimen	ITS$_d$ [MPa]	ITS$_w$ [MPa]	ITSR [%]	V$_m$ [%]
0% RAP - M (AR)	Marshall	2.112	1.915	91.00	3.5
0% RAP	Cored	2.352	2.245	95.45	0.8
75% RAP - M	Marshall	3.208	2.767	86.24	3.4
75% RAP	Cored	2.816	2.692	95.62	1.5
75% RAP (Aged)	Cored	3.496	3.150	90.11	1.5
75% RAP (2^{nd} phase)	Cored	2.172	1.977	91.06	1.2

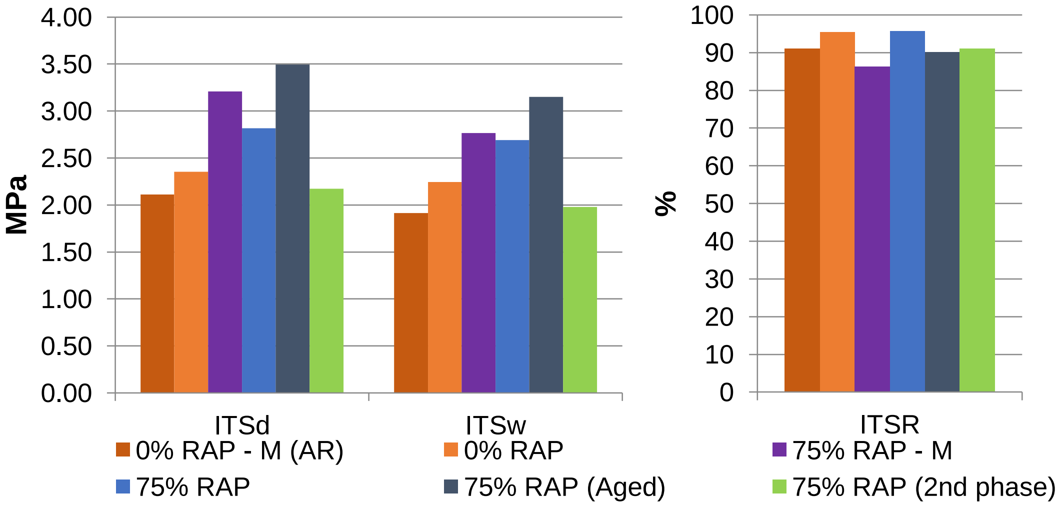

Figure 4.12: Indirect tensile strengths and indirect tensile strength ratio of the mixtures

The ITS values varied between approximately 2.0 MPa and 3.5 MPa and the ITSR between 86 % to 96 %, being all the mixtures in compliance with Brisa's required ITSR values. The mixture with the highest ITS (both on dry and wet conditions) was the aged 75% RAP, followed by the 75% RAP on Marshall specimens. However, those were not the mixtures with the highest ITSR, being the 75% RAP on Marshall specimens the one with the lowest value. The ones with highest ITSR were the 0% RAP and the 75% RAP, showing similar performance between them, yet in the individual ITS values, the 75% RAP one presented higher strength. Even though the 75% RAP (2^{nd} phase) mixture presents an ITSR on par with the median (91 %), its ITS values are the lowest among the ones obtained for cored specimens.

Regarding the mixture's air voids content, the difference between the Marshall specimens and the cored specimens is evident. It is also noticeable that the Marshall specimens had lower ITSR than the cored specimens.

This difference could be related to the compaction method: in their study, Pimentel (2013) compared impact compacted specimens to specimens cored from roller compacted slabs and to cores extracted from pavements in service, concluding that the roller compacted specimens were more representative of the ones extracted from the pavement in service. It was observed that impact compacted specimens had lower bulk density than roller compacted ones, thus having higher air voids content. It was also observed that the ITS values were higher for Marshall specimens than for roller compacted ones, yet the ITSR value was higher for the roller compacted specimens, which was the case for the mixtures produced for this study (75% RAP - M vs. 75% RAP).

That is not the case for the 0% RAP mixtures, where the Marshall specimens were produced differently: in this study and the one carried out by Pimentel, they were compacted with 75 blows while those analysed in the aggregates and RAP supplier's laboratory were compacted with 50 blows, so it might be related to the compaction of specimens as lower compaction energy leads to lower resistance.

4.6. Macro-texture

The volumetric patch technique was carried out in every slab of the mixtures produced in the laboratory during this study, including slabs that went through short term conditioning (denoted as 75% RAP (STOA)). A side by side comparison of the slabs from each 75% RAP phase is presented in Figure 4.13. That amounted to 6 slabs for every mixture that did not go through any ageing process (0% RAP, 75% RAP and 75% RAP (2nd phase)), 9 slabs for the 75% RAP (STOA) mixture and 11 slabs for the 75% RAP (Aged) mixture. The mean texture depth (MTD) and that parameter's standard deviation (σ) are presented in Table 4.6. The graphic representation of the MTD is shown in Figure 4.14. A synthesis of the collected data is presented in Annex A.4.

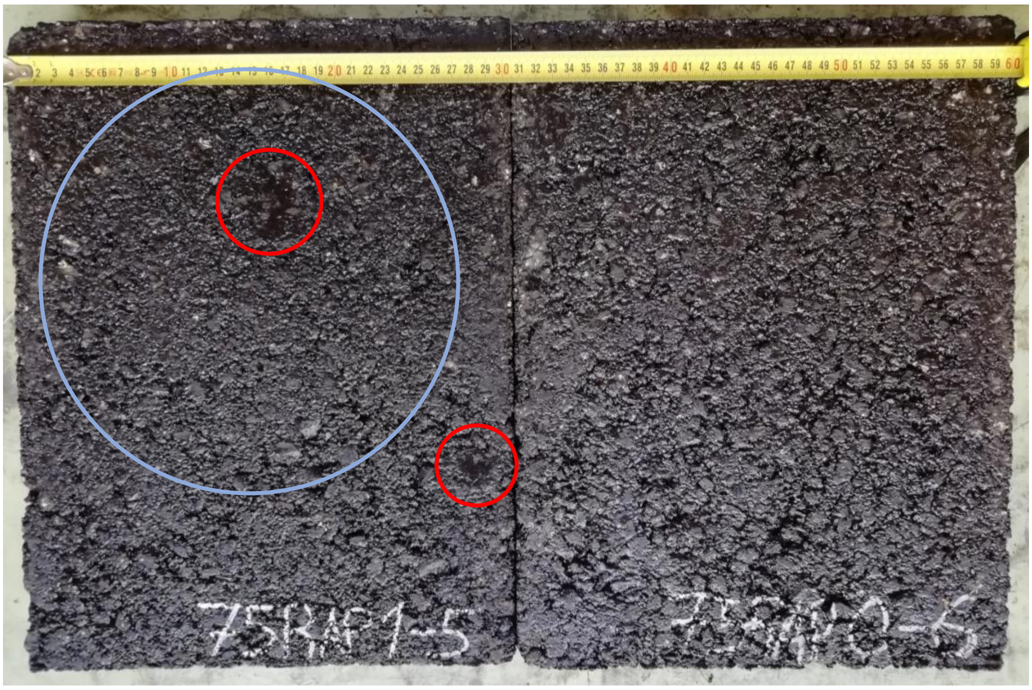

Figure 4.13: Surface texture comparison between 75% RAP (2nd phase) (left) and 75% RAP (right)

To analyse this data, it is important to have in mind that the minimum value for the MTD set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014b) for an AC 14 surf mixture is of 0.7 mm (represented in Figure 4.14 as a red dashed line).

Table 4.6: Mean texture depth of the mixtures

Mixture	MTD [mm]	σ	V_m [%]
0% RAP	0.76	0.13	1.5
75% RAP	0.64	0.07	2.4
75% RAP (STOA)	0.67	0.07	2.7
75% RAP (Aged)	0.66	0.07	2.2
75% RAP (2nd phase)	0.53	0.05	1.7

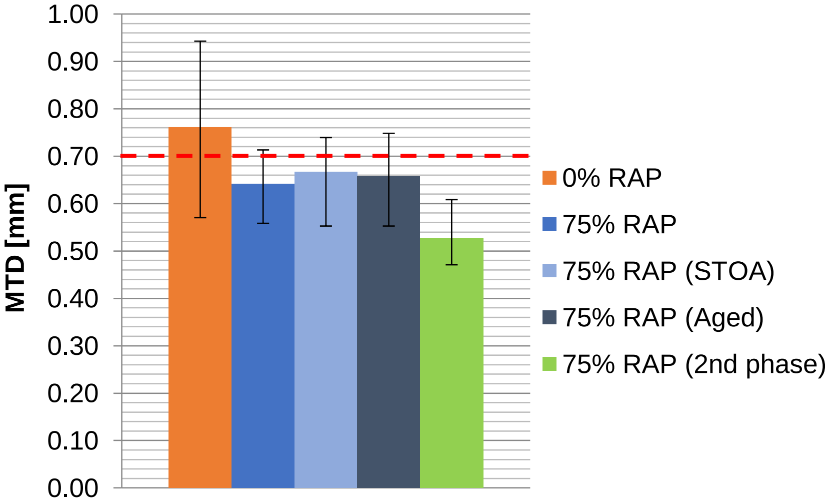

Figure 4.14: Mean texture depth of the mixtures

The mean MTD value varied between 0.53 mm to 0.76 mm. The 0% RAP mixture has the highest MTD, while the 75% RAP (2nd phase) one has the lowest. Among the 75% RAP mixtures from the first phase, it is noticeable that the oven ageing process has no significant effect on a mixture's macro-texture.

When it comes to the minimum MTD set in the specifications, only the 0% RAP mixture was in compliance. However, that mixture has the highest standard deviation with its minimum value in line with those from the 75% RAP mixtures from the first phase. The maximum values from the 75% RAP mixtures from the first phase, though, are above the 0.70 mm mark.

The differing results between the virgin mixture and each phase of the recycled mixtures might be related to the mixtures' gradation. Table 4.7. shows the differences in gradation between the mixtures and it is clear that both 75% RAP mixtures have more fine aggregates in the 0.5 mm to 0.063 mm fractions and less coarse aggregates in the 16 mm and 14 mm fractions, which lead to less macro-texture.

Table 4.7: Reference and recycled mixtures' (1^{st} and 2^{nd} phase) gradation comparison

Sieve Size [mm]		20	16	14	12.5	10	4	2	0.5	0.125	0.063
Passing [%]	0% RAP	100.0	100.0	94.2	84.2	71.0	45.2	31.5	14.8	9.0	7.2
	75% RAP	100.0	99.2	93.6	86.0	75.4	41.0	30.6	16.4	9.8	7.9
	75%RAP (2^{nd} phase)	100.0	99.4	93.5	85.0	74.2	45.0	32.7	16.2	9.5	7.6
75% RAP vs. 0% RAP		0.0	-0.8	-0.7	1.8	4.5	-4.2	-0.9	1.6	0.8	0.7
75% RAP (2^{nd} phase) vs. 0% RAP		0.0	-0.6	-0.7	0.8	3.2	-0.2	1.2	1.3	0.5	0.4
75% RAP (2^{nd} phase) vs. 75% RAP		0.0	0.2	-0.1	-1.0	-1.3	4.0	2.1	-0.3	-0.3	-0.4

When comparing both phases of the 75% RAP mixture, the 75% RAP (2^{nd} phase) mixture has less fine aggregates in the 0.5 mm to 0.063 mm fractions and less coarse aggregates in the 14 mm to 10 mm fractions and also having lower air voids content. Additionally, in the second phase, the aged bitumen was not evaluated, thus the rejuvenator dosage used might not have been the most suitable. In fact, in Figure 4.13 it is visible that the texture from the 2^{nd} phase's slab is smoother overall (a large smooth area is marked in a blue circle) and it even has several patches of flushing (marked in the red circles), that might be caused either by excess bitumen/rejuvenator or by the lower air voids content.

From the previous analysis, the influence of gradation in the macro-texture parameter is perceptible. As such, to ensure that this parameter is within a level that complies with the specifications, there should be adjustments to the gradation curves of the mixtures. Additionally, the application of a surface treatment could also be a solution to improve the macro-texture.

4.7. Micro-texture

The pendulum test was carried out in every slab of the mixtures produced in the laboratory during this study, including slabs that went through short term conditioning. That amounted to 6 slabs for the 0% RAP and 75% RAP (2^{nd} phase) mixtures, 5 slabs for the 75% RAP mixture, 7 slabs for the 75% RAP (STOA) mixture and 11 slabs for the 75% RAP (Aged) mixture. The pendulum test value (PTV) and that parameter's standard deviation (σ) are presented in Table 4.8. The graphic representation of the PTV is shown in Figure 4.15, and a synthesis of the collected data is presented in Annex A.5.

To analyse this data, it is important to have in mind that the minimum value for the PTV set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014b) for an AC 14 surf mixture is of 60 (represented in Figure 4.15 as a red dashed line).

Table 4.8: Mean pendulum test value of the mixtures

Mixture	PTV	σ	Vm [%]
0% RAP	58.2	4.62	1.5
75% RAP	58.0	5.07	2.4
75% RAP (STOA)	58.1	2.52	2.7
75% RAP (Aged)	57.8	3.32	2.2
75% RAP (2nd phase)	58.0	2.97	1.7

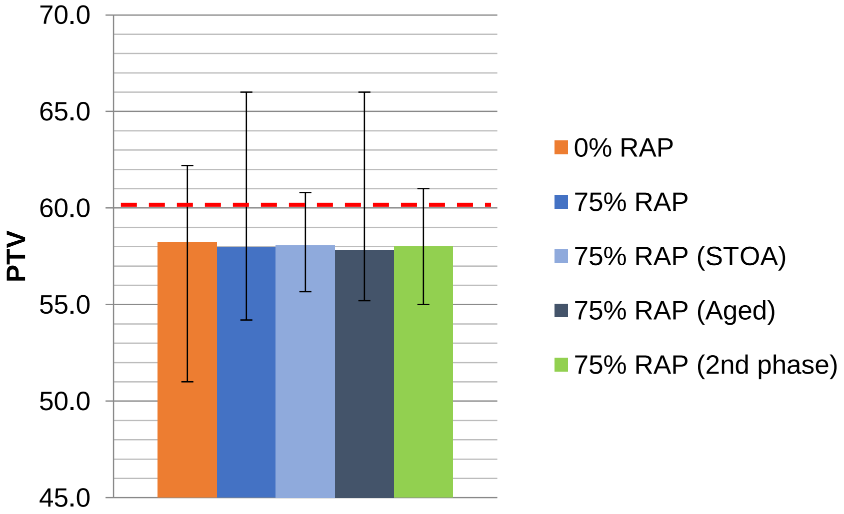

Figure 4.15: Mean pendulum test value of mixtures

The mean PTV varied between 57.8 to 58.2, displaying insignificant differences between the mixtures. Akin to the macro-texture parameter, the oven ageing process had no significant effect on a mixture's micro-texture. And, although close, none of the mixtures met the minimum PTV set in the Portuguese Road authority's specifications (EP - Estradas de Portugal, 2014b).

In spite of all, it has been documented (Chen et al., 2016; Do et al., 2014; Kane et al., 2013, 2010) that after construction there is an increase in a pavement's skid-resistance due to the removal of the binder coating the aggregate's surface by the action of traffic. After peaking, the skid-resistance decreases until it reaches an equilibrium phase, in a rate that is dependent mainly on the aggregate's properties, but also on the bitumen, traffic intensity and environmental conditions.

4.8. Final Remarks

From a general standpoint, the performance level of the recycled mixtures compared with that of the virgin one was distinct in the mechanical performance parameters and those related to the mixtures' surface characteristics.

On one hand, regarding the mechanical performance parameters, the recycled mixtures had equivalent or better performance than the virgin one. There was an exception, though, as the aged recycled mixture exhibited the worst performance on the fatigue resistance parameter.

On the other hand, regarding the surface characteristics of the mixtures, the minimum values of the specifications were not met in most of the analysed specimens. However, that should not be a deterrent to the application of recycled mixtures, as in every mixture there were specimens that were compliant with the specifications and also because those mixtures show good structural performance: the surface characteristics of a pavement can be improved by adjusting the mixture's gradation or even applying superficial treatments to the pavements. Furthermore, the results demonstrated that the oven ageing process had no effect on the surface characteristics of the mixtures.

In light of the air void contents exhibited by the roller compacted slabs throughout this study not being within the limits set by the Portuguese Road authority's specifications (presented in 3.4.5 in Table 3.10), it should be emphasized that those values (3-5 %) are specified for Marshall specimens, i.e. for impact compacted specimens.

According to Mollenhauer and Wistuba (2016), different compaction methods lead to different air voids content in specimens from the same mixture. This can be explained by the friction forces in the mould, during compaction, causing the impact compacted specimens to contain more voids in their outer diameter, whereas the cylindrical specimens obtained from the field or roller compacted are cut from a larger specimen. The difference in air voids content from one type of specimen to the other can be observed in 4.5: the impact compacted specimens had higher air voids content than the roller compacted ones. Additionally, Pimentel (2013) and Mollenhauer and Wistuba (2016) verified that the behaviour of the roller compacted specimens better represented that of the pavement in service.

Finally, the last aspects to consider are the potential reduction of the environmental impacts and production costs from using recycled mixtures instead of virgin ones. Vandewalle (2019) has performed a life cycle assessment (LCA), analysing the impact that the incorporation of RAP in a pavement structure has on the environment; as well as a life cycle cost analysis (LCCA) for the same structure.

In terms of environmental impact, the production and maintenance of a structure using a recycled bituminous mixture (which incorporates 75% RAP) could have a 25% decrease in environmental impacts when compared to a structure that was produced and maintained using only virgin materials. Even though this analysis was only performed for the production and maintenance of a pavement structure; and, according to Antunes et al. (2019), the savings in emissions during these stages are not significant when compared to those generated by the vehicles throughout the whole life of a pavement, that decrease is still a contribution to the environmental sustainability of the paving industry.

Table 4.9 presents the cost comparison between a mixture that was produced with virgin materials and one produced with 75% RAP. The materials' prices were retrieved from Vandewalle (2019), except for the rejuvenator price, which was provided by its supplier. Thus, as shown by the aforementioned table, in terms of economic benefits, there can be a reduction of more than 50 % in the material costs when comparing a recycled mixture to a virgin one. When considering the landfilling costs, the cost reduction in the production of a mixture could be greater, as applying a virgin mixture in a pavement maintenance operation entails the landfilling of the entirety of the milled layers while applying a recycled mixture would only send to a portion to the landfill.

Table 4.9: Bituminous mixture production costs comparison

		Virgin Mixture		**Recycled Mixture**	
Materials	**Price [€/ton]** (Vandewalle, 2019)	**Quantity [ton]**	**Material Cost [€]**	**Quantity [ton]**	**Material Cost [€]**
Bitumen	450.00	0.048	21.43	0.013	5.67
Rejuvenator	2500.00	-	-	0.001	3.08
Basalt 10/16	12.00	0.229	2.74	0.067	0.81
Basalt 4/12	12.00	0.314	3.77	0.038	0.46
Limestone 0/4	3.50	0.276	0.97	0.077	0.27
Basalt 0/4	12.00	0.105	1.26	0.058	0.69
Commercial Filler	17.50	0.029	0.50	-	-
RAP 12.5/19	4.00	-	-	0.228	0.91
RAP 4.75/12.5	4.00	-	-	0.436	1.75
RAP 0/4.75	4.00	-	-	0.082	0.33
TOTAL	-	1	30.67	1	13.96

5. CONCLUSION AND FURTHER RESEARCH

5.1. Conclusion

The main objectives of this thesis were to analyse the performance of a recycled bituminous mixture incorporating high RAP content after going through an ageing process, as well as the re-recycling capacity of RAP in new bituminous mixtures. These were assessed through stiffness, fatigue resistance, water sensitivity and permanent deformation tests, for the mechanical behaviour, and macro and micro-texture tests, for the surface characteristics. These tests were carried out on: (i) a recycled mixture incorporating 75% RAP before and after going through an ageing process; (ii) a recycled mixture incorporating 75% RAP, whose aggregates and bitumen had already completed their second life cycle, and (iii) a reference mixture produced only with virgin materials, whose performance results were used as a benchmark.

Preceding the production of the recycled mixtures, it was important to assess the degree of mobilization of the aged binder so that the aged RAP binder could be accounted for in the mixture production. Upon visual inspection of the blue Marshall specimens produced to that effect, it was observed that the specimens were homogenous and did not exhibit aged binder film surrounding the aggregates, independently of the aggregate and RAP heating temperatures or the presence of the rejuvenator. Nevertheless, the mixing procedure that was adopted to continue this study was the one described in the rejuvenator's guidelines.

The first recycled mixture, 75% RAP, was designed through the Marshall method and the performance tests were carried out on it. Then, for this same mixture, test specimens were produced integrating short-term oven conditioning in the production stage and further ageing them with long-term oven conditioning so that its performance after long-term ageing could be tested.

For the second recycled mixture, 75% RAP (2nd phase), the one that incorporated RAP whose aggregates and bitumen had already completed their second life cycle, the required RAP was produced in the laboratory through the ageing of slabs from the previous mixture and their manual separation into bitumen coated aggregates. Some hypotheses were assumed regarding this mixture's production parameters (aggregate gradation, bitumen and rejuvenator content and maximum density) so that it was possible to carry out performance tests on the mixture in a timely manner.

The following points present a summary of the results of the performance tests carried out on the aforementioned mixtures:

- In the parameters evaluated through the stiffness tests, all the mixtures' curves had similar development with the increase in frequency. All the recycled mixtures exhibited higher stiffness than the virgin one and had a predominantly elastic behaviour, being the aged 75% RAP mixture the one with the highest stiffness.

- All the non-aged mixtures had a similar fatigue law, while the aged 75% RAP mixture had the lowest of all. However, for the 1,000,000 cycles, the difference in failure strain between the mixtures is minimal.
- The aged 75% RAP mixture exhibited the highest permanent deformation resistance, followed by the 75%RAP mixture, then the 75% RAP (2nd phase), being the virgin mixture the one with the worst performance.
- Regarding the water sensitivity, the mixtures that exhibited the highest ITSR were the virgin and the 75% RAP mixtures, showing similar performance between them, yet the 75% RAP mixture presented higher values for the ITS on both wet and dry conditions. The lowest ITSR was exhibited by the aged 75% RAP mixture and the 75% RAP (2nd phase) mixture, however their ITS values on both wet and dry conditions were opposite: the aged 75% RAP mixture exhibited the highest ITS values, while the 75% RAP (2nd phase) mixture exhibited the lowest.
- The virgin mixture had the highest macro-texture, being the only one that complied with the minimum value set in the Portuguese Road authority's specifications; and the lowest MTD was exhibited by the 75% RAP (2nd phase) mixture. As to the macro-texture for the 75% RAP mixture, it was similar between the evaluated ageing stages.
- All the mixtures' micro-texture surrounded the same value, which was below the minimum value set in the Portuguese Road authority's specifications.

Through the analysis and comparison of the performance tests, it was possible to conclude that:

- As expected, due to the aged binder, the recycled mixtures presented higher stiffness than the virgin one, which was reflected in the stiffness and permanent deformation tests results. However, the expected lowering of the fatigue resistance was not observed for the non-aged recycled mixtures.
- The ageing process had a stiffening effect on the 75% RAP mixture, reflected on the highest stiffness and permanent deformation resistance and lowest fatigue resistance. However, it did not affect the surface characteristics of the mixture.
- The effect of the rejuvenator on the 75% RAP (2nd phase) mixture was evident: this mixture's stiffness and fatigue resistance were on par with that of the 75% RAP mixture.

All in all, the better mechanical performance in most of the parameters of the recycled mixtures in comparison with the virgin mixture demonstrates the viability of this recycled mixture to be used by the paving industry. Despite the surface characteristics not being in compliance with the Portuguese Road authority's specifications, and given the importance they have in the safety of the users, they might be improved either with the tuning of the gradation curve or via a surface treatment.

Finally, given the inferior performance demonstrated by the 75% RAP (2nd phase) mixture in the permanent deformation, water sensitivity and macro-texture tests, the importance of RAP characterisation and fractionation and the characterisation of the aged bitumen, in order to determine the optimum rejuvenator content, followed by a mixture design procedure to determine the optimum bitumen dosage, should be emphasized, as those are paramount steps to optimize a recycled mixture's performance.

5.2. Further research

The performance results obtained from this thesis contribute to the demonstration of the viability of RAP recycling and the introduction of this type of mixture. Yet, as the laboratory mixture production and ageing process do not simulate the exact conditions of mixture production in a plant, compaction on-site and ageing throughout its service life, a full-scale trial would be the only way to assess this type of mixture's performance in real circumstances.

Regarding the capacity of re-recycling RAP, the performance of a mixture whose aggregates and bitumen have already completed their second life cycle should be further studied, as the hypotheses assumed for this mixture's production would not guarantee the best performance results that could be achieved but would provide an insight into what they could be. Therefore, it is recommended to begin such studies with the RAP characterisation and fractionation and the characterisation of the aged bitumen, in order to determine the optimum rejuvenator content, followed by a mixture design procedure to determine the optimum bitumen dosage.

Finally, with the intent to fully transition to a circular economy, it would be constructive to deepen the knowledge on the capacity of multi-recycling bituminous mixtures, evaluating the viability of the same RAP to endure multiple service lives while maintaining better or equivalent performance levels as virgin mixtures.

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ANNEXES

A.1. Stiffness test results

Table A.1: Mean values for each mixture's stiffness, phase angle, E_1 and E_2

Freq. [Hz]	Stiffness [MPa]				Phase Angle [°]				E_1 [MPa]				E_2 [MPa]			
	0% RAP	75% RAP	75% RAP (Aged)	75% RAP (2nd phase)	0% RAP	75% RAP	75% RAP (Aged)	75% RAP (2nd phase)	0% RAP	75% RAP	75% RAP (Aged)	75% RAP (2nd phase)	0% RAP	75% RAP	75% RAP (Aged)	75% RAP (2nd phase)
0.1	669	1429	2301	1348	46	32	25	32	466	1214	2094	1145	480	754	955	710
0.2	1029	1849	2816	1719	43	30	23	31	755	1605	2596	1480	698	918	1090	874
0.3	1277	2122	3134	1962	41	29	22	30	969	1864	2912	1707	831	1013	1160	967
0.4	1468	2324	3361	2151	39	28	21	29	1140	2060	3138	1885	924	1076	1202	1035
0.5	1627	2486	3543	2303	38	27	20	28	1285	2219	3321	2032	998	1122	1234	1085
0.6	1764	2623	3693	2434	37	26	20	28	1410	2353	3472	2157	1059	1159	1256	1128
0.7	1881	2738	3820	2549	36	26	20	27	1522	2467	3600	2268	1105	1189	1277	1162
0.8	1987	2844	3934	2648	35	25	19	27	1622	2571	3716	2366	1147	1216	1291	1190
0.9	2083	2932	4031	2740	35	25	19	26	1715	2659	3815	2456	1183	1234	1301	1214
1	2171	3017	4116	2820	34	25	19	26	1799	2745	3901	2535	1214	1251	1313	1235
2	2768	3584	4688	3382	30	22	17	24	2389	3320	4486	3095	1397	1351	1359	1362
3	3152	3930	5037	3743	28	21	16	22	2780	3677	4848	3462	1484	1388	1366	1421
4	3438	4187	5285	4007	27	20	15	21	3075	3942	5107	3734	1537	1411	1361	1452
5	3664	4390	5482	4215	25	19	14	20	3313	4155	5314	3951	1564	1415	1348	1467
6	3849	4555	5642	4388	24	18	14	20	3511	4334	5485	4136	1577	1400	1323	1465
7	4019	4697	5785	4543	23	17	13	19	3697	4492	5641	4303	1575	1372	1284	1454
8	4157	4818	5899	4673	22	16	12	18	3851	4626	5765	4447	1565	1347	1250	1436
9	4305	4936	6014	4803	21	16	12	17	4012	4755	5891	4589	1562	1326	1213	1416
10	4407	5033	6104	4910	20	15	11	17	4136	4864	5989	4710	1520	1292	1176	1387
15	4838	5414	6456	5305	17	12	9	14	4630	5293	6383	5154	1402	1136	962	1259
20	5216	5724	6741	5645	16	11	8	13	5038	5628	6686	5518	1348	1043	855	1186
25	5518	5973	6996	5909	14	10	7	12	5367	5894	6953	5802	1280	967	771	1119
30	5770	6192	7198	6112	12	8	5	10	5660	6141	7173	6038	1119	792	584	952
1	2181	3025	4134	2831	34	25	18	26	1810	2752	3921	2544	1216	1256	1310	1241
0.1	846	1508	2519	1424	44	33	24	32	612	1262	2303	1208	585	823	1020	754

A.2. Fatigue resistance results

Table A.2:Strain and number of cycles endured by each specimen on the fatigue resistance test

Bituminous Mixture	Specimen	Strain [µm]	N [cycles]
0% RAP	V3-1	200	420,018
	V3-2	400	18,149
	V3-3	300	81,521
	V3-4	200	287,655
	V3-5	400	12,545
	V4-2	200	588,359
	V4-3	400	21,580
	V4-4	300	101,085
	V4-5	300	83,380
75% RAP	75RAP03-1	400	9,942
	75RAP03-2	400	40,412
	75RAP03-3	400	26,979
	75RAP03-4	300	92,997
	75RAP03-5	200	662,146
	75RAP04-1	300	135,663
	75RAP04-2	200	268,883
	75RAP04-3	300	85,560
	75RAP04-4	200	392,084
	75RAP04-5	200	415,705
75% RAP (Aged)	75RAP0A-31	200	201,758
	75RAP0A-32	300	55,961
	75RAP0A-33	400	4,950
	75RAP0A-34	200	617,382
	75RAP0A-35	300	101,878
	75RAP0A-41	400	9,711
	75RAP0A-42	200	203,424
	75RAP0A-43	300	35,166
	75RAP0A-44	400	11,215
	75RAP0A-45	200	59,170
75% RAP (2nd phase)	75RAP1-31	200	430,369
	75RAP1-32	300	54,249
	75RAP1-33	400	21,171
	75RAP1-34	200	354,188
	75RAP1-35	300	56,027
	75RAP1-51	400	18,331
	75RAP1-52	200	279,918
	75RAP1-53	300	51,740
	75RAP1-54	400	19,895
	75RAP1-55	200	693,710

A.3. Permanent deformation test results

Table A.3: V_m, RD_{AIR}, WTS_{AIR} and PRD_{AIR} values for each specimen

Parameter	**Specimen**	**0%RAP**	**75%RAP**	**75%RAP (Aged)**	**75% RAP (2^{nd} phase)**
V_m [%]		1.4	2.5	2.3	1.6
Rut depth at 10,000 cycles [mm]	1	5.78	2.02	1.68	2.38
	2	6.04	2.00	1.55	2.98
Mean rut depth at 10,000 cycles, RD_{AIR} [mm]		5.9	2.0	1.6	2.7
Wheel-tracking slope (between cycle 5,000 and 10,000) [mm/10^3 cycles]	1	0.27	0.03	0.03	0.04
	2	0.29	0.03	0.02	0.05
Mean wheel-tracking slope, WTS_{AIR} [mm/10^3 cycles]		0.28	0.03	0.03	0.05
Proportional rut depth at 10.000 cycles [%]	1	11.34	3.97	3.31	4.70
	2	12.03	3.94	3.09	5.94
Mean proportional rut depth, PRD_{AIR} [%]		11.7	4.0	3.2	5.3

A.4. Macro-texture test results

Table A.4: Texture depth measurements for each specimen

Bituminous Mixture	Specimen	Texture depth [mm]	MTD [mm]
0% RAP	V3	0.816	0.761
	V4	0.730	
	V1	0.943	
	V2	0.570	
	V3-R	0.681	
	V4-R	0.827	
75% RAP	75RAP0-1	0.681	0.642
	75RAP0-2	0.713	
	75RAP0-3	0.697	
	75RAP0-4	0.636	
	75RAP0-5	0.564	
	75RAP0-6	0.558	
75% RAP (STOA)	75RAP0A-3	0.553	0.667
	75RAP0A-4	0.730	
	75RAP0A-1	0.576	
	75RAP0A-2	0.650	
	75RAP0A-7	0.650	
	75RAP0A-8	0.739	
	75RAP0A-9	0.681	
	75RAP0A-10	0.739	
	75RAP0A-11	0.681	
75% RAP (Aged)	75RAP0A-1	0.553	0.658
	75RAP0A-2	0.673	
	75RAP0A-3	0.576	
	75RAP0A-4	0.697	
	75RAP0A-7	0.643	
	75RAP0A-8	0.748	
	75RAP0A-9	0.705	
	75RAP0A-10	0.722	
	75RAP0A-11	0.681	
	75RAP0A-5	0.673	
	75RAP0A-6	0.570	
75% RAP (2^{nd} phase)	75RAP1-1	0.558	0.527
	75RAP1-2	0.471	
	75RAP1-3	0.504	
	75RAP1-4	0.608	
	75RAP1-5	0.471	
	75RAP1-6	0.547	

A.5. Micro-texture test results

Table A.5: Pendulum test values for each specimen

Bituminous Mixture	**Specimen**	**PTV**	**PTV (Mean)**
0% RAP	V1	58	58.2
	V2	55	
	V1R	62	
	V2R	62	
	V3R	51	
	V4R	62	
75% RAP	75RAP0-1	55	58.0
	75RAP0-3	60	
	75RAP0-2	54	
	75RAP0-4	55	
	75RAP0-6	66	
75% RAP (STOA)	75RAP0A-3	56	58.1
	75RAP0A-4	56	
	75RAP0A-7	61	
	75RAP0A-8	61	
	75RAP0A-9	61	
	75RAP0A-10	57	
	75RAP0A-11	56	
75% RAP (Aged)	75RAP0A-2	57	57.8
	75RAP0A-1	60	
	75RAP0A-3	55	
	75RAP0A-4	58	
	75RAP0A-7	56	
	75RAP0A-8	56	
	75RAP0A-9	56	
	75RAP0A-10	55	
	75RAP0A-11	55	
	75RAP0A-5	66	
	75RAP0A-6	61	
75% RAP (2nd phase)	75RAP1-1	61	58.0
	75RAP1-2	56	
	75RAP1-3	60	
	75RAP1-4	61	
	75RAP1-5	55	
	75RAP1-6	55	