Politecnico di Torino

Master's Degree in Civil Engineering
Specialization in Infrastructure and Transportation Systems

A.y. 2024/2025
10/10/2025

Rejuvenation of Bituminous Binders through Non-Petroleum Based Products:
A Rheological Characterization

Supervisor:
Professor Lucia Tsantilis

Co-supervisors:
Professor Orazio Baglieri
Professor Davide Dalmazzo
Professor Ezio Santagata

Student:
Federica Raimo

Abstract

The reuse and valorization of materials derived from deconstructed pavements (Reclaimed Asphalt Pavement, RAP), represent a key strategy to enhance the sustainability of the road sector. However, the aging of the bituminous binder contained in RAP compromises its rheological properties, making the use of rejuvenating agents essential. This research, developed within the framework of the PRIN SMASHit project, aimed to evaluate the effectiveness of three non-petroleum based agents: two intended for application in bituminous mixtures (RA and RB) and a sunflower oil traditionally employed for food purposes (RC), tested for the restoration of the viscoelastic properties of aged binders.

The experimental program involved the preparation of bitumen–rejuvenator blends at dosages of 4% and 6% by weight, subjected to standardized aging through the Rolling Thin Film Oven Test (RTFOT) and the Pressure Aging Vessel (PAV). Rheological characterization was performed using a Dynamic Shear Rheometer (DSR) in frequency sweep mode and complemented with dynamic viscosity measurements with a coaxial cylinder viscometer, in order to describe the viscoelastic behavior and workability of the modified binders.

The results confirmed the ability of non-petroleum based agents to influence the properties of aged binders. Overall, the study highlights their potential as a sustainable alternative to petroleum-derived products and provides a basis for further research and practical applications in the field of road pavements.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Purpose and Research Goals

Road infrastructures represent a key element for the economic, social, and territorial development of a country, as they ensure the mobility of people and goods, foster connections between urban and rural areas, and support the functioning of the productive system. The growing number of vehicles and the intensification of traffic loads have led to a considerable increase in stress on the road network, causing progressive pavement deterioration, further exacerbated by weathering and seasonal thermal variations.

Among the different layers that make up a flexible pavement, the wearing course is the most exposed to external agents and, consequently, the most prone to early degradation. The adoption of appropriate technical solutions for the maintenance of this surface layer is therefore a priority from both a technical and environmental economic perspective. In recent years, the increasing focus on sustainability has driven scientific research towards the development of strategies that promote the reuse and valorization of materials, reduce waste and the consumption of new resources, and ultimately minimize the environmental impact associated with road construction and maintenance activities.

In this context, there is growing interest in the reuse of bituminous materials from reclaimed pavements, commonly referred to as RAP (Reclaimed Asphalt Pavement). The use of RAP in new bituminous mixtures helps reduce the need for virgin aggregates and binders, lowers material procurement costs, and limits waste production. However, one of the main challenges associated with RAP is the aging condition of the bituminous binder it contains. Over time, bitumen undergoes oxidative processes that alter its chemical structure and rheological response , resulting in increased stiffness, reduced elasticity, and a general loss of performance.

To counteract these effects and enable the effective use of RAP, the scientific community has investigated various additives capable of partially restoring the original properties of aged bitumen. Among them, specific products are developed and classified as rejuvenators, while other substances, such as vegetable oils commonly intended for food use, can act as rejuvenating agents even if not originally designed for this function. In particular, bio-based solutions are gaining increasing attention, as they combine good technical performance with favorable environmental profiles, being derived from renewable and biodegradable sources.

It is within this framework that the **PRIN SMASHit Project – Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks**, funded by the Italian Ministry of University and Research (MUR), was launched. The project involves several Italian universities and aims to develop innovative and sustainable solutions for the maintenance of secondary road networks, through the use of alternative materials, advanced technologies, and integrated approaches to asphalt mixture design. The project is organized into several work packages, each with specific objectives, and is developed following a multidisciplinary logic that integrates technical, environmental, and economic aspects.

This thesis is part of the SMASHit project, specifically within Work Package 3 – Experimental Investigations and Technology Development of New Materials, and more precisely in Task 3.1, coordinated by the Politecnico di Torino.

The aim of this thesis is to investigate the rheological response of aged bitumen when treated with rejuvenating agents, with a particular focus on the influence of dosage. Both commercial products and a non-conventional alternative have been considered. The experimental work is aimed at assessing the extent to which the treatments are able to restore the viscoelastic properties of the binder and at identifying an optimal dosage range capable of bringing the material closer to the conditions of the unaged binder.

1.2 Structure of the Thesis

This thesis is structured into 6 main chapters, that goes from the theoretical background to the experimental procedures and final discussion of results.

Chapter 2 presents a critical literature review, starting with an analysis of the challenges posed by Reclaimed Asphalt Pavement (RAP), with particular focus on the aging of the bituminous binder, considered the primary cause of performance loss in recycled mixtures. The chapter then explores the most widely adopted mitigation strategy namely, the use of rejuvenating additives by clearly distinguishing between fluxing agents and true rejuvenators, and comparing petroleum-based products with bio-based alternatives. The final section examines the effects of bio-based rejuvenators on both the binder and the asphalt mixture, highlighting key findings from the scientific literature.

Chapter 3 describes the materials and experimental methods adopted in the research. The chapter outlines the characteristics of the base bitumen and the three selected rejuvenators, followed by a detailed explanation of the laboratory aging procedures (RTFOT and PAV) used to simulate field conditions. It also discusses the rationale behind dosage selection and presents the mixing protocol, with emphasis on maintaining consistent conditions to ensure reliable and reproducible results.

Chapter 4 focuses on the experimental procedure adopted for the rheological and viscosity testing of the binders. The methodological framework includes both the use of the Dynamic Shear Rheometer (DSR) in frequency sweep mode and the determination of dynamic viscosity with the coaxial cylinder method. The chapter describes in detail the operational procedure, sample preparation, instrumentation, and data modeling approach based on the construction of master curves. Particular attention is devoted to ensuring uniform test conditions, which are essential for meaningful comparisons across different materials. Finally, the rheological behavior of the rejuvenated binders is analyzed at typical mixing and compaction temperatures, as a function of temperature and additive content.

Chapter 5 presents and discusses the experimental results in an integrated manner. Specifically, for the rheological analyses, both Black Diagrams and Master Curves are reported and interpreted to assess the effectiveness of the various rejuvenators in restoring the viscoelastic properties of the aged binder. As for the viscosity tests, the chapter focuses on the evolution of viscosity over time, in order to evaluate the rheological response and stability of the modified binders.

Chapter 6 provides the final conclusions. This section summarizes the most significant findings of the study, highlighting distinct behaviors of the three rejuvenators, the influence of dosage, and the comparison with manufacturer recommendations, while also defining optimal ranges and emphasizing the relevance of a multiparametric evaluation.

Chapter 2

Literature review

2.1 Reclaimed Asphalt Pavement (RAP)

About 95% of the world's modern pavements are made of Hot Mix Asphalt (HMA) [1], a material consisting of a mix of aggregates (coarse, fine, and filler) and bituminous binder [2] . Recent studies have shown that annual asphalt production exceeds 1 billion tons [1]. However, during its service life, the pavement turns out to be subject to many degradation phenomena, such as vehicular traffic and environmental changes, as a result, the performance of the HMA decreases over time until it becomes unfit for service.

When HMA deteriorates and is no longer capable of adequate performance, the material recovered through process such as removal, milling and crushing of old pavement structures, results in what is commonly known as Reclaimed Asphalt Pavement (RAP) [3]. The amount of RAP has increased significantly over the years, from from 67.2 million tons in 2009 to 112.6 million tons in 2022 [1]. This is because it turns out to be an excellent alternative to be used for the construction of asphalt pavements, both from the economic point of view by lowering production costs, and from the environmental point of view by preserving natural resources.

Concerning the economical aspect was demonstrated by Baghaee Moghaddam et Al. (2016) [3] , that using 100% of RAP in construction project there is a saving ranging from 50% to 70%:

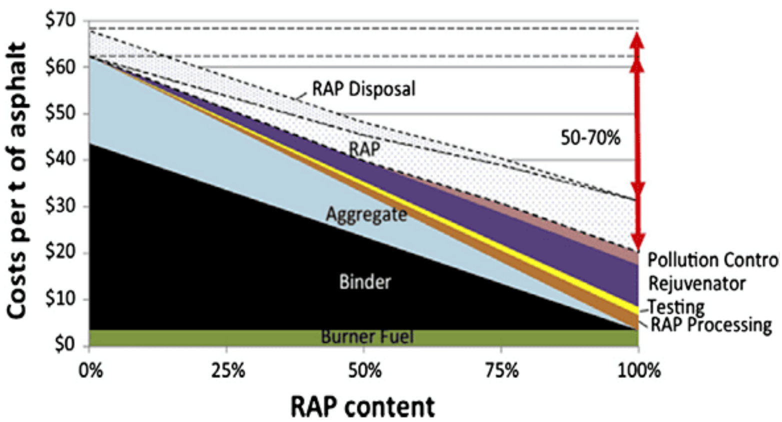


Figure 2.1: Costs of materials in hot mix recycling (Baghaee Moghaddam et Al., 2016) [3].

From an environmental perspective, the use of recycled asphalt mix (RAP) has three main benefits: a significant reduction in air emissions and energy consumption, reduced dependence on non-renewable resources, and a significant decrease in the volume of waste going to landfill [3]:

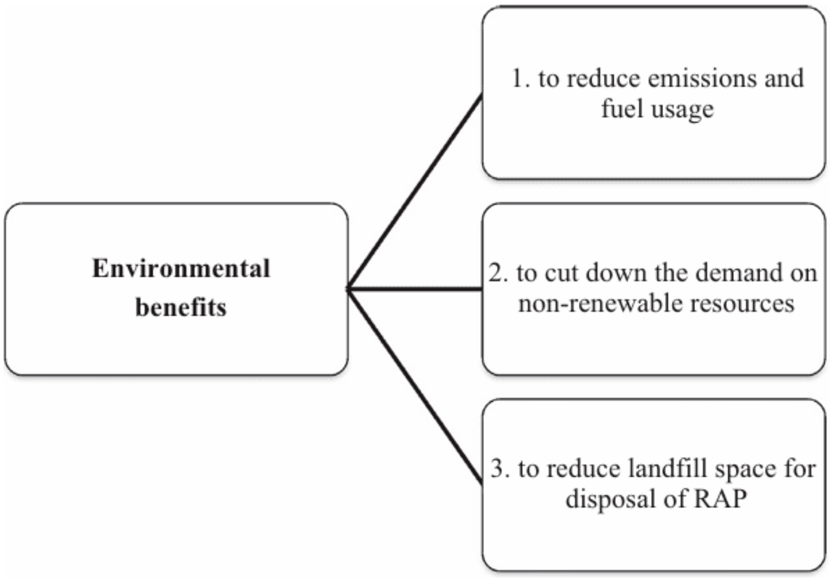


Figure 2.2: Environmental benefits of using RAP in construction of new pavement structure (Baghaee Moghaddam et Al., 2016) [3].

However, some critical issues are also highlighted in the literature, mainly related to the greater complexity of the mix design of RAP. Inadequate design can lead to increased maintenance costs and promote the early appearance of surface degradation phenomena (distresses) [3].

It was amply accredited that the loss performance is mainly attributable to the aging of the bituminous binder, which is the component most sensitive to environmental and mechanical factors. This aging process, as will be discussed in more detail in the following chapters, involves a series of chemical and physical transformations that irreversibly alter the composition of the binder: there is a loss of light components (maltenes), an increase in the asphaltenic fraction, increased viscosity and reduced elasticity [1]. As a result, the aged binder present in RAP tends to be stiffer and more brittle, compromising the performance of the new mix.

To overcome this problem, the use of rejuvenators, that is an additives capable of restoring the chemical-rheological properties of the aged binder, is essential to re-establishing a balance between its fractions and improving its workability and adhesion capacity.

2.2 The Aging Phenomenon in Bituminous Materials

2.2.1 Aging Mechanisms in Bitumen

Bitumen is one of the most commonly used materials in road pavements due to its viscoelastic properties, that give it an ideal combination of strength and deformability.

Over time, however, bitumen undergoes aging processes that significantly affect its performance. The aging mechanisms of bitumen can be divided into two main phases:

- **Short-term aging**, which already occurs during the production, transport, laying and compaction of asphalt, as the material is more exposed to high temperatures and air (oxidative phenomenon);
- **Long-term aging**, which continues throughout the life of the pavement, and is mainly due to exposure to traffic and exhaust gases, but also to atmospheric and environmental causes such as UV rays, seasonal and daily temperature variations, sunlight and humidity.

These processes result in significant changes to the chemical and physical matrix of the binder, leading to increased stiffness, reduced elasticity, and increased susceptibility to cracking.

An aspect analyzed in many studies, is the chemical composition of bitumen, specifically its division into two main components: **asphaltenes**, the solid phase consisting of polar compounds, and **maltenes**, the less polar liquid phase. Maltenes are further divided into three components: saturates, aromatics and resins. This subdivision is known as **SARA** analysis, named after the initials of the components: Saturates (S), Aromatics (A), Resins (R) and Asphaltenes (A). During aging, an increase in the fraction of asphaltenes is observed, because of the condensation of polar species, along with a decrease in the aromatic components caused by volatilization and oxidation.

As reported by Karlsson and Isacsson and summarized by Urbano (2023) [4], aging can be be observed through four main mechanisms:

- **Oxidation**: caused by the reaction of bitumen with oxygen, accentuated by high temperatures and UV radiation. This leads to the formation of oxygen groups and a progressive increase in viscosity [4];
- **Volatilization**: of light components, such as aromatic and saturated fractions, which volatilise during exposure to heat, altering the colloidal balance and increasing stiffness [4];
- **Exudation**: the migration of oily components towards the aggregates, favoured by their porosity, resulting in the loss of the maltenic components. The associated weakening of adhesion is due to their subsequent adsorption onto the aggregates (as illustrated in the Figure 2.3) [4];
- **Physical hardening**: linked to the molecular reorganisation of bitumen at low temperature. Unlike the other mechanisms, this is a reversible process, which can be recovered by heating [4]. For this reason, it is generally not considered among the aging mechanisms that can be compensated by the use of rejuvenators.

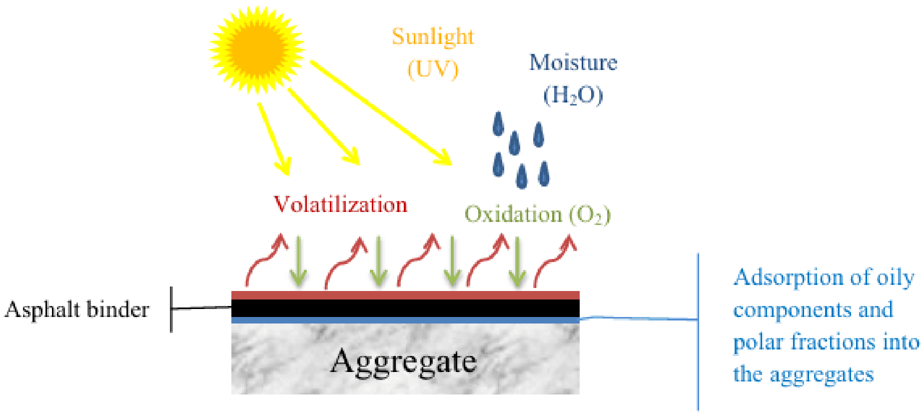


Figure 2.3: Asphalt binder aging phenomena (Baghaee Moghaddam et Al., 2016) [3].

To simulate the aging mechanisms described above in the laboratory, two standard test methods are commonly adopted:

- **Rolling Thin Film Oven Test (RTFOT)**: used to simulate short-term aging by reproducing the conditions to which the binder is subjected during production and laying;
- **Pressure Aging Vessel (PAV)**: used to simulate long-term aging by reproducing the conditions of exposure to oxygen and heat during the service life of pavements.

Thanks to the large number of scientific investigations carried out over the years, these methods have been thoroughly studied, which has generated extensive knowledge and made them a reliable reference in bitumen research. For this reason, they were also adopted in the present work.

It should be remembered, as highlighted by Abouelsaad, as pointed out by Abouelsaad et al (2024) [5], these laboratory tests, although standardized, cannot faithfully reproduce real aging in the field, since they neglect determining factors such as UV radiation, humidity, temperature excursions, and the nonuniform distribution of degradation in the vertical profile of the pavement. For this reason, the results obtained from RTFOT and PAV should be interpreted with caution and, where possible, supplemented with the analysis of samples taken directly from operating pavements, in order to better understand the actual behavior of the bitumen over time.

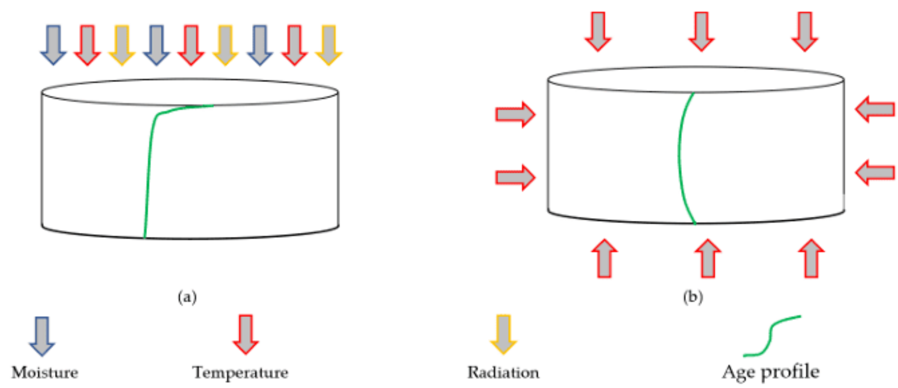


Figure 2.4: Schematic illustration of asphalt aged in the (a) field and (b) laboratory oven (Abouelsaad et al.,2024) [5].

Looking specifically at the chemical aspect of bitumen aging, the study by Mirwald et al. (2020) [6] analysed three binders subjected to both standard laboratory aging (RTFOT + PAV) and an alternative low-temperature aging method (VBA). The results show significant variations in the composition of the SARA fractions, as shown in the Figure 2.5:

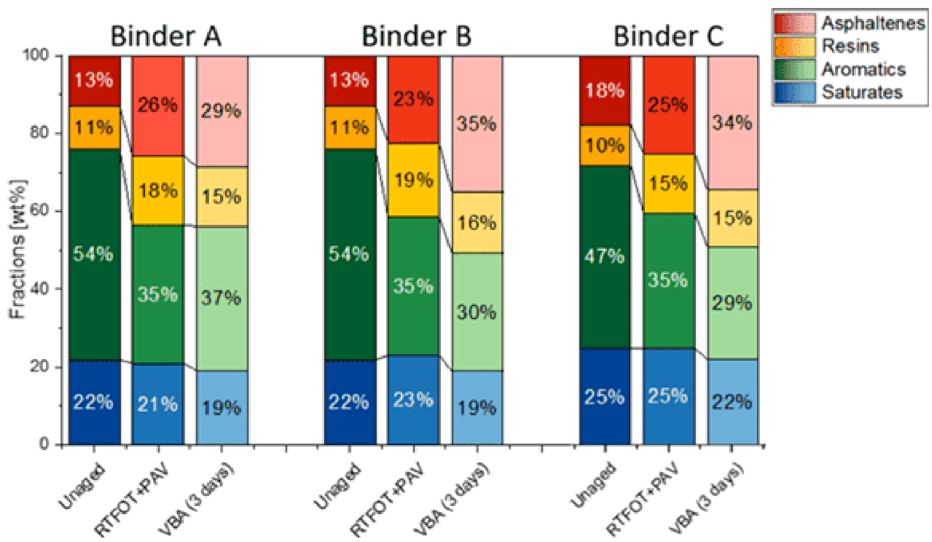


Figure 2.5: Results from the polarity based separation into the SARA fractions (Mirwald et al.,2020) [6].

The analysis confirms, that in the aged samples there is a decrease in aromatics and an increase in asphaltenes, in particular:

- **Satures**: in all cases the variations were minimal, in fact the range is between +1 and -3 wt% [6];
- **Aromatics**: there was a decrease ranging from 12 to 24 wt%, in particular binder B showed the greatest decrease between 19 and 24 wt% [6];
- **Resins**: here there is a noticeable increase [6];

- **Asphaltenes**: there was generally an increase from 7 to 22 wt% [6].

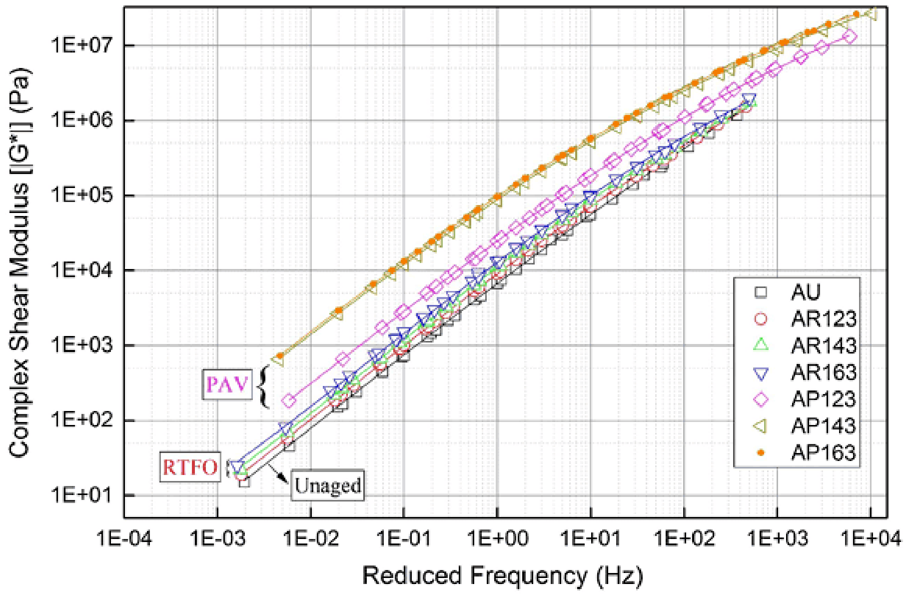
For the sake of clarity, a table showing the percentage differences of the various fractions from the virgin sample is shown below for all 3 bitumens:

Binder	**Method**	Δ Satures [%]	Δ Aromatics [%]	Δ Resins [%]	Δ Asphaltenes [%]
A	RTFOT + PAV	−1	0	−4	+5
A	VBA (3gg)	−3	+2	−15	+16
B	RTFOT + PAV	+1	−24	+5	+18
B	VBA (3gg)	−3	−29	+8	+22
C	RTFOT + PAV	0	−12	+5	+7

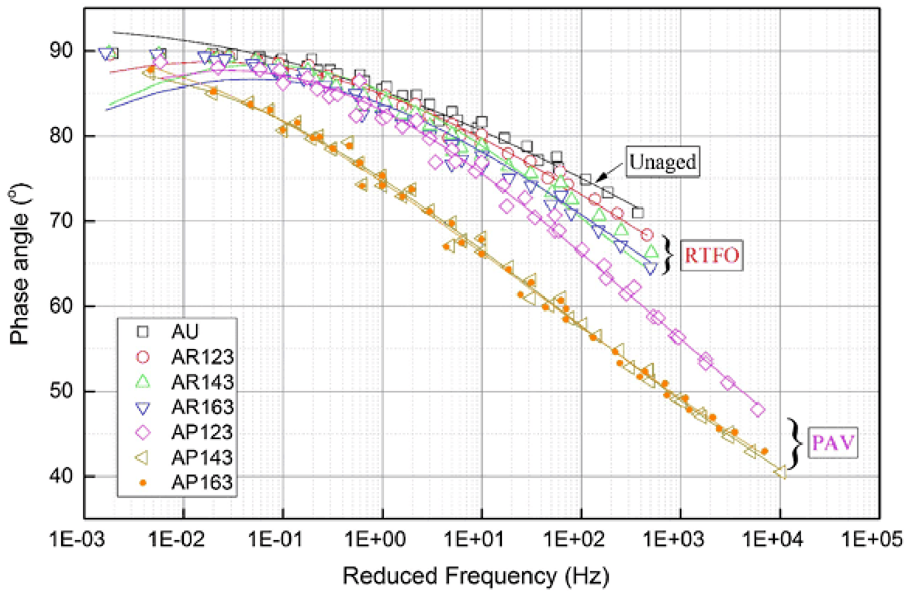
Table 2.1: Mass difference of the LTA fractions compared to the respective unaged fractions (Mirwald et al.,2020) [6].

From the rheological point of view, the two main properties analyzed in numerous studies are the complex modulus ($|G^*|$) and the phase angle (δ).

In the study by Ge et al. (2019) [7] , the behavior of a virgin bitumen and the same bitumen subjected to short and long-term aging processes at three different temperatures (123 °C, 143 °C and 163 °C) was analyzed. It was noted that as the degree of aging increases, the value of the stiffness modulus at the same reduced frequency tends to increase, indicating an increase in binder stiffness. At the same time, a decrease in phase angle is observed, suggesting an evolution of material behavior from a predominantly viscous condition toward a more elastic one.



(a)



(b)

Figure 2.6: (a) Master curve of $|G^*|$ Ge et al. (2019) [7] ; **(b)** Master curve of phase angle (Ge et al.,2019) [7].

These results confirm that aging, influenced by temperature and exposure duration, has a direct impact on the mechanical response of bitumen, reducing its elasticity and increasing its tendency to brittleness, especially at low temperatures

2.2.2 Effects of Aging on Asphalt Mixtures

As described in **Subsection 2.2.1**, bitumen aging significantly alters the rheological properties of the binder, which in turn affects the overall performance of the asphalt mixture. The increase in viscosity and stiffness caused by aging reduces the material's ability to accommodate imposed deformations, facilitating the development of various distress mechanisms.

Among the various mechanisms, the loss of adhesion at the binder–aggregate interface is particularly critical. The interaction between bitumen and aggregate, governed by physico-chemical bonds, is essential to ensure the internal cohesion of the mix. When this adhesion weakens—due, for example, to the aging of the bitumen—the presence of water can promote the detachment of the binder from the aggregate surface. This process initiates surface degradation phenomena such as **stripping**, defined as the loss of the asphalt coating from the aggregate surface [8]. Under these conditions, vehicular traffic further contributes to the acceleration of moisture damage, ultimately leading to the formation of **potholes** over time.

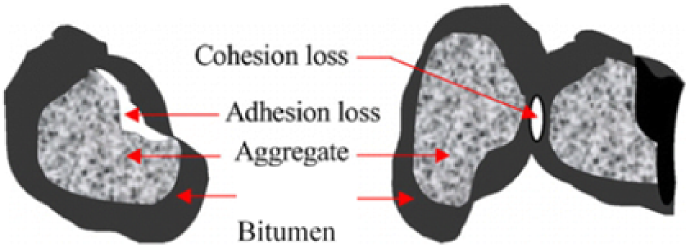


Figure 2.7: low-adhesion in bitumen (Pstrowska et al.,2022) [8].

Figure 2.8: Potholes phenomenon in asphalt pavement.

Similarly, Abouelsaad and White et Al (2022) [9] found that aging reduces the micro-mechanical adhesion force between binder and aggregate. Under critical horizontal loading, this can lead to **ravelling**, as the weakened matrix causes aggregate particles to detach. Once initiated, the process can rapidly propagate, leading to widespread surface disintegration through a domino effect.

From a material property perspective, binder hardening due to aging is reflected in conventional parameters: a reduction in ductility and penetration, combined with an increase in softening point and viscosity. These changes indicate a stiffer and more brittle binder, less capable of sustaining stresses and strains without damage. Consequently, the aged mixture becomes more prone to cracking and fatigue, while the reduced cohesion of the mastic and the weakened binder–aggregate bond can accelerate surface distresses such as ravelling.

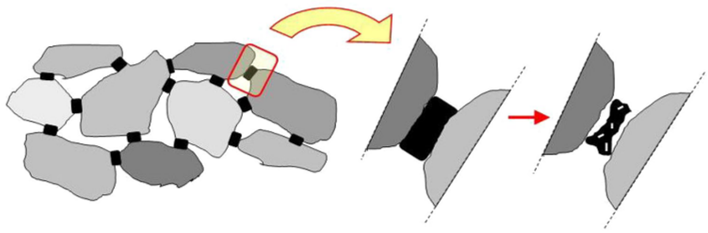


Figure 2.9: Mechanism of ravelling (Abouelsaad and White et Al.,2022) [8].

Sreedhar and Coleri (2020) [10] investigated the effects of long-term aging on **fatigue resistance** in asphalt mixtures, highlighting that oxidation leads to increased stiffness and greater fragility of the material. To quantify this behavior, they employed the Flexibility Index (FI), defined as the ratio between fracture energy and the post-peak slope of the load–displacement curve, scaled by a coefficient. A lower FI value indicates a more brittle mixture, with a higher crack growth rate and, consequently, a greater susceptibility to fatigue-related distresses.

Further insight into fatigue behavior was provided by Singh et al. (2021) [11], who performed the Linear Amplitude Sweep (LAS) test at three different temperatures and two strain levels (2.5% and 5.0%). The objective was to estimate the number of cycles to failure under repeated loading. The results confirmed that fatigue resistance decreases with increasing aging. This decline is attributed to the stiffening of the aged binder, which becomes less elastic and thus more vulnerable to cracking under cyclic loads, limiting its ability to absorb and dissipate stress.

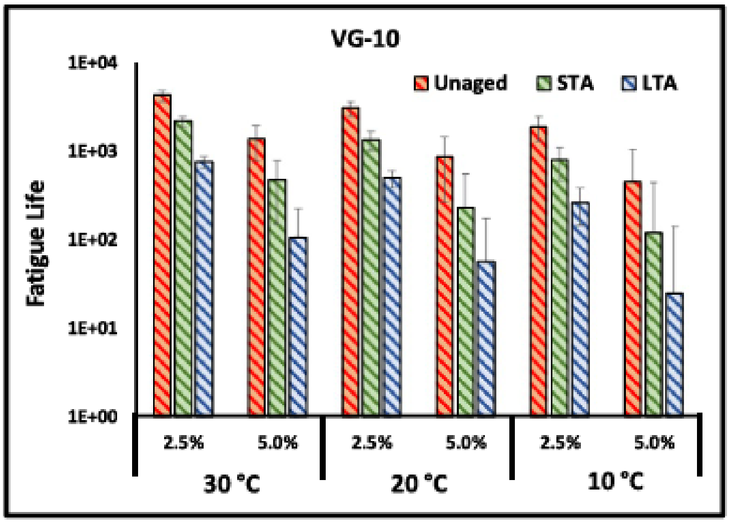
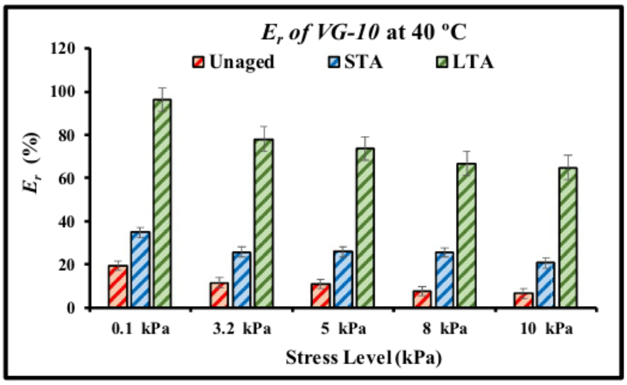


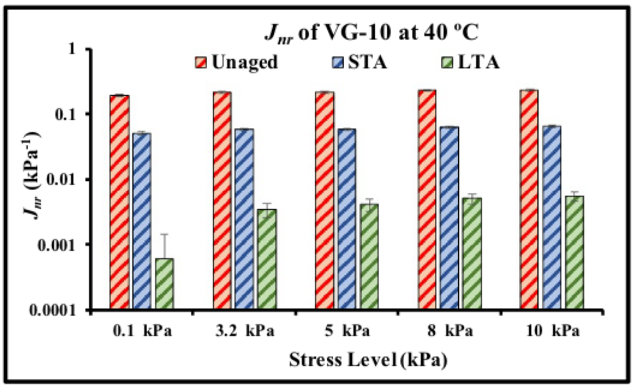
Figure 2.10: Fatigue life of asphalt binders at different aging conditions (Singh et al.,2021) [11].

Figure 2.11: Fatigue cracking phenomenon in asphalt pavement.

In parallel, Singh et al. (2021) [10] also examined the **rutting resistance** of asphalt binders by using the Multiple Stress Creep Recovery (MSCR) test, which provides two key parameters: percent recovery (E_r) and non-recoverable creep compliance (J_{nr}). Higher values of E_r indicate greater elastic recovery, while lower J_{nr} values correspond to reduced permanent deformation, both considered favorable for rutting resistance. Their findings revealed notable differences among unaged, short-term, and long-term aged binders, with oxidation contributing to increased stiffness. While this stiffening effect may enhance rutting resistance, it simultaneously reduces fatigue performance, emphasizing the complex trade-off introduced by binder aging.



(a)



(b)

Figure 2.12: **(a)** E_r of asphalt binders at different aging conditions; **(b)** J_{nr} of asphalt binders at different ageng conditions (Singh et al.,2021) [11].

Figure 2.13: Rutting phenomenon in asphalt pavement.

2.3 Rejuvenators

Previous chapters have extensively analyzed the causes of aging in asphalt mixtures, both from the point of view of the asphalt binder and from that of the asphalt mix. In the present chapter, however, we take a closer look at what the scientific literature suggests is one of the main strategies for counteracting these phenomena: the use of regenerating additives (rejuvenators) within mixtures containing RAP.

Rejuvenator is defined as an agent that can restore the original rheological properties of aged bitumen [12]. Its main function is to reduce the stiffness and viscosity of the binder while increasing its ductility. The first mechanism by which recovery of bitumen properties is achieved is by rebalancing between the solid (asphaltenes) and fluid (maltenes) fractions, generally achieved by increasing the maltenes content.

In addition to international research, national specifications also play a crucial role in guiding the use of such additives. In Italy, for example, the ANAS Technical Specifications require the use of chemical softening agents (ACF) in both hot and cold recycling processes involving RAP. These additives must enhance key binder properties such as adhesion, thermal susceptibility, cohesion, viscosity, and aging resistance with a recommended dosage between 0.2% and 0.8 % by weight of the total binder. The method of incorporation may vary (e.g., added to water, virgin binder, or directly to RAP during milling), and all products must be tested and approved by accredited laboratories. Full technical documentation and site verification procedures are also required for acceptance [13].

2.3.1 Rejuvenators and Fluxants

The study by Loise et al. (2023) [12] points out that the term rejuvenator is often used loosely to refer to any additive capable of improving the properties of an aged binder. However, it is crucial to distinguish between **fluxing (or softening) agents**, which simply reduce viscosity, and **real rejuvenating agents**, which act more profoundly on the chemical balance of the binder, promoting true regeneration of the RAP.

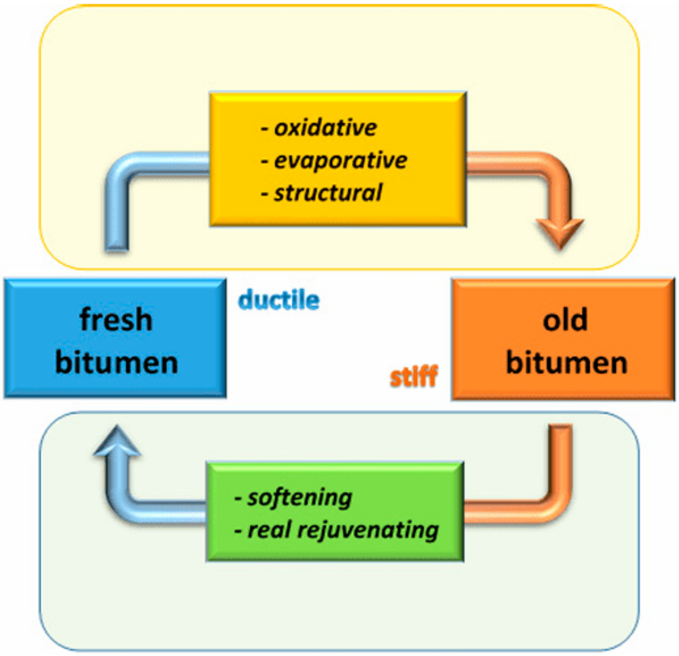


Figure 2.14: Scheme showing the main processes involved in bitumen aging and its rejuvenation (Loise et al.,2023) [12].

The author of this thesis, believes that the clearest and most accurate definition, could be the one proposed by (Abe et al.,2023) [12]:

- **Real rejuvenating agents**: is able to act on the internal colloidal structure of aged bitumen, changing its organization and helping to restore the correct ratio of asphaltenes to maltenes. This type of mechanism reproduces a condition similar to that of virgin bitumen, both compositionally and structurally [12];
- **Fluxing agents (i.e., softening agent)**: acts mainly by reducing the viscosity and modulus of the bitumen through a diluting action of the continuous (maltenic) phase. Although it improves the workability of the material, it does not have a significant impact on the internal molecular aggregation or self-assembly processes of polar micelles. For this reason, its effect is to be considered more superficial and temporary than that of a true rejuvenator [12].

The difference between a softening agents and real rejuvenators has also been studied from the point of view of physical performance, as these are different mechanisms of action [14]. While the stiffness of bitumen is often evaluated by rapid empirical methods developed primarily for engineering applications (such as penetration test, softening point or viscosity), the distinction between softening agents and real rejuvenators requires analysis techniques with a more advanced physical basis.

One of the most effective techniques in this area is *Small Amplitude Oscillatory Shear* (SAOS) rheometry, or small-amplitude oscillatory rheometry, which allows fundamental physical quantities of the material to be determined through the use of sample-specific geometries and precise mathematical interpretation of the data. Specifically, we evaluate the **complex module** G^*, which represents the total energy required to deform the bitumen during an oscillation. This modulus is composed of:

- G': elastic modulus (or storage modulus), which expresses the energy stored in the material;
- G'': viscous modulus (or loss modulus), which represents the energy dissipated as heat.

The relationship between these two parameters is defined as:

$$|G^*| = \sqrt{(G')^2 + (G'')^2}$$

In the same study, the use of so called *black diagrams*, in which G^* is represented as a function of the phase angle δ, is also explored in depth, with:

$$\tan(\delta) = \frac{G''}{G'}$$

These diagrams make it possible to compare the viscoelastic properties of binders without explicitly considering either temperature or frequency, thus offering a more direct and comparative view of rheological performance [14]. However, the test under review does not explicitly report the specific conclusions or results obtained from these studies using black diagrams to explain how this difference between softening agents and real rejuvenators manifests itself. It simply indicates that the technique was used for that purpose.

More advanced techniques such as low-frequency *Nuclear Magnetic Resonance* (NMR) are also being mentioned are showing great promise for distinguishing between the two effects [14]. This technique makes it possible to analyze the *relaxation times* T_2, which provide insights into the degree of molecular freedom within the bitumen. Stiffer materials or aggregates show shorter values of T_2 due to greater dynamic constraints. NMR analysis, often performed by *Inverse Laplace Transform* (ILT), allows the different molecular populations and their mobility to be mapped, thus providing an in-depth readout of the internal microstructure of the binder [14].

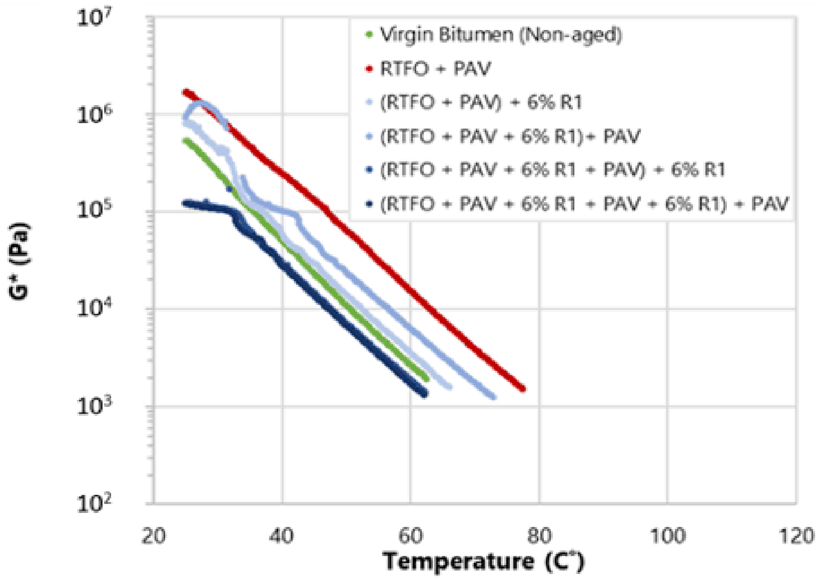
In order to better understand the mechanisms of softening agents and real rejuvenators, it was interesting to analyze the study of the differences the study by Abe et al. (2023) [12], in which the effect of recycling agents on aged bitumen is studied.

The bitumen used in the study is a 70/100, while the recycling agents used are two, referred to as R1 and R2, both dosed at 6% by weight relative to the bitumen content. These additives were introduced after the application of multiple aging cycles of the binder, performed in order to reproduce as realistically as possible the operating conditions to which the material is subjected during its service life.

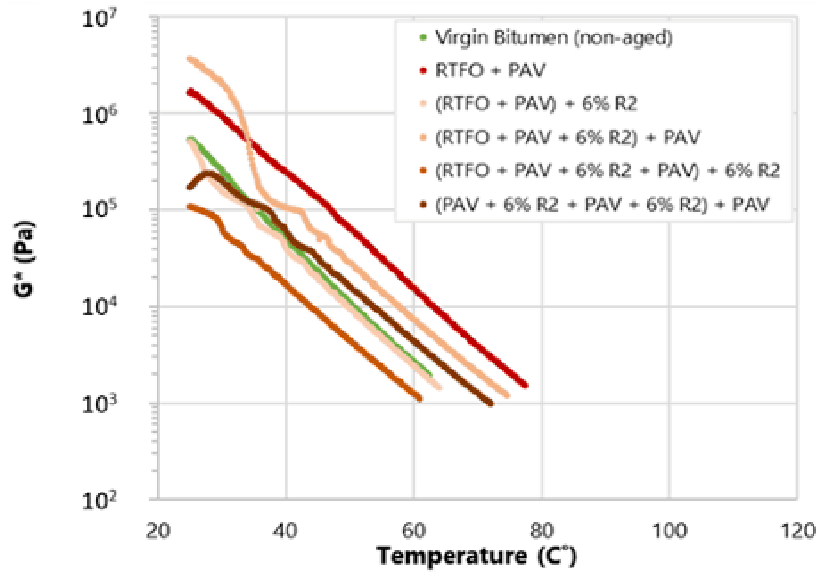
Three types of analysis were conducted in the work, of which, in this paper, the first two are discussed in detail. The choice is motivated by the fact that the first analysis is methodologically akin to those conducted by the author of this thesis (i.e., rheological analyses using DSR), while the second provides results that are particularly significant for the purpose of assessing the effectiveness of rejuvenators.

The first analysis is rheological (Dynamic Shear Rheometer - DSR): in this case, the mechanical properties of the bitumen were evaluated by means of a temperature sweep (TS) test, which consists of a controlled and gradual change in temperature during the test.

In the graph below are reported the values of the complex modulus G* corresponding to the crossover temperatures of the samples.



(**a**)



(**b**)

Figure 2.15: **(a)** Complex modulus G* vs. temperature of R1-modified samples; **(b)** Complex modulus G* vs. temperature of R2-modified samples (Abe et al.,2023) [12].

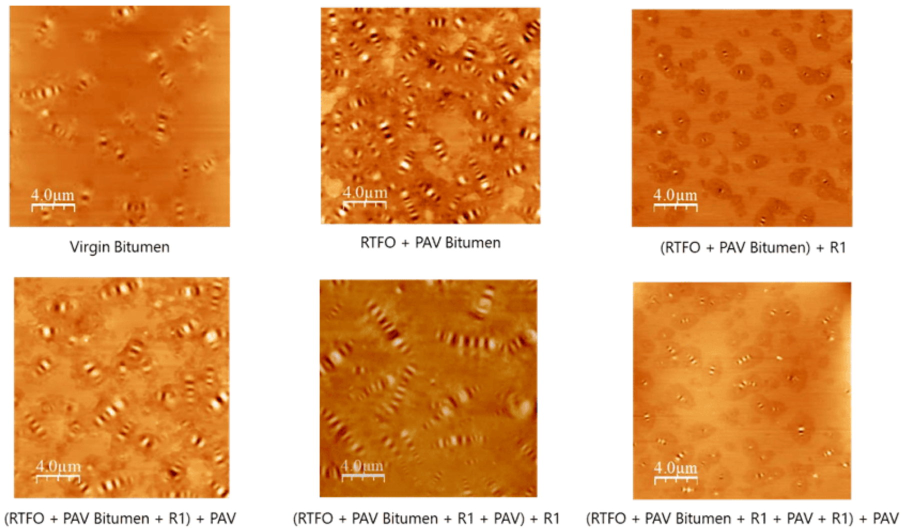
The results show that both recycling agents helped to reduce the stiffness of aged bitumen, improving its physical properties. In particular, agent R1 proved more effective, succeeding in restoring the material to a condition very similar to that of virgin bitumen, even after multiple aging cycles. In contrast, R2 showed a more pronounced softening effect, so much so that it even made the bitumen softer than virgin bitumen in case of double application, but without fully restoring its initial structure.

These observations indicate that R1 has greater potential for structural recovery, while the effect of R2 appears closer to simple softening. Although rheological data are useful in assessing the mechanical performance of the binder, they do not always allow a clear distinction between a regenerating and a fluxing action.

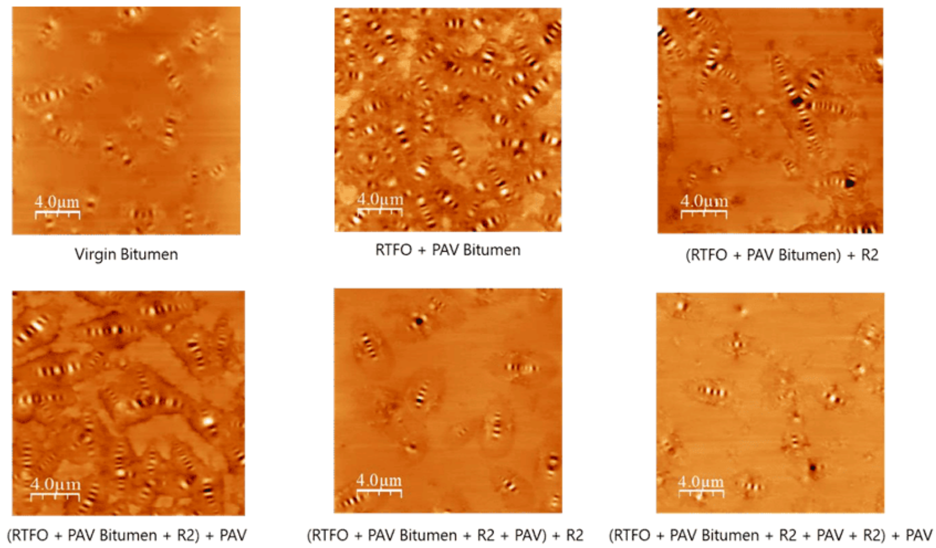
The second analysis conducted investigates Morphological Properties, which allows for high-resolution topographic images of the material surface. This type of observation made it possible to identify several morphological phases in the bitumen, including so-called honeycomb structures (also known as bee structures), related to the presence of asphaltenes, and a smoother matrix consisting of aromatic and saturated components, associated with the maltenic fraction.

Application of the regenerating agent R1 showed the ability to partially reverse these effects: the stiff structures are reduced in size and the maltenic matrix is restored, giving the bitumen morphological characteristics similar to those of virgin material. This behavior suggests that R1 interacts selectively with the asphaltenic fraction, probably through mechanisms that hinder its molecular aggregation.

In contrast, agent R2 manifested a milder action attributable to a simple softening effect. Although it too promotes a partial dispersion of aggregated structures and an apparent increase in the fluid phase, no significant changes to the morphology of honeycomb structures are observed. This suggests that R2 acts mainly by diluting the continuous phase, without directly affecting the balance between asphaltenes and maltenes.



(a)



(b)

Figure 2.16: (a) Master curve of $|G^*|$; **(b)** Master curve of phase angle (Abe et al.,2023) [12].

2.3.2 Types of Rejuvenators

Rejuvenators are classified into five categories: **paraffinic oils**, **aromatic extracts**, **naphthenic oils**, **triglyceride and fatty acids**, and **tall oils**. The first three belong to the category of **petroleum-derived oils**, and are used to replenish the maltenic fraction of bitumen. Whereas the other two, are derived from agricultural sources and contribute fatty acids and/or esters, which are used as solubilization media. In the literature, the use of aromatic extracts (which is a refined crude oil product) as a rejuvenator, is well-established; but in the in recent years, the use of **bio-based rejuvenators** has become more widespread, both for their lower environmental impact and for their efficacy [15].

Petroleum-based and bio-based rejuvenators will be compared on two scales of analysis: of the binder, to understand how the rejuvenators affect the rheological properties of the aged bitumen; and of the asphalt mixture, to evaluate the mechanical performance of the mixture in situations that simulate real-world conditions such as stresses or environmental conditions.

2.3.2.1 Binder testing

The **Performance Grade (PG)** classification was used to evaluate the rheological performance of rejuvenated binders across a range of temperatures. Testing was carried out using the *Dynamic Shear Rheometer* (DSR) for high temperatures and the *Bending Beam Rheometer* (BBR) for low temperatures. Zaumanis et al. (2014) [16] investigated six rejuvenators applied at the same dosage (12%), including four bio-based products (Waste Vegetable Oil, Waste Vegetable Grease, Organic Oil, Distilled Tall Oil) and two petroleum-based products (Aromatic Extract, Waste Engine Oil). The results showed that bio-based rejuvenators were more effective in lowering the low PG temperature, reaching values as low as −26 °C, which were even lower than those of the virgin binder:

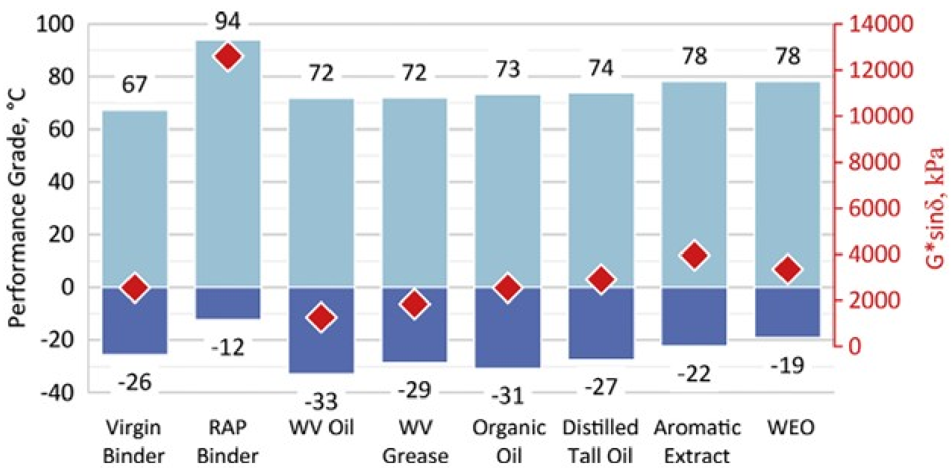


Figure 2.17: Continuous performance grade of rejuvenated binders and G*sin δ at 25 °C (C. Zaumanis et al.,2014) [16].

Nevertheless, all rejuvenators adequately decreased the intermediate temperature fatigue parameter G*sin δ, meeting the Superpave requirement [16].

Arafat et al. (2023) [15] confirmed these trends using different dosages for the two types of rejuvenators (bio-based and petroleum-based). In both cases, BBR results indicated a reduction in binder stiffness and an improvement in stress relaxation capacity, suggesting that the addition of rejuvenators effectively counteracts the aging effects of RAP and enhances binder performance at low service temperatures.It obtained that the optimum dosage for bio-oil rejuvenators was 15% of the RAP binder, compared to the required dosage for petroleum-based which turns out to be 35% of the RAP binder [15].

To understand the **susceptibility to aging** , mass loss tests were performed after aging at RTFOT and PAV. WEO and WV Grease showed an increase in PG temperature of about 4 °C after aging, suggesting accelerated aging compared with virgin binder and unmodified RAP. WEO was the only one to exceed the allowed volatilization limits for its “rejuvenator portion” after aging RTFO [16].

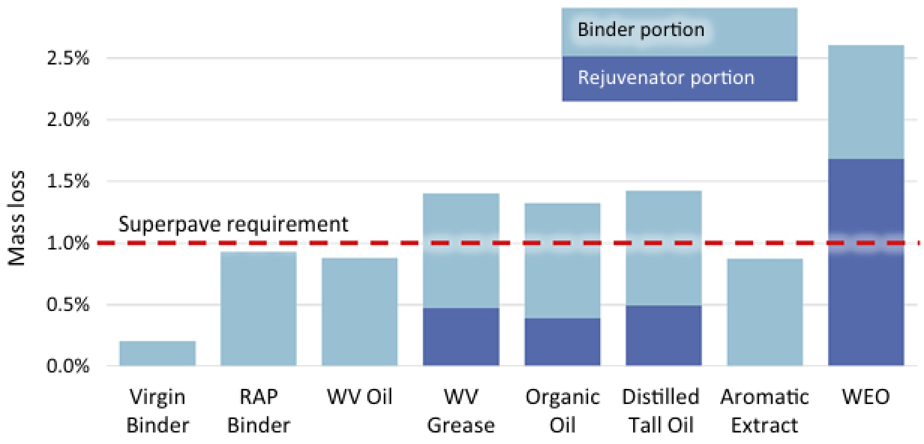


Figure 2.18: Mass loss after RTFO (Zaumanis et al.,2014) [16].

Following a more analytical approach, Arafat et al.(2023) [15] evaluated the aging index, calculated as the area between the master curves of the aged and unaged binder. The results showed that the binder with bio-oil has an aging index of about 13, which is higher than both the binder with aromatic oil, about 9, confirming a greater susceptibility to aging of the first.

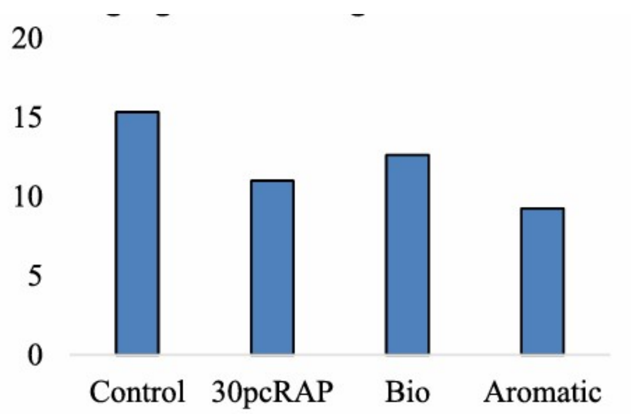


Figure 2.19: Aging Index of aged binder calculated from the master curve (Arafat et al.,2023) [15].

2.3.2.2 Mix testing

The **rutting resistance** was tested with the Hamburg WTT by Zaumanis et al. (2014) [16], the results show that rutting resistance decreases with the addition of the rejuvenators, particularly with WV Grease and WV Oil, compared with RAP Mix.

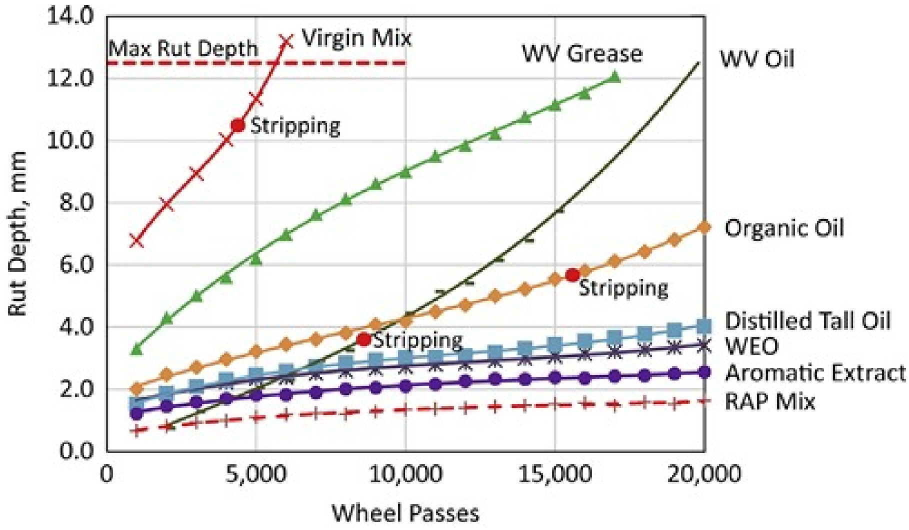


Figure 2.20: Hamburg WTT rutting results (Zaumanis et al.,2014) [16].

The authors emphasize that notwithstanding the results, with proper mix and the right doses, there is no risk of increased susceptibility to rutting. This assertion is shared by Arafat et al. (2023) [15], who employing The Asphalt Pavement Analyzer (APA) point out anceh that with petroleum-based rejuvenators with a higher dosage than organic ones increases rutting reistance.

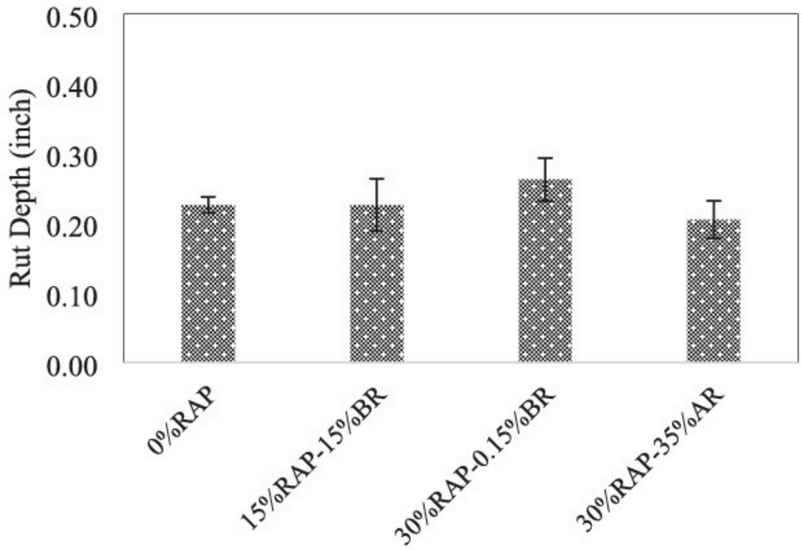


Figure 2.21: APA rutting test results for selected mixed (Arafat et al.,2023) [15].

The **cracking resistance** was evaluated through the Coaxial Shear Test (CAST) [16], which monitors the variation of the complex modulus as a function of load application. In the present study, up to 1.4 million cycles are recorded, with the goal of extrapolating the breaking point (50% reduction in initial stiffness). The results show that mixtures containing RAP in the highest percentage, exhibit high stiffness compared to virgin or low RAP content mixtures, this due to the presence of aged bitumen. Most of the rejuvenators reduced stiffness, however Organic Oil and for Distillated Tall Oil, showed the opposite behavior, increasing it. Thus with almost all rejuvenators there was an increase in cracking resistance.

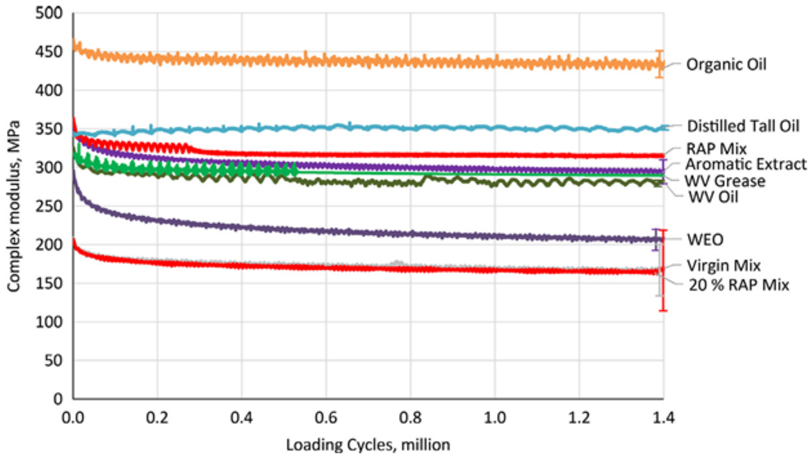


Figure 2.22: Complex modulus as determined using CAST (Zaumanis et al.,2014) [16].

At same time Al Mamun et al. (2020) [17] performed Indirect Tensile Strenght (ITS) to analyze **fatigue**, on mixtures containing WCO and WEO. In agreement with the previously analyzed study, there is a decrease in ITS values with both mixtures, due to binder softening, but the mixtures rejuvenated with WCO show higher ITS values than the corresponding mixtures rejuvenated with WEO. This suggests that, in terms of tensile strength, WCO tends to maintain greater structural integrity.

To assess the durability of bituminous mixtures, and in particular their **resistance to moisture damage**, the Tensile Strength Ratio (TSR) value was evaluated. According to Superpave criteria, to ensure good resistance to moisture, the minimum TSR value must be 80%. The study by Arafat et al. (2023) [15], showed that the mixtures containing regenerants, consistently exhibited TSR values above the minimum limit of 80%, and even higher than the control mixture (without RAP). This improvement was attributed to slightly lower air voids and higher total binder content in the regenerated mixtures. Al Mamun et al. (2020) [17], delved into the dosage of the specific regenerants on moisture durability went into more detail trying to understand the dosage that improved moisture durability, highlighting that: 7% of WEO is effective up to 40% of RAP, while 13% of WCO can be used up to 50% of RAP.

However, the study also pointed out that excessive dosages of regenerant can compromise durability, causing a decrease in cohesion and adhesion and leading to TSR values that approach or fall below the minimum limit of 80%.

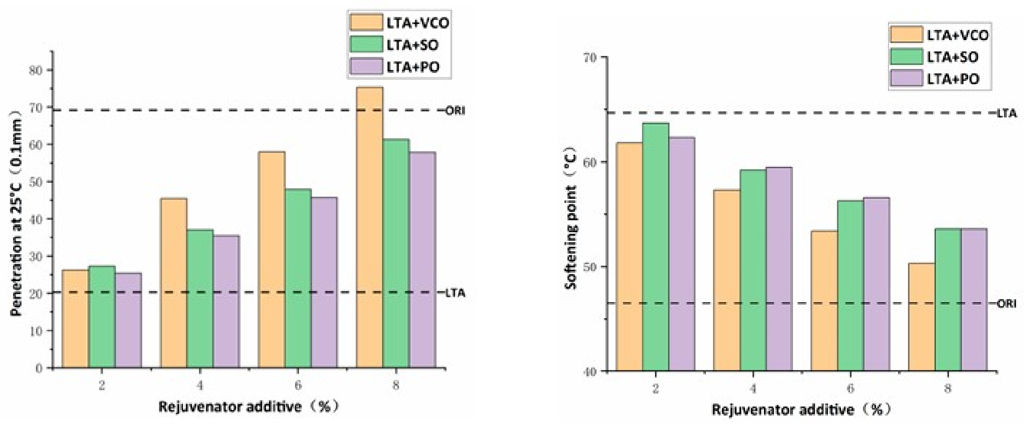
2.3.3 Commercial Rejuvenators

This thesis exclusively employed bio-based rejuvenators. Among them, a widely available and commonly used product was selected typically found as a cooking oil and not originally intended for industrial applications. The selected material was **sunflower oil**, a choice supported by its well documented characteristics in the scientific literature.

A common feature of bio-oils is their high content of unsaturated fatty acids (UFAs).

The type and proportion of these fatty acids significantly influence the physical and chemical properties of the oils, and consequently affect the performance of the asphalt mixtures to which they are added. Soybean oil, in particular, has been extensively studied and validated as a rejuvenator, with various demonstration projects currently underway to assess its long-term performance under real traffic and environmental conditions. Sunflower oil exhibits a fatty acid profile very similar to that of soybean oil, especially in terms of oleic and linoleic acid content, making it a viable alternative for road engineering applications. Furthermore, high oleic variants of these oils offer superior oxidation stability compared to conventional ones a property that can be especially beneficial in enhancing the durability of asphalt materials [18].

Supporting this hypothesis, the study by J. Wang et al.,2024 [19] compared sunflower oil (VCO) with soybean oil (SO) and palm oil (PO) at equal dosages ranging from 2% to 8%.



(a) (b)

Figure 2.23: (a) Penetration of rejuvenated asphalt with the three bio-oils at different dosages; **(b)** Softening point of rejuvenated asphalt with the three bio-oils at different dosages (J. Wang et al.,2024) [19].

The results clearly show that long-term aged asphalt (LTA) treated with sunflower oil exhibited the highest penetration values at 25 °C, indicating a more pronounced softening effect. Moreover, it also presented the lowest softening point values, suggesting a reduction in stiffness and improved workability of the binder.

An in-depth analysis was also carried out on the rheological properties of the rejuvenated asphalt, considering the complex shear modulus (G*), the phase angle (δ), and the rutting resistance parameter. The following tables show the results for an 8% dosage at various temperatures for asphalt modified with different oils:

Temperature (°C)	ORI	LTA	LTA + 8VCO	LTA + 8SO	LTA + 8PO
30	5.35	6.07	5.22	5.33	5.34
40	4.83	5.74	4.74	4.88	4.89
50	4.28	5.21	4.28	4.45	4.44
60	3.65	4.61	3.72	3.91	3.87
70	3.08	4.01	3.19	3.38	3.33
80	2.56	3.45	2.70	2.87	2.81

Table 2.2: Log of complex shear modulus of rejuvenated asphalt at the dosage of 8% (Pa) (J. Wang et al.,2024) [19].

Temperature (°C)	ORI	LTA	LTA + 8VCO	LTA + 8SO	LTA + 8PO
30	73.52	54.73	64.89	61.55	63.05
40	76.23	61.80	68.28	64.72	66.75
50	78.88	66.60	71.38	67.32	69.91
60	81.90	70.94	75.71	71.44	74.62
70	84.77	76.01	80.11	76.43	79.44
80	86.91	80.82	84.10	81.47	83.60

Table 2.3: The phase angle of rejuvenated asphalt at the dosage of 8% (°) (J. Wang et al.,2024) [19].

Temperature (°C)	ORI	LTA	LTA + 8VCO	LTA + 8SO	LTA + 8PO
30	232,000	1,260,000	182,000	251,000	264,000
40	70,110	624,000	58,765	84,107	85,104
50	19,601	178,000	20,165	30,341	29,226
60	4,505	43,113	5,465	8,576	7,739
70	1,216	10,633	1,590	2,495	2,156
80	366	2,861	497	745	643

Table 2.4: The rutting parameter of rejuvenated asphalt at the dosage of 8% (Pa) (J. Wang et al.,2024) [19].

The addition of VCO resulted in the lowest complex modulus values (5.22 Pa), indicating improved workability of the binder. At the same time, an increase in the phase angle (64.89°) was observed, reflecting enhanced viscoelastic behavior. Finally, the rutting parameter reached a stable value (182,000 Pa), suggesting a balanced compromise between workability and resistance.

This initial comparison shows that sunflower oil performs slightly better than soybean oil in both rheological and physical aspects.

The study by Some et al. (2016) [20] also examined a direct comparison with rapeseed oil. Although both are rich in unsaturated fatty acids, sunflower oil demonstrated superior results: higher penetration, a slightly higher softening point, and reduced rut depth.The master curves confirmed improved rheological behavior, with a lower Complex Modulus (E*) and a higher phase angle.

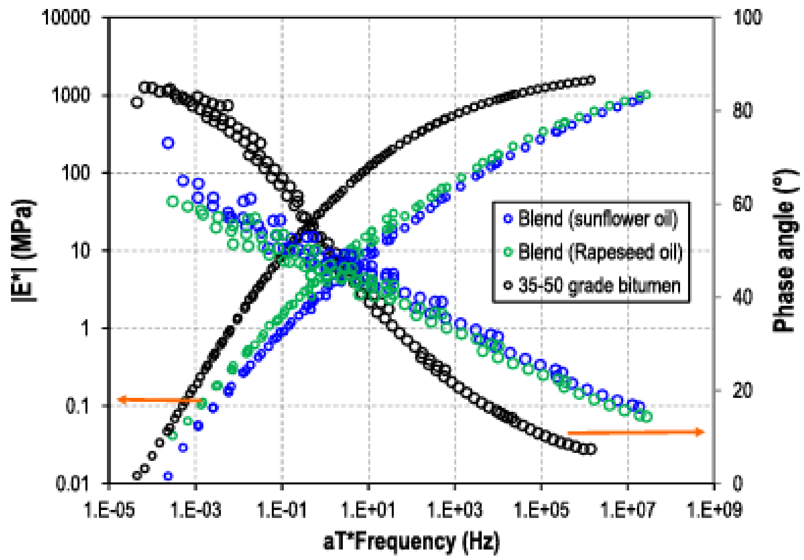


Figure 2.24: Binders complex modulus and phase angle master curves at 15 °C (Some et al.,2016) [20].

All of this supports the author's decision to use sunflower oil as the rejuvenating agent in the experimental phase of this study, due to its proven rheological and physical properties.

Chapter 3

Materials and Methods

3.1 Bitumen

Bitumen is defined as a mixture of paraffinic and aromatic hydrocarbons with high molecular weight, soluble in carbon disulfide (CS_2) [21].

The colour is black, and it is a viscous material that becomes progressively more fluid as the temperature increase at around 100 °C, it reaches a workable consistency, while at room temperature it is significantly more rigid.

Approximately 85% of bitumen applications are related to road infrastructure construction, due to its favourable properties: thermoplastic, waterproof, sealing, adhesive, resistant to acids, alkalis, and salts, durable, modifiable and recyclable [21]. These characteristics make bitumen an ideal binder, used to hold together mineral aggregates in asphalt mixtures. The effectiveness of this binding action is associated with a fundamental property known as **consistency**, which varies with temperature and loading time.

From a chemical point of view, bitumen can be described using the colloidal model introduced by Nellensteyn (1924). In this representation, bitumen is considered a colloidal system composed of: a continuous oily phase (maltene) made up of saturates and aromatics, which give the material its viscous nature; and solid dispersed particles known as asphaltenes, which, due to their polar nature, tend to agglomerate.

This agglomeration is prevented by the presence of resins, which surround the asphaltenes and generate electrostatic repulsion forces that stabilize the dispersion.

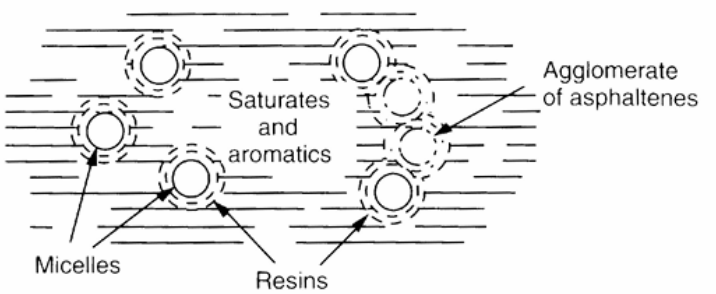


Figure 3.1: Colloidal model - Nellensteyn (1924) [21].

In Italy, bitumen is traditionally classified through empirical tests such as the

Penetration Test, *Softening Point Test*, *Fraass Breaking Point Test*, and *Ductility Test*.

In the context of this research, the bitumen employed has been classified thanks to parallel thesis work as a **70/100 penetration grade**, which is widely used in road paving applications for its optimal balance of stiffness and flexibility in temperate climates.

3.2 Vegetable Oil Rejuvenators

The use of oils of vegetable origin as rejuvenators for Reclaimed Asphalt Pavement (RAP) has been extensively studied in recent years. These oils are not only effective in restoring the properties of aged asphalt, but also have significant advantages in terms of sustainability, accessibility and reduced costs compared to rejuvenators of petrol origin. Vegetable oils are biodegradable, renewable and can also be easily found in supermarkets.

In the present study, are used three oils of vegetable origin, as rejuvenating agents for bitumen. To simplify the discussion, these rejuvenating agents were identified as "**RA**", "**RB**" and "**RC**" (**Figure 3.2**). Specifically, RA consists of a mixture of fatty acids and glycerophospholipids, RB is composed of a blend of vegetable oils, while RC corresponds to a commercial sunflower oil. Each rejuvenating agent was mixed with grade 70/100 bitumen, previously described in the materials section (**Section 3.1**).

(a) (b) (c)

Figure 3.2: **(a)** RA; **(b)** RB; **(c)** RC.

The main physical characteristics, density $\boldsymbol{\rho}$ and viscosity $\boldsymbol{\eta}$ of the rejuvenator analyzed are shown below, to highlight the differences and assess their effectiveness in restoring the rheological properties of the aged bitumen.

Rejuvenator	$\boldsymbol{\rho}$	$\boldsymbol{\eta}$
(-)	g/cm^3	mPa · s
RA	0.95 (20 °C)	50–90 (40 °C)
RB	0.85–0.95 (25 °C)	50–150 (25 °C)
RC	0.918—0.923 (20–25 °C)	29.7 (40 °C)

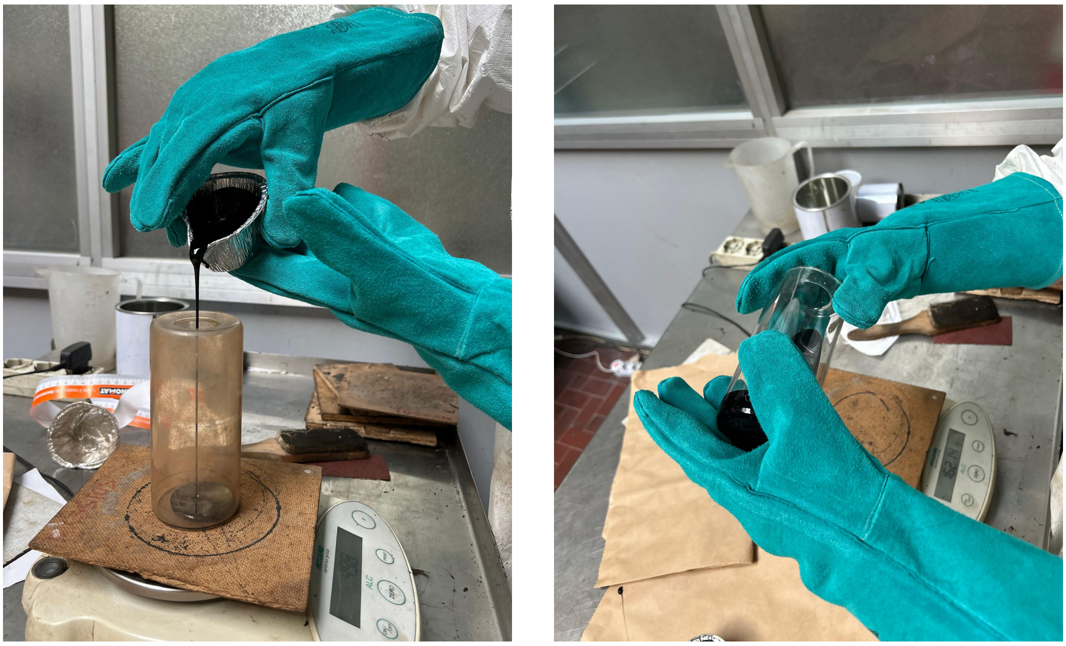
Table 3.1: Physical properties of rejuvenators

The density and viscosity values attributed to the sunflower oil (RC) are approximate and do not derive from the specific technical datasheet of the product used. Instead, they are based on general characteristics of commercially available sunflower oils.

3.3 Bitumen Aging Methods

The bitumen was initially subjected to a short-term aging process using the RTFOT (Rolling Thin Film Oven Test) method, performed according to BS EN 12607-1:2014 - BRITISH STANDARD [22], to simulate the short-term aging conditions that the material undergoes during mixing with aggregates and paving.

For the test, 8 glass cylinders were prepared, each containing (35 ± 0.5) g of bitumen, totaling approximately 280 g. According to the RTFOT procedure [22], the cylinders were then rotated to ensure that the bitumen spread uniformly along the inner surface, creating a thin film. This operation is essential to simulate the short-term aging conditions during mixing and laying phases, allowing the hot air to effectively interact with the exposed bitumen surface during oven conditioning.



(a) (b)

Figure 3.3: **(a)** Filling the glass with bitumen ; **(b)** Rolling the glass to create a thin film.

The cylinders were placed on a cooling rack for a period of 60 minutes, before being quickly inserted into the special holes of the oven, to minimize temperature variations. Once the cylinders have been inserted, a rotation at 15 ± 0.2 r/min is activated, while maintaining an air flow set at (4,0 ± 0,2) l/min, as the procedure. To ensured a stable thermal condition the oven temperature had to (163 ± 1) °C within 15 minutes [22].

Figure 3.4: Glass cylinder on the cooling rack.

Figure 3.5: Glass cylinder in the oven.

Once the set temperature was reached, the timer was started for a duration of (75 ± 1) minutes. At the end of the test, the cylinders were removed, making sure to recover at least 90% of the material, corresponding to 252 g in the case of the 280 g total, and 32 g for each cylinder. In total, two RTFOT tests were performed.

Subsequently, the bitumen was subjected to a long-term aging process using the Pressure Aging Vessel (PAV) method, conducted according to BS EN 14769:2023 - BRITISH STANDARD [23], to simulate the changes that the binder undergoes in situ after approximately 5 to 10 years of service.

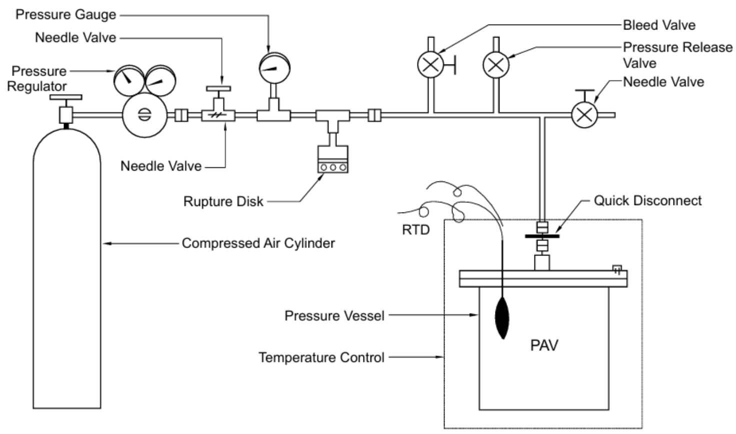


Figure 3.6: Schematic of Typical PAV Test System (AASHTO R 28-22) [24].

The previously RTFOT-aged material was distributed into 10 PAV pans, each containing 50 g of bitumen, placed inside the pan holder and inserted into the hermetically sealed pressure vessel.

Figure 3.7: 4 PAV pans filled with 50 g of RTFOT aged bitumen.

Figure 3.8: PAV holder.

When the internal temperature of the vessel reached between 5 °C and 20 °C below the aging temperature of 100 °C, compressed air was activated, which reached a pressure of (2.1 ± 0.2) MPa. The aging process was maintained for a duration of 20 hours (±10 minutes). At the end of the treatment, it was verified that the pressure never fell outside the range of (2.1 ± 0.2) MPa for a period of more than 30 minutes.

The appearance of the aged binder at the end of the PAV test is shown in (**Figure 3.9**).

Figure 3.9: Pan filled with PAV aged bitumen.

3.4 Preparation of Bitumen–Rejuvenator Blends

The rejuvenators described in **Section 3.2** were subsequently mixed with bitumen grade 70/100.

For all three rejuvenators tested, two dosages were adopted, equal to **4%** and **6%** by weight of bitumen. This choice was made in order to enable a direct comparison between the different products, while maintaining consistent experimental conditions.

The selected dosages were based on the recommendations provided by the manufacturers. For the rejuvenator **RA**, a dosage range between **0.2% and 0.4% on RAP** is suggested. Assuming an average bitumen content in RAP of **5%**, the corresponding amount to be added directly to the bitumen was calculated as follows:

$$\frac{0.2\%}{5\%} = 4\%, \quad \frac{0.4\%}{5\%} = 8\%$$

Thus, the dosage on the bitumen ranges between **4%** and **8%**. Initially, a single dosage of **6%** was selected, representing an intermediate value within the defined range for RA. Subsequently, with the introduction of the rejuvenator **RB**, for which the manufacturer recommends a range of **0.1%–0.3% on RAP**, the same calculation was applied:

$$\frac{0.1\%}{5\%} = 2\%, \quad \frac{0.3\%}{5\%} = 6\%$$

This indicates that the dosage on the bitumen should range from **2%** to **6%**. In order to ensure a consistent comparison with RA, the **6%** dosage was also used for RB. However, an additional dosage of **4%** was also considered, representing the average of the recommended range for RB. In this way:

- RA was tested at its **minimum (4%)** and **intermediate (6%)** values;
- RB was tested at its **intermediate (4%)** and **maximum (6%)** values.

To maintain methodological consistency, the same dosages (**4%** and **6%**) were also applied to the rejuvenator **RC**, introduced later in the study.

Finally, considering a fixed binder quantity of **50 g** for each test, the amount of rejuvenator to be added was calculated as:

$$50\,\mathrm{g} \times 0.04 = 2.0\,\mathrm{g}, \quad 50\,\mathrm{g} \times 0.06 = 3.0\,\mathrm{g}$$

Therefore, for each dosage:

- **2.0 g** of rejuvenator were added for the **4%** dosage;
- **3.0 g** of rejuvenator were added for the **6%** dosage.

Mixing was carried out using a mechanical rod mixer RZR 2041 'Heidolph', set at a speed of approximately 200 rpm (revolutions per minute) for a duration of **3 minutes**.

Figure 3.10: RZR 2041 “Heidolph”.

The temperature during this phase was maintained at approximately 140 °C. To reach and sustain this level, the container ("cookie") holding the 50 g of bitumen was placed on a heated support inside an oven set to the same temperature. The support consisted of a vessel filled with refractory stones that surrounded the can on which the cookie was placed, thereby creating a thermally insulated and stable environment. This setup ensured uniform temperature distribution throughout the treatment process.

Figure 3.11: Heated support for mixing process.

The rejuvenator was added gradually to the bitumen, using a pipette. This method ensured an even distribution within the bitumen matrix. The addition was carried out in small quantities to avoid excessive viscosity variations and to ensure uniform mixing.

Figure 3.12: Addition of the rejuvenator using a pipette.

During the mixing process of all three rejuvenators, no issues were encountered. All three products exhibited satisfactory consistency, although the RA appeared slightly more filamentous compared to the other two.

Chapter 4

Experimental Tests

4.1 Rheological Testing

4.1.1 Frequency Sweep Test

Continuous loading tests do not realistically represent the stresses transmitted by vehicles to road pavements, as the loads applied under real conditions vary over time and are not constant. For this reason, rheological tests adopt an **oscillatory** regime, in which the material is subjected to a stress that follows a sinusoidal law:

$$\tau(t) = \tau_0 \cdot \sin(\omega t) \tag{4.1}$$

where:

- $\tau(t)$ is the instantaneous shear stress;
- τ_0 is the amplitude of the applied stress;
- ω is the angular frequency (rad/s);
- t is the time.

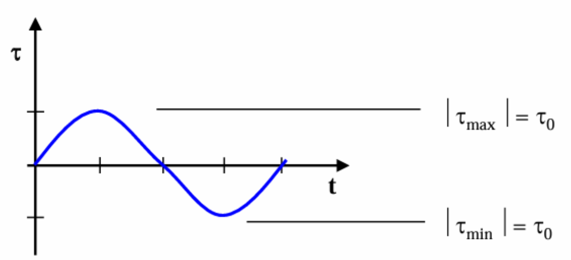


Figure 4.1: Harmonic stress applied in the linear viscoelastic regime [21].

Considering the viscoelastic nature of bitumen, the strain response is not in phase with the applied stress, but is delayed in time. This behavior is expressed by the following relationship:

$$\gamma(t) = \gamma_0 \cdot \sin(\omega t - \delta) \tag{4.2}$$

where:

- $\gamma(t)$ is the instantaneous strain;
- γ_0 is the strain amplitude;
- δ is the phase angle, representing the time shift between stress and response.

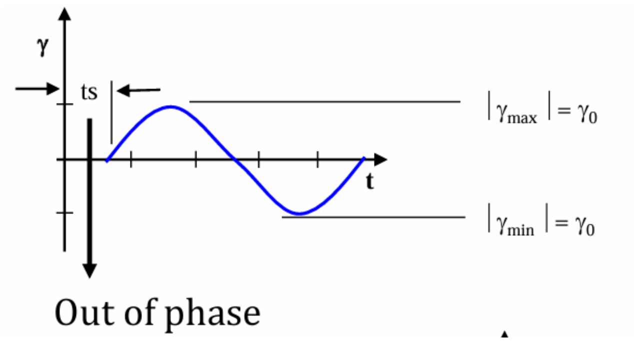


Figure 4.2: Strain out of phase with respect to stress: viscoelastic behavior [21].

The phase angle δ provides a direct indication of the balance between the elastic (recoverable) and viscous (dissipative) components of the material:

- for $\delta = 0°$, the material behaves as a purely elastic solid;
- for $\delta = 90°$, the behavior is typical of an ideal viscous fluid.

Given the stress and strain values, the **complex modulus** G^* can be defined, representing the ratio between the two quantities:

$$G^* = \frac{\tau(t)}{\gamma(t)} \tag{4.3}$$

The complex modulus can be represented as a vector in the complex plane, with a real part G' (elastic component) and an imaginary part G'' (viscous component). The relationships linking these components are:

$$G' = |G^*| \cdot \cos\delta \qquad G'' = |G^*| \cdot \sin\delta \qquad |G^*| = \sqrt{G'^2 + G''^2} \tag{4.4}$$

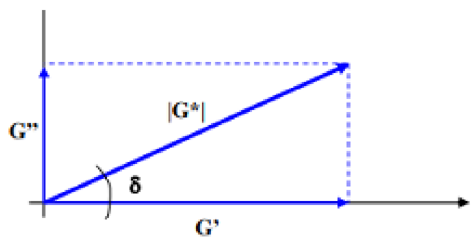


Figure 4.3: Vector representation of the complex modulus G^* [21].

The harmonic behavior described above forms the theoretical basis of the rheological test known as the **frequency sweep**, which is fundamental for the viscoelastic characterization of bituminous binders. The aim of this test is to evaluate the evolution of the **complex modulus** G^* and the **phase angle** δ as a function of **angular frequency**, within a range between **1 and 100 rad/s**.

The test is conducted within the linear viscoelastic range (LVE), ensuring that the material response remains independent of the strain amplitude. Under these conditions, it is possible to observe how the binder shifts from a predominantly viscous behavior, typical of low frequencies or high temperatures, to a more elastic response, which occurs at high frequencies or low temperatures.

The experimental outputs of the frequency sweep test allow for the interpretation of the binder's rheological behavior through various graphical representations. Among these,a particularly useful tool is the **Black diagram**, it correlates the logarithmic value of the complex modulus ($\log |G^*|$) with the corresponding phase angle (δ). This representation enables the assessment of the consistency of the material's viscoelastic behavior and the comparison of binders with different rheological characteristics or aging levels.

Another fundamental representation is the **Master Curve**, which describes the trend of the complex modulus as a function of reduced frequency, combining on a single curve the data obtained at different temperatures. This procedure is based on the application of the time–temperature superposition principle, which allows for a virtual extension of the analyzable frequency range.

4.1.1.1 Master Curve Modeling Using the CAM Model

The Master Curves obtained were modeled using the **Christensen–Anderson–Marasteanu (CAM) analytical model**, which allows for the description of bitumen's viscoelastic behavior over a wide range of reduced frequencies through a continuous mathematical formulation. To apply this model, it was necessary to identify an optimal set of parameters, using an optimization process conducted with Microsoft Excel Solver.

The main parameters of the CAM model are:

- G_g: the **glassy modulus**, represents the limiting stiffness of the material at extremely high frequencies. It is considered constant for each type of bitumen and, in this study, an initial value of $\log G_g = 6$, corresponding to $G_g = 1\,\text{MPa}$, was assumed.
- ω_c: the **crossover frequency**, that is, the frequency at which the equality between the elastic and viscous components of the complex modulus occurs ($G' = G''$), corresponding to $\tan\delta = 1$ or $\delta = 45°$. This value was estimated from the experimental data by identifying the point at which δ approaches 45°.
- R: the **rheological index**, which describes the difference between the glassy modulus and the complex modulus at the crossover frequency. It expresses how quickly the curve approaches the glassy asymptote. In the model, it is expressed as:
$$R = \log\left(\frac{G_g}{G^*(\omega_c)}\right) \tag{4.5}$$
- m: a shape parameter.

The CAM model is defined by the following equations:

$$|G^*| = G_g \left[1 + \left(\frac{\omega_c}{\omega_r} \right)^{\frac{\log 2}{R}} \right]^{-\frac{mR}{\log 2}} \tag{4.6}$$

$$\delta = \frac{90 \cdot m}{1 + \left(\frac{\omega_r}{\omega_c} \right)^{\frac{\log 2}{R}}} \tag{4.7}$$

To determine the reduced frequency ω_r, necessary for constructing the Master Curve, the **time–temperature superposition principle** was applied using the **Williams–Landel–Ferry (WLF)** equation:

$$\log a_T = -\frac{C_1(T - T_0)}{C_2 + (T - T_0)} \tag{4.8}$$

where:

- T: test temperature;
- T_0: reference temperature (assumed equal to 20 °C);
- $C_1 = 19$ and $C_2 = 92$: values suggested for road bitumens.

Through the optimization performed with Solver, the sum of the deviations between the experimental and theoretical values of G^* and δ was minimized by adjusting the parameters $\log G_g$, $\log \omega_c$, R, C_1, C_2 and m in order to improve the model's fit to the experimental data. The final goal was not to obtain a punctual value of G^*_{LVE}, but rather an **optimized continuous curve** describing the rheological behavior of bitumen across the entire spectrum of reduced frequencies.

Below are reported $\mathbf{C_1}$, $\mathbf{C_2}$ and the CAM model parameters obtained from the analysis:

Material	$\mathbf{T_0}$ [°C]	$\mathbf{C_1}$ [-]	$\mathbf{C_2}$ [°C]	log($\mathbf{G_g}$) [kPa]	log($\boldsymbol{\omega_c}$) [rad/s]	**R** [kPa]	**m** [-]
O	20	12,27	110,12	5,52	2,81	1,32	1,03
R	20	14,20	121,23	5,64	1,76	1,69	1,08
P	20	18,64	159,84	5,65	0,00	2,12	1,18
RA4_p	20	15,35	130,74	5,82	0,26	2,31	1,25
RA6_p	20	14,46	134,67	5,62	1,26	2,16	1,19
RB4_p	20	13,98	117,24	5,73	1,16	1,97	1,15
RB6_p	20	13,09	112,15	5,61	2,01	1,72	1,08
RC4_p	20	15,43	132,49	5,77	0,65	2,21	1,19
RC6_p	20	15,05	131,01	5,72	0,86	2,18	1,19

Table 4.1: C_1 and C_2 coefficients and CAM model parameters.

Passing from the unaged condition to more severe states, the crossover frequencies decrease (reduction of $\log(\omega_c)$), confirming the progressive hardening of the binder. Compared to sample O, both material P and the regenerated mixtures show lower $\log(\omega_c)$ values, with a less pronounced reduction in some formulations (e.g., RB6_P), which indicates a more stable rheological response. With regard to the rheological index R, aging consistently leads to an increase in this parameter, resulting in flatter master curves and a more gradual transition from the viscous to the glassy state. The magnitude of this increase is not uniform: in some mixtures (e.g., RB6_P) it is more limited, while in others (e.g., RA4_P) it is more evident. The glassy modulus ($\log(G_g)$) remains relatively stable across the different materials, with only minor variations: in some cases (e.g., RA4_P) a slight increase is observed, whereas in others the variation is less significant. Finally, the coefficients C_1 and C_2 highlight differences among the binders, pointing to a distinct thermal sensitivity. In particular, some regenerated mixtures exhibit a moderate reduction in these parameters compared to the reference material, an effect associated with the combined influence of aging and the presence of the rejuvenating additive.

4.1.2 Dynamic Shear Rheometer

The rheological characterization of bituminous binders was carried out using a Dynamic Shear Rheometer (DSR), an essential tool for evaluating viscoelastic parameters, particularly the complex modulus (G*) and the phase angle (δ). These parameters describe the behavior of bitumen as a function of temperature and loading frequency, simulating the actual operating conditions to which the material is subjected in road pavements.

The Dynamic Shear Rheometer (DSR) applies a sinusoidal torque T to a sample positioned between two surfaces one fixed and one movable inducing a shear deformation. This deformation is expressed as a rotational displacement, denoted by the angle φ, and allows for the determination of the material's stress and strain responses. Depending on the characteristics of the binder and the testing conditions, two different measurement geometries can be adopted:

- **Plate–plate**: the sample is placed between two parallel circular plates, the parameters are evaluated as:

$$\tau = \frac{2T}{\pi r^3} \tag{4.9}$$

$$\gamma = \varphi \cdot \frac{r}{h} \tag{4.10}$$

  Where:

  r and h are respectively the radius and the height of the specimen.

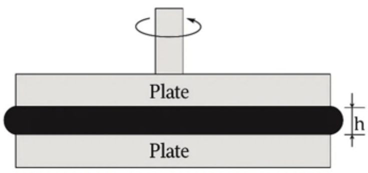


Figure 4.4: Plate-Plate System.

- **Cone–plate**: the upper plate is replaced by a cone with a defined angle (θ), ensuring a uniform stress distribution.The parameters are evaluated as:

$$\tau = \frac{3T}{2\pi r^3} \tag{4.11}$$

$$\gamma = \varphi \cdot \frac{r}{h} = \varphi \cdot \frac{r}{r \cdot \tan(\theta)} = \frac{\varphi}{\tan(\theta)} = \frac{\varphi}{\theta} \tag{4.12}$$

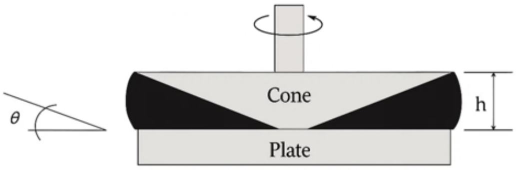


Figure 4.5: Cone-Plate System.

4.1.3 Laboratory Equipment and Testing protocol

In the present thesis, the tests were conducted using Anton Paar MCR 301 and MCR 302 rheometers (**Figure 4.6**), both using **plate–plate configuration**, following the AASHTO T 315-22 standard [25]. The rheometers are equipped with a thermostatically controlled upper hood and a refrigerated lower plate connected to an external cryostat, which maintains a constant testing temperature. The thermal circuit pressure is regulated between 4 and 5 bar via a pressure gauge.

(a)

(b)

Figure 4.6: Rheometers: **(a)** MCR 301 "*Anton Paar*"; **(b)** MCR 302 "*Anton Paar*".

Depending on the temperature range, two different geometries were adopted:

- **2**5 mm plate-plate with 1 mm gap, for medium/high temperature tests (34-82 °C), used with MCR 302 rheometer;

- **8** mm plate-plate with 2 mm gap, for low-temperature tests (4-34 °C), conducted with the MCR 301 rheometer.

(a) (b)

Figure 4.7: Parallel plate geometries:**(a)** PP08; **(b)** PP25.

Plate dimensions and gap values are in accordance with the standard [25], which defines specifications for the accurate determination of the viscoelastic properties of bituminous binders.

The specimens were prepared using silicone moulds of 8 mm and 25 mm diameter, filled with bitumen taken from previously cast beams. To determine the quantity of bitumen to be poured into the silicone moulds, the theoretical volume of the specimen was first calculated based on the selected geometry and standard gap setting.

For the **25 mm** specimens, assuming a height (gap) of 1 mm, the corresponding volume was calculated as:

$$V = \pi \cdot \left(\frac{25}{2} \ \text{mm} \right)^2 \cdot 1 \ \text{mm} = 490.62 \ \text{mm}^3 \tag{4.13}$$

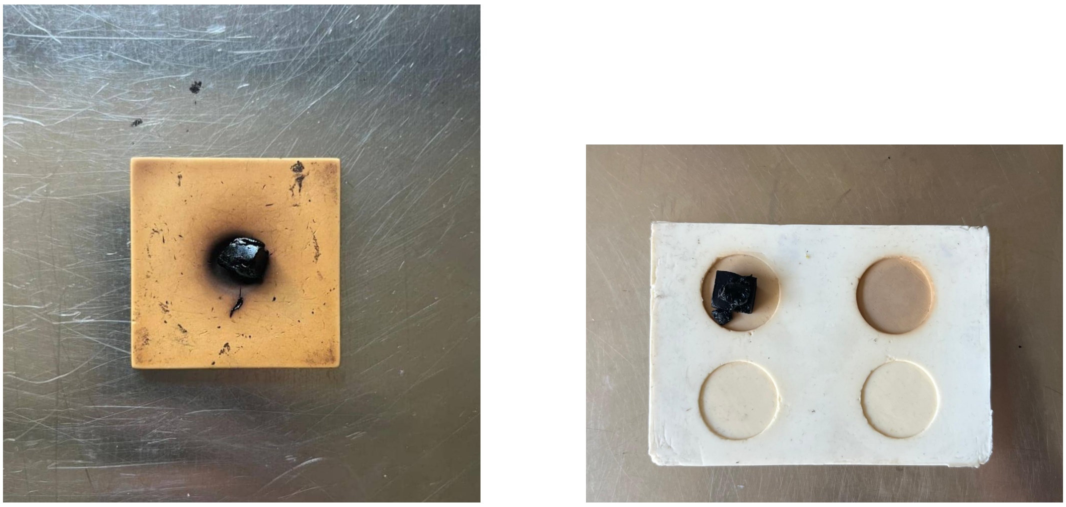
Considering a bitumen density of approximately 1 g/cm^3 (i.e., $1\,\text{g} = 1000 \ \text{mm}^3$), this volume corresponds to about 0.49 g. However, to ensure complete filling of the mould and compensate for potential material loss during handling, a mass of approximately **1 g**, roughly twice the theoretical value, was used.

For the **8 mm** specimens, the required mass was determined empirically based on preliminary tests, and ranged between **0.230 g** and **0.250 g**.

The bitumen was previously heated to facilitate pouring:

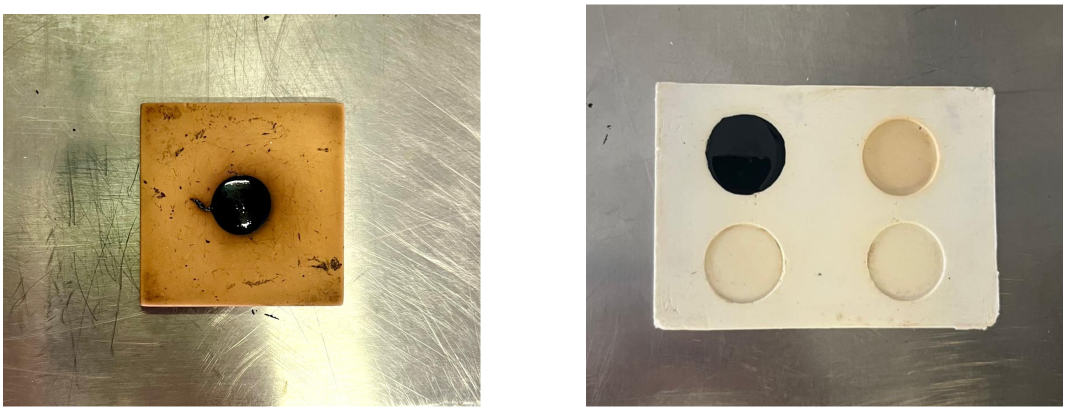
- **Aged or rejuvenated bitumens:** heating at 150 °C for 10 minutes;
- **Virgin bitumen:** heating at 130 °C for 5 minutes.

Next, for all geometries and levels of aging, the samples were allowed to cool for 5 minutes at room temperature, followed by further cooling in the freezer for another 5 minutes to facilitate handling and installation on the rheometer.



(a) (b)

Figure 4.8: Bitumen samples placed in silicone molds before oven heating:**(a)** 8 mm; **(b)** 25 mm.



(a) (b)

Figure 4.9: Bitumen samples placed in silicone molds after oven heating: **(a)** 8 mm; **(b)** 25 mm.

Removed from the silicone mold, the specimen is placed on the lower plate of the rheometer, which is previously heated so as to ensure thermal uniformity before measurement begins, specifically:

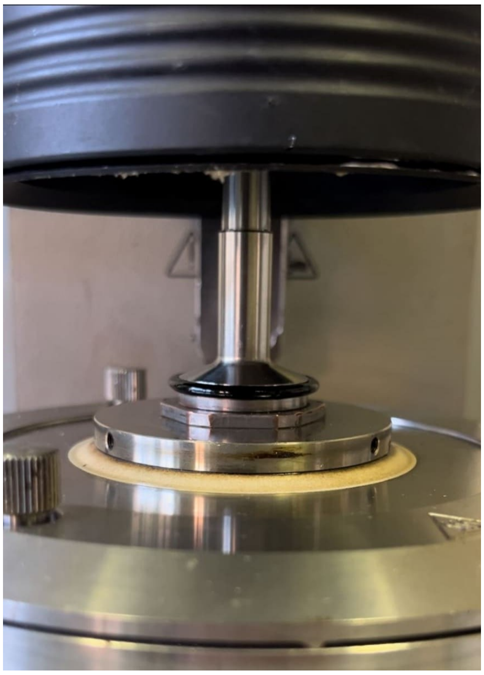
- **Aged or rejuvenated bitumens:** the preheating temperature is set at 50 °C;
- **Virgin bitumen:** the preheating temperature is set at 46 °C

Once the specimen was placed on the bottom plate, the positioning between the plates was managed using RheoPlus software, which allows automatic control of the distance (gap) between the surfaces. By clicking on the "*Measuring Position*" option, the plates are initially brought to a distance slightly larger than the nominal gap:

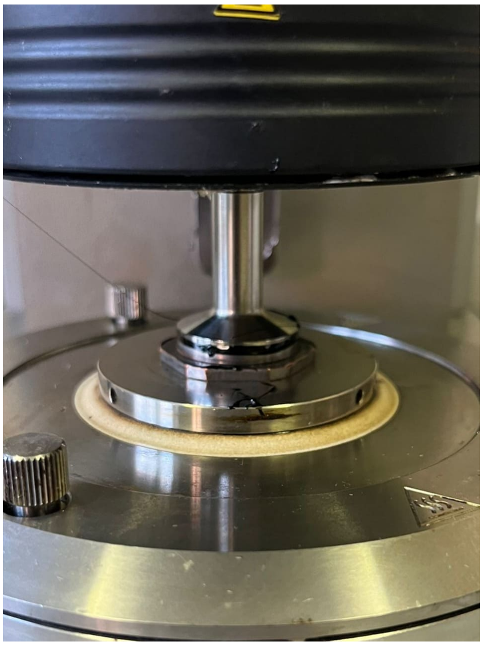
- 2,100 mm for the geometry of 8 mm;
- 1,050 mm for the geometry of 25 mm.

This slight excess space promotes the formation of a thin curvature of the excess bitumen beyond the edge of the specimen. Once this step is completed, the excess material is carefully trimming with a spatula, following a standardized procedure to obtain a flat, even surface. Only after this operation is the 'Continue' command clicked, which automatically lowers the top plate to its final measurement position, i.e., 2,000 mm for the 8 mm plate and 1,000 mm for the 25 mm plate [25].

(**a**)



(**b**)



(**c**)

Figure 4.10: (**a**) placement of the sample on the lower plate; (**b**) sample before trimming, after the gap has been set; (**c**) sample after trimming.

After this procedure, the actual test begins. For both geometries used (8 mm and 25 mm), an initial thermal conditioning phase of 30 minutes is carried out to ensure uniform temperature distribution within the sample. The oscillatory frequency sweep test then starts, with a total duration that varies depending on the geometry selected.

4.2 Viscosity Testing

4.2.1 Coaxial cylinders method

In order to complete the rheological analysis of the binders, the **dynamic viscosity** of the bitumen samples blended with the three different rejuvenators was also determined. This parameter describes the material's resistance to flow and is defined as the ratio between the applied shear stress and the shear rate, expressed in Pa · s.

According to the BS EN 13702-2:2003 standard [26], the test principle involves placing the sample in a beaker, into which a cylinder is inserted. The material is subjected to stress through the rotation of either the cylinder or the beaker itself. The torque applied is then measured and, combined with the shear rate data, allows the dynamic viscosity to be calculated. This parameter represents the material's resistance to deformation under flow.

Operationally, viscosity is determined by measuring the torque required to maintain a constant rotational speed of the metal cylinder immersed in the bitumen. Since the shear stress is proportional to the product of viscosity and shear rate, the viscosity value can be obtained by knowing the applied flow conditions.

The test was carried out using a Dynamic Shear Rheometer (DSR) MCR 302 by Anton Paar (**Figure 4.6**), equipped with the coaxial cylinder system CC17/T200/SS, also manufactured by Anton Paar.

(**a**) (**b**)

Figure 4.11: **(a)** Anton Paar MCR 302 DSR configured with coaxial cylinder geometryn ; **(b)** Coaxial cylinder system CC17/T200/SS.

The analysis was carried out at three different reference temperatures: 160 °C, 135 °C, and 100 °C. For each temperature, different shear rate values were applied in order to evaluate the material's response under various deformation regimes.

- **160 °C**: 30 s^{-1}, 100 s^{-1} e 300 s^{-1};
- **135 °C**: 10 s^{-1}, 30 s^{-1} e 100 s^{-1};
- **100 °C**: 3 s^{-1}, 10 s^{-1}, 30 s^{-1} e 100 s^{-1}.

The test procedure involves preheating the instrument to 160 °C, followed by heating the bitumen sample to 170 °C for a sufficient time to ensure adequate fluidity. The material is then poured into the coaxial cylinder system up to the reference mark indicating the correct volume. Once the upper cylinder is lowered, the sample aligns flush with the lower cylinder, a necessary condition for starting the test. At this point, the test can begin, during which the system applies the predefined shear rate values, allowing the dynamic viscosity to be recorded as a function of temperature and the imposed shear rate.

Chapter 5

Discussion of Results

5.1 Analysis of Frequency Sweep Test Results

The data obtained from the frequency sweep tests were initially represented as Black Diagrams, with the aim of detecting any inconsistencies and validating the applicability of the time–temperature superposition principle.

A total of nine diagrams were produced, one for each material and aging condition, all of which confirmed the consistency and reliability of the experimental data. Were performed two repetitions using the 8 mm plate, and two repetitions with the 25 mm plate. The use of duplicate tests was intended to assess the repeatability and reliability of the measurements, which was confirmed by the strong agreement observed between repetitions.

The different materials and their respective aging or treatment conditions are identified by specific labels:

- **O**: original binder;
- **R**: binder aged with RTFOT;
- **P**: binder aged with PAV;
- **RA4_P and RA6_P**:PAV-aged binder treated with rejuvenator A at 4% and 6%, respectively;
- **RB4_P and RB6_P**: PAV-aged binder treated with rejuvenator B at 4% and 6%, respectively;
- **RC4_P and RC6_P**: PAV-aged binder treated with rejuvenator C at 4% and 6%, respectively;

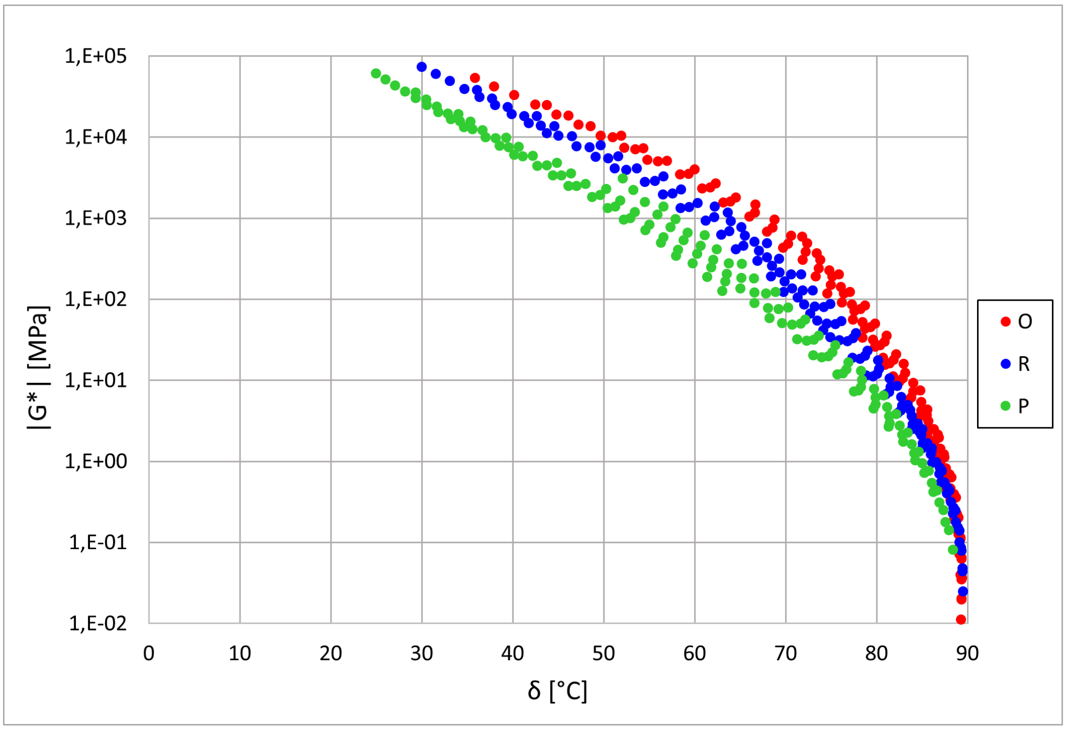


Figure 5.1: Black Diagram of the base bitumen in Original, RTFOT and PAV-aged conditions.

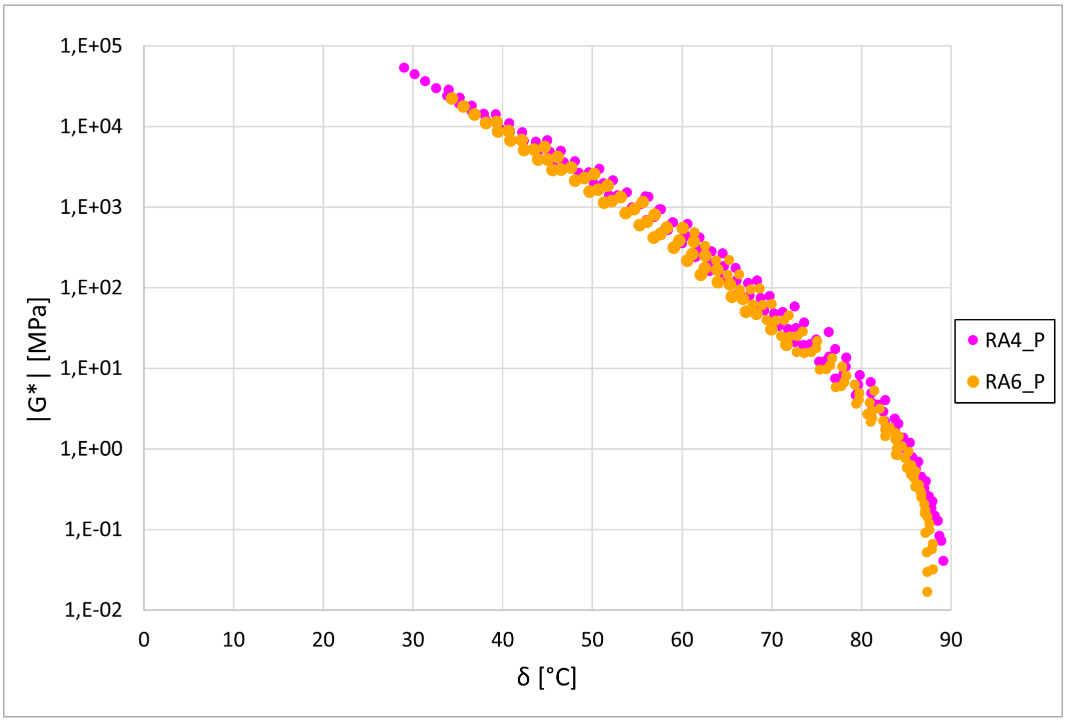


Figure 5.2: Black Diagram of PAV-aged bitumen rejuvenated with RA at 4% and 6%.

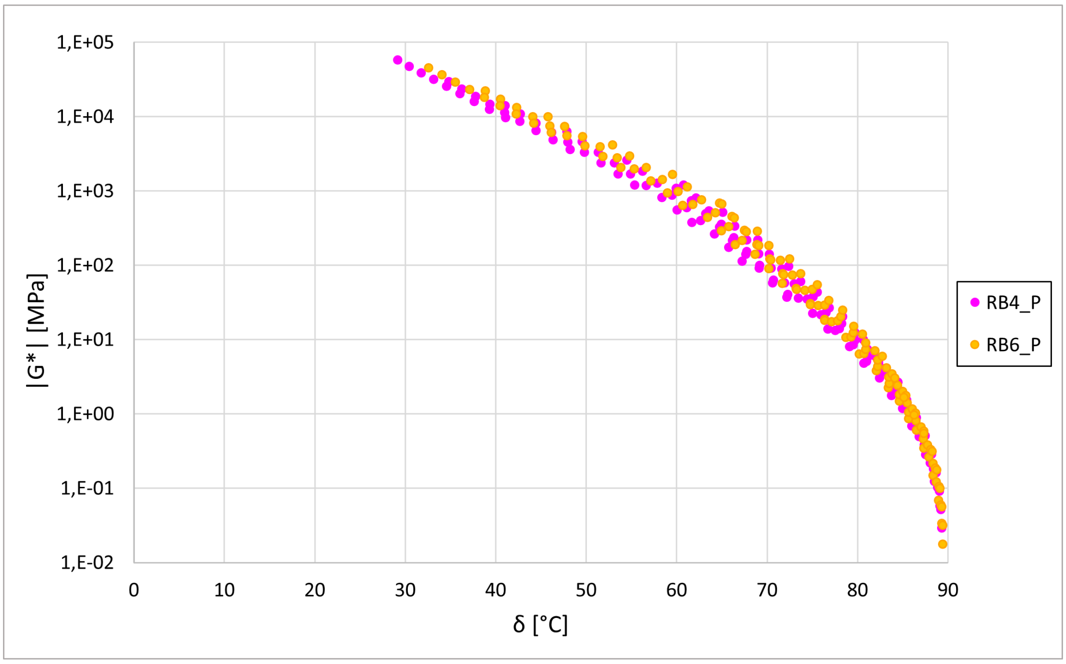


Figure 5.3: Black Diagram of PAV-aged bitumen rejuvenated with RB at 4% and 6%.

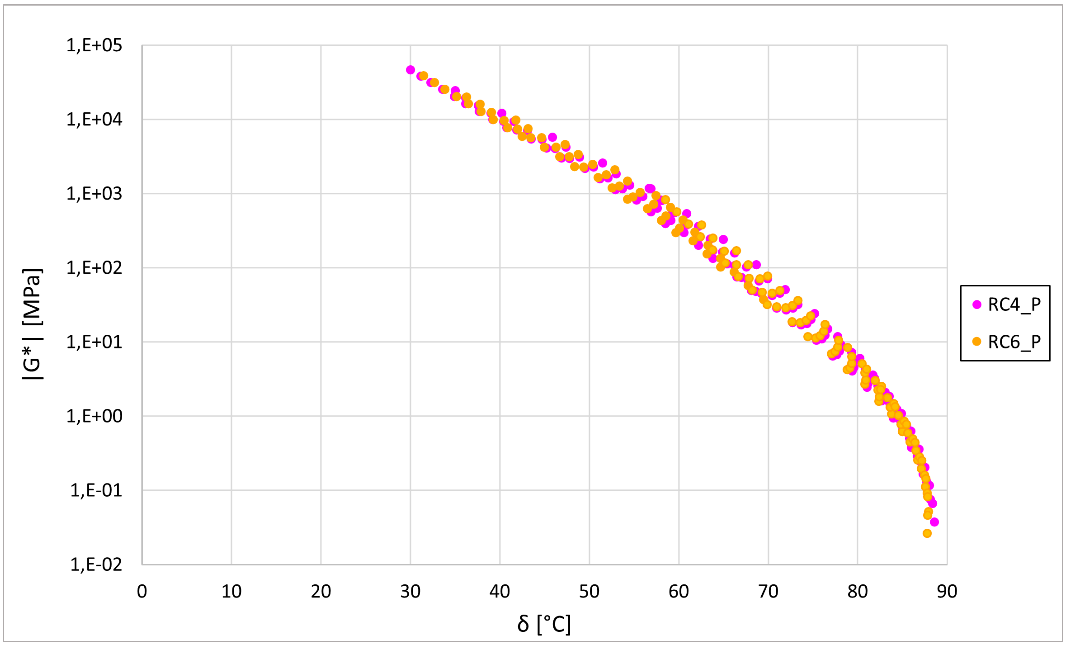


Figure 5.4: Black Diagram of PAV-aged bitumen rejuvenated with RC at 4% and 6%.

As shown in **Figure 5.1**, the comparison between the original bitumen (O, red), the short-term aged binder (R, blue), and the long-term aged binder (P, green) clearly highlights the effect of oxidation. With increasing aging, a progressive increase in $|G*|$ can be observed, indicating higher stiffness, together with a reduction in δ, which reflects the predominance of the elastic over the viscous component. This behavior confirms that the binder, as it undergoes aging, progressively loses its dissipative capacity and becomes more brittle.

Building on this initial evidence, the analysis was extended to rejuvenated binders, with the aim of evaluating the influence of the different additives and their dosage. The graphs report the comparisons between PAV-aged binders treated with three types of rejuvenators (RA, RB, and RC), each applied at two dosages (4% and 6%).

Regarding **RA** (**Figure 5.2**), the effect of dosage appears quite evident. The curve corresponding to 6% (RA6_P, orange) is slightly shifted to the left compared to the 4% curve (RA4_P, pink), indicating a reduction in the phase angle and thus an increase in the elastic component. At the same time, a moderate increase in the complex modulus can be noted, suggesting a stiffer response. It is worth noting, however, that the two curves remain very close in the range between 40° and 70° of δ, suggesting that the additional dosage mainly affects the extreme regions of the viscoelastic behavior.

A different trend is observed with **RB** (**Figure 5.3**). The comparison between RB4_P and RB6_P shows that, at low δ values, the two curves are almost coincident, while at medium-to-high values the 4% sample exhibits higher $|G*|$ and lower δ than the 6%. In this case, therefore, the increase in dosage does not provide any additional benefit and even seems to result in a slight deterioration in performance. This behavior suggests the existence of a threshold beyond which the action of the rejuvenator becomes less effective, possibly due to saturation phenomena or a non-optimal distribution of the additive within the binder matrix.

Finally, **RC** (**Figure 5.4**) stands out for its remarkable stability with respect to dosage variation. The curves corresponding to RC4_P and RC6_P are practically overlapping throughout the entire δ range, indicating that the additive already reaches its full effectiveness at the 4% dosage. In other words, increasing the content from 4% to 6% does not produce any significant variation, highlighting a more linear and predictable behavior compared to the other rejuvenators.

Overall, the analysis of Black Diagrams reveals a clear differentiation among the three additives. RA shows a certain sensitivity to dosage, with moderate but appreciable effects; RB displays a non-linear behavior, with the risk of overdosing; while RC appears to be the most stable and independent of the applied quantity. These results provide useful insights not only into the reactivity of the different rejuvenators but also into their optimal management in practical applications, underlining the importance of carefully calibrating dosage in relation to the characteristics of the base binder and the desired performance targets.

Master curves were constructed from the data obtained through the frequency sweep test. The experimental results, i.e. the direct output of the rheometer, were compared with the modeling performed using the CAM model, already described in Section **4.1.1.1**, in order to provide a continuous and comparable representation of the viscoelastic behavior.

The master curves were developed in four different configurations: the complex modulus (G^*) as a function of the reduced frequency (ω_r), the phase angle (δ) as a function of the reduced frequency (ω_r), and the variations of G^* and δ as a function of the temperature, fixing the reference frequency at 10 rad/s.

Since the aim of the study was to evaluate the effectiveness of RA, RB, and RC, each set of curves was constructed considering all the material combinations under analysis.

So we have a direct comparison between the behavior of the original and aged binders and that of the binders modified with rejuvenators, in order to assess the actual capability of the additives to restore the viscoelastic properties.

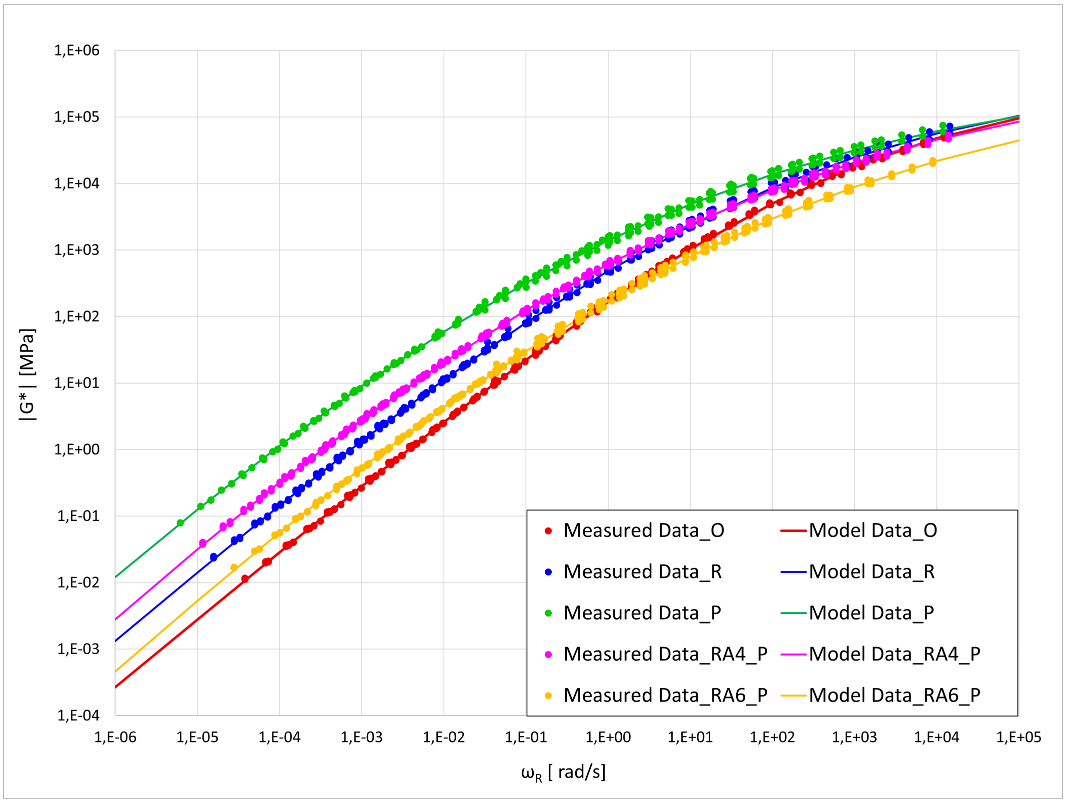


Figure 5.5: Master Curve - Normalized Complex Modulus with RA.

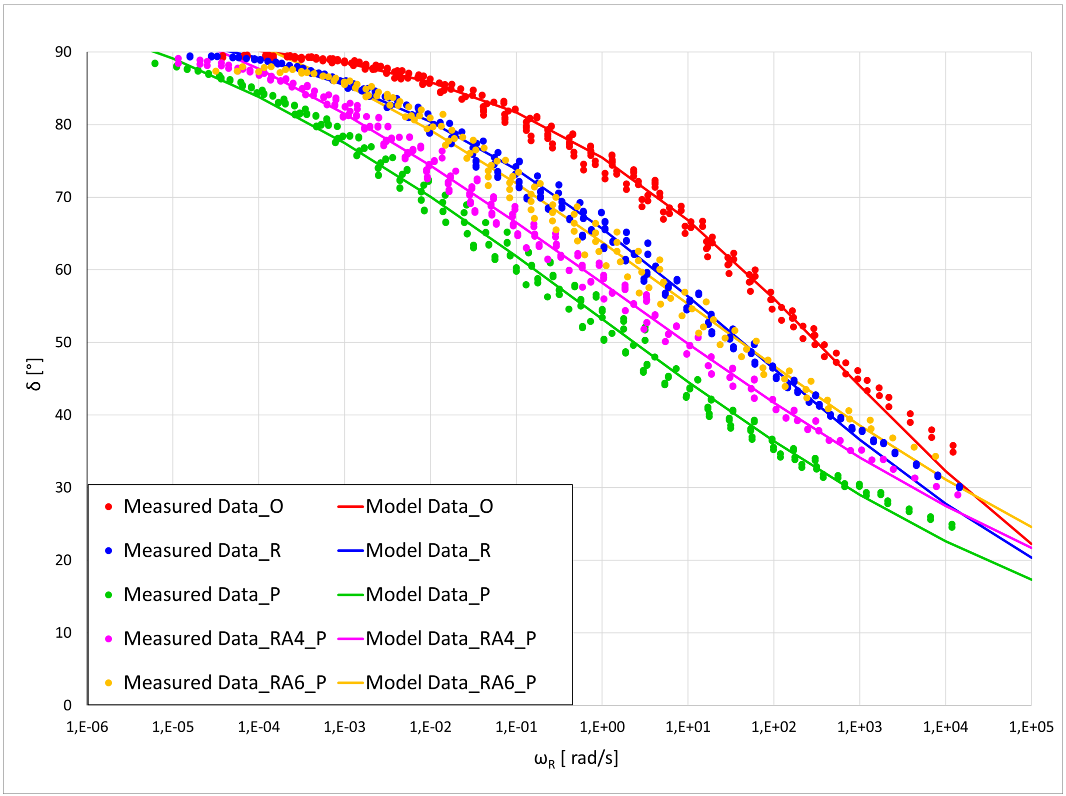


Figure 5.6: Master Curve - Phase Angle with RA.

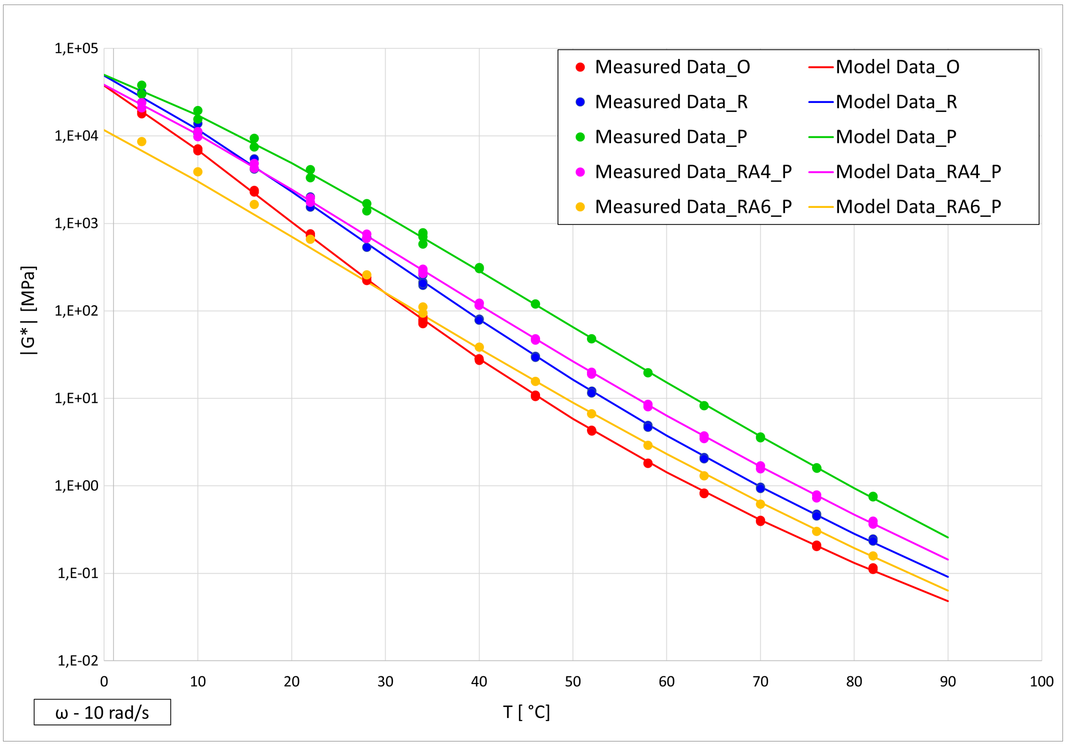


Figure 5.7: Master Curve - Normalized Complex Modulus vs. Temperature with RA.

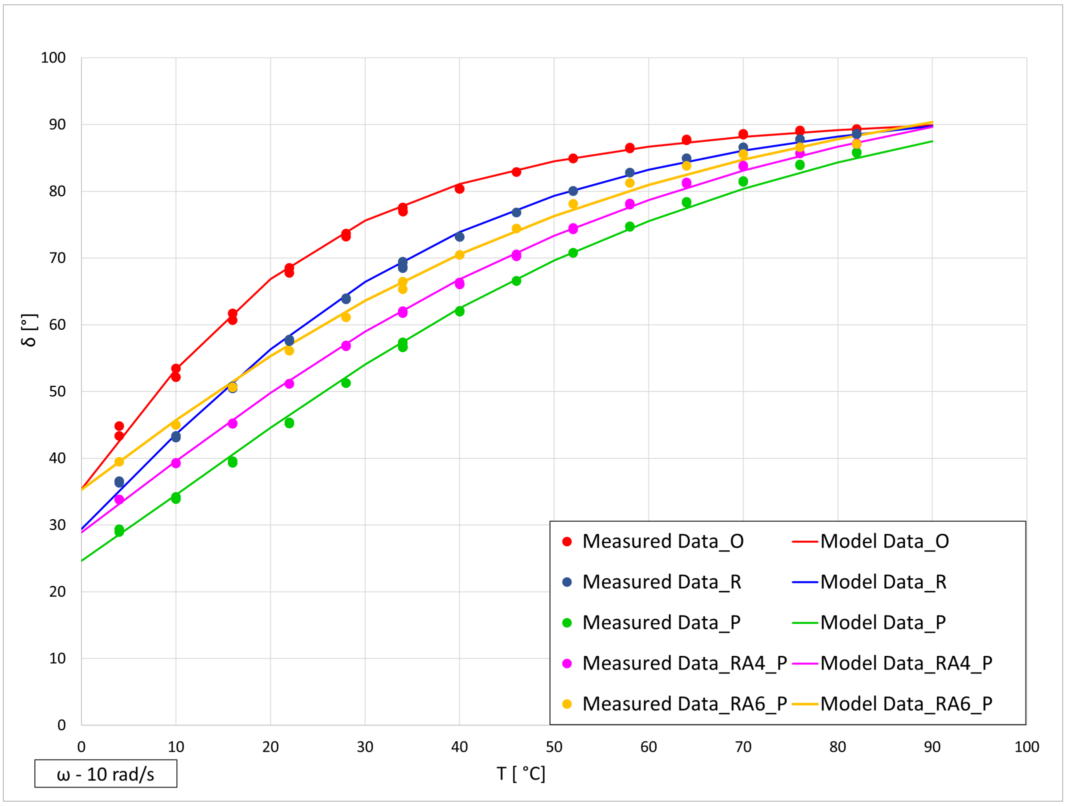


Figure 5.8: Master Curve - Phase Angle vs. Temperature with RA.

Related to **RA**, in the graph of the complex modulus (G^*) (**Figure 5.5**) as a function of the reduced frequency (ω_r), it is possible to observe how the binder behavior changes depending on the aging state and the presence of the rejuvenator. The red curve, corresponding to the original material (O), lies at the lowest values for low reduced frequencies; however, around $\omega_r \approx 1$ rad/s, it intersects with the yellow curve, representing the binder with 6% rejuvenator (RA6_P), thus inverting their relative positions. As expected, the green curve, corresponding to the binder aged with PAV (P), is located at the top, consistent with the higher stiffness induced by long-term aging, while the blue curve, representing the RTFOT-aged material (R), is positioned in between, reflecting the less severe oxidation.

Considering the rejuvenated binders, the pink curve (RA4_P) is located between P and R, indicating a partial recovery of properties with respect to the PAV-aged binder, while the yellow curve (RA6_P) shifts even lower, highlighting a greater rejuvenating effectiveness at higher dosage.

The graph of the phase angle (**Figure 5.6**) is consistent with these observations: the curve of the original binder is the highest, followed by R, while P shows the lowest values. Similarly, the rejuvenated binders progressively move closer to the original binder, with the effect being more pronounced for the 6% dosage.

The second pair of graphs (**Figure 5.7** and **Figure 5.8**), showing the variation of G^* and δ as a function of temperature at a constant frequency (10 rad/s), further confirms these findings. The PAV-aged binder displays significantly higher G^* values, indicating greater rigidity and resistance to deformation, whereas the original binder maintains the lowest values between approximately 30 °C and 90 °C, before intersecting with the RA6_P curve and inverting the relative trend. The observation that the binder rejuvenated with 6% additive appears softer than the virgin binder is consistent with the results reported by Abe et al.,2023 [12]. In that study, under the same dosage conditions, the curve of the PAV-aged binder treated with 6% rejuvenator was observed to lie entirely below that of the virgin binder. The introduction of the rejuvenator results in a progressive reduction of the complex modulus, with a clear distinction between RA4_P and RA6_P: the latter approaches the behavior of the original binder more closely, confirming the higher effectiveness of the increased dosage. At the same time, the phase angle increases, indicating an enhanced viscous component and a reduction of the brittleness induced by aging.

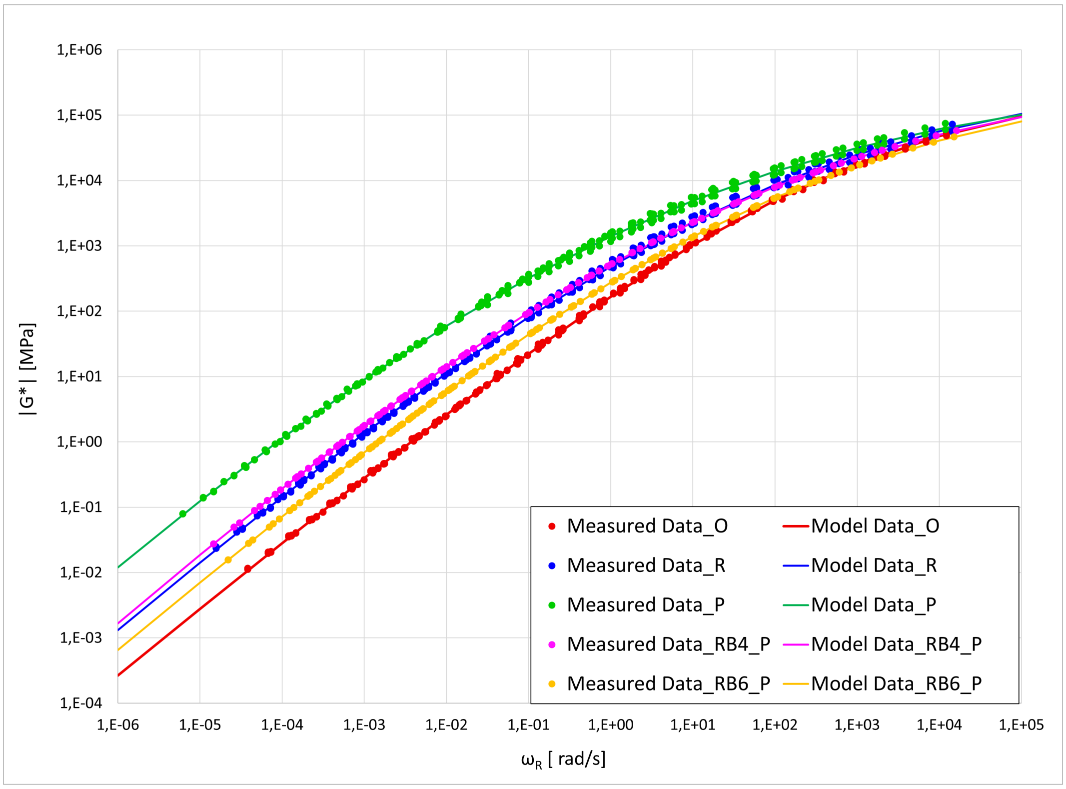


Figure 5.9: Master Curve - Normalized Complex Modulus with RB.

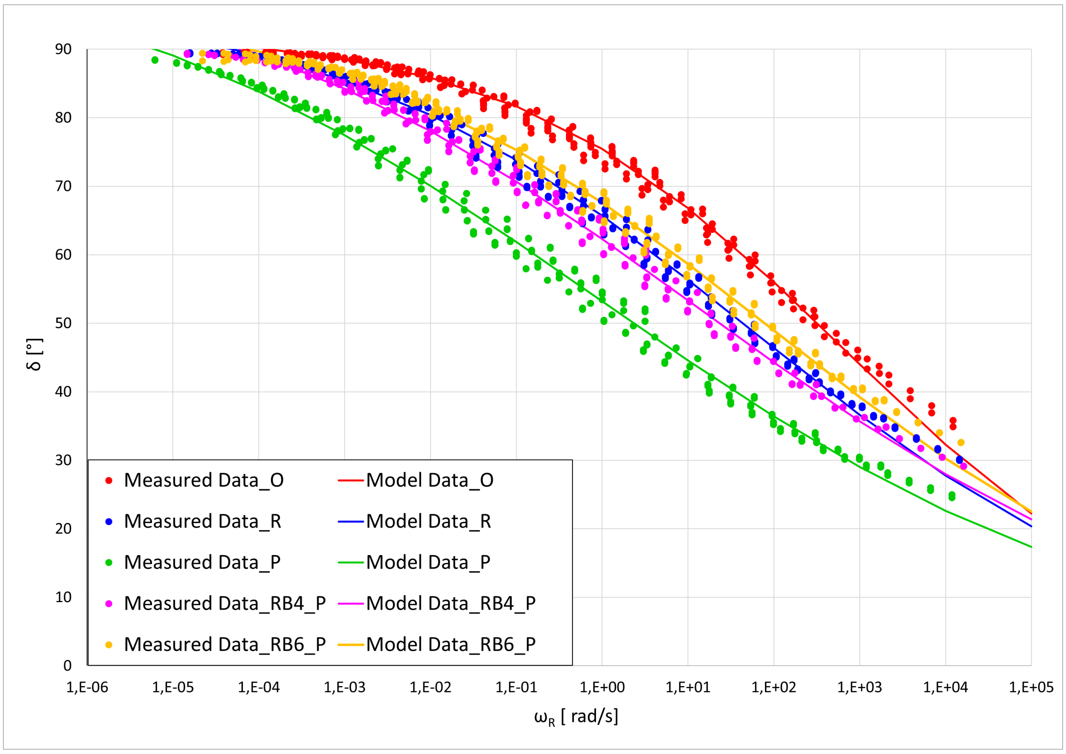


Figure 5.10: Master Curve - Phase Angle with RB.

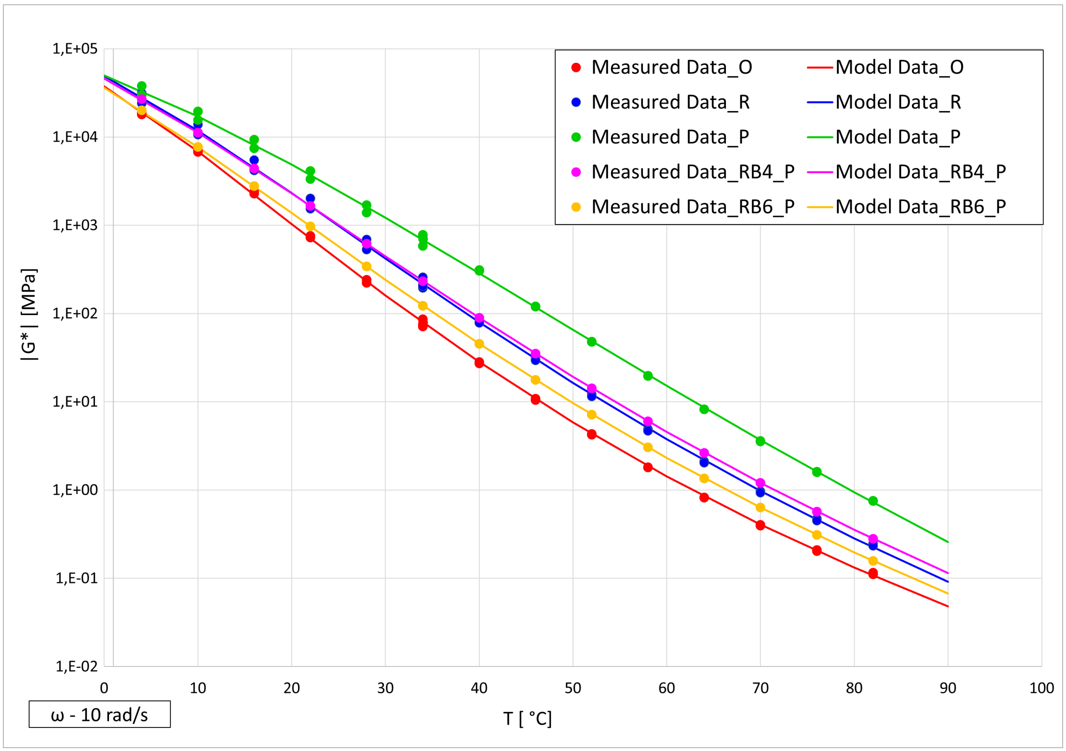


Figure 5.11: Master Curve - Normalized Complex Modulus vs. Temperature with RB.

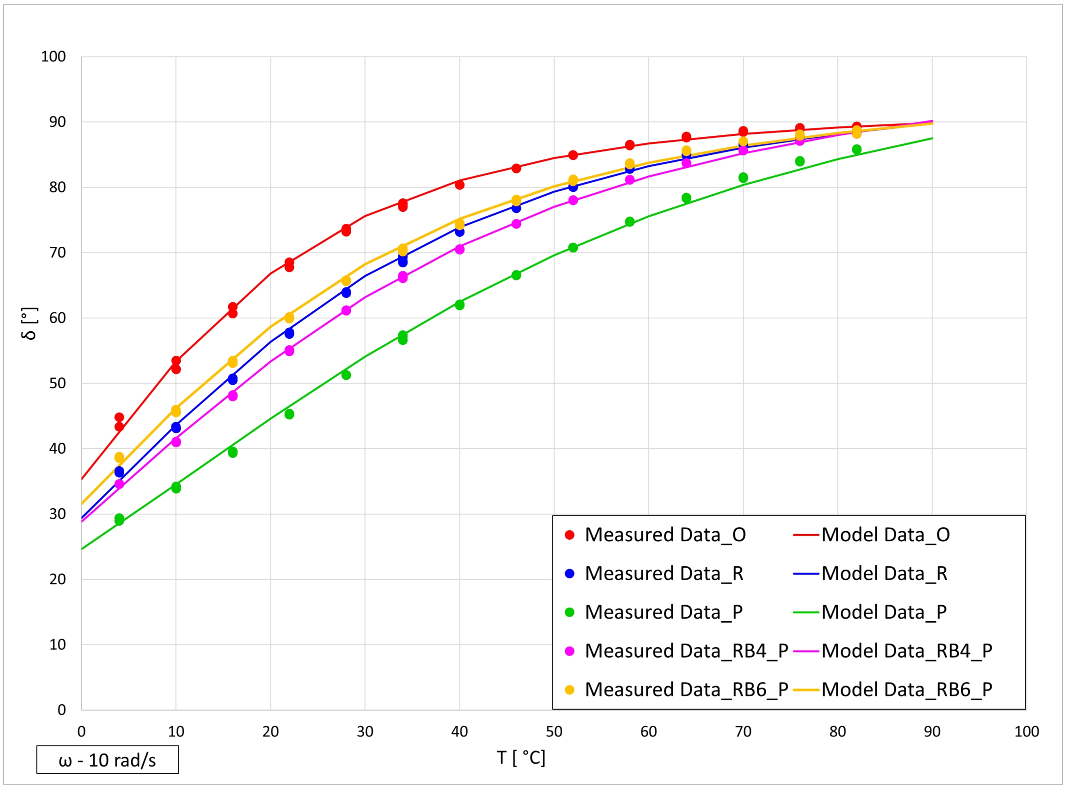


Figure 5.12: Master Curve - Phase Angle vs. Temperature with RB.

Also in the case of **(RB)**, the reference curves – namely those of the original binder (O), the RTFOT-aged binder (R), and the PAV-aged binder (P) – remain the same as those considered for the analysis of RA, and therefore represent the baseline for evaluating the effectiveness of the treatment.

In the graph of the complex modulus (G^*) (**Figure 5.9**) as a function of the reduced frequency, the pink curve (RB4_P) is consistently located between the green curve (P) and the blue curve (R), but it lies closer to the latter, indicating a greater attenuation of the aging effects compared to what was observed for RA4_P. The yellow curve (RB6_P), while maintaining the same relative position already observed for RA6_P, also tends to move closer to the blue curve (R), showing a behavior more similar to the RTFOT-aged binder rather than to the PAV-aged one. The intersection with the red curve (O) occurs only at very high values of ω_r, confirming a partial but not complete recovery of the properties of the original binder.

The graph of the phase angle (δ) (**Figure 5.10**) is consistent with these observations: the yellow curve (RB6_P) shows higher values, approaching those of the blue curve (R), suggesting a stronger viscous component compared to the PAV. Similarly, the pink curve (RB4_P) is positioned in an intermediate location but closer to R, confirming a more pronounced rejuvenating effect than that obtained with RA.

Turning to the graphs describing the variation of G^* and δ as a function of temperature at 10 rad/s (**Figure 5.11** and **Figure 5.12**), it can be seen that the pink curve (RB4_P) approaches the blue curve (R), becoming almost superimposed on it over a wide temperature range, while the yellow curve (RB6_P) is located closer to the red curve (O) compared to what was observed for RA, highlighting greater effectiveness in restoring the mechanical properties. Consistently, the δ values confirm this trend: the increase in the phase angle of the rejuvenated samples, particularly at the 6% dosage, indicates a reduction in brittleness and an enhancement of the viscous component, pointing to a better balance between elastic and viscous responses of the material.

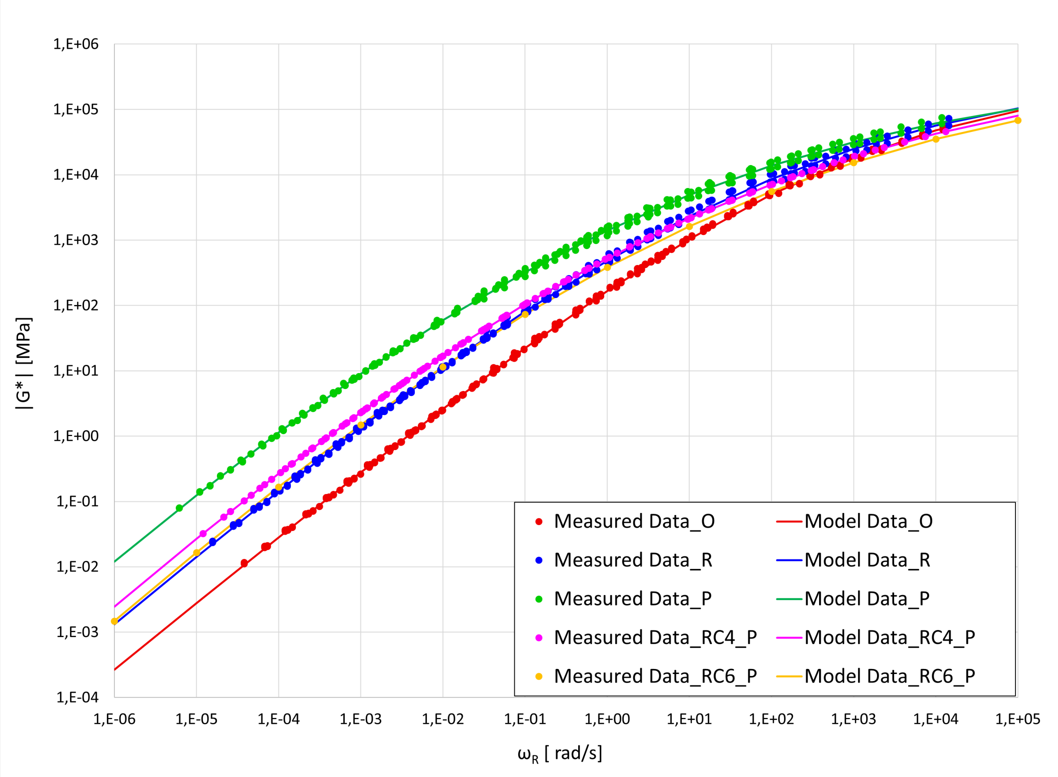


Figure 5.13: Master Curve - Normalized Complex Modulus with RC.

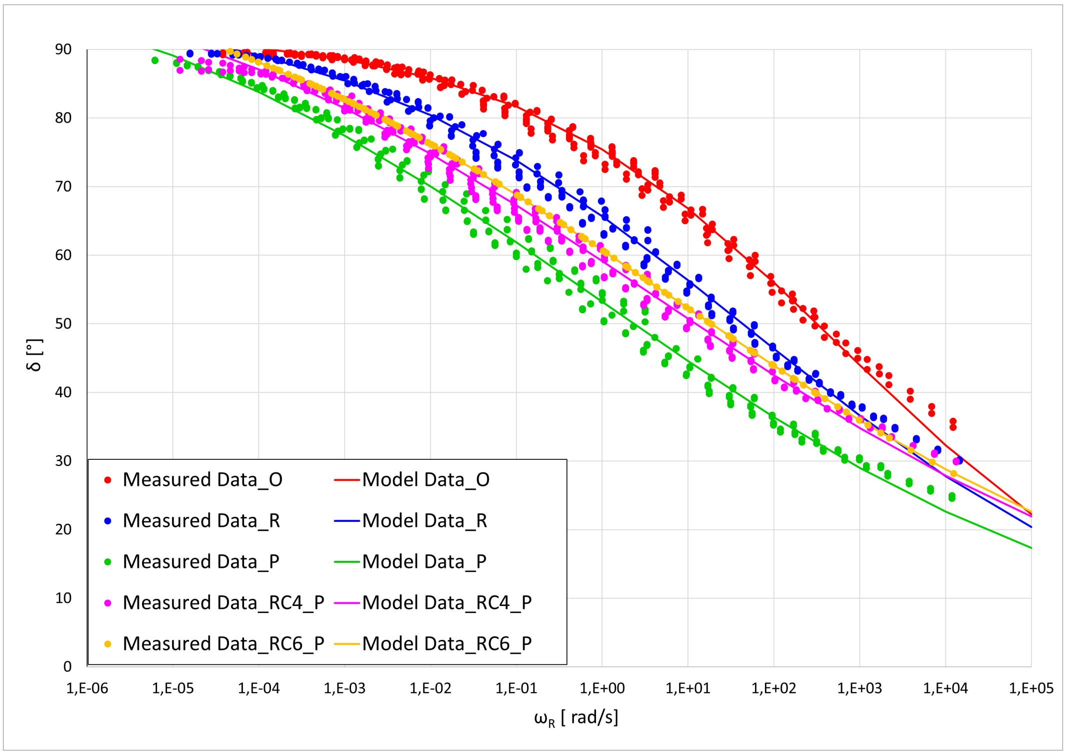


Figure 5.14: Master Curve - Phase Angle with RC.

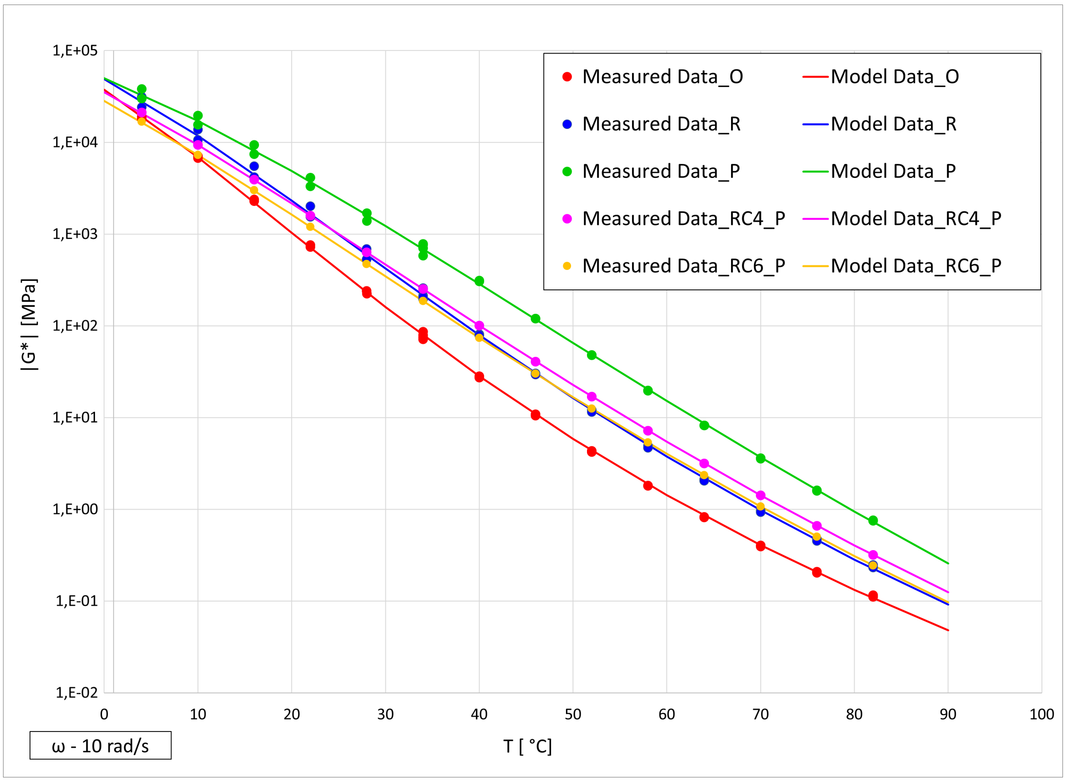


Figure 5.15: Master Curve - Normalized Complex Modulus vs. Temperature with RC.

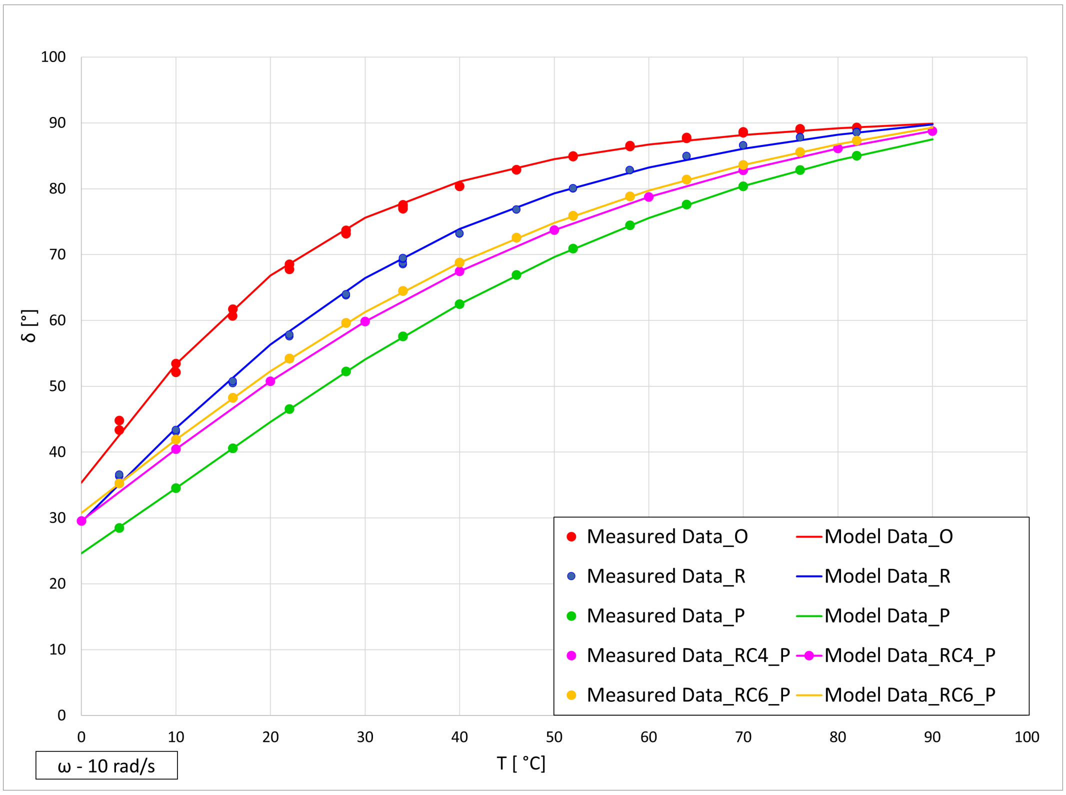


Figure 5.16: Master Curve - Phase Angle vs. Temperature with RC.

Also in the case of **(RC)**, the reference curves remain unchanged and serve as the baseline for evaluating the effectiveness of the treatment.

In the graph of the complex modulus (G^*) (**Figure 5.13**) as a function of the reduced frequency, it can be observed that the yellow curve (RC6_P) largely overlaps with the blue curve (R) at low values of ω_r, showing an almost identical stiffness behavior. The pink curve (RC4_P), on the other hand, behaves similarly to what was observed for RB4_P: it is positioned between P and R but much closer to the blue curve. This indicates that the addition of RC, both at 4% and 6%, tends to reduce the stiffness of the PAV-aged binder to values comparable with those of the RTFOT-aged binder, rather than restoring it to the original material.

The graph of the phase angle (δ) (**Figure 5.14**) confirms these trends. The yellow curve (RC6_P) is very close to the blue curve (R), suggesting a similar viscoelastic response, while the pink curve (RC4_P) also shows an increase in δ, positioning itself in an intermediate range but still closer to the RTFOT-aged binder. Overall, this behavior highlights an increase in the viscous component and a reduction in brittleness compared to the PAV-aged binder.

In the graphs describing the variation of G^* and δ as a function of temperature at 10 rad/s (**Figure 5.15** and **Figure 5.12**), it can be seen that the yellow curve (RC6_P) is almost superimposed on the blue curve (R) over the temperature range between 30 °C and 90 °C, indicating a close similarity with the behavior of the RTFOT-aged binder. The pink curve (RC4_P), while still remaining close to the blue curve, intersects it at one point, thus confirming an intermediate behavior. From the perspective of the complex modulus, both RC dosages reduce stiffness compared to PAV, bringing it closer to R. Regarding the phase angle, the addition of RC leads to an increase in δ, more evident at the 6% dosage, indicating a higher viscous component and a partial mitigation of the long-term aging effects.

To synthesize the results of the master curves, comparative histograms of G^*-CAM and δ-CAM were developed, allowing both a qualitative and quantitative assessment of the rejuvenating effect.

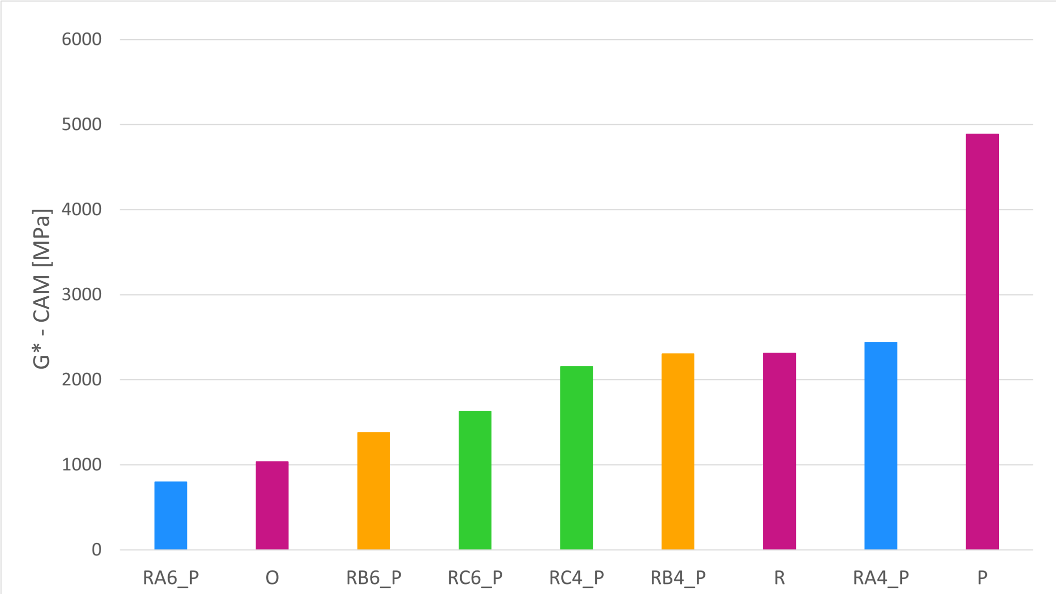


Figure 5.17: (G^*-CAM) values for the different aging conditions and rejuvenated binders.

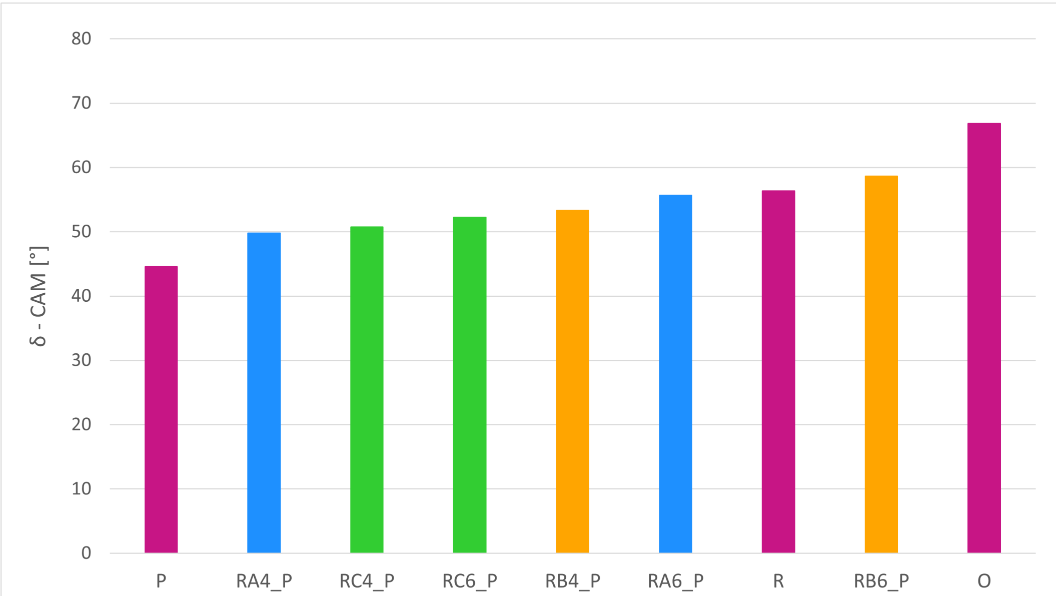


Figure 5.18: (δ-CAM) values for the different aging conditions and rejuvenated binders.

The histogram of the complex modulus (Figure 5.17) confirms the expected hierarchy: the PAV-aged binder (P) shows the highest stiffness, with a G^* value of about **4886 MPa**, whereas the original binder (O) is considerably softer, with **1035 MPa**. The RTFOT-aged binder (R) occupies an intermediate position (**2313 MPa**), and several rejuvenated binders fall close to this reference. Notably, **RB4_P (2302 MPa)** and **RA4_P (2439 MPa)** are practically aligned with R, suggesting that at 4%

dosage both additives reproduce the mechanical condition of a short-term aged binder. **RC4_P (2157 MPa)** also remains in this range, although slightly lower. The effect of increasing dosage is particularly evident for **RC6_P (1631 MPa)** and **RB6_P (1380 MPa)**, which approach the modulus of O and thus display a stronger softening action. A remarkable case is **RA6_P**, which drops to only **796 MPa**, even lower than the original binder. This over-softening indicates that the higher dosage of RA does not simply restore the aged properties, but exceeds them, leading to a binder more deformable than O.

The phase angle results (Figure 5.18) complement this analysis. As expected, P shows the lowest value (**44.6°**), consistent with its brittle and stiff character, while O reaches the maximum (**66.8°**), reflecting the higher viscous contribution. R, with **56.4°**, again represents the intermediate condition. Most rejuvenated binders fall between P and R: **RA4_P (49.8°)**, **RC4_P (50.8°)**, **RC6_P (52.3°)**, and **RB4_P (53.3°)**, indicating only partial recovery of viscous behavior. **RA6_P (55.7°)** is almost coincident with R, confirming the softening capacity of RA though not sufficient to reproduce O. The best performance is observed for **RB6_P (58.7°)**, which moves beyond R and closer to O, representing the most balanced compromise.

Taken together, these results show that **RA and RB at 4% dosages reproduce the RTFOT condition with great accuracy**, whereas higher dosages, particularly RA6_P, may lead to excessive softening. **RB6_P proves the most effective in recovering viscous behavior** without overshooting stiffness, while **RC shows a moderate but consistent action**, less efficient than RA and RB. Overall, RB emerges as the most balanced rejuvenator in terms of restoring binder properties within practical dosage ranges.

5.2 Analysis of Viscosity Test Results

This part focuses on the analysis of experimental results derived from coaxial viscometer testing. For each material analyzed, including samples representing different aging levels (virgin, RTFOT, and PAV) as well as bitumens modified with different rejuvenators and dosages, two full repetitions of the test were performed in order to improve result reliability and assess the repeatability of the experimental procedure.

The two repetitions showed good consistency. To provide a quantitative evaluation, the relative difference between the two datasets was calculated and is reported in **Table 5.1**. In all cases, the values remained below 10%, with the majority of materials exhibiting very limited variations (generally around 1–3%). Only in a few cases, such as RB6_P and RC4_P, slightly higher fluctuations were observed, although still within an acceptable range. These findings confirm the robustness and repeatability of the experimental procedure.

		160			135			100				[°C]
		30	100	300	10	100	300	3	10	100	300	[s^{-1}]
Material	**O**	2.82	2.78	2.95	3.06	3.14	3.12	4.39	4.35	4.59	4.57	
	R	0.51	0.51	0.07	0.46	0.48	0.56	0.77	0.88	0.74	0.79	
	P	1.63	1.54	1.53	1.21	1.86	1.94	1.30	1.46	1.48	0.88	
	RA4_P	4.76	1.38	5.31	3.47	4.44	6.23	0.24	0.35	0.47	0.30	
	RA6_P	1.43	3.30	6.54	3.30	4.36	6.33	0.66	0.74	1.36	1.60	
	RB4_P	0.26	1.26	1.45	0.24	0.21	0.23	0.24	0.06	0.11	0.13	
	RB6_P	7.15	8.26	10.22	4.52	4.42	4.19	6.89	6.84	6.73	6.56	
	RC4_P	6.49	4.82	9.90	3.81	4.63	4.54	7.28	6.80	7.35	7.54	
	RC6_P	3.07	2.86	6.70	6.83	7.72	8.07	3.83	3.99	3.52	2.67	

Table 5.1: Relative difference between repetitions [%].

		160			135			100				[°C]
		30	100	300	10	100	300	3	10	100	300	[s^{-1}]
Material	**O**	142	143	142	414	414	414	3400	3399	3392	3367	
	R	196	196	195	616	616	616	6105	6108	6093	5983	
	P	292	291	289	1034	1030	1030	13722	13700	13500	12876	
	RA4_P	211	207	200	670	666	661	7484	7475	7427	7220	
	RA6_P	167	164	155	521	518	514	5200	5195	5165	5061	
	RB4_P	200	199	189	647	647	646	6721	6714	6706	6572	
	RB6_P	155	152	147	466	462	458	4238	4293	4232	4190	
	RC4_P	209	207	201	684	681	684	7421	7428	7489	7201	
	RC6_P	184	184	180	579	576	579	5949	5960	5918	5769	

Table 5.2: Mean of Dynamic viscosity values [$mPa \cdot s$] – Between Repetition 1 and Repetition 2

After reporting the average values of dynamic viscosity obtained from the two experimental repetitions, the graphical representation of viscosity over time was carried out. Each graph refers to a specific type of rejuvenator (RA, RB, and RC), analyzed at two different dosages (4% and 6%), and compared with the reference binders: original (O), short-term aged (R), and long-term aged (P):

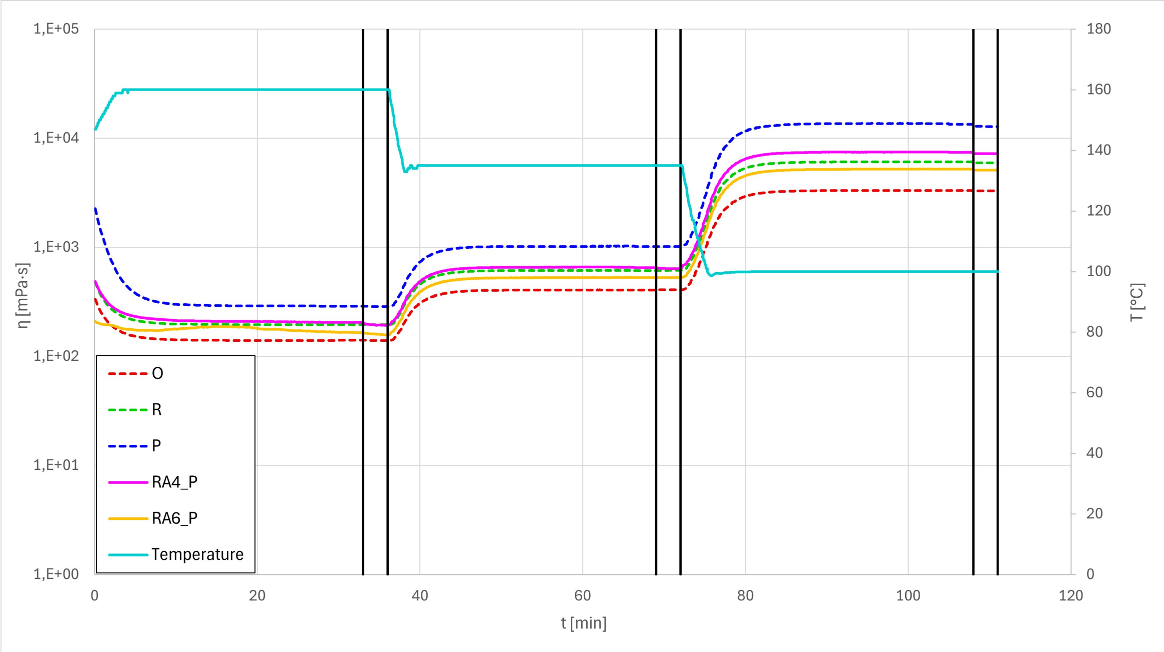


Figure 5.19: Dynamic viscosity over time for bitumen samples modified with rejuvenator RA.

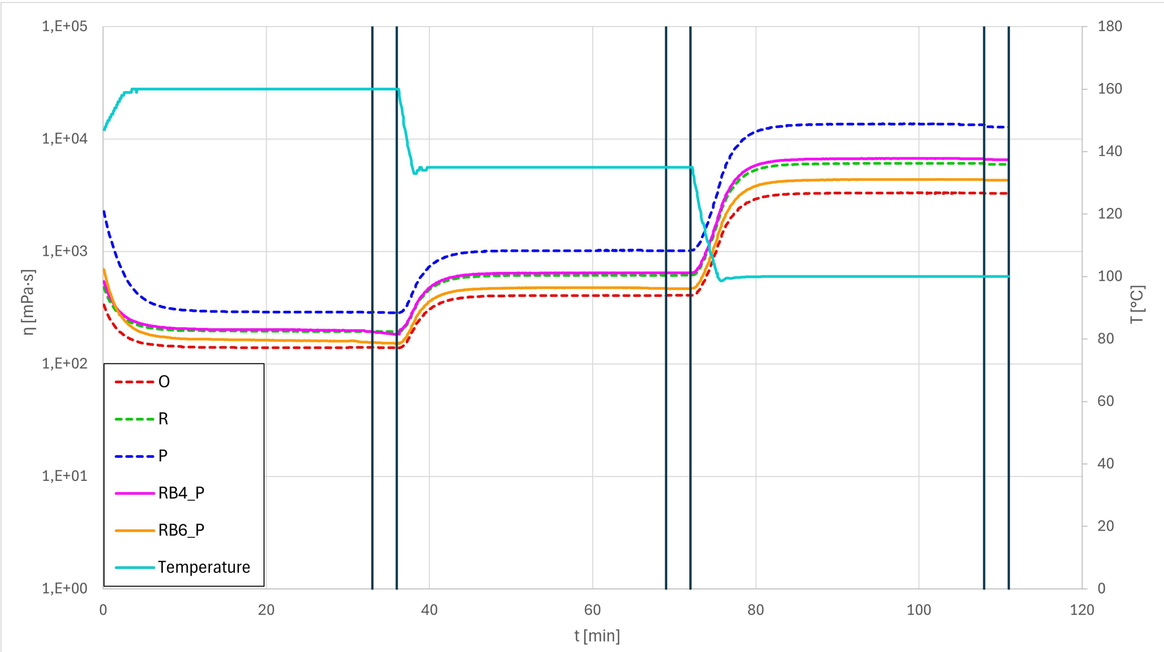


Figure 5.20: Dynamic viscosity over time for bitumen samples modified with rejuvenator RB.

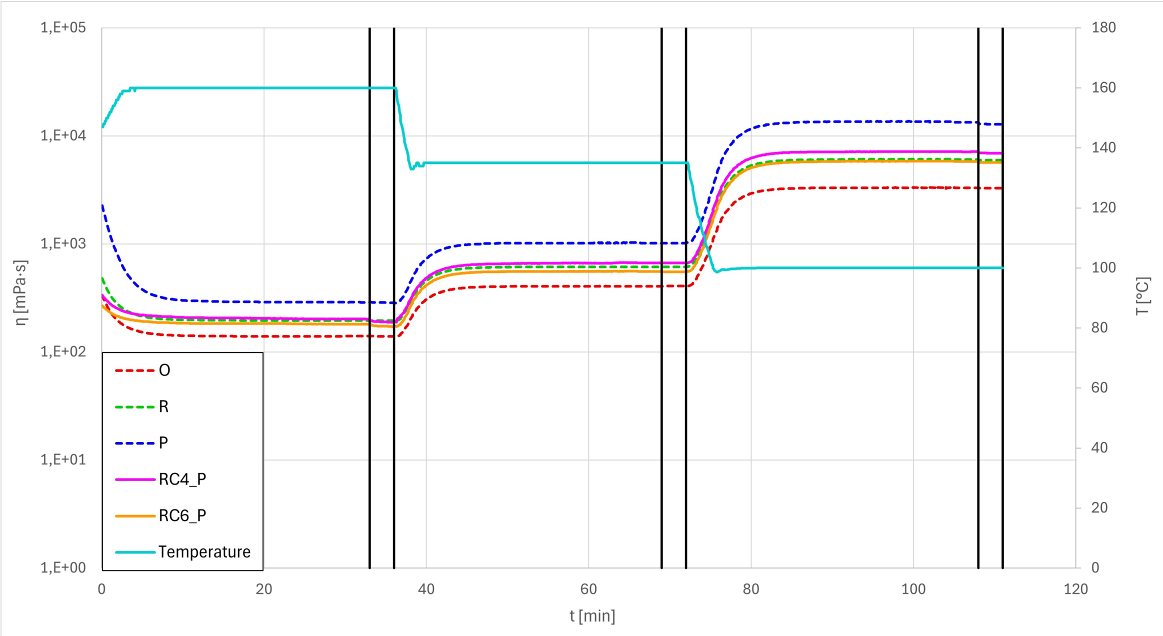


Figure 5.21: Dynamic viscosity over time for bitumen samples modified with rejuvenator RC.

The graphs illustrate the time-dependent behavior of the tested binders' dynamic viscosity (η), expressed in mPa·s and plotted on a logarithmic scale to more effectively highlight the differences among materials. The temperature profile (cyan line), shown on the secondary vertical axis, allows for a direct correlation between viscosity variations and the corresponding thermal changes imposed during the test. The black vertical lines indicate the final three minutes of the test, during which both temperature and shear rate remain stable; this interval was selected for the calculation of average values, assumed to be representative of each binder's steady-state behavior.

The dashed lines represent the reference binders:

- Red: original binder (O);
- Green: short-term aged binder (R);
- Blue: long-term aged binder (P).

Conversely, the continuous lines represent the binders modified with rejuvenator:

- Pink: 4% dosage;
- Yellow: 6% dosage.

In the first graph (**Figure 5.19**), related to the rejuvenator **RA**, it is evident that the addition at 4% (RA4_P) leads to a significant decrease in viscosity compared to the severely aged binder P, placing it between P and R. This indicates that the rejuvenating effect is already visible at a relatively low dosage. When the content is increased to 6% (RA6_P), the curve moves closer to R, suggesting a more advanced recovery of fluidity, although with a potential risk of over-softening if higher dosages are used.

The rejuvenator **RB** (**Figure 5.20**) exhibits a similar behavior but with slightly greater intensity. At 4% (RB4_P), the viscosity nearly reaches the level of the R binder, demonstrating strong regeneration efficiency. At a 6% dosage (RB6_P), the curve approaches the original binder (O), highlighting the ability of RB to significantly reduce viscosity while maintaining mechanical balance. These results suggest that RB is particularly suited for binders with advanced aging.

The rejuvenator **RC** (**Figure 5.21**), on the other hand, displays a more restrained but remarkably stable behavior. Even at a 4% dosage (RC4_P), the viscosity values are already close to R, and the increase to 6% (RC6_P) results in only a modest further reduction. This consistent and controlled response indicates that RC operates in a more conservative manner compared to RA and RB, making it suitable in cases where preserving the original viscoelastic balance is a priority.

Overall, all three rejuvenators demonstrate the ability to restore the fluidity of aged binders, albeit with different degrees of intensity. RA and RB stand out for their more pronounced action, particularly at 4%, which already provides substantial recovery without risk of over-regeneration. RC, by contrast, appears more stable and conservative, ideal for situations that require fine control over mechanical properties.

These observations align with the findings obtained from dynamic rheological tests: RA and RB had already shown superior performance in recovering the viscoelastic behavior of aged binders through the master curves of G^* and δ, confirming their effectiveness from both a viscosimetric and performance-based perspective.

After collecting all the viscometric data, the rheological behavior of the materials was analyzed, with particular focus on the relationship between viscosity and shear rate. At each test temperature, the viscosity values measured across different shear rates showed limited variation, suggesting asubstantial independence of viscosity with respect to shear rate.

To verify this observation more rigorously, the following power-law expression was applied:

$$\eta = K \cdot \dot{\gamma}^{n-1} \tag{5.1}$$

where:

- η is the apparent viscosity ($\mathrm{Pa} \cdot \mathrm{s}$);
- $\dot{\gamma}$ is the shear rate (s^{-1});
- K is the consistency index;
- n is the flow behavior index.

The values of $n-1$ were calculated and, in the Table **??**, the mean of the two repetitions together with their semi-difference is reported for each temperature and across the different shear rates:

Material	160 °C	135 °C	100 °C
O	0.001 ± 0.000	0.000 ± 0.000	-0.001 ± 0.000
R	-0.001 ± 0.001	0.000 ± 0.000	-0.002 ± 0.000
P	-0.004 ± 0.000	-0.001 ± 0.001	-0.008 ± 0.000
RA4_P	-0.022 ± 0.001	-0.002 ± 0.002	-0.004 ± 0.000
RA6_P	-0.031 ± 0.011	-0.002 ± 0.002	-0.004 ± 0.001
RB4_P	-0.023 ± 0.003	0.000 ± 0.000	-0.002 ± 0.000
RB6_P	-0.024 ± 0.007	-0.003 ± 0.000	-0.001 ± 0.000
RC4_P	-0.017 ± 0.007	0.000 ± 0.001	-0.003 ± 0.000
RC6_P	-0.010 ± 0.008	0.000 ± 0.002	-0.004 ± 0.001

Table 5.3: Mean $n-1$ values with standard deviation.

The parameter $n-1$ provides a direct indication of how strongly viscosity depends on shear rate and allows for the classification of the material's rheological behavior:

- When $n-1=0$, viscosity is completely independent of shear rate, and the material exhibits an ideally constant behavior. This condition characterizes *Newtonian fluids*, such as water or light oils, though it is rarely observed in bituminous binders.
- When $n-1<0$, the material shows a *shear-thinning* behavior, in which viscosity decreases as shear rate increases. This is typical of bitumens and complex polymeric materials, where internal structures tend to break down under stress, promoting flow.
- When $n-1>0$, the material displays a *shear-thickening* behavior, where viscosity increases with shear rate. Although uncommon in bituminous binders, this behavior may occur in the presence of unstable dispersions or structures that stiffen under stress.

In the analyzed materials, the calculated values of $n-1$, determined at each temperature and confirmed through two independent replicates, were consistently negative but close to zero. This confirms a slightly shear-thinning behavior, with a modest dependence of viscosity on shear rate, which becomes even less significant at higher temperatures. As such, this dependence was considered negligible for comparative purposes.

In light of these considerations, a common shear rate value of 300 s^{-1} was selected for the direct comparison of viscosity across the tested materials. This approach simplifies the analysis while remaining consistent with both the experimental observations and the numerical interpretation derived from the applied rheological model.

Table 5.4 reports the mean dynamic viscosity values [mPa · s] obtained at 300 s^{-1}, considering only the final stabilized condition of each test. The data represent the average between the two experimental repetitions carried out for each material at three reference temperatures: 160 °C, 135 °C, and 100 °C.

Material	160 °C	135 °C	100 °C
O	142	414	3392
R	195	616	6093
P	289	1030	13500
RA4_P	200	666	7427
RA6_P	155	518	5165
RB4_P	189	647	6702
RB6_P	147	462	4232
RC4_P	201	684	7409
RC6_P	180	579	5918

Table 5.4: Dynamic viscosity values at 300 s^{-1} [mPa · s] – Mean of two repetitions.

Based on these values, the following graph shows the viscosity distribution for all materials at the same reference temperatures. Vertical lines are used to highlight the spread between binders at each temperature, emphasizing the differences in their rheological response.

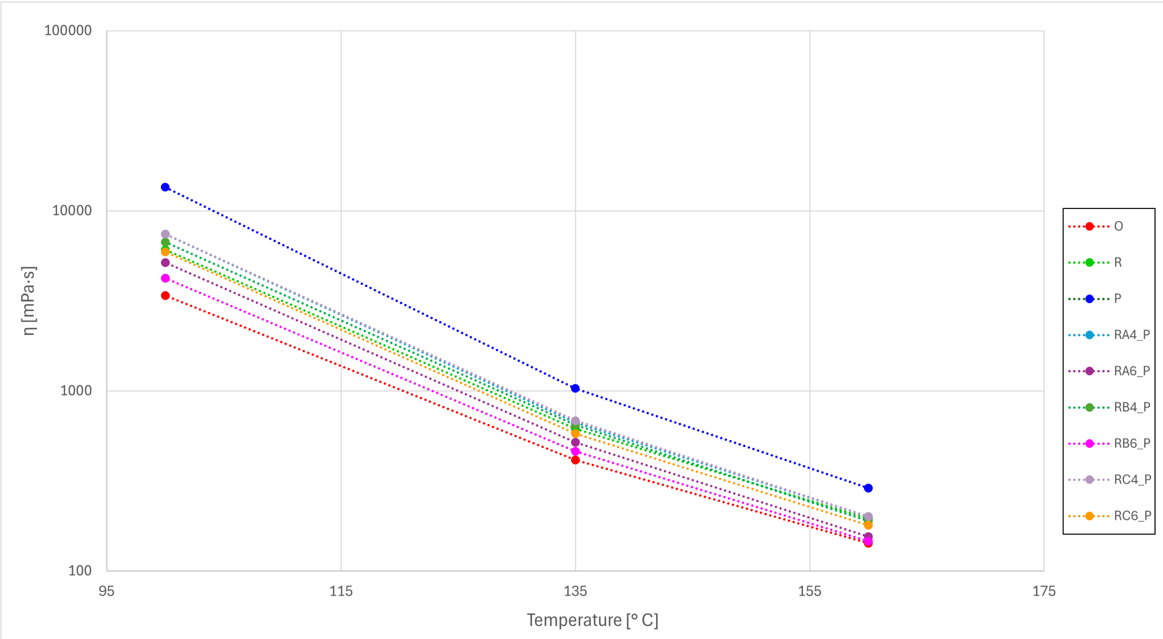


Figure 5.22: Viscosity spread between materials at fixed temperature.

Based on the previously discussed results, an additional analysis was carried out to investigate the relative viscosity behavior of the tested materials. Specifically, the logarithmic ratio between the viscosity of each binder and that of the long-term aged binder (P) was computed, in order to quantify the deviation from the reference condition. This method provides a normalized measure of viscosity variation and offers a direct evaluation of the effectiveness of each rejuvenating treatment.

This approach is particularly relevant since all the rejuvenated binders were formulated by modifying the aged binder P with different types and dosages of rejuvenators. As such, evaluating the deviation from P allows for a direct assessment of how much each treatment was able to reduce the viscosity and improve the flowability of the aged binder.

Table 5.5 presents the calculated values of $\log_{10}(\eta/\eta_P)$ for each material at three reference temperatures: 160 °C, 135 °C, and 100 °C. As expected, the P binder exhibits a value of zero in all cases, while all other binders show negative values, indicating lower viscosity (i.e., higher fluidity) compared to P.

Notably, the differences become more pronounced as the temperature decreases. At 100 °C, the original binder (O) shows a deviation of −0.60, which corresponds to a viscosity approximately one quarter that of P. The binder RB6_P also displays a significant reduction (−0.50), while RA4_P and RC4_P exhibit values of −0.26, indicating a viscosity that is closer to the aged binder.

At higher temperatures (160 °C), the deviations are generally smaller. The maximum deviation is observed again in binder O (−0.31), while the majority of the rejuvenated binders range between −0.16 and −0.30. This trend confirms that at elevated temperatures, the natural softening of bitumen reduces the differences between binders, and the influence of rejuvenators becomes less pronounced.

Material	**160 °C**	**135 °C**	**100 °C**
O	-0.31	-0.40	-0.60
R	-0.17	-0.22	-0.35
P	0.00	0.00	0.00
RA4_P	-0.16	-0.19	-0.26
RA6_P	-0.27	-0.30	-0.42
RB4_P	-0.18	-0.20	-0.30
RB6_P	-0.30	-0.35	-0.50
RC4_P	-0.16	-0.18	-0.26
RC6_P	-0.21	-0.25	-0.36

Table 5.5: Logarithmic viscosity ratio $\log_{10}(\eta/\eta_P)$ at 300 s^{-1}.

To provide a clearer overview of the viscosity test results, a comparative histogram was constructed using viscosity values measured at 135 °C and at a constant shear rate of 300 s^{-1}. This condition was selected as representative, since the relative trends among the binders were consistent across the other tested temperatures.

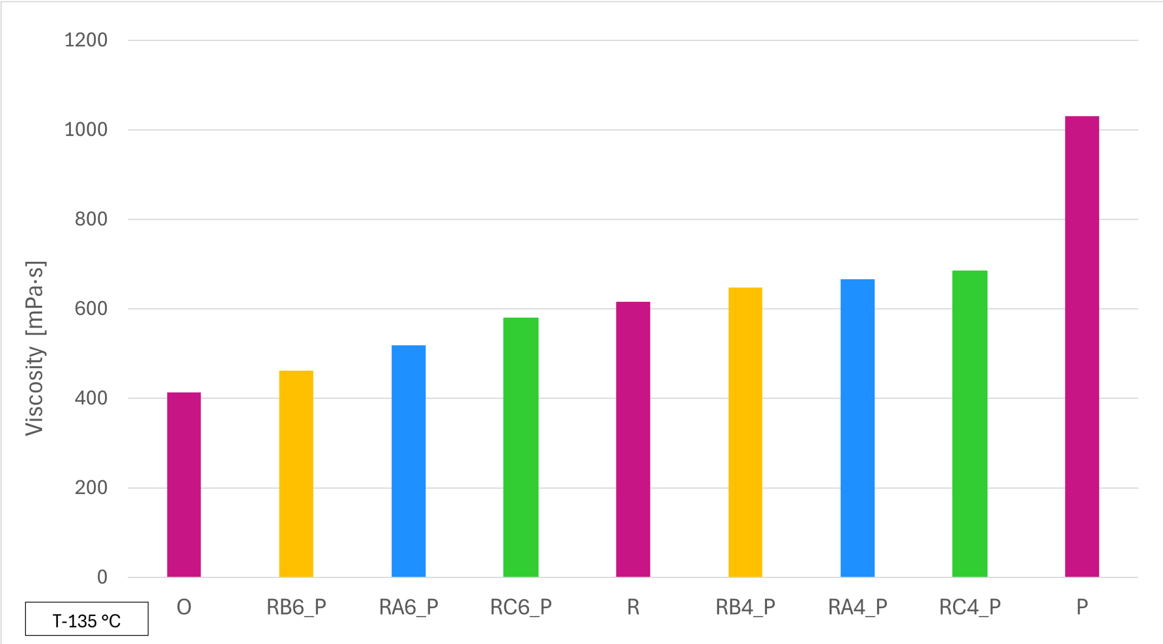


Figure 5.23: Viscosity values for the different aging conditions and rejuvenated binders.

From the comparison it is evident that the original binder (O) shows the lowest viscosity value (414 mPa·s), while the long-term aged binder (P) reaches the highest value (1030 mPa·s), confirming the pronounced hardening effect induced by oxidation. The short-term aged binder (R, RTFOT) is positioned at an intermediate level (616 mPa·s), as expected for a less severe aging condition.

The rejuvenated binders display a behavior consistent with what was previously observed in the viscosity curves. The binders treated with a 6% dosage (RB6_P, 462 mPa·s; RA6_P, 518 mPa·s; RC6_P, 579 mPa·s) are positioned close to the original binder, thus indicating an effective recovery of fluidity. The corresponding samples with a 4% dosage (RB4_P, 647 mPa·s; RA4_P, 666 mPa·s; RC4_P, 684 mPa·s) are instead closer to the R binder, showing a noticeable but less pronounced rejuvenating effect compared to the higher dosage.

Overall, the histogram confirms the general trend: the original binder maintains the highest fluidity, the PAV binder represents the stiffest condition, and the rejuvenated binders lie in between, with a clear improvement at increasing dosages. Among the three additives, RB at 6% appears the closest to the original binder, while RA and RC provide a more moderate yet stable recovery.

5.3 Determination of Optimal Rejuvenator Dosage

The initial dosages of RA, RB, and RC were set at 4% and 6%, with the aim of evaluating the effectiveness of the treatment in restoring the rheological properties of the aged binder. Beyond the direct comparison of the results at these two fixed dosages, a further analysis was carried out in order to estimate the optimal dosage required to match the target values of the reference binders, namely the original binder (O) and the RTFOT-aged binder (R).

This procedure was applied both to the frequency sweep test results (through the complex modulus G^* and the phase angle δ) and to the viscosity data, thereby providing a more comprehensive evaluation of the rejuvenating effect. The general approach consisted in calculating, for each treated material, the position of the sample relative to the reference binders within the rheological framework defined by the O–R–P system. In this way, it was possible to quantify the rejuvenating action independently of the specific test performed.

To determine the exact dosage, the results obtained at 4% and 6% were interpolated using the following formula:

$$\%\text{opt} = \%_1 + \left(\frac{X_1 - X_{O/R}}{X_1 - X_2} \right) \cdot (\%_2 - \%_1) \tag{5.2}$$

where:

- %opt is the optimal rejuvenator dosage to be calculated;
- %1 and %2 are the two tested dosages (e.g., 4% and 6%);
- X_1 and X_2 are the average rheological parameters (e.g., η, G^*, or δ) at dosages %1 and %2;
- $X_{O/R}$ is the target value corresponding to the reference binder, either the original (O) or the RTFOT-aged binder (R).

This generalized formulation made it possible to identify, for each rejuvenator, the optimal dosage capable of restoring the binder properties to levels comparable with those of the selected references:

Rejuvenator	**Dosage for O** [%]	**Dosage for R** [%]	Δ **Dosage** [%]
RA	5.7	4.2	27
RB	6.7	4.0	41
RC	8.3	3.4	59

Table 5.6: Optimal dosages (%) of each rejuvenator to match the **complex modulus** of reference binders O and R.

Rejuvenator	**Dosage for O** [%]	**Dosage for R** [%]	Δ **Dosage** [%]
RA	9.8	6.2	37
RB	9.1	5.1	43
RC	25.2	11.4	55

Table 5.7: Optimal dosages (%) of each rejuvenator to match the **phase angle** of reference binders O and R.

Rejuvenator	**Dosage for O** [%]	**Dosage for R** [%]	Δ **Dosage** [%]
RA	7.5	5.0	33
RB	6.4	4.4	31
RC	11.0	6.0	45

Table 5.8: Optimal dosages (%) of each rejuvenator to match the **viscosity** of reference binders O and R.

The evaluation of the optimal dosages of the three rejuvenators, carried out with reference to the complex modulus, phase angle, and viscosity, highlights both common trends and significant differences among the products. Considering first the complex modulus, RA emerges as the most balanced solution, since both the RTFOT-aged and the original binder can be matched with dosages (4.2% and 5.7%) that fall well within or close to the investigated range. RB, although effective in reproducing the RTFOT-aged condition with 4.0%, requires slightly higher amounts to reach the modulus of the original binder (6.7%), thus proving less versatile than RA. RC, on the other hand, shows the least favorable behavior: while the dosage to match the RTFOT-aged binder (3.4%) falls below the tested interval, the recovery of the original binder requires 8.3%, far beyond the practical experimental range. Interestingly, these values align with the findings of J. Wang et al.,2024 [19], where sunflower oil was tested between 2% and 8%, thus falling within the optimal range identified here.

A similar trend can be observed for the phase angle, though with more pronounced differences. RA shows an appreciable effect, with values of 6.2% and 9.8% required for RTFOT and original binders respectively, yet these lie outside or above the experimental window, indicating only partial recovery within the tested dosages. RB confirms its reliability, since 5.1% is sufficient to match the aged binder, although restoring the original binder would require 9.1%, beyond the tested conditions. RC again appears the least effective, with very high dosages (11.3% and 25.1%) needed to reproduce R and O, values that highlight its limited applicability in practical terms.

Finally, viscosity analysis further consolidates this hierarchy. RA and RB both show good alignment with the experimental dosages: RA requires 5.0% to reproduce R and 7.5% for O, while RB requires 4.4% and 6.4% respectively, thus confirming RB as the closest to optimal within the tested range. RC, in contrast, can reproduce the aged binder with 6.0% but needs as much as 11.0% for the original condition, underscoring once again its lower efficiency compared with RA and RB.

An interesting aspect that emerged from the analysis of the optimal dosages, obtained by considering the complex modulus, the phase angle, and the viscosity, is that the increase required to shift from the RTFOT-aged binder to the original binder is approximately constant for each rejuvenating agent. Specifically, this increase is around 30% for RA, 40% for RB, and 50% for RC, confirming a consistent behavior regardless of the rheological parameter considered.

Moreover, it is worth noting that the optimal dosage values identified through viscosity lie in an intermediate position between those obtained from the complex modulus and the phase angle. This suggests that viscosity can represent a reliable and balanced parameter to be considered when defining the most appropriate rejuvenator dosage.

Chapter 6

Conclusion

This thesis aimed at the rheological characterization of an aged bituminous binder subsequently treated with three non-petroleum based rejuvenating agents (RA, RB, and RC). The study was carried out on a 70/100 penetration grade binder, subjected to standardized short-term (RTFOT) and long-term (PAV) aging to simulate in-service conditions, and subsequently blended with the selected rejuvenators at 4% and 6% by weight.

The experimental program combined oscillatory shear tests with the Dynamic Shear Rheometer, from which master curves of complex modulus and phase angle were obtained, with dynamic viscosity measurements performed through a coaxial viscometer to evaluate binder workability at typical production and laying temperatures. This dual approach enabled an integrated interpretation of the results and allowed a direct comparison of the different "rheological fingerprints" imparted by each rejuvenator.

The outcomes highlighted clear differences in performance:

- **RA** exhibited the highest rejuvenating efficiency, restoring the rheological properties of the aged binder to values close to those of the virgin binder. However, at higher dosages it led to *over-softening*, reflected in an excessive reduction of stiffness and increased thermal susceptibility, requiring careful control of the applied percentages.
- **RB** demonstrated the strongest sensitivity to dosage, with coherent and measurable variations in complex modulus (G^*) and phase angle (δ). These shifts enabled a gradual recovery towards both the virgin and the RTFOT-aged binders, making RB particularly suitable for dosage calibration.
- **RC** provided only partial recovery, positioning the binder in an intermediate condition. Comparable effects with respect to the commercial rejuvenators were achieved only at significantly higher dosages, reducing its competitiveness from both a technical and economic perspective.

Overall, the results confirmed that commercial rejuvenators specifically developed for bituminous applications are more effective than the non-conventional agent, which, despite its non-petroleum origin and potential sustainability interest, showed limited efficiency and required elevated percentages to approach similar performance levels.

Moreover, the comparative analysis revealed that even among commercial products the response to dosage variation is not uniform: while RA induced more pronounced rheological shifts, RB allowed for more controlled adjustments of G^* and δ.

Finally, by integrating the results of DSR and viscosity tests, it was possible to identify an **optimal dosage**, defined at intermediate frequencies and temperatures for the complex modulus and at typical mixing temperatures for viscosity, capable of balancing binder workability with adequate mechanical performance.

Bibliography

[1] Mayank Sukhija and Erdem Coleri. “A systematic review on the role of reclaimed asphalt pavement materials: Insights into performance and sustainability”. In: *Cleaner Materials* 16 (2025). Open access under CC BY-NC-ND license, p. 100316. ISSN: 2772-3976. DOI: 10.1016/j.clema.2025.100316. URL: https://www.sciencedirect.com/science/article/pii/S2772397625000255 (cit. on pp. 4, 5).

[2] Rebecca S. McDaniel and Randy M. Anderson. *Reclaimed Asphalt Pavement – A Literature Review*. Technical Report FHWA-ICT-07-001. This report provides a comprehensive literature review on the use, performance, and challenges of reclaimed asphalt pavement (RAP) in new pavement construction. Washington, D.C.: Federal Highway Administration (FHWA), Oct. 2007. URL: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/07001/07001.pdf (cit. on p. 4).

[3] Taher Baghaee Moghaddam and Hassan Baaj. “The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review”. In: *Construction and Building Materials* 114 (2016), pp. 805–816. ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2016.04.015. URL: https://www.sciencedirect.com/science/article/pii/S0950061816305499 (cit. on pp. 4, 5, 7).

[4] Leonardo Urbano. “The role of additives in the rejuvenation of Reclaimed Asphalt: Tools, modelling and perspectives”. Doctoral Program in Civil and Environmental Engineering (34th Cycle). Ph.D. thesis. Torino, Italy: Politecnico di Torino, 2022. URL: https://www.polito.it (cit. on p. 6).

[5] Ahmed Abouelsaad, Greg White, and Ali Jamshidi. “State of the Art Review of Ageing of Bituminous Binders and Asphalt Mixtures: Ageing Simulation Techniques, Ageing Inhibitors and the Relationship between Simulated Ageing and Field Ageing”. In: *Infrastructures* 9.1 (2024). ISSN: 2412-3811. DOI: 10.3390/infrastructures9010008. URL: https://www.mdpi.com/2412-3811/9/1/8 (cit. on pp. 7, 8).

[6] Johannes Mirwald, Stefan Werkovits, Ingrid Camargo, Daniel Maschauer, Bernhard Hofko, and Hinrich Grothe. “Investigating bitumen long-term-ageing in the laboratory by spectroscopic analysis of the SARA fractions”. In: *Construction and Building Materials* 258 (2020), p. 119577. ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119577. URL: https://www.sciencedirect.com/science/article/pii/S0950061820315828 (cit. on pp. 8, 9).

[7] Dongdong Ge, Siyu Chen, Zhanping You, Xu Yang, Hui Yao, Mingxiao Ye, and Yoke Khin Yap. “Correlation of DSR Results and FTIR’s Carbonyl and Sulfoxide Indexes: Effect of Aging Temperature on Asphalt Rheology”. In:

Journal of Materials in Civil Engineering 31.7 (2019), p. 04019115. DOI: 10.1061/(ASCE)MT.1943-5533.0002781. eprint: https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29MT.1943-5533.0002781. URL: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29MT.1943-5533.0002781 (cit. on pp. 9, 10).

[8] Katarzyna Pstrowska, Volodymyr Gunka, Iurii Sidun, Yuriy Demchuk, Nataliya Vytrykush, Marek Kułażyński, and Michael Bratychak. "Adhesion in Bitumen/Aggregate System: Adhesion Mechanism and Test Methods". In: *Coatings* 12.12 (2022), p. 1934. DOI: 10.3390/coatings12121934. URL: https://doi.org/10.3390/coatings12121934 (cit. on pp. 11, 12).

[9] Ahmed Abouelsaad and Greg White. "Review of Asphalt Mixture Ravelling Mechanisms, Causes and Testing". In: *International Journal of Pavement Research and Technology* 15.6 (2022), pp. 1448–1462. DOI: 10.1007/s42947-021-00100-7. URL: https://doi.org/10.1007/s42947-021-00100-7 (cit. on p. 11).

[10] Shashwath Sreedhar and Erdem Coleri. "The effect of long-term aging on fatigue cracking resistance of asphalt mixtures". In: *International Journal of Pavement Engineering* Published online (2020). DOI: 10.1080/10298436.2020.1745206. URL: https://doi.org/10.1080/10298436.2020.1745206 (cit. on pp. 12, 13).

[11] Bhupendra Singh and Praveen Kumar. "Rutting and Fatigue Performance of Aged Modified Asphalt Binders". In: *International Journal of Pavement Research and Technology* 14.6 (2021), pp. 725–740. DOI: 10.1007/s42947-021-00053-x. URL: https://doi.org/10.1007/s42947-021-00053-x (cit. on pp. 12, 13).

[12] Abraham A. Abe, Paolino Caputo, Shahin Eskandarsefat, Valeria Loise, Michele Porto, Eugenia Giorno, Loretta Venturini, and Cesare Oliviero Rossi. "Rejuvenating Agents vs. Fluxing Agents: Their Respective Mechanisms of Action on Bitumen Subjected to Multiple Aging Cycles". In: *Applied Sciences* 13.2 (2023). ISSN: 2076-3417. DOI: 10.3390/app13020698. URL: https://www.mdpi.com/2076-3417/13/2/698 (cit. on pp. 14–17, 19, 54).

[13] ANAS S.p.A. *Capitolato Speciale d'Appalto – Lavori stradali*. https://www.stradeanas.it. Comune di Rocca di Papa (RM), Progetto definitivo per la realizzazione di due rotatorie sulla SP 18/C. 2020 (cit. on p. 14).

[14] Valeria Loise, Paolino Caputo, Michele Porto, Pietro Calandra, Ruggero Angelico, and Cesare Oliviero Rossi. "A Review on Bitumen Rejuvenation: Mechanisms, Materials, Methods and Perspectives". In: *Applied Sciences* 9.20 (2019). Review article, p. 4316. DOI: 10.3390/app9204316. URL: https://www.mdpi.com/2076-3417/9/20/4316 (cit. on pp. 15, 16).

[15] Sadman Sakib Arafat, Misgana Aboye Weldegiorgis, Ishtiaque Ahmed, and Eshan V. Dave. "Rheological and performance evaluation of bio-based rejuvenators on highly aged asphalt binders and mixtures". In: *Construction and Building Materials* 373 (2023), p. 130829. ISSN: 0950-0618. DOI: 10.1016/j.conbuildmat.2023.130829. URL: https://doi.org/10.1016/j.conbuildmat.2023.130829 (cit. on pp. 19–23).

[16] Martins Zaumanis, Rajib B. Mallick, Lily Poulikakos, and Robert Frank. "Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures". In: *Construction and Building Materials* 71 (2014), pp. 538–550. DOI: 10.1016/j.conbuildmat.2014.08.073. URL: https://doi.org/10.1016/j.conbuildmat.2014.08.073 (cit. on pp. 20–23).

[17] Abdullah Al Mamun, H. I. Al-Abdul Wahhab, and M. A. Dalhat. "Comparative Evaluation of Waste Cooking Oil and Waste Engine Oil Rejuvenated Asphalt Concrete Mixtures". In: *Arabian Journal for Science and Engineering* 45.11 (2020). Open Access article licensed under CC BY 4.0, pp. 7987–7997. ISSN: 2191-4281. DOI: 10.1007/s13369-020-04523-5. URL: https://doi.org/10.1007/s13369-020-04523-5 (cit. on p. 23).

[18] Conglin Chen, Jinbo Lu, Tao Ma, Yang Zhang, Linhao Gu, and Xiang Chen. "Applications of vegetable oils and their derivatives as Bio-Additives for use in asphalt binders: A review". In: *Construction and Building Materials* 383 (2023), p. 131312. DOI: 10.1016/j.conbuildmat.2023.131312. URL: https://doi.org/10.1016/j.conbuildmat.2023.131312 (cit. on p. 24).

[19] Jintao Wang, Shi Xu, Sifan Zhu, Qin Tian, Xinkui Yang, Georgios Pipintakos, Shisong Ren, and Shaopeng Wu. "The Rejuvenation Effect of Bio-Oils on Long-Term Aged Asphalt". In: *Materials* 17.13 (2024), p. 3316. DOI: 10.3390/ma17133316. URL: https://doi.org/10.3390/ma17133316 (cit. on pp. 24, 25, 72).

[20] Saannibe Ciryle Somé, Alexandre Pavoine, and Emmanuel Chailleux. "Evaluation of the Potential Use of Waste Sunflower and Rapeseed Oils-Modified Natural Bitumen as Binders for Asphalt Pavement Design". In: *International Journal of Pavement Research and Technology* 9.5 (2016), pp. 368–375. DOI: 10.1016/j.ijprt.2016.09.001. URL: https://doi.org/10.1016/j.ijprt.2016.09.001 (cit. on pp. 25, 26).

[21] Politecnico di Torino. *Lecture notes from Construction of Transportation Infrastructures.* A.Y. 2023–2024, Master's Degree in Civil Engineering, Politecnico di Torino. 2024 (cit. on pp. 27, 36, 37).

[22] British Standards Institution (BSI). *BS EN 12607-1:2014 - Bitumen and Bituminous Binders — Determination of the Resistance to Hardening under Influence of Heat and Air - Part 1: RTFOT Method.* Standard. London, UK, 2014. URL: https://www.bsigroup.com (cit. on p. 29).

[23] British Standards Institution (BSI). *BS EN 14769:2023 - Bitumen and Bituminous Binders — Accelerated Long-Term Ageing Conditioning by a Pressure Ageing Vessel (PAV).* Standard. London, UK, 2023. URL: https://www.bsigroup.com (cit. on p. 30).

[24] American Association of State Highway and Transportation Officials. *Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV).* AASHTO Designation: R 28-22. Technically Revised 2022. Technical Subcommittee 2b, Liquid Asphalt. 555 12th Street NW, Suite 1000, Washington, D.C. 20004, 2022 (cit. on p. 31).

[25] AASHTO. *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).* Standard Test Method T 315-22. Washington, D.C.: American Association of State Highway and Transportation Officials, 2022 (cit. on pp. 41, 42, 44).

[26] British Standards Institution. *BS EN 13702-2:2003 — Bitumen and bituminous binders – Determination of dynamic viscosity of modified bitumen – Part 2: Coaxial cylinders method*. https://www.bsigroup.com. Identical with IP 514-2004. London, UK, 2003 (cit. on p. 45).

Appendix A

This appendix reports the results of the two repetitions of the dynamic viscosity measurements at different temperatures and shear rates, as well as the corresponding first and second repetitions of the calculated $n-1$ values.

		160			**135**			**100**				**[°C]**
		30	100	300	10	100	300	3	10	100	300	[s^{-1}]
Material	O	140	141	140	407	407	408	3325	3325	3290	3314	
	R	195	195	195	615	614	615	6081	6081	5959	6070	
	P	289	289	287	1028	1021	1020	13633	13600	12819	13400	
	RA4_P	206	206	195	658	652	640	7493	7488	7231	7445	
	RA6_P	168	166	160	530	530	530	5217	5214	5101	5200	
	RB4_P	200	198	188	646	647	646	6729	6706	6577	6706	
	RB6_P	160	158	154	476	472	468	4384	4383	4327	4375	
	RC4_P	202	202	191	671	668	666	7150	7175	6930	7137	
	RC6_P	181	181	174	559	556	553	5836	5841	5692	5814	

Table 1: Dynamic viscosity values [mPa · s] – Repetition 1

		160			**135**			**100**				**[°C]**
		30	100	300	10	100	300	3	10	100	300	[s^{-1}]
Material	O	144	145	144	420	421	421	3474	3474	3440	3444	
	R	196	196	195	618	617	618	6128	6135	6115	6007	
	P	294	293	291	1040	1030	1040	13811	13900	13560	12831	
	RA4_P	216	209	206	682	681	681	7475	7410	7410	7209	
	RA6_P	166	161	159	514	510	510	5200	5136	5060	5011	
	RB4_P	200	194	188	646	645	648	6690	6690	6660	6568	
	RB6_P	149	146	144	490	482	480	4299	4303	4275	4239	
	RC4_P	216	216	211	697	690	702	7483	7481	7411	7405	
	RC6_P	187	186	186	599	601	600	6063	6070	6023	5846	

Table 2: Dynamic viscosity values [mPa · s] – Repetition 2

Material	160 °C	135 °C	100 °C
O	0.001	-0.336	-0.157
R	0.000	-0.362	-0.169
P	-0.003	-0.402	-0.188
RA4_P	-0.023	-0.380	-0.203
RA6_P	-0.020	-0.374	-0.176
RB4_P	-0.025	-0.386	-0.174
RB6_P	-0.017	-0.367	-0.167
RC4_P	-0.025	-0.393	-0.186
RC6_P	-0.017	-0.366	-0.172

Table 3: $n - 1$ values – Repetition 1

Material	160 °C	135 °C	100 °C
O	0.001	-0.336	-0.157
R	0.000	-0.363	-0.169
P	-0.004	-0.409	-0.187
RA4_P	-0.024	-0.379	-0.200
RA6_P	-0.020	-0.383	-0.178
RB4_P	-0.026	-0.389	-0.180
RB6_P	-0.016	-0.369	-0.165
RC4_P	-0.020	-0.377	-0.175
RC6_P	-0.002	-0.369	-0.171

Table 4: $n - 1$ values – Repetition 2

Appendix B

This appendix presents the test reports of the frequency sweep and viscosity test carried out with the DSR.

The reference code that is used in this research is defined as 3.1./3.1.X.Y./Z:

- 3.1 = Task 3.1 from PRIN project
- X = Material type, non-petroleum based rejuvenator;
- Y = Experimental test
  - 1 = Complex Modulus and Phase Angle;
  - 2 = Viscosity test;
- Z= Number of report.

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/1

Temperatu [°C]	Angular Freq. [rad/s]	Complex Mo [kPa]	Phase Angle [°]
34	1,00	11,229	81,820
34	1,78	18,882	80,731
34	3,16	31,543	79,582
34	5,62	52,300	78,445
34	10,00	86,134	77,292
34	17,78	140,826	76,091
34	31,62	228,532	74,815
34	56,23	367,787	73,406
34	100,00	587,167	71,844
28	1,00	33,65	78,45
28	1,78	55,70	77,38
28	3,16	91,46	76,21
28	5,62	149,01	74,99
28	10,00	240,51	73,66
28	17,78	384,80	72,19
28	31,62	609,87	70,58
28	56,23	955,93	68,79
28	100,00	1481,43	66,71
22	1,00	117,93	74,56
22	1,78	190,85	73,30
22	3,16	305,67	71,85
22	5,62	484,40	70,28
22	10,00	759,06	68,54
22	17,78	1174,80	66,63
22	31,62	1793,06	64,55
22	56,23	2698,06	62,32
22	100,00	4001,19	60,00
16	1,00	431,13	69,71
16	1,78	676,43	67,98
16	3,16	1046,29	66,01
16	5,62	1593,94	63,93
16	10,00	2392,09	61,70
16	17,78	3534,39	59,36
16	31,62	5128,70	56,93
16	56,23	7307,88	54,37
16	100,00	10333,50	51,90
10	1,00	1558,70	63,12
10	1,78	2338,07	60,83
10	3,16	3446,30	58,39
10	5,62	4987,48	55,94
10	10,00	7096,28	53,46
10	17,78	9921,24	50,99
10	31,62	13657,80	48,54
10	56,23	18502,10	46,13
10	100,00	24670,30	43,77

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
4	1,00	5238,66	54,82
4	1,78	7432,79	52,26
4	3,16	10348,90	49,69
4	5,62	14145,20	47,21
4	10,00	19010,20	44,81
4	17,78	25166,10	42,46
4	31,62	32813,50	40,19
4	56,23	42166,70	37,98
4	100,00	53417,30	35,83

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/2

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	10,403	81,331	4	1,00	5179,99	53,07
34	1,78	17,442	80,329	4	1,78	7262,29	50,55
34	3,16	29,057	79,222	4	3,16	9991,23	48,04
34	5,62	48,088	78,112	4	5,62	13499,80	45,66
34	10,00	79,024	76,970	4	10,00	17949,30	43,36
34	17,78	128,947	75,763	4	17,78	23518,60	41,15
34	31,62	208,801	74,431	4	31,62	30388,70	39,01
34	56,23	335,557	72,914	4	56,23	38728,40	36,94
34	100,00	535,159	71,382	4	100,00	48707,50	34,91
28	1,00	31,58	77,79				
28	1,78	52,11	76,81				
28	3,16	85,35	75,69				
28	5,62	138,66	74,49				
28	10,00	223,27	73,18				
28	17,78	356,14	71,72				
28	31,62	562,48	70,06				
28	56,23	879,34	68,19				
28	100,00	1360,60	66,01				
22	1,00	114,71	73,76				
22	1,78	184,75	72,53				
22	3,16	294,41	71,09				
22	5,62	464,16	69,51				
22	10,00	723,91	67,77				
22	17,78	1114,56	65,84				
22	31,62	1692,20	63,73				
22	56,23	2533,62	61,47				
22	100,00	3737,95	59,12				
16	1,00	422,29	68,72				
16	1,78	657,63	66,99				
16	3,16	1010,66	65,02				
16	5,62	1530,40	62,93				
16	10,00	2282,45	60,69				
16	17,78	3350,56	58,33				
16	31,62	4829,96	55,90				
16	56,23	6838,21	53,35				
16	100,00	9597,82	50,95				
10	1,00	1533,16	61,81				
10	1,78	2281,73	59,51				
10	3,16	3336,55	57,06				
10	5,62	4788,74	54,60				
10	10,00	6754,48	52,13				
10	17,78	9362,12	49,70				
10	31,62	12780,80	47,31				
10	56,23	17177,40	44,97				
10	100,00	22738,80	42,70				

Politecnico di Torino   Finanziato dall'Unione europea NextGenerationEU   MUR   Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	**Strumento:**	MCR 302	**Aging:**	Original
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/3

Temperature [°C]	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	100,00	491,615	72,365	64	100,00	7,47	84,78
34	56,23	307,441	73,806	64	56,23	4,33	85,58
34	31,62	190,505	75,142	64	31,62	2,49	86,30
34	17,78	117,155	76,387	64	17,78	1,43	87,01
34	10,00	71,509	77,562	64	10,00	0,82	87,63
34	5,62	43,344	78,700	64	5,62	0,46	88,13
34	3,16	26,100	79,819	64	3,16	0,26	88,52
34	1,78	15,610	80,920	64	1,78	0,15	88,79
34	1,00	9,274	82,001	64	1,00	0,08	88,97
40	100,00	201,49	75,83	70	100,00	3,702	85,541
40	56,23	123,54	77,06	70	56,23	2,130	86,724
40	31,62	75,21	78,21	70	31,62	1,218	87,426
40	17,78	45,43	79,31	70	17,78	0,694	88,001
40	10,00	27,25	80,38	70	10,00	0,394	88,481
40	5,62	16,22	81,44	70	5,62	0,223	88,809
40	3,16	9,59	82,48	70	3,16	0,126	89,027
40	1,78	5,63	83,48	70	1,78	0,071	89,136
40	1,00	3,28	84,44	70	1,00	0,040	89,201
46	100,00	83,33	78,75	76	100,00	1,952	86,873
46	56,23	50,17	79,84	76	56,23	1,116	87,439
46	31,62	29,99	80,88	76	31,62	0,634	88,208
46	17,78	17,80	81,90	76	17,78	0,359	88,751
46	10,00	10,50	82,89	76	10,00	0,203	88,978
46	5,62	6,15	83,83	76	5,62	0,114	89,243
46	3,16	3,58	84,72	76	3,16	0,065	89,346
46	1,78	2,08	85,55	76	1,78	0,036	89,364
46	1,00	1,20	86,31	76	1,00	0,020	89,359
52	100,00	35,52	81,12	82	100,00	1,082	86,431
52	56,23	21,06	82,16	82	56,23	0,616	87,600
52	31,62	12,40	83,14	82	31,62	0,349	88,476
52	17,78	7,26	84,05	82	17,78	0,197	88,914
52	10,00	4,23	84,90	82	10,00	0,111	89,238
52	5,62	2,44	85,68	82	5,62	0,062	89,323
52	3,16	1,41	86,40	82	3,16	0,035	89,317
52	1,78	0,81	87,06	82	1,78	0,020	89,310
52	1,00	0,46	87,65	82	1,00	0,011	89,252
58	100,00	15,89	82,97				
58	56,23	9,31	84,04				
58	31,62	5,42	84,93				
58	17,78	3,14	85,71				
58	10,00	1,81	86,40				
58	5,62	1,04	87,05				
58	3,16	0,59	87,63				
58	1,78	0,34	88,12				
58	1,00	0,19	88,51				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	**Strumento:**	MCR 302	**Aging:**	Original
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/4

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	512,793	72,076	64	100,00	7,55	84,76
34	56,23	321,384	73,558	64	56,23	4,37	85,56
34	31,62	199,669	74,973	64	31,62	2,52	86,32
34	17,78	122,987	76,263	64	17,78	1,44	87,09
34	10,00	75,172	77,484	64	10,00	0,82	87,78
34	5,62	45,618	78,664	64	5,62	0,47	88,34
34	3,16	27,488	79,826	64	3,16	0,27	88,78
34	1,78	16,437	80,974	64	1,78	0,15	89,09
34	1,00	9,761	82,097	64	1,00	0,08	89,29
40	100,00	210,38	75,72	70	100,00	3,814	85,534
40	56,23	128,78	76,95	70	56,23	2,194	86,700
40	31,62	78,25	78,12	70	31,62	1,255	87,439
40	17,78	47,22	79,25	70	17,78	0,714	88,075
40	10,00	28,31	80,36	70	10,00	0,405	88,621
40	5,62	16,86	81,45	70	5,62	0,229	88,999
40	3,16	9,98	82,52	70	3,16	0,129	89,268
40	1,78	5,86	83,54	70	1,78	0,073	89,408
40	1,00	3,42	84,52	70	1,00	0,041	89,496
46	100,00	86,20	78,65	76	100,00	2,018	86,777
46	56,23	51,94	79,76	76	56,23	1,153	87,152
46	31,62	31,06	80,83	76	31,62	0,656	88,120
46	17,78	18,44	81,87	76	17,78	0,371	88,825
46	10,00	10,86	82,89	76	10,00	0,210	89,109
46	5,62	6,36	83,88	76	5,62	0,118	89,359
46	3,16	3,70	84,81	76	3,16	0,067	89,503
46	1,78	2,15	85,69	76	1,78	0,037	89,547
46	1,00	1,24	86,51	76	1,00	0,021	89,587
52	100,00	36,21	80,95	82	100,00	1,128	87,307
52	56,23	21,48	82,05	82	56,23	0,644	87,778
52	31,62	12,67	83,09	82	31,62	0,365	88,495
52	17,78	7,43	84,05	82	17,78	0,206	89,094
52	10,00	4,33	84,95	82	10,00	0,116	89,322
52	5,62	2,50	85,78	82	5,62	0,065	89,472
52	3,16	1,44	86,57	82	3,16	0,037	89,540
52	1,78	0,82	87,30	82	1,78	0,021	89,553
52	1,00	0,47	87,96	82	1,00	0,012	89,510
58	100,00	16,07	83,23				
58	56,23	9,40	84,08				
58	31,62	5,46	84,94				
58	17,78	3,16	85,78				
58	10,00	1,82	86,55				
58	5,62	1,04	87,26				
58	3,16	0,59	87,90				
58	1,78	0,34	88,43				
58	1,00	0,19	88,85				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of RTFOT-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/5

Temperatu [°C]	Angular Freq. [rad/s]	Complex Mo [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	41,657	74,134	4	1,00	11172,10	43,77
34	1,78	66,556	72,720	4	1,78	14755,80	41,78
34	3,16	105,490	71,305	4	3,16	19223,70	39,87
34	5,62	165,745	69,906	4	5,62	24699,80	38,06
34	10,00	258,166	68,503	4	10,00	31354,50	36,33
34	17,78	398,648	67,053	4	17,78	39383,10	34,68
34	31,62	610,011	65,540	4	31,62	48935,70	33,08
34	56,23	924,120	63,952	4	56,23	60180,60	31,53
34	100,00	1386,120	62,187	4	100,00	73297,00	30,01
28	1,00	123,24	69,80				
28	1,78	192,46	68,38				
28	3,16	297,48	66,91				
28	5,62	455,35	65,38				
28	10,00	689,81	63,80				
28	17,78	1033,71	62,13				
28	31,62	1532,12	60,35				
28	56,23	2245,96	58,49				
28	100,00	3252,44	56,59				
22	1,00	413,58	64,55				
22	1,78	625,32	62,93				
22	3,16	934,26	61,22				
22	5,62	1379,44	59,41				
22	10,00	2011,23	57,55				
22	17,78	2895,50	55,63				
22	31,62	4111,09	53,65				
22	56,23	5759,53	51,61				
22	100,00	7984,44	49,68				
16	1,00	1338,68	58,45				
16	1,78	1946,36	56,53				
16	3,16	2791,26	54,50				
16	5,62	3942,13	52,49				
16	10,00	5488,93	50,48				
16	17,78	7537,31	48,47				
16	31,62	10200,60	46,49				
16	56,23	13670,90	44,56				
16	100,00	18060,50	42,64				
10	1,00	4113,99	51,19				
10	1,78	5690,79	49,11				
10	3,16	7760,25	47,03				
10	5,62	10428,50	45,04				
10	10,00	13832,50	43,11				
10	17,78	18120,50	41,25				
10	31,62	23466,00	39,45				
10	56,23	30043,50	37,73				
10	100,00	38034,60	36,05				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/6

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	31,346	74,388	4	1,00	8564,49	44,07
34	1,78	50,213	72,942	4	1,78	11325,40	42,06
34	3,16	79,719	71,519	4	3,16	14770,10	40,13
34	5,62	125,453	70,109	4	5,62	18999,40	38,32
34	10,00	195,746	68,716	4	10,00	24136,00	36,59
34	17,78	302,638	67,267	4	17,78	30355,90	34,92
34	31,62	463,704	65,720	4	31,62	37769,60	33,31
34	56,23	704,245	64,063	4	56,23	46526,90	31,76
34	100,00	1061,230	62,101	4	100,00	56765,20	30,22
28	1,00	94,41	70,01				
28	1,78	147,84	68,57				
28	3,16	228,97	67,09				
28	5,62	350,81	65,56				
28	10,00	532,02	63,97				
28	17,78	798,89	62,30				
28	31,62	1186,78	60,54				
28	56,23	1742,43	58,70				
28	100,00	2526,74	56,81				
22	1,00	314,49	64,81				
22	1,78	476,83	63,19				
22	3,16	713,78	61,47				
22	5,62	1054,89	59,67				
22	10,00	1539,84	57,81				
22	17,78	2219,73	55,88				
22	31,62	3157,57	53,91				
22	56,23	4433,79	51,87				
22	100,00	6150,84	49,89				
16	1,00	1014,07	58,77				
16	1,78	1478,48	56,84				
16	3,16	2123,85	54,81				
16	5,62	3004,68	52,80				
16	10,00	4190,10	50,78				
16	17,78	5760,97	48,76				
16	31,62	7802,30	46,78				
16	56,23	10465,80	44,82				
16	100,00	13854,40	42,81				
10	1,00	3126,44	51,52				
10	1,78	4344,52	49,42				
10	3,16	5943,83	47,31				
10	5,62	8007,00	45,31				
10	10,00	10639,80	43,37				
10	17,78	13937,80	41,50				
10	31,62	18091,80	39,69				
10	56,23	23188,60	37,94				
10	100,00	29404,90	36,25				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of RTFOT-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 302	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/7

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1171,080	63,649	64	100,00	17,614	80,155
34	56,23	775,827	65,134	64	56,23	10,494	81,459
34	31,62	508,940	66,572	64	31,62	6,202	82,683
34	17,78	330,832	67,977	64	17,78	3,636	83,842
34	10,00	213,237	69,337	64	10,00	2,117	84,932
34	5,62	136,347	70,690	64	5,62	1,223	85,955
34	3,16	86,470	72,047	64	3,16	0,702	86,903
34	1,78	54,378	73,450	64	1,78	0,400	87,711
34	1,00	33,902	74,893	64	1,00	0,227	88,384
40	100,00	490,986	67,930	70	100,00	8,488	82,234
40	56,23	316,464	69,272	70	56,23	4,984	83,447
40	31,62	202,296	70,579	70	31,62	2,905	84,549
40	17,78	128,306	71,871	70	17,78	1,683	85,600
40	10,00	80,714	73,173	70	10,00	0,969	86,577
40	5,62	50,347	74,513	70	5,62	0,554	87,450
40	3,16	31,128	75,908	70	3,16	0,315	88,179
40	1,78	19,064	77,356	70	1,78	0,178	88,745
40	1,00	11,558	78,841	70	1,00	0,100	89,138
46	100,00	202,271	71,722	76	100,00	4,322	83,705
46	56,23	127,341	72,970	76	56,23	2,512	84,996
46	31,62	79,539	74,214	76	31,62	1,450	86,047
46	17,78	49,292	75,491	76	17,78	0,832	86,976
46	10,00	30,301	76,815	76	10,00	0,475	87,801
46	5,62	18,461	78,185	76	5,62	0,269	88,475
46	3,16	11,143	79,590	76	3,16	0,152	88,969
46	1,78	6,662	80,984	76	1,78	0,086	89,280
46	1,00	3,945	82,334	76	1,00	0,048	89,451
52	100,00	87,298	74,892	82	100,00	2,327	84,669
52	56,23	53,892	76,131	82	56,23	1,340	86,036
52	31,62	33,009	77,396	82	31,62	0,767	87,160
52	17,78	20,049	78,700	82	17,78	0,437	88,006
52	10,00	12,069	80,032	82	10,00	0,247	88,643
52	5,62	7,197	81,362	82	5,62	0,140	89,085
52	3,16	4,253	82,654	82	3,16	0,079	89,341
52	1,78	2,493	83,870	82	1,78	0,044	89,463
52	1,00	1,449	85,005	82	1,00	0,025	89,494
58	100,00	38,285	77,742				
58	56,23	23,178	79,004				
58	31,62	13,924	80,281				
58	17,78	8,298	81,554				
58	10,00	4,904	82,800				
58	5,62	2,874	83,983				
58	3,16	1,671	85,095				
58	1,78	0,964	86,116				
58	1,00	0,552	87,054				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of RTFOT-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 302	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/8

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1135,380	63,737	64	100,00	17,028	80,202
34	56,23	751,708	65,222	64	56,23	10,140	81,516
34	31,62	492,743	66,673	64	31,62	5,990	82,724
34	17,78	320,037	68,079	64	17,78	3,511	83,865
34	10,00	206,092	69,453	64	10,00	2,043	84,946
34	5,62	131,595	70,809	64	5,62	1,181	85,964
34	3,16	83,350	72,184	64	3,16	0,678	86,890
34	1,78	52,350	73,595	64	1,78	0,387	87,696
34	1,00	32,603	75,060	64	1,00	0,219	88,362
40	100,00	475,934	67,879	70	100,00	8,172	82,415
40	56,23	306,955	69,261	70	56,23	4,800	83,607
40	31,62	196,430	70,598	70	31,62	2,797	84,653
40	17,78	124,646	71,902	70	17,78	1,619	85,657
40	10,00	78,468	73,218	70	10,00	0,931	86,587
40	5,62	49,000	74,569	70	5,62	0,533	87,435
40	3,16	30,323	75,977	70	3,16	0,303	88,143
40	1,78	18,585	77,442	70	1,78	0,171	88,705
40	1,00	11,270	78,933	70	1,00	0,097	89,094
46	100,00	197,209	71,689	76	100,00	4,120	83,744
46	56,23	124,057	72,943	76	56,23	2,394	85,003
46	31,62	77,481	74,199	76	31,62	1,382	86,065
46	17,78	48,008	75,486	76	17,78	0,793	86,981
46	10,00	29,504	76,813	76	10,00	0,452	87,769
46	5,62	17,982	78,199	76	5,62	0,257	88,400
46	3,16	10,858	79,609	76	3,16	0,145	88,872
46	1,78	6,493	81,019	76	1,78	0,082	89,193
46	1,00	3,846	82,382	76	1,00	0,046	89,355
52	100,00	83,672	74,981	82	100,00	2,191	84,758
52	56,23	51,589	76,194	82	56,23	1,262	86,057
52	31,62	31,571	77,447	82	31,62	0,722	87,053
52	17,78	19,167	78,744	82	17,78	0,411	87,905
52	10,00	11,533	80,070	82	10,00	0,233	88,543
52	5,62	6,878	81,400	82	5,62	0,132	88,946
52	3,16	4,065	82,686	82	3,16	0,074	89,194
52	1,78	2,383	83,912	82	1,78	0,042	89,324
52	1,00	1,386	85,056	82	1,00	0,024	89,345
58	100,00	36,612	77,753				
58	56,23	22,150	79,037				
58	31,62	13,302	80,321				
58	17,78	7,928	81,588				
58	10,00	4,687	82,821				
58	5,62	2,748	83,993				
58	3,16	1,597	85,098				
58	1,78	0,921	86,126				
58	1,00	0,527	87,055				

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/9

Temperatu [°C]	Angular Freq. [rad/s]	Complex Mo [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	126,158	63,044	4	1,00	13218,70	34,66
34	1,78	187,726	61,429	4	1,78	16459,60	33,23
34	3,16	276,653	59,809	4	3,16	20308,60	31,85
34	5,62	403,358	58,209	4	5,62	24819,90	30,57
34	10,00	581,852	56,614	4	10,00	30079,20	29,37
34	17,78	831,020	55,027	4	17,78	36204,40	28,21
34	31,62	1175,070	53,438	4	31,62	43253,90	27,10
34	56,23	1644,470	51,862	4	56,23	51316,80	26,03
34	100,00	2277,830	50,305	4	100,00	60444,40	24,99
28	1,00	341,67	57,99				
28	1,78	493,87	56,31				
28	3,16	705,22	54,61				
28	5,62	995,02	52,93				
28	10,00	1388,54	51,28				
28	17,78	1917,25	49,64				
28	31,62	2619,84	48,01				
28	56,23	3545,31	46,42				
28	100,00	4748,01	44,91				
22	1,00	947,70	52,23				
22	1,78	1320,25	50,47				
22	3,16	1817,65	48,73				
22	5,62	2473,61	47,02				
22	10,00	3326,38	45,37				
22	17,78	4424,78	43,77				
22	31,62	5822,15	42,23				
22	56,23	7585,61	40,71				
22	100,00	9812,26	39,32				
16	1,00	2480,03	46,16				
16	1,78	3323,56	44,42				
16	3,16	4402,36	42,71				
16	5,62	5760,59	41,11				
16	10,00	7457,68	39,58				
16	17,78	9557,65	38,12				
16	31,62	12139,50	36,73				
16	56,23	15289,40	35,39				
16	100,00	19078,80	34,05				
10	1,00	5975,54	40,18				
10	1,78	7709,36	38,57				
10	3,16	9840,51	37,02				
10	5,62	12421,50	35,58				
10	10,00	15532,60	34,22				
10	17,78	19258,00	32,92				
10	31,62	23686,40	31,68				
10	56,23	28907,20	30,50				
10	100,00	35014,40	29,36				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen

Data:	08/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/10

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	152,062	63,075	4	1,00	16944,00	34,23
34	1,78	226,122	61,459	4	1,78	21030,20	32,79
34	3,16	333,177	59,838	4	3,16	25850,30	31,43
34	5,62	485,685	58,239	4	5,62	31491,10	30,15
34	10,00	700,953	56,644	4	10,00	38039,70	28,95
34	17,78	1001,480	55,059	4	17,78	45623,20	27,80
34	31,62	1416,560	53,469	4	31,62	54308,50	26,70
34	56,23	1983,700	51,889	4	56,23	64218,40	25,62
34	100,00	2749,970	50,326	4	100,00	75448,90	24,57
28	1,00	414,63	57,96				
28	1,78	599,07	56,28				
28	3,16	855,89	54,59				
28	5,62	1208,83	52,92				
28	10,00	1688,13	51,27				
28	17,78	2331,19	49,64				
28	31,62	3183,14	48,02				
28	56,23	4304,79	46,40				
28	100,00	5768,50	44,85				
22	1,00	1183,43	52,05				
22	1,78	1647,49	50,30				
22	3,16	2264,82	48,57				
22	5,62	3075,91	46,86				
22	10,00	4128,61	45,22				
22	17,78	5482,41	43,62				
22	31,62	7202,33	42,07				
22	56,23	9361,63	40,54				
22	100,00	12106,80	39,09				
16	1,00	3139,81	45,89				
16	1,78	4198,48	44,16				
16	3,16	5548,02	42,45				
16	5,62	7243,35	40,85				
16	10,00	9356,64	39,33				
16	17,78	11963,30	37,87				
16	31,62	15173,60	36,47				
16	56,23	19065,40	35,13				
16	100,00	23712,60	33,77				
10	1,00	7620,64	39,82				
10	1,78	9800,76	38,22				
10	3,16	12469,20	36,67				
10	5,62	15689,90	35,24				
10	10,00	19555,90	33,88				
10	17,78	24177,50	32,59				
10	31,62	29651,20	31,36				
10	56,23	36086,40	30,18				
10	100,00	43606,50	29,03				

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen

Data:	06/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/11

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	3070,300	52,134	64	100,00	55,927	72,202
34	56,23	2197,860	53,299	64	56,23	35,131	73,684
34	31,62	1559,480	54,580	64	31,62	21,878	75,181
34	17,78	1096,600	55,945	64	17,78	13,495	76,727
34	10,00	764,038	57,365	64	10,00	8,237	78,316
34	5,62	527,486	58,822	64	5,62	4,970	79,921
34	3,16	360,738	60,315	64	3,16	2,964	81,486
34	1,78	244,402	61,839	64	1,78	1,747	82,956
34	1,00	164,134	63,413	64	1,00	1,021	84,285
40	100,00	1385,250	56,614	70	100,00	26,866	75,487
40	56,23	961,220	57,914	70	56,23	16,526	76,929
40	31,62	661,098	59,272	70	31,62	10,065	78,402
40	17,78	450,658	60,665	70	17,78	6,066	79,911
40	10,00	304,376	62,086	70	10,00	3,616	81,403
40	5,62	203,878	63,545	70	5,62	2,133	82,831
40	3,16	135,251	65,043	70	3,16	1,246	84,152
40	1,78	88,863	66,614	70	1,78	0,721	85,294
40	1,00	57,741	68,236	70	1,00	0,416	86,292
46	100,00	610,839	61,136	76	100,00	12,921	78,334
46	56,23	411,785	62,448	76	56,23	7,791	79,735
46	31,62	275,187	63,790	76	31,62	4,652	81,181
46	17,78	182,211	65,172	76	17,78	2,751	82,589
46	10,00	119,580	66,600	76	10,00	1,612	83,907
46	5,62	77,744	68,095	76	5,62	0,936	85,078
46	3,16	50,043	69,661	76	3,16	0,539	86,085
46	1,78	31,891	71,316	76	1,78	0,309	86,926
46	1,00	20,098	73,066	76	1,00	0,176	87,605
52	100,00	272,465	65,229	82	100,00	6,444	80,810
52	56,23	178,834	66,520	82	56,23	3,826	82,153
52	31,62	116,400	67,864	82	31,62	2,249	83,443
52	17,78	75,105	69,274	82	17,78	1,311	84,661
52	10,00	48,008	70,757	82	10,00	0,758	85,755
52	5,62	30,386	72,329	82	5,62	0,436	86,658
52	3,16	19,038	73,990	82	3,16	0,249	87,386
52	1,78	11,796	75,726	82	1,78	0,142	87,961
52	1,00	7,226	77,518	82	1,00	0,080	88,399
58	100,00	122,285	68,944				
58	56,23	78,458	70,275				
58	31,62	49,904	71,668				
58	17,78	31,457	73,140				
58	10,00	19,640	74,696				
58	5,62	12,128	76,330				
58	3,16	7,402	78,022				
58	1,78	4,466	79,718				
58	1,00	2,660	81,352				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen

Data:	09/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/12

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	3111,720	51,727	64	100,00	56,552	72,435
34	56,23	2232,530	52,914	64	56,23	35,445	73,826
34	31,62	1587,220	54,286	64	31,62	22,015	75,291
34	17,78	1117,690	55,731	64	17,78	13,538	76,830
34	10,00	779,661	57,203	64	10,00	8,238	78,431
34	5,62	538,400	58,706	64	5,62	4,957	80,042
34	3,16	368,478	60,233	64	3,16	2,950	81,611
34	1,78	249,702	61,800	64	1,78	1,738	83,097
34	1,00	167,749	63,374	64	1,00	1,013	84,427
40	100,00	1411,920	56,260	70	100,00	26,508	75,470
40	56,23	981,057	57,657	70	56,23	16,275	76,984
40	31,62	675,679	59,070	70	31,62	9,901	78,515
40	17,78	461,018	60,499	70	17,78	5,962	80,045
40	10,00	311,952	61,944	70	10,00	3,552	81,553
40	5,62	209,117	63,418	70	5,62	2,094	82,986
40	3,16	138,807	64,936	70	3,16	1,223	84,307
40	1,78	91,252	66,512	70	1,78	0,706	85,438
40	1,00	59,369	68,150	70	1,00	0,406	86,446
46	100,00	612,745	60,963	76	100,00	12,767	78,174
46	56,23	413,116	62,331	76	56,23	7,691	79,769
46	31,62	276,265	63,697	76	31,62	4,589	81,279
46	17,78	183,107	65,094	76	17,78	2,713	82,709
46	10,00	120,308	66,531	76	10,00	1,589	84,029
46	5,62	78,338	68,023	76	5,62	0,922	85,215
46	3,16	50,547	69,601	76	3,16	0,532	86,234
46	1,78	32,270	71,250	76	1,78	0,304	87,072
46	1,00	20,383	73,001	76	1,00	0,173	87,735
52	100,00	271,143	65,186	82	100,00	6,401	80,586
52	56,23	178,030	66,531	82	56,23	3,793	82,146
52	31,62	115,912	67,896	82	31,62	2,227	83,536
52	17,78	74,816	69,312	82	17,78	1,297	84,775
52	10,00	47,857	70,807	82	10,00	0,749	85,870
52	5,62	30,315	72,386	82	5,62	0,430	86,787
52	3,16	19,001	74,055	82	3,16	0,245	87,533
52	1,78	11,778	75,807	82	1,78	0,139	88,097
52	1,00	7,212	77,595	82	1,00	0,079	88,477
58	100,00	123,220	68,972				
58	56,23	78,959	70,312				
58	31,62	50,170	71,714				
58	17,78	31,579	73,201				
58	10,00	19,679	74,773				
58	5,62	12,133	76,420				
58	3,16	7,397	78,124				
58	1,78	4,459	79,824				
58	1,00	2,658	81,469				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA4

Data:	20/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/13

Temperatu [°C]	**Angular Freq. [rad/s]**	**Complex M [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	1,00	57,026	68,045	4	1,00	9348,26	39,65
34	1,78	87,570	66,421	4	1,78	12030,50	38,08
34	3,16	133,207	64,843	4	3,16	15319,70	36,56
34	5,62	200,541	63,325	4	5,62	19287,80	35,15
34	10,00	299,013	61,847	4	10,00	24042,90	33,83
34	17,78	441,853	60,390	4	17,78	29723,90	32,55
34	31,62	647,234	58,940	4	31,62	36442,90	31,33
34	56,23	939,383	57,461	4	56,23	44346,90	30,16
34	100,00	1352,880	55,902	4	100,00	53578,40	29,02
28	1,00	161,33	63,08				
28	1,78	240,85	61,52				
28	3,16	355,80	59,96				
28	5,62	520,40	58,42				
28	10,00	753,22	56,90				
28	17,78	1078,85	55,38				
28	31,62	1530,52	53,84				
28	56,23	2151,45	52,29				
28	100,00	2996,13	50,76				
22	1,00	483,34	57,62				
22	1,78	697,65	56,02				
22	3,16	995,24	54,40				
22	5,62	1404,21	52,78				
22	10,00	1959,92	51,20				
22	17,78	2708,28	49,62				
22	31,62	3702,14	48,05				
22	56,23	5011,94	46,48				
22	100,00	6723,23	45,00				
16	1,00	1387,97	51,85				
16	1,78	1929,57	50,17				
16	3,16	2652,80	48,46				
16	5,62	3603,90	46,83				
16	10,00	4840,56	45,23				
16	17,78	6433,97	43,68				
16	31,62	8451,45	42,18				
16	56,23	11026,60	40,71				
16	100,00	14245,00	39,24				
10	1,00	3749,91	45,72				
10	1,78	5014,44	44,03				
10	3,16	6629,17	42,37				
10	5,62	8660,86	40,81				
10	10,00	11197,60	39,32				
10	17,78	14322,60	37,89				
10	31,62	18196,50	36,52				
10	56,23	22895,80	35,21				
10	100,00	28557,00	33,95				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA4

Data:	20/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/14

Temperature [°C]	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	1,00	51,120	67,935	4	1,00	8194,49	39,59
34	1,78	78,419	66,318	4	1,78	10517,50	38,03
34	3,16	119,190	64,740	4	3,16	13362,70	36,52
34	5,62	179,280	63,222	4	5,62	16800,60	35,13
34	10,00	267,154	61,746	4	10,00	20937,80	33,82
34	17,78	394,346	60,284	4	17,78	25885,80	32,56
34	31,62	576,944	58,799	4	31,62	31746,80	31,36
34	56,23	837,297	57,274	4	56,23	38643,50	30,20
34	100,00	1207,150	55,664	4	100,00	46728,80	29,06
28	1,00	144,37	63,01				
28	1,78	215,43	61,44				
28	3,16	318,01	59,88				
28	5,62	464,59	58,33				
28	10,00	671,82	56,81				
28	17,78	961,98	55,27				
28	31,62	1364,43	53,73				
28	56,23	1917,63	52,19				
28	100,00	2669,00	50,68				
22	1,00	429,01	57,62				
22	1,78	619,31	55,99				
22	3,16	883,81	54,36				
22	5,62	1246,74	52,73				
22	10,00	1738,66	51,14				
22	17,78	2398,53	49,55				
22	31,62	3273,41	47,96				
22	56,23	4426,75	46,37				
22	100,00	5937,08	44,82				
16	1,00	1230,05	51,83				
16	1,78	1709,59	50,13				
16	3,16	2348,42	48,41				
16	5,62	3185,12	46,77				
16	10,00	4271,09	45,17				
16	17,78	5666,10	43,61				
16	31,62	7433,47	42,10				
16	56,23	9654,15	40,57				
16	100,00	12508,00	39,14				
10	1,00	3315,63	45,64				
10	1,78	4424,03	43,95				
10	3,16	5835,74	42,29				
10	5,62	7608,97	40,74				
10	10,00	9821,81	39,25				
10	17,78	12548,20	37,83				
10	31,62	15921,00	36,47				
10	56,23	20015,10	35,16				
10	100,00	24963,30	33,88				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA4

Data:	20/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/15

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1344,250	56,269	64	100,00	27,974	76,359
34	56,23	934,473	57,619	64	56,23	17,186	77,063
34	31,62	643,635	58,993	64	31,62	10,433	78,254
34	17,78	439,471	60,387	64	17,78	6,265	79,665
34	10,00	297,463	61,801	64	10,00	3,724	81,161
34	5,62	199,629	63,237	64	5,62	2,193	82,626
34	3,16	132,752	64,737	64	3,16	1,283	83,999
34	1,78	87,467	66,301	64	1,78	0,748	85,230
34	1,00	57,099	67,935	64	1,00	0,431	86,306
40	100,00	618,253	60,612	70	100,00	13,461	78,328
40	56,23	417,680	61,942	70	56,23	8,157	79,791
40	31,62	279,797	63,285	70	31,62	4,887	81,115
40	17,78	185,849	64,653	70	17,78	2,894	82,445
40	10,00	122,435	66,058	70	10,00	1,695	83,741
40	5,62	79,970	67,545	70	5,62	0,983	84,959
40	3,16	51,735	69,118	70	3,16	0,566	86,054
40	1,78	33,139	70,781	70	1,78	0,324	86,982
40	1,00	21,004	72,540	70	1,00	0,185	87,776
46	100,00	265,548	64,530	76	100,00	6,689	81,025
46	56,23	174,956	65,950	76	56,23	3,988	82,645
46	31,62	114,501	67,339	76	31,62	2,351	83,697
46	17,78	74,327	68,768	76	17,78	1,368	84,666
46	10,00	47,854	70,263	76	10,00	0,789	85,672
46	5,62	30,536	71,847	76	5,62	0,453	86,669
46	3,16	19,297	73,524	76	3,16	0,259	87,530
46	1,78	12,066	75,283	76	1,78	0,148	88,208
46	1,00	7,451	77,093	76	1,00	0,083	88,697
52	100,00	121,915	68,337	82	100,00	3,508	81,868
52	56,23	78,363	69,767	82	56,23	2,055	84,115
52	31,62	50,013	71,208	82	31,62	1,195	85,408
52	17,78	31,662	72,709	82	17,78	0,689	86,333
52	10,00	19,865	74,291	82	10,00	0,394	87,191
52	5,62	12,340	75,952	82	5,62	0,224	87,912
52	3,16	7,582	77,663	82	3,16	0,127	88,516
52	1,78	4,605	79,384	82	1,78	0,072	88,908
52	1,00	2,761	81,058	82	1,00	0,041	89,144
58	100,00	58,593	72,525				
58	56,23	36,742	73,602				
58	31,62	22,808	74,933				
58	17,78	14,021	76,417				
58	10,00	8,530	77,999				
58	5,62	5,134	79,627				
58	3,16	3,056	81,224				
58	1,78	1,802	82,738				
58	1,00	1,056	84,119				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA4

Data:	20/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/16

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1288,860	56,611	64	100,00	25,797	75,432
34	56,23	895,210	57,933	64	56,23	15,843	76,808
34	31,62	616,171	59,278	64	31,62	9,658	78,298
34	17,78	420,383	60,651	64	17,78	5,829	79,826
34	10,00	284,299	62,053	64	10,00	3,481	81,333
34	5,62	190,612	63,488	64	5,62	2,055	82,761
34	3,16	126,610	64,977	64	3,16	1,201	84,069
34	1,78	83,374	66,532	64	1,78	0,697	85,203
34	1,00	54,353	68,166	64	1,00	0,400	86,162
40	100,00	589,374	60,980	70	100,00	12,539	78,256
40	56,23	397,587	62,267	70	56,23	7,566	79,688
40	31,62	265,922	63,583	70	31,62	4,521	81,125
40	17,78	176,387	64,938	70	17,78	2,675	82,523
40	10,00	116,024	66,340	70	10,00	1,568	83,834
40	5,62	75,603	67,821	70	5,62	0,911	84,996
40	3,16	48,795	69,385	70	3,16	0,525	85,989
40	1,78	31,165	71,048	70	1,78	0,301	86,779
40	1,00	19,683	72,810	70	1,00	0,172	87,375
46	100,00	259,099	65,044	76	100,00	6,187	80,925
46	56,23	170,399	66,343	76	56,23	3,672	82,168
46	31,62	111,252	67,662	76	31,62	2,158	83,414
46	17,78	72,000	69,066	76	17,78	1,258	84,636
46	10,00	46,195	70,551	76	10,00	0,728	85,707
46	5,62	29,358	72,127	76	5,62	0,418	86,569
46	3,16	18,450	73,798	76	3,16	0,239	87,257
46	1,78	11,459	75,551	76	1,78	0,136	87,771
46	1,00	7,025	77,351	76	1,00	0,077	88,131
52	100,00	118,052	68,762	82	100,00	3,252	82,964
52	56,23	75,755	70,081	82	56,23	1,903	84,111
52	31,62	48,207	71,474	82	31,62	1,104	85,216
52	17,78	30,402	72,956	82	17,78	0,636	86,205
52	10,00	18,990	74,523	82	10,00	0,364	87,051
52	5,62	11,744	76,170	82	5,62	0,207	87,651
52	3,16	7,180	77,870	82	3,16	0,118	88,086
52	1,78	4,339	79,574	82	1,78	0,067	88,336
52	1,00	2,590	81,220	82	1,00	0,038	88,443
58	100,00	54,498	72,261				
58	56,23	34,197	73,609				
58	31,62	21,273	75,062				
58	17,78	13,109	76,599				
58	10,00	7,995	78,190				
58	5,62	4,823	79,797				
58	3,16	2,875	81,365				
58	1,78	1,696	82,837				
58	1,00	0,990	84,153				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani Piano Nazionale di Ripresa e Resilienza

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA6

Data:	09/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/17

Temperatı [°C]	Angular Freq. [rad/s]	Complex Mc [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	19,379	71,612	4	1,00	2895,03	45,58
34	1,78	30,427	69,935	4	1,78	3869,04	43,95
34	3,16	47,283	68,305	4	3,16	5112,63	42,37
34	5,62	72,729	66,770	4	5,62	6678,09	40,89
34	10,00	110,809	65,321	4	10,00	8637,81	39,48
34	17,78	167,406	63,934	4	17,78	11062,70	38,13
34	31,62	250,770	62,579	4	31,62	14065,20	36,85
34	56,23	372,493	61,288	4	56,23	17735,80	35,61
34	100,00	549,627	60,084	4	100,00	22150,20	34,33
28	1,00	50,23	67,09				
28	1,78	76,84	65,53				
28	3,16	116,38	64,01				
28	5,62	174,34	62,53				
28	10,00	259,02	61,11				
28	17,78	381,32	59,70				
28	31,62	556,35	58,31				
28	56,23	804,52	56,94				
28	100,00	1153,78	55,60				
22	1,00	144,43	62,09				
22	1,78	214,44	60,58				
22	3,16	314,92	59,06				
22	5,62	457,94	57,57				
22	10,00	659,50	56,11				
22	17,78	940,30	54,64				
22	31,62	1327,60	53,16				
22	56,23	1857,67	51,67				
22	100,00	2577,01	50,21				
16	1,00	414,63	56,82				
16	1,78	595,65	55,28				
16	3,16	846,41	53,69				
16	5,62	1188,74	52,14				
16	10,00	1651,79	50,62				
16	17,78	2272,14	49,10				
16	31,62	3093,85	47,60				
16	56,23	4177,41	46,11				
16	100,00	5589,32	44,69				
10	1,00	1129,64	51,32				
10	1,78	1564,53	49,71				
10	3,16	2143,08	48,07				
10	5,62	2899,83	46,51				
10	10,00	3883,22	44,99				
10	17,78	5146,94	43,51				
10	31,62	6751,46	42,08				
10	56,23	8772,93	40,62				
10	100,00	11376,80	39,30				

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA6

Data:	09/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/18

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	14,200	72,900	4	1,00	2540,00	46,40
34	1,78	22,400	71,100	4	1,78	3410,00	44,80
34	3,16	35,100	69,500	4	3,16	4530,00	43,10
34	5,62	54,300	67,900	4	5,62	5940,00	41,60
34	10,00	83,400	66,400	4	10,00	7720,00	40,20
34	17,80	127,000	65,000	4	17,80	9930,00	38,80
34	31,60	191,000	63,700	4	31,60	12700,00	37,50
34	56,20	286,000	62,500	4	56,20	16000,00	36,20
34	100,00	425,000	61,300	4	100,00	20100,00	34,80
28	1,00	39,00	68,10				
28	1,78	60,20	66,50				
28	3,16	91,60	64,90				
28	5,62	138,00	63,40				
28	10,00	207,00	62,00				
28	17,80	306,00	60,60				
28	31,60	449,00	59,20				
28	56,20	653,00	57,90				
28	100,00	942,00	56,70				
22	1,00	114,00	63,10				
22	1,78	171,00	61,60				
22	3,16	252,00	60,00				
22	5,62	369,00	58,50				
22	10,00	535,00	57,10				
22	17,80	768,00	55,60				
22	31,60	1090,00	54,20				
22	56,20	1540,00	52,70				
22	100,00	2140,00	51,30				
16	1,00	332,00	57,90				
16	1,78	481,00	56,40				
16	3,16	688,00	54,80				
16	5,62	973,00	53,20				
16	10,00	1360,00	51,70				
16	17,80	1890,00	50,10				
16	31,60	2590,00	48,60				
16	56,20	3510,00	47,10				
16	100,00	4730,00	45,70				
10	1,00	943,00	52,30				
10	1,78	1320,00	50,70				
10	3,16	1810,00	49,00				
10	5,62	2470,00	47,50				
10	10,00	3330,00	45,90				
10	17,80	4450,00	44,40				
10	31,60	5870,00	42,90				
10	56,20	7670,00	41,40				
10	100,00	10000,00	40,10				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+ RA6

Data:	09/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/19

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	482,664	61,400	64	100,00	10,374	77,879
34	56,23	325,098	62,565	64	56,23	6,234	79,266
34	31,62	217,010	63,803	64	31,62	3,723	80,933
34	17,78	143,587	65,103	64	17,78	2,208	82,461
34	10,00	94,173	66,460	64	10,00	1,299	83,796
34	5,62	61,189	67,906	64	5,62	0,756	84,928
34	3,16	39,363	69,447	64	3,16	0,435	85,873
34	1,78	25,053	71,086	64	1,78	0,249	86,677
34	1,00	15,770	72,818	64	1,00	0,143	87,352
40	100,00	219,408	65,239	70	100,00	5,246	81,450
40	56,23	143,917	66,407	70	56,23	3,109	82,062
40	31,62	93,600	67,662	70	31,62	1,824	83,203
40	17,78	60,355	68,993	70	17,78	1,064	84,504
40	10,00	38,581	70,447	70	10,00	0,617	85,584
40	5,62	24,427	72,007	70	5,62	0,355	86,397
40	3,16	15,305	73,656	70	3,16	0,203	87,038
40	1,78	9,485	75,390	70	1,78	0,116	87,588
40	1,00	5,808	77,177	70	1,00	0,066	87,973
46	100,00	96,714	68,693	76	100,00	2,689	80,677
46	56,23	62,044	70,028	76	56,23	1,570	83,725
46	31,62	39,539	71,416	76	31,62	0,913	85,276
46	17,78	25,011	72,880	76	17,78	0,526	86,020
46	10,00	15,679	74,438	76	10,00	0,301	86,588
46	5,62	9,722	76,070	76	5,62	0,172	87,162
46	3,16	5,950	77,752	76	3,16	0,098	87,600
46	1,78	3,593	79,445	76	1,78	0,056	87,856
46	1,00	2,144	81,080	76	1,00	0,032	87,991
52	100,00	44,895	71,906	82	100,00	1,423	84,194
52	56,23	28,236	73,469	82	56,23	0,836	83,841
52	31,62	17,636	74,992	82	31,62	0,481	85,518
52	17,78	10,914	76,536	82	17,78	0,276	86,703
52	10,00	6,673	78,111	82	10,00	0,158	87,102
52	5,62	4,025	79,699	82	5,62	0,090	87,167
52	3,16	2,398	81,252	82	3,16	0,051	87,300
52	1,78	1,415	82,710	82	1,78	0,029	87,364
52	1,00	0,826	84,024	82	1,00	0,017	87,355
58	100,00	21,431	75,116				
58	56,23	13,207	76,779				
58	31,62	8,062	78,304				
58	17,78	4,861	79,785				
58	10,00	2,898	81,254				
58	5,62	1,711	82,659				
58	3,16	1,002	83,945				
58	1,78	0,581	85,069				
58	1,00	0,334	86,041				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RA6

Data:	09/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n° :**	3.1/3.1.1.1/20

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	473,262	61,297	64	100,00	10,710	78,271
34	56,23	319,235	62,518	64	56,23	6,463	79,664
34	31,62	213,598	63,782	64	31,62	3,860	81,032
34	17,78	141,760	65,089	64	17,78	2,285	82,409
34	10,00	93,354	66,442	64	10,00	1,340	83,670
34	5,62	60,916	67,883	64	5,62	0,779	84,765
34	3,16	39,365	69,412	64	3,16	0,450	85,696
34	1,78	25,165	71,046	64	1,78	0,259	86,444
34	1,00	15,911	72,775	64	1,00	0,148	87,026
40	100,00	221,208	65,131	70	100,00	5,299	80,286
40	56,23	145,237	66,337	70	56,23	3,144	82,000
40	31,62	94,632	67,610	70	31,62	1,849	83,332
40	17,78	61,208	68,941	70	17,78	1,077	84,501
40	10,00	39,254	70,387	70	10,00	0,624	85,518
40	5,62	24,955	71,932	70	5,62	0,358	86,327
40	3,16	15,708	73,577	70	3,16	0,205	86,929
40	1,78	9,776	75,305	70	1,78	0,117	87,349
40	1,00	6,006	77,086	70	1,00	0,067	87,617
46	100,00	100,573	68,699	76	100,00	2,742	81,895
46	56,23	64,672	70,003	76	56,23	1,604	83,927
46	31,62	41,224	71,360	76	31,62	0,931	85,045
46	17,78	26,032	72,803	76	17,78	0,537	85,996
46	10,00	16,273	74,337	76	10,00	0,308	86,762
46	5,62	10,067	75,957	76	5,62	0,176	87,228
46	3,16	6,163	77,631	76	3,16	0,100	87,527
46	1,78	3,731	79,310	76	1,78	0,057	87,645
46	1,00	2,230	80,934	76	1,00	0,032	87,665
52	100,00	46,652	72,176	82	100,00	1,458	83,750
52	56,23	29,296	73,522	82	56,23	0,865	84,940
52	31,62	18,243	74,954	82	31,62	0,497	86,115
52	17,78	11,254	76,461	82	17,78	0,284	86,855
52	10,00	6,867	78,020	82	10,00	0,162	87,322
52	5,62	4,144	79,591	82	5,62	0,092	87,502
52	3,16	2,475	81,129	82	3,16	0,053	87,558
52	1,78	1,463	82,560	82	1,78	0,030	87,519
52	1,00	0,857	83,845	82	1,00	0,017	87,404
58	100,00	22,208	75,295				
58	56,23	13,667	76,736				
58	31,62	8,330	78,206				
58	17,78	5,028	79,694				
58	10,00	3,003	81,151				
58	5,62	1,775	82,529				
58	3,16	1,040	83,781				
58	1,78	0,604	84,868				
58	1,00	0,349	85,792				

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB4

Data:	16/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/21

Temperati [°C]	Angular Freq. [rad/s]	Complex Mo [kPa]	Phase Angle [°]
34	1,00	36,997	72,167
34	1,78	58,359	70,621
34	3,16	91,181	69,098
34	5,62	141,177	67,622
34	10,00	216,509	66,178
34	17,78	328,908	64,714
34	31,62	495,109	63,201
34	56,23	738,634	61,619
34	100,00	1091,980	59,956
28	1,00	113,88	67,24
28	1,78	174,82	65,73
28	3,16	265,51	64,20
28	5,62	399,24	62,66
28	10,00	594,05	61,10
28	17,78	874,84	59,50
28	31,62	1274,55	57,86
28	56,23	1836,41	56,20
28	100,00	2614,34	54,50
22	1,00	375,12	61,67
22	1,78	555,58	60,04
22	3,16	814,01	58,36
22	5,62	1179,14	56,63
22	10,00	1687,73	54,90
22	17,78	2387,60	53,13
22	31,62	3336,67	51,34
22	56,23	4609,97	49,54
22	100,00	6296,15	47,85
16	1,00	1200,66	55,36
16	1,78	1707,51	53,54
16	3,16	2398,22	51,66
16	5,62	3323,62	49,81
16	10,00	4548,69	47,99
16	17,78	6148,56	46,19
16	31,62	8201,26	44,44
16	56,23	10845,50	42,73
16	100,00	14172,40	41,02
10	1,00	3597,42	48,24
10	1,78	4887,22	46,34
10	3,16	6550,09	44,46
10	5,62	8662,64	42,68
10	10,00	11321,40	40,97
10	17,78	14613,00	39,34
10	31,62	18714,80	37,77
10	56,23	23705,90	36,27
10	100,00	29740,70	34,82

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
4	1,00	9676,68	41,09
4	1,78	12546,50	39,32
4	3,16	16079,70	37,62
4	5,62	20363,10	36,05
4	10,00	25516,20	34,56
4	17,78	31700,50	33,13
4	31,62	39005,00	31,76
4	56,23	47591,80	30,44
4	100,00	57597,50	29,14

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB4

Data:	16/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/22

Temperature [°C]	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	1,00	37,290	72,200	4	1,00	9534,79	41,20
34	1,78	58,815	70,600	4	1,78	12380,50	39,40
34	3,16	91,868	69,100	4	3,16	15891,40	37,70
34	5,62	142,216	67,600	4	5,62	20135,60	36,10
34	10,00	218,077	66,100	4	10,00	25260,00	34,60
34	17,78	331,518	64,700	4	17,78	31404,20	33,20
34	31,62	499,281	63,200	4	31,62	38665,80	31,80
34	56,23	744,430	61,800	4	56,23	47205,00	30,50
34	100,00	1099,520	60,300	4	100,00	57135,10	29,20
28	1,00	112,38	67,30				
28	1,78	172,58	65,80				
28	3,16	262,31	64,30				
28	5,62	394,66	62,70				
28	10,00	587,60	61,20				
28	17,78	865,86	59,60				
28	31,62	1262,09	57,90				
28	56,23	1820,04	56,20				
28	100,00	2595,93	54,50				
22	1,00	367,71	61,90				
22	1,78	545,89	60,20				
22	3,16	800,99	58,60				
22	5,62	1161,19	56,80				
22	10,00	1663,28	55,10				
22	17,78	2354,58	53,30				
22	31,62	3291,52	51,50				
22	56,23	4549,90	49,60				
22	100,00	6221,03	47,80				
16	1,00	1173,11	55,60				
16	1,78	1672,36	53,80				
16	3,16	2354,88	51,90				
16	5,62	3270,30	50,00				
16	10,00	4482,59	48,20				
16	17,78	6067,86	46,30				
16	31,62	8102,03	44,50				
16	56,23	10723,20	42,80				
16	100,00	14020,00	41,10				
10	1,00	3521,08	48,50				
10	1,78	4792,88	46,60				
10	3,16	6438,43	44,60				
10	5,62	8528,57	42,80				
10	10,00	11162,10	41,10				
10	17,78	14426,00	39,40				
10	31,62	18494,60	37,80				
10	56,23	23443,70	36,30				
10	100,00	29425,00	34,90				

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB4

Data:	16/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/23

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1195,170	60,787	64	100,00	20,555	78,336
34	56,23	807,120	62,162	64	56,23	12,414	79,726
34	31,62	540,225	63,552	64	31,62	7,420	81,085
34	17,78	358,447	64,936	64	17,78	4,389	82,415
34	10,00	235,694	66,327	64	10,00	2,573	83,691
34	5,62	153,689	67,739	64	5,62	1,498	84,862
34	3,16	99,371	69,192	64	3,16	0,865	85,914
34	1,78	63,630	70,709	64	1,78	0,496	86,794
34	1,00	40,371	72,298	64	1,00	0,283	87,515
40	100,00	516,845	65,084	70	100,00	9,938	80,637
40	56,23	339,202	66,402	70	56,23	5,899	82,015
40	31,62	220,760	67,726	70	31,62	3,470	83,336
40	17,78	142,476	69,071	70	17,78	2,024	84,555
40	10,00	91,221	70,459	70	10,00	1,171	85,645
40	5,62	57,876	71,906	70	5,62	0,673	86,602
40	3,16	36,382	73,435	70	3,16	0,384	87,387
40	1,78	22,649	75,041	70	1,78	0,219	88,025
40	1,00	13,946	76,707	70	1,00	0,124	88,494
46	100,00	218,434	68,973	76	100,00	5,011	82,328
46	56,23	140,046	70,267	76	56,23	2,934	83,857
46	31,62	89,101	71,597	76	31,62	1,706	85,158
46	17,78	56,217	72,971	76	17,78	0,983	86,197
46	10,00	35,147	74,420	76	10,00	0,563	87,088
46	5,62	21,765	75,941	76	5,62	0,321	87,841
46	3,16	13,333	77,521	76	3,16	0,182	88,406
46	1,78	8,078	79,123	76	1,78	0,103	88,839
46	1,00	4,838	80,696	76	1,00	0,058	89,087
52	100,00	96,845	72,408	82	100,00	2,665	84,444
52	56,23	60,681	73,705	82	56,23	1,544	85,408
52	31,62	37,705	75,067	82	31,62	0,887	86,517
52	17,78	23,228	76,503	82	17,78	0,507	87,471
52	10,00	14,180	77,994	82	10,00	0,288	88,168
52	5,62	8,572	79,515	82	5,62	0,163	88,698
52	3,16	5,129	81,013	82	3,16	0,092	89,034
52	1,78	3,039	82,442	82	1,78	0,052	89,226
52	1,00	1,782	83,755	82	1,00	0,029	89,279
58	100,00	43,870	75,539				
58	56,23	26,944	76,858				
58	31,62	16,404	78,258				
58	17,78	9,899	79,699				
58	10,00	5,917	81,137				
58	5,62	3,501	82,524				
58	3,16	2,051	83,809				
58	1,78	1,192	84,972				
58	1,00	0,688	85,993				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB4

Data:	16/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/24

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1228,180	61,157	64	100,00	20,852	79,222
34	56,23	828,999	62,439	64	56,23	12,566	80,035
34	31,62	554,375	63,769	64	31,62	7,488	81,178
34	17,78	367,481	65,113	64	17,78	4,415	82,441
34	10,00	241,480	66,477	64	10,00	2,580	83,707
34	5,62	157,301	67,868	64	5,62	1,498	84,895
34	3,16	101,593	69,308	64	3,16	0,865	85,954
34	1,78	64,968	70,822	64	1,78	0,497	86,852
34	1,00	41,147	72,415	64	1,00	0,284	87,589
40	100,00	531,663	65,387	70	100,00	9,958	80,523
40	56,23	348,626	66,606	70	56,23	5,898	81,790
40	31,62	226,554	67,873	70	31,62	3,464	83,136
40	17,78	145,929	69,181	70	17,78	2,020	84,436
40	10,00	93,163	70,538	70	10,00	1,171	85,616
40	5,62	58,937	71,981	70	5,62	0,675	86,613
40	3,16	36,912	73,516	70	3,16	0,386	87,417
40	1,78	22,881	75,134	70	1,78	0,219	88,051
40	1,00	14,022	76,816	70	1,00	0,124	88,551
46	100,00	214,252	68,818	76	100,00	4,989	83,230
46	56,23	137,313	70,195	76	56,23	2,923	84,294
46	31,62	87,384	71,550	76	31,62	1,696	85,195
46	17,78	55,188	72,930	76	17,78	0,978	86,185
46	10,00	34,551	74,419	76	10,00	0,561	87,091
46	5,62	21,430	75,973	76	5,62	0,319	87,809
46	3,16	13,156	77,573	76	3,16	0,181	88,421
46	1,78	7,994	79,200	76	1,78	0,102	88,868
46	1,00	4,801	80,793	76	1,00	0,058	89,174
52	100,00	99,570	72,771	82	100,00	2,659	85,244
52	56,23	62,252	73,961	82	56,23	1,540	85,383
52	31,62	38,647	75,154	82	31,62	0,883	86,112
52	17,78	23,736	76,552	82	17,78	0,505	87,248
52	10,00	14,436	78,032	82	10,00	0,288	88,219
52	5,62	8,687	79,565	82	5,62	0,163	88,748
52	3,16	5,171	81,085	82	3,16	0,092	89,069
52	1,78	3,047	82,534	82	1,78	0,052	89,302
52	1,00	1,779	83,868	82	1,00	0,029	89,412
58	100,00	43,839	75,280				
58	56,23	26,926	76,735				
58	31,62	16,412	78,207				
58	17,78	9,923	79,693				
58	10,00	5,943	81,163				
58	5,62	3,522	82,574				
58	3,16	2,065	83,882				
58	1,78	1,199	85,066				
58	1,00	0,691	86,094				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB6

Data:	26/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/25

Temperat [°C]	Angular Freq. [rad/s]	Complex M [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	18,672	76,391	4	1,00	6070,80	46,17
34	1,78	30,251	74,787	4	1,78	8128,53	44,21
34	3,16	48,516	73,212	4	3,16	10742,10	42,29
34	5,62	77,044	71,721	4	5,62	14008,20	40,50
34	10,00	121,191	70,295	4	10,00	18054,60	38,78
34	17,78	189,151	68,908	4	17,78	23023,90	37,15
34	31,62	292,616	67,532	4	31,62	29066,70	35,58
34	56,23	449,113	66,159	4	56,23	36324,90	34,08
34	100,00	684,395	64,785	4	100,00	44980,10	32,62
28	1,00	56,66	71,71				
28	1,78	89,47	70,20				
28	3,16	139,79	68,70				
28	5,62	216,13	67,24				
28	10,00	331,28	65,78				
28	17,78	503,12	64,30				
28	31,62	756,78	62,76				
28	56,23	1127,13	61,17				
28	100,00	1661,20	59,57				
22	1,00	189,75	66,50				
22	1,78	290,14	64,99				
22	3,16	438,73	63,41				
22	5,62	656,49	61,82				
22	10,00	972,11	60,18				
22	17,78	1422,96	58,47				
22	31,62	2058,73	56,67				
22	56,23	2945,71	54,80				
22	100,00	4166,77	52,92				
16	1,00	636,32	60,69				
16	1,78	938,03	58,99				
16	3,16	1365,83	57,17				
16	5,62	1963,06	55,34				
16	10,00	2786,07	53,46				
16	17,78	3904,13	51,55				
16	31,62	5393,95	49,62				
16	56,23	7352,92	47,64				
16	100,00	9951,41	45,80				
10	1,00	2050,85	53,85				
10	1,78	2892,15	51,88				
10	3,16	4022,13	49,87				
10	5,62	5510,75	47,91				
10	10,00	7447,33	45,99				
10	17,78	9936,68	44,12				
10	31,62	13109,00	42,32				
10	56,23	17089,60	40,58				
10	100,00	22033,80	38,89				

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB6

Data:	26/05/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/26

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	20,245	76,036
34	1,78	32,741	74,522
34	3,16	52,443	73,004
34	5,62	83,229	71,562
34	10,00	130,876	70,175
34	17,78	203,951	68,804
34	31,62	315,246	67,439
34	56,23	483,168	66,035
34	100,00	735,361	64,531
28	1,00	61,82	71,41
28	1,78	97,46	69,96
28	3,16	152,09	68,49
28	5,62	235,03	67,05
28	10,00	359,74	65,60
28	17,78	545,33	64,12
28	31,62	818,70	62,55
28	56,23	1217,28	60,91
28	100,00	1793,18	59,18
22	1,00	207,28	66,19
22	1,78	316,33	64,70
22	3,16	477,63	63,14
22	5,62	713,69	61,55
22	10,00	1055,34	59,92
22	17,78	1542,93	58,21
22	31,62	2228,29	56,43
22	56,23	3181,75	54,57
22	100,00	4491,40	52,70
16	1,00	698,47	60,27
16	1,78	1026,03	58,58
16	3,16	1489,46	56,77
16	5,62	2134,92	54,95
16	10,00	3022,18	53,09
16	17,78	4224,47	51,21
16	31,62	5822,97	49,31
16	56,23	7917,59	47,37
16	100,00	10698,60	45,56
10	1,00	2265,08	53,28
10	1,78	3182,32	51,33
10	3,16	4409,07	49,35
10	5,62	6019,48	47,43
10	10,00	8112,45	45,56
10	17,78	10789,60	43,75
10	31,62	14201,30	42,00
10	56,23	18479,90	40,32
10	100,00	23785,90	38,70

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
4	1,00	6593,95	45,70
4	1,78	8800,22	43,79
4	3,16	11600,50	41,93
4	5,62	15092,90	40,20
4	10,00	19413,80	38,55
4	17,78	24722,60	36,97
4	31,62	31170,90	35,47
4	56,23	38933,40	34,01
4	100,00	48182,70	32,60

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB6

Data:	26/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/27

Temperature [°C]	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	100,00	660,832	65,025	64	100,00	11,792	80,585
34	56,23	434,065	66,393	64	56,23	7,004	81,937
34	31,62	282,732	67,739	64	31,62	4,126	83,232
34	17,78	182,682	69,079	64	17,78	2,409	84,419
34	10,00	117,086	70,429	64	10,00	1,396	85,502
34	5,62	74,473	71,823	64	5,62	0,803	86,465
34	3,16	46,940	73,277	64	3,16	0,459	87,273
34	1,78	29,311	74,804	64	1,78	0,261	87,892
34	1,00	18,125	76,383	64	1,00	0,148	88,363
40	100,00	285,746	68,921	70	100,00	5,890	82,756
40	56,23	183,088	70,201	70	56,23	3,449	83,838
40	31,62	116,397	71,490	70	31,62	2,004	84,999
40	17,78	73,443	72,818	70	17,78	1,157	86,085
40	10,00	45,932	74,202	70	10,00	0,664	87,016
40	5,62	28,459	75,659	70	5,62	0,378	87,771
40	3,16	17,457	77,171	70	3,16	0,214	88,337
40	1,78	10,597	78,711	70	1,78	0,121	88,735
40	1,00	6,363	80,228	70	1,00	0,068	88,969
46	100,00	121,745	72,506	76	100,00	3,050	84,134
46	56,23	76,264	73,736	76	56,23	1,767	85,368
46	31,62	47,388	75,030	76	31,62	1,017	86,442
46	17,78	29,182	76,394	76	17,78	0,581	87,363
46	10,00	17,804	77,820	76	10,00	0,331	88,123
46	5,62	10,757	79,281	76	5,62	0,187	88,637
46	3,16	6,437	80,729	76	3,16	0,106	89,005
46	1,78	3,817	82,110	76	1,78	0,060	89,213
46	1,00	2,244	83,396	76	1,00	0,034	89,311
52	100,00	54,364	75,585	82	100,00	1,668	85,157
52	56,23	33,397	76,822	82	56,23	0,960	86,252
52	31,62	20,330	78,143	82	31,62	0,548	87,349
52	17,78	12,260	79,519	82	17,78	0,311	88,245
52	10,00	7,329	80,907	82	10,00	0,176	88,784
52	5,62	4,343	82,250	82	5,62	0,099	89,131
52	3,16	2,552	83,501	82	3,16	0,056	89,332
52	1,78	1,488	84,642	82	1,78	0,031	89,422
52	1,00	0,861	85,662	82	1,00	0,018	89,438
58	100,00	24,857	78,360				
58	56,23	14,991	79,592				
58	31,62	8,960	80,910				
58	17,78	5,309	82,224				
58	10,00	3,120	83,478				
58	5,62	1,819	84,625				
58	3,16	1,053	85,654				
58	1,78	0,606	86,549				
58	1,00	0,346	87,354				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani Piano Nazionale di Ripresa e Resilienza

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RB6

Data:	26/05/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/28

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	643,721	65,356	64	100,00	10,877	81,080
34	56,23	421,956	66,682	64	56,23	6,446	82,341
34	31,62	274,156	68,005	64	31,62	3,787	83,554
34	17,78	176,687	69,335	64	17,78	2,207	84,673
34	10,00	112,953	70,688	64	10,00	1,277	85,662
34	5,62	71,630	72,080	64	5,62	0,734	86,504
34	3,16	45,020	73,538	64	3,16	0,420	87,157
34	1,78	28,025	75,058	64	1,78	0,239	87,607
34	1,00	17,270	76,621	64	1,00	0,136	87,909
40	100,00	273,492	69,204	70	100,00	5,315	82,994
40	56,23	175,125	70,475	70	56,23	3,108	84,288
40	31,62	111,243	71,764	70	31,62	1,803	85,339
40	17,78	70,107	73,084	70	17,78	1,039	86,257
40	10,00	43,782	74,473	70	10,00	0,595	87,040
40	5,62	27,082	75,922	70	5,62	0,339	87,602
40	3,16	16,583	77,420	70	3,16	0,192	87,950
40	1,78	10,049	78,925	70	1,78	0,109	88,182
40	1,00	6,025	80,395	70	1,00	0,062	88,375
46	100,00	115,078	72,727	76	100,00	2,702	84,828
46	56,23	71,938	73,996	76	56,23	1,563	85,769
46	31,62	44,643	75,315	76	31,62	0,898	86,657
46	17,78	27,498	76,691	76	17,78	0,513	87,381
46	10,00	16,782	78,112	76	10,00	0,292	87,867
46	5,62	10,141	79,549	76	5,62	0,166	88,137
46	3,16	6,060	80,949	76	3,16	0,094	88,276
46	1,78	3,585	82,263	76	1,78	0,053	88,388
46	1,00	2,102	83,464	76	1,00	0,030	88,474
52	100,00	50,736	75,798	82	100,00	1,427	85,695
52	56,23	31,061	77,034	82	56,23	0,832	86,548
52	31,62	18,951	78,483	82	31,62	0,475	87,443
52	17,78	11,436	79,853	82	17,78	0,270	87,890
52	10,00	6,829	81,203	82	10,00	0,153	88,153
52	5,62	4,036	82,494	82	5,62	0,087	88,147
52	3,16	2,366	83,663	82	3,16	0,049	88,171
52	1,78	1,379	84,708	82	1,78	0,028	88,251
52	1,00	0,797	85,617	82	1,00	0,016	88,346
58	100,00	23,229	78,692				
58	56,23	13,982	79,929				
58	31,62	8,339	81,228				
58	17,78	4,934	82,514				
58	10,00	2,895	83,716				
58	5,62	1,685	84,793				
58	3,16	0,973	85,724				
58	1,78	0,559	86,495				
58	1,00	0,319	87,088				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC4

Data:	17/06/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/29

Temperatı [°C]	Angular Freq. [rad/s]	Complex Mı [kPa]	Phase Angle [°]
34	1,00	47,963	68,600
34	1,78	73,877	67,000
34	3,16	112,609	65,400
34	5,62	170,129	63,800
34	10,00	254,703	62,300
34	17,78	377,692	60,900
34	31,62	555,076	59,500
34	56,23	807,963	58,100
34	100,00	1165,080	56,900
28	1,00	133,67	63,80
28	1,78	200,50	62,20
28	3,16	297,52	60,60
28	5,62	436,92	59,10
28	10,00	634,90	57,60
28	17,78	913,36	56,00
28	31,62	1301,40	54,50
28	56,23	1837,60	53,00
28	100,00	2570,24	51,50
22	1,00	392,04	58,50
22	1,78	569,33	56,90
22	3,16	817,21	55,30
22	5,62	1160,19	53,70
22	10,00	1629,32	52,10
22	17,78	2264,32	50,50
22	31,62	3113,13	48,90
22	56,23	4239,83	47,40
22	100,00	5719,55	45,90
16	1,00	1125,64	52,90
16	1,78	1576,24	51,20
16	3,16	2181,85	49,50
16	5,62	2982,94	47,80
16	10,00	4033,67	46,20
16	17,78	5394,61	44,70
16	31,62	7134,95	43,10
16	56,23	9334,92	41,60
16	100,00	12173,40	40,20
10	1,00	3034,78	46,90
10	1,78	4088,57	45,20
10	3,16	5444,23	43,50
10	5,62	7163,39	41,90
10	10,00	9326,61	40,40
10	17,78	12015,50	39,00
10	31,62	15363,50	37,60
10	56,23	19460,60	36,20
10	100,00	24432,70	35,00

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
4	1,00	7673,09	40,80
4	1,78	9949,22	39,20
4	3,16	12759,40	37,70
4	5,62	16184,80	36,20
4	10,00	20336,20	34,90
4	17,78	25332,50	33,60
4	31,62	31298,50	32,30
4	56,23	38361,70	31,20
4	100,00	46669,30	30,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC4

Data:	17/06/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/30

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	48,300	68,500	4	1,00	7570,00	40,70
34	1,78	74,300	66,800	4	1,78	9790,00	39,10
34	3,16	113,000	65,200	4	3,16	12500,00	37,60
34	5,62	171,000	63,700	4	5,62	15900,00	36,10
34	10,00	256,000	62,200	4	10,00	19900,00	34,80
34	17,80	379,000	60,700	4	17,80	24800,00	33,50
34	31,60	556,000	59,300	4	31,60	30600,00	32,20
34	56,20	808,000	57,900	4	56,20	37400,00	31,00
34	100,00	1160,000	56,500	4	100,00	45400,00	29,90
28	1,00	135,00	63,60				
28	1,78	203,00	62,00				
28	3,16	300,00	60,40				
28	5,62	441,00	58,80				
28	10,00	640,00	57,30				
28	17,80	919,00	55,80				
28	31,60	1310,00	54,30				
28	56,20	1840,00	52,70				
28	100,00	2570,00	51,20				
22	1,00	396,00	58,30				
22	1,78	575,00	56,70				
22	3,16	823,00	55,10				
22	5,62	1170,00	53,40				
22	10,00	1630,00	51,80				
22	17,80	2260,00	50,20				
22	31,60	3110,00	48,70				
22	56,20	4220,00	47,10				
22	100,00	5690,00	45,60				
16	1,00	1120,00	52,70				
16	1,78	1570,00	51,00				
16	3,16	2170,00	49,30				
16	5,62	2960,00	47,60				
16	10,00	4000,00	46,00				
16	17,80	5340,00	44,50				
16	31,60	7050,00	43,00				
16	56,20	9220,00	41,40				
16	100,00	12000,00	40,00				
10	1,00	3040,00	46,70				
10	1,78	4090,00	45,00				
10	3,16	5440,00	43,30				
10	5,62	7140,00	41,70				
10	10,00	9280,00	40,20				
10	17,80	11900,00	38,80				
10	31,60	15200,00	37,40				
10	56,20	19200,00	36,00				
10	100,00	24100,00	34,70				

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC4

Data:	17/06/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/31

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1171,000	56,670	64	100,00	24,270	75,200
34	56,20	812,600	57,990	64	56,20	14,970	76,650
34	31,60	559,100	59,330	64	31,60	9,128	78,100
34	17,80	381,300	60,690	64	17,80	5,506	79,600
34	10,00	257,900	62,070	64	10,00	3,286	81,100
34	5,62	172,900	63,490	64	5,62	1,944	82,560
34	3,16	114,900	64,970	64	3,16	1,140	83,890
34	1,78	75,690	66,500	64	1,78	0,662	85,050
34	1,00	49,390	68,130	64	1,00	0,381	86,000
40	100,00	538,900	60,900	70	100,00	11,880	77,780
40	56,20	363,700	62,200	70	56,20	7,176	79,340
40	31,60	243,400	63,510	70	31,60	4,296	80,830
40	17,80	161,600	64,860	70	17,80	2,547	82,270
40	10,00	106,400	66,250	70	10,00	1,495	83,590
40	5,62	69,360	67,720	70	5,62	0,870	84,790
40	3,16	44,800	69,280	70	3,16	0,502	85,810
40	1,78	28,640	70,940	70	1,78	0,289	86,640
40	1,00	18,120	72,690	70	1,00	0,165	87,300
46	100,00	240,200	64,970	76	100,00	6,001	80,260
46	56,20	157,800	66,250	76	56,20	3,567	81,710
46	31,60	102,900	67,570	76	31,60	2,100	83,080
46	17,80	66,490	68,950	76	17,80	1,227	84,360
46	10,00	42,600	70,420	76	10,00	0,711	85,470
46	5,62	27,040	71,990	76	5,62	0,409	86,390
46	3,16	17,000	73,650	76	3,16	0,234	87,120
46	1,78	10,570	75,400	76	1,78	0,133	87,690
46	1,00	6,495	77,200	76	1,00	0,076	88,130
52	100,00	110,500	68,660	82	100,00	3,177	81,900
52	56,20	70,950	69,940	82	56,20	1,862	83,530
52	31,60	45,190	71,310	82	31,60	1,083	84,910
52	17,80	28,520	72,770	82	17,80	0,625	85,970
52	10,00	17,830	74,340	82	10,00	0,359	86,870
52	5,62	11,030	75,980	82	5,62	0,205	87,530
52	3,16	6,752	77,680	82	3,16	0,117	88,010
52	1,78	4,083	79,390	82	1,78	0,066	88,370
52	1,00	2,440	81,040	82	1,00	0,037	88,590
58	100,00	50,980	71,890				
58	56,20	32,050	73,320				
58	31,60	19,990	74,800				
58	17,80	12,350	76,350				
58	10,00	7,555	77,950				
58	5,62	4,568	79,570				
58	3,16	2,729	81,160				
58	1,78	1,611	82,650				
58	1,00	0,942	83,990				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC4

Data:	17/06/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/32

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	1080,000	57,250	64	100,00	21,560	75,850
34	56,20	746,500	58,550	64	56,20	13,240	77,220
34	31,60	511,800	59,870	64	31,60	8,045	78,640
34	17,80	347,700	61,230	64	17,80	4,836	80,090
34	10,00	234,200	62,610	64	10,00	2,877	81,550
34	5,62	156,400	64,030	64	5,62	1,697	82,930
34	3,16	103,600	65,510	64	3,16	0,992	84,150
34	1,78	67,900	67,060	64	1,78	0,575	85,190
34	1,00	44,100	68,690	64	1,00	0,331	85,990
40	100,00	486,300	61,440	70	100,00	10,560	78,420
40	56,20	327,300	62,750	70	56,20	6,358	79,910
40	31,60	218,500	64,070	70	31,60	3,796	81,360
40	17,80	144,800	65,420	70	17,80	2,244	82,710
40	10,00	95,140	66,830	70	10,00	1,314	83,910
40	5,62	61,950	68,300	70	5,62	0,762	84,970
40	3,16	39,930	69,870	70	3,16	0,440	85,820
40	1,78	25,470	71,530	70	1,78	0,253	86,440
40	1,00	16,050	73,290	70	1,00	0,145	86,870
46	100,00	217,200	65,520	76	100,00	5,315	80,770
46	56,20	142,300	66,800	76	56,20	3,147	82,180
46	31,60	92,420	68,120	76	31,60	1,849	83,520
46	17,80	59,540	69,510	76	17,80	1,077	84,630
46	10,00	38,010	70,990	76	10,00	0,623	85,530
46	5,62	24,030	72,560	76	5,62	0,358	86,210
46	3,16	15,040	74,230	76	3,16	0,205	86,640
46	1,78	9,310	75,970	76	1,78	0,118	86,910
46	1,00	5,695	77,750	76	1,00	0,067	87,100
52	100,00	98,370	69,180	82	100,00	2,743	83,230
52	56,20	62,980	70,470	82	56,20	1,604	84,100
52	31,60	40,010	71,900	82	31,60	0,930	85,070
52	17,80	25,160	73,350	82	17,80	0,536	85,870
52	10,00	15,680	74,910	82	10,00	0,308	86,390
52	5,62	9,666	76,550	82	5,62	0,176	86,650
52	3,16	5,891	78,230	82	3,16	0,101	86,730
52	1,78	3,550	79,900	82	1,78	0,058	86,820
52	1,00	2,113	81,490	82	1,00	0,033	86,970
58	100,00	45,410	72,620				
58	56,20	28,450	73,980				
58	31,60	17,670	75,410				
58	17,80	10,860	76,930				
58	10,00	6,604	78,500				
58	5,62	3,973	80,080				
58	3,16	2,365	81,610				
58	1,78	1,393	83,020				
58	1,00	0,813	84,260				

Politecnico di Torino · Finanziato dall'Unione europea NextGenerationEU · MUR · Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC6

Data:	17/06/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	1
Operatore	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/33

Temperatu [°C]	**Angular Freq. [rad/s]**	**Complex Mo [kPa]**	**Phase Angle [°]**	**Temperature [°C]**	**Angular Freq. [rad/s]**	**Complex Mod. [kPa]**	**Phase Angle [°]**
34	1,00	36,851	69,500	4	1,00	5851,98	42,50
34	1,78	57,046	67,800	4	1,78	7667,53	40,90
34	3,16	87,510	66,200	4	3,16	9933,78	39,30
34	5,62	132,864	64,700	4	5,62	12723,30	37,90
34	10,00	199,858	63,300	4	10,00	16141,30	36,50
34	17,80	297,885	61,800	4	17,80	20295,60	35,20
34	31,60	440,287	60,500	4	31,60	25311,60	33,90
34	56,20	645,112	59,100	4	56,20	31311,40	32,70
34	100,00	939,747	57,500	4	100,00	38448,50	31,50
28	1,00	101,81	64,70				
28	1,78	153,58	63,20				
28	3,16	229,11	61,60				
28	5,62	338,22	60,10				
28	10,00	494,82	58,60				
28	17,80	717,19	57,20				
28	31,60	1029,76	55,70				
28	56,20	1464,81	54,30				
28	100,00	2063,57	52,90				
22	1,00	295,22	59,70				
22	1,78	430,99	58,10				
22	3,16	623,22	56,50				
22	5,62	891,50	54,90				
22	10,00	1262,09	53,40				
22	17,80	1768,61	51,90				
22	31,60	2452,97	50,40				
22	56,20	3369,35	48,80				
22	100,00	4581,95	47,30				
16	1,00	835,22	54,30				
16	1,78	1179,76	52,60				
16	3,16	1647,60	51,00				
16	5,62	2273,30	49,40				
16	10,00	3102,92	47,80				
16	17,80	4190,65	46,30				
16	31,60	5598,79	44,70				
16	56,20	7409,43	43,20				
16	100,00	9756,12	41,80				
10	1,00	2303,58	48,40				
10	1,78	3133,04	46,70				
10	3,16	4213,09	45,00				
10	5,62	5597,55	43,50				
10	10,00	7360,73	42,00				
10	17,80	9577,59	40,50				
10	31,60	12358,70	39,10				
10	56,20	15802,20	37,80				
10	100,00	19981,10	36,30				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC6

Data:	18/06/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP08	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/34

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	1,00	35,468	69,600	4	1,00	5628,96	42,40
34	1,78	54,956	67,900	4	1,78	7360,83	40,80
34	3,16	84,345	66,300	4	3,16	9526,15	39,30
34	5,62	128,069	64,800	4	5,62	12190,10	37,80
34	10,00	192,637	63,300	4	10,00	15453,10	36,40
34	17,80	287,370	61,900	4	17,80	19417,60	35,10
34	31,60	424,918	60,500	4	31,60	24206,00	33,90
34	56,20	622,415	59,100	4	56,20	29928,30	32,60
34	100,00	905,908	57,600	4	100,00	36747,30	31,50
28	1,00	98,03	64,80				
28	1,78	147,85	63,20				
28	3,16	220,77	61,60				
28	5,62	326,35	60,10				
28	10,00	477,22	58,70				
28	17,80	691,22	57,20				
28	31,60	992,26	55,70				
28	56,20	1411,03	54,20				
28	100,00	1989,10	52,70				
22	1,00	285,46	59,70				
22	1,78	416,92	58,10				
22	3,16	602,99	56,50				
22	5,62	862,62	54,90				
22	10,00	1220,99	53,40				
22	17,80	1710,57	51,90				
22	31,60	2372,12	50,30				
22	56,20	3257,72	48,80				
22	100,00	4429,06	47,30				
16	1,00	814,39	54,20				
16	1,78	1150,38	52,60				
16	3,16	1606,47	50,90				
16	5,62	2217,03	49,30				
16	10,00	3025,71	47,70				
16	17,80	4084,23	46,20				
16	31,60	5449,04	44,70				
16	56,20	7197,68	43,10				
16	100,00	9457,18	41,70				
10	1,00	2237,54	48,40				
10	1,78	3040,41	46,70				
10	3,16	4084,47	45,00				
10	5,62	5418,32	43,40				
10	10,00	7110,47	41,90				
10	17,80	9236,60	40,40				
10	31,60	11896,90	39,00				
10	56,20	15193,30	37,70				
10	100,00	19211,20	36,20				

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1 - Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC6

Data:	18/06/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/35

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	826,103	58,530	64	100,00	17,198	76,390
34	56,20	566,680	59,800	64	56,20	10,497	77,880
34	31,60	385,494	61,090	64	31,60	6,345	79,360
34	17,80	260,124	62,410	64	17,80	3,799	80,840
34	10,00	174,043	63,780	64	10,00	2,251	82,290
34	5,62	115,438	65,190	64	5,62	1,320	83,640
34	3,16	75,886	66,670	64	3,16	0,768	84,860
34	1,78	49,432	68,240	64	1,78	0,443	85,880
34	1,00	31,876	69,910	64	1,00	0,254	86,710
40	100,00	376,511	62,580	70	100,00	8,403	78,900
40	56,20	251,392	63,840	70	56,20	5,034	80,540
40	31,60	166,559	65,130	70	31,60	2,987	81,980
40	17,80	109,454	66,460	70	17,80	1,757	83,330
40	10,00	71,370	67,870	70	10,00	1,024	84,560
40	5,62	46,103	69,360	70	5,62	0,592	85,630
40	3,16	29,487	70,960	70	3,16	0,340	86,510
40	1,78	18,662	72,670	70	1,78	0,194	87,160
40	1,00	11,671	74,460	70	1,00	0,110	87,610
46	100,00	167,603	66,490	76	100,00	4,246	81,040
46	56,20	109,250	67,760	76	56,20	2,503	82,710
46	31,60	70,612	69,080	76	31,60	1,464	84,040
46	17,80	45,249	70,480	76	17,80	0,849	85,190
46	10,00	28,708	71,990	76	10,00	0,489	86,180
46	5,62	18,034	73,600	76	5,62	0,280	86,950
46	3,16	11,212	75,300	76	3,16	0,160	87,470
46	1,78	6,893	77,060	76	1,78	0,091	87,790
46	1,00	4,182	78,840	76	1,00	0,052	87,920
52	100,00	77,070	69,960	82	100,00	2,271	82,610
52	56,20	49,102	71,320	82	56,20	1,323	84,180
52	31,60	31,040	72,750	82	31,60	0,765	85,470
52	17,80	19,444	74,250	82	17,80	0,439	86,450
52	10,00	12,048	75,840	82	10,00	0,251	87,190
52	5,62	7,378	77,490	82	5,62	0,143	87,630
52	3,16	4,466	79,170	82	3,16	0,081	87,820
52	1,78	2,674	80,810	82	1,78	0,046	87,850
52	1,00	1,582	82,370	82	1,00	0,026	87,790
58	100,00	35,872	73,320				
58	56,20	22,342	74,740				
58	31,60	13,792	76,230				
58	17,80	8,433	77,780				
58	10,00	5,103	79,360				
58	5,62	3,052	80,920				
58	3,16	1,806	82,420				
58	1,78	1,058	83,800				
58	1,00	0,614	85,000				

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.1- Evaluation of the Complex Modulus and Phase Angle of PAV-aged bitumen+RC6

Data:	18/06/2025	**Strumento:**	MCR 302	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	PP25	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.1/36

Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]	Temperature [°C]	Angular Freq. [rad/s]	Complex Mod. [kPa]	Phase Angle [°]
34	100,00	849,317	58,560	64	100,00	17,832	76,290
34	56,20	582,837	59,830	64	56,20	10,902	77,810
34	31,60	396,740	61,130	64	31,60	6,602	79,310
34	17,80	267,809	62,450	64	17,80	3,953	80,780
34	10,00	179,175	63,820	64	10,00	2,342	82,220
34	5,62	118,805	65,250	64	5,62	1,375	83,580
34	3,16	78,037	66,740	64	3,16	0,800	84,790
34	1,78	50,732	68,320	64	1,78	0,462	85,830
34	1,00	32,658	69,990	64	1,00	0,265	86,660
40	100,00	389,324	62,650	70	100,00	8,714	79,110
40	56,20	259,747	63,890	70	56,20	5,224	80,420
40	31,60	171,887	65,180	70	31,60	3,103	81,860
40	17,80	112,854	66,530	70	17,80	1,827	83,240
40	10,00	73,489	67,940	70	10,00	1,066	84,480
40	5,62	47,431	69,430	70	5,62	0,617	85,560
40	3,16	30,317	71,030	70	3,16	0,354	86,440
40	1,78	19,176	72,720	70	1,78	0,202	87,130
40	1,00	11,987	74,510	70	1,00	0,115	87,630
46	100,00	173,900	66,570	76	100,00	4,378	80,710
46	56,20	113,312	67,810	76	56,20	2,586	82,680
46	31,60	73,187	69,120	76	31,60	1,513	84,000
46	17,80	46,829	70,510	76	17,80	0,878	85,150
46	10,00	29,677	72,010	76	10,00	0,507	86,140
46	5,62	18,627	73,610	76	5,62	0,290	86,910
46	3,16	11,574	75,300	76	3,16	0,166	87,470
46	1,78	7,117	77,050	76	1,78	0,094	87,850
46	1,00	4,322	78,830	76	1,00	0,054	88,100
52	100,00	79,752	70,000	82	100,00	2,323	83,040
52	56,20	50,797	71,330	82	56,20	1,371	84,170
52	31,60	32,094	72,730	82	31,60	0,793	85,400
52	17,80	20,095	74,230	82	17,80	0,456	86,420
52	10,00	12,450	75,800	82	10,00	0,261	87,150
52	5,62	7,627	77,450	82	5,62	0,148	87,640
52	3,16	4,621	79,130	82	3,16	0,084	87,910
52	1,78	2,770	80,780	82	1,78	0,048	88,050
52	1,00	1,640	82,340	82	1,00	0,027	88,110
58	100,00	37,231	73,300				
58	56,20	23,212	74,710				
58	31,60	14,339	76,190				
58	17,80	8,776	77,720				
58	10,00	5,314	79,300				
58	5,62	3,179	80,860				
58	3,16	1,880	82,360				
58	1,78	1,102	83,740				
58	1,00	0,640	84,950				

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n° :**	3.1/3.1.1.2/1

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	141,00	42,28	299,94	548,00	33,10
160	141,00	42,25	299,93	548,00	33,20
160	141,00	42,24	299,93	548,00	33,30
160	141,00	42,21	299,93	547,00	33,30
160	141,00	42,22	299,94	547,00	33,40
160	141,00	42,19	299,96	547,00	33,50
160	141,00	42,17	299,97	547,00	33,60
160	141,00	42,17	299,98	547,00	33,70
160	140,00	42,13	299,99	546,00	33,80
160	140,00	42,15	299,99	546,00	33,80
160	140,00	42,11	299,99	546,00	33,90
160	140,00	42,11	300,00	546,00	34,00
160	140,00	42,10	300,00	546,00	34,10
160	140,00	42,07	300,00	545,00	34,20
160	140,00	42,09	300,00	546,00	34,30
160	140,00	42,05	300,00	545,00	34,30
160	140,00	42,06	300,00	545,00	34,40
160	140,00	42,05	300,00	545,00	34,50
160	140,00	42,03	300,00	545,00	34,60
160	140,00	42,04	300,00	545,00	34,70
160	140,00	42,01	300,00	545,00	34,80
160	140,00	42,02	300,00	545,00	34,80
160	140,00	42,01	300,00	545,00	34,90
160	140,00	41,99	300,00	544,00	35,00
160	140,00	42,00	300,00	545,00	35,10
160	140,00	41,97	300,00	544,00	35,20
160	140,00	41,98	300,00	544,00	35,30
160	140,00	41,97	300,00	544,00	35,30
160	140,00	41,95	300,00	544,00	35,40
160	140,00	41,97	300,00	544,00	35,50
160	140,00	41,94	300,00	544,00	35,60
160	140,00	41,95	300,00	544,00	35,70
160	140,00	41,94	300,00	544,00	35,80
160	140,00	41,93	300,00	544,00	35,80
160	140,00	41,94	300,00	544,00	35,90
160	140,00	41,92	300,00	544,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/2

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	407,00	40,74	99,98	528,00	69,10
135	408,00	40,75	99,98	528,00	69,20
135	408,00	40,76	99,98	528,00	69,30
135	408,00	40,77	99,98	529,00	69,30
135	408,00	40,78	99,98	529,00	69,40
135	408,00	40,79	99,99	529,00	69,50
135	408,00	40,79	99,99	529,00	69,60
135	408,00	40,79	99,99	529,00	69,70
135	408,00	40,80	100,00	529,00	69,80
135	408,00	40,80	100,00	529,00	69,80
135	408,00	40,80	100,00	529,00	69,90
135	408,00	40,80	100,00	529,00	70,00
135	408,00	40,81	100,00	529,00	70,10
135	408,00	40,81	100,00	529,00	70,20
135	408,00	40,81	100,00	529,00	70,30
135	408,00	40,82	100,00	529,00	70,30
135	408,00	40,82	100,00	529,00	70,40
135	408,00	40,82	100,00	529,00	70,50
135	408,00	40,82	100,00	529,00	70,60
135	408,00	40,82	100,00	529,00	70,70
135	408,00	40,81	100,00	529,00	70,80
135	408,00	40,81	100,00	529,00	70,80
135	408,00	40,81	100,00	529,00	70,90
135	408,00	40,81	100,00	529,00	71,00
135	408,00	40,81	100,00	529,00	71,10
135	408,00	40,80	100,00	529,00	71,20
135	408,00	40,81	100,00	529,00	71,30
135	408,00	40,81	100,00	529,00	71,30
135	408,00	40,81	100,00	529,00	71,40
135	408,00	40,81	100,00	529,00	71,50
135	408,00	40,82	100,00	529,00	71,60
135	408,00	40,82	100,00	529,00	71,70
135	408,00	40,82	100,00	529,00	71,80
135	408,00	40,82	100,00	529,00	71,80
135	408,00	40,83	100,00	529,00	71,90
135	408,00	40,83	100,00	529,00	72,00

Politecnico di Torino
Finanziato dall'Unione europea NextGenerationEU
MUR
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/3

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	3290,00	329,30	99,98	4270,00	108,00
100	3290,00	329,30	99,98	4270,00	108,00
100	3290,00	329,20	99,98	4270,00	108,00
100	3290,00	329,20	99,98	4270,00	108,00
100	3290,00	329,10	99,99	4270,00	108,00
100	3290,00	329,10	99,99	4270,00	109,00
100	3290,00	329,10	99,99	4270,00	109,00
100	3290,00	329,00	99,99	4270,00	109,00
100	3290,00	329,10	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,10	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4260,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4270,00	109,00
100	3290,00	329,00	100,00	4260,00	110,00
100	3290,00	329,00	100,00	4270,00	110,00
100	3290,00	329,00	100,00	4270,00	110,00
100	3290,00	329,00	100,00	4270,00	110,00
100	3290,00	329,00	100,00	4270,00	110,00
100	3290,00	328,90	100,00	4260,00	110,00
100	3290,00	328,90	100,00	4260,00	110,00
100	3290,00	328,90	100,00	4260,00	110,00
100	3290,00	329,00	100,00	4270,00	110,00
100	3290,00	328,90	100,00	4260,00	110,00
100	3290,00	329,00	100,00	4260,00	110,00
100	3290,00	328,90	100,00	4260,00	110,00
100	3290,00	328,90	100,00	4260,00	111,00
100	3290,00	328,90	100,00	4260,00	111,00
100	3290,00	328,90	100,00	4260,00	111,00
100	3290,00	328,90	100,00	4260,00	111,00
100	3290,00	328,90	100,00	4260,00	111,00
100	3290,00	328,80	100,00	4260,00	111,00
100	3290,00	328,90	100,00	4260,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/4

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	145,00	43,64	299,94	566,00	33,10
160	145,00	43,61	299,93	565,00	33,20
160	145,00	43,60	299,93	565,00	33,30
160	145,00	43,56	299,93	565,00	33,30
160	145,00	43,58	299,94	565,00	33,40
160	145,00	43,53	299,96	564,00	33,50
160	145,00	43,53	299,97	564,00	33,60
160	145,00	43,51	299,98	564,00	33,70
160	145,00	43,47	299,99	564,00	33,80
160	145,00	43,49	299,99	564,00	33,80
160	145,00	43,44	300,00	563,00	33,90
160	145,00	43,43	300,00	563,00	34,00
160	145,00	43,42	300,00	563,00	34,10
160	145,00	43,38	300,00	562,00	34,20
160	145,00	43,40	300,00	563,00	34,30
160	144,00	43,35	300,00	562,00	34,30
160	144,00	43,35	300,00	562,00	34,40
160	144,00	43,33	300,00	562,00	34,50
160	144,00	43,30	300,00	561,00	34,60
160	144,00	43,32	300,00	562,00	34,70
160	144,00	43,27	300,00	561,00	34,80
160	144,00	43,28	300,00	561,00	34,80
160	144,00	43,26	300,00	561,00	34,90
160	144,00	43,24	300,00	561,00	35,00
160	144,00	43,25	300,00	561,00	35,10
160	144,00	43,21	300,00	560,00	35,20
160	144,00	43,23	300,00	560,00	35,30
160	144,00	43,21	300,00	560,00	35,30
160	144,00	43,19	300,00	560,00	35,40
160	144,00	43,21	300,00	560,00	35,50
160	144,00	43,17	300,00	560,00	35,60
160	144,00	43,19	300,00	560,00	35,70
160	144,00	43,17	300,00	560,00	35,80
160	144,00	43,15	300,00	559,00	35,80
160	144,00	43,17	300,00	560,00	35,90
160	144,00	43,13	300,00	559,00	36,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/5

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	420,00	42,01	99,98	545,00	69,10
135	420,00	42,02	99,98	545,00	69,20
135	420,00	42,03	99,98	545,00	69,30
135	420,00	42,03	99,98	545,00	69,30
135	421,00	42,05	99,98	545,00	69,40
135	421,00	42,05	99,99	545,00	69,50
135	421,00	42,06	99,99	545,00	69,60
135	421,00	42,06	99,99	545,00	69,70
135	421,00	42,06	100,00	545,00	69,80
135	421,00	42,07	100,00	545,00	69,80
135	421,00	42,06	100,00	545,00	69,90
135	421,00	42,07	100,00	545,00	70,00
135	421,00	42,07	100,00	545,00	70,10
135	421,00	42,07	100,00	545,00	70,20
135	421,00	42,07	100,00	545,00	70,30
135	421,00	42,07	100,00	546,00	70,30
135	421,00	42,07	100,00	545,00	70,40
135	421,00	42,07	100,00	545,00	70,50
135	421,00	42,07	100,00	545,00	70,60
135	421,00	42,07	100,00	545,00	70,70
135	421,00	42,07	100,00	545,00	70,80
135	421,00	42,07	100,00	545,00	70,80
135	421,00	42,07	100,00	545,00	70,90
135	421,00	42,07	100,00	545,00	71,00
135	421,00	42,07	100,00	545,00	71,10
135	421,00	42,06	100,00	545,00	71,20
135	421,00	42,07	100,00	545,00	71,30
135	421,00	42,06	100,00	545,00	71,30
135	421,00	42,07	100,00	545,00	71,40
135	421,00	42,07	100,00	545,00	71,50
135	421,00	42,08	100,00	546,00	71,60
135	421,00	42,07	100,00	545,00	71,70
135	421,00	42,08	100,00	546,00	71,80
135	421,00	42,07	100,00	545,00	71,80
135	421,00	42,08	100,00	546,00	71,90
135	421,00	42,07	100,00	545,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of Neat Bitumen

Data:	14/07/2025	**Strumento:**	MCR 301	**Aging:**	Original
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/6

Temperature [°C]	**Viscosity [mPa·s]**	**Shear Stress [Pa]**	**Shear Rate [1/s]**	**Torque [µNm]**	**Time [min]**
100	3460,00	345,40	99,98	4480,00	108,00
100	3450,00	345,40	99,98	4480,00	108,00
100	3450,00	345,10	99,98	4470,00	108,00
100	3450,00	345,10	99,98	4470,00	108,00
100	3450,00	344,90	99,99	4470,00	108,00
100	3450,00	345,00	99,99	4470,00	109,00
100	3450,00	344,90	99,99	4470,00	109,00
100	3450,00	344,90	99,99	4470,00	109,00
100	3450,00	344,70	100,00	4470,00	109,00
100	3450,00	344,80	100,00	4470,00	109,00
100	3450,00	344,60	100,00	4470,00	109,00
100	3450,00	344,60	100,00	4470,00	109,00
100	3450,00	344,50	100,00	4470,00	109,00
100	3440,00	344,50	100,00	4470,00	109,00
100	3440,00	344,40	100,00	4470,00	109,00
100	3440,00	344,40	100,00	4460,00	109,00
100	3440,00	344,40	100,00	4470,00	109,00
100	3440,00	344,20	100,00	4460,00	110,00
100	3440,00	344,30	100,00	4460,00	110,00
100	3440,00	344,20	100,00	4460,00	110,00
100	3440,00	344,30	100,00	4460,00	110,00
100	3440,00	344,10	100,00	4460,00	110,00
100	3440,00	344,20	100,00	4460,00	110,00
100	3440,00	344,00	100,00	4460,00	110,00
100	3440,00	344,10	100,00	4460,00	110,00
100	3440,00	344,00	100,00	4460,00	110,00
100	3440,00	344,00	100,00	4460,00	110,00
100	3440,00	343,90	100,00	4460,00	110,00
100	3440,00	343,90	100,00	4460,00	110,00
100	3440,00	343,90	100,00	4460,00	111,00
100	3440,00	343,80	100,00	4460,00	111,00
100	3440,00	343,80	100,00	4460,00	111,00
100	3440,00	343,70	100,00	4460,00	111,00
100	3440,00	343,80	100,00	4460,00	111,00
100	3440,00	343,60	100,00	4460,00	111,00
100	3440,00	343,70	100,00	4460,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/7

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	196,00	58,75	299,94	762,00	33,10
160	196,00	58,71	299,93	761,00	33,20
160	196,00	58,69	299,93	761,00	33,30
160	196,00	58,68	299,93	761,00	33,30
160	196,00	58,68	299,94	761,00	33,40
160	195,00	58,64	299,96	760,00	33,50
160	196,00	58,64	299,97	760,00	33,60
160	195,00	58,63	299,98	760,00	33,70
160	195,00	58,61	299,99	760,00	33,80
160	195,00	58,65	299,99	760,00	33,80
160	195,00	58,59	300,00	760,00	33,90
160	195,00	58,60	300,00	760,00	34,00
160	195,00	58,58	300,00	759,00	34,10
160	195,00	58,58	300,00	760,00	34,20
160	195,00	58,59	300,00	760,00	34,30
160	195,00	58,54	300,00	759,00	34,30
160	195,00	58,54	300,00	759,00	34,40
160	195,00	58,53	300,00	759,00	34,50
160	195,00	58,51	300,00	759,00	34,60
160	195,00	58,52	300,00	759,00	34,70
160	195,00	58,47	300,00	758,00	34,80
160	195,00	58,48	300,00	758,00	34,80
160	195,00	58,45	300,00	758,00	34,90
160	195,00	58,44	300,00	758,00	35,00
160	195,00	58,44	300,00	758,00	35,10
160	195,00	58,41	300,00	757,00	35,20
160	195,00	58,43	300,00	758,00	35,30
160	195,00	58,41	300,00	757,00	35,30
160	195,00	58,39	300,00	757,00	35,40
160	195,00	58,40	300,00	757,00	35,50
160	195,00	58,36	300,00	757,00	35,60
160	195,00	58,40	300,00	757,00	35,70
160	195,00	58,35	300,00	757,00	35,80
160	195,00	58,36	300,00	757,00	35,80
160	195,00	58,37	300,00	757,00	35,90
160	194,00	58,32	300,00	756,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/8

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	614,00	61,40	99,98	796,00	69,10
135	614,00	61,40	99,98	796,00	69,20
135	614,00	61,41	99,98	796,00	69,30
135	614,00	61,41	99,98	796,00	69,30
135	614,00	61,42	99,98	796,00	69,40
135	614,00	61,41	99,99	796,00	69,50
135	614,00	61,42	99,99	796,00	69,60
135	614,00	61,42	99,99	796,00	69,70
135	614,00	61,42	100,00	796,00	69,80
135	614,00	61,42	100,00	796,00	69,80
135	614,00	61,42	100,00	796,00	69,90
135	614,00	61,43	100,00	796,00	70,00
135	614,00	61,43	100,00	796,00	70,10
135	614,00	61,44	100,00	797,00	70,20
135	614,00	61,43	100,00	796,00	70,30
135	614,00	61,45	100,00	797,00	70,30
135	614,00	61,44	100,00	797,00	70,40
135	615,00	61,45	100,00	797,00	70,50
135	615,00	61,45	100,00	797,00	70,60
135	615,00	61,45	100,00	797,00	70,70
135	615,00	61,45	100,00	797,00	70,80
135	615,00	61,46	100,00	797,00	70,80
135	615,00	61,47	100,00	797,00	70,90
135	615,00	61,47	100,00	797,00	71,00
135	615,00	61,47	100,00	797,00	71,10
135	615,00	61,48	100,00	797,00	71,20
135	615,00	61,49	100,00	797,00	71,30
135	615,00	61,48	100,00	797,00	71,30
135	615,00	61,49	100,00	797,00	71,40
135	615,00	61,49	100,00	797,00	71,50
135	615,00	61,49	100,00	797,00	71,60
135	615,00	61,48	100,00	797,00	71,70
135	615,00	61,49	100,00	797,00	71,80
135	615,00	61,49	100,00	797,00	71,80
135	615,00	61,49	100,00	797,00	71,90
135	615,00	61,48	100,00	797,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/9

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	5980,00	597,70	99,98	7750,00	108,00
100	5980,00	597,60	99,98	7750,00	108,00
100	5970,00	597,30	99,98	7740,00	108,00
100	5970,00	597,30	99,98	7740,00	108,00
100	5970,00	596,90	99,99	7740,00	108,00
100	5970,00	597,00	99,99	7740,00	109,00
100	5970,00	596,60	99,99	7740,00	109,00
100	5970,00	596,70	100,00	7740,00	109,00
100	5960,00	596,40	100,00	7730,00	109,00
100	5970,00	596,50	100,00	7730,00	109,00
100	5960,00	596,20	100,00	7730,00	109,00
100	5960,00	596,20	100,00	7730,00	109,00
100	5960,00	596,10	100,00	7730,00	109,00
100	5960,00	596,00	100,00	7730,00	109,00
100	5960,00	595,90	100,00	7730,00	109,00
100	5960,00	595,80	100,00	7720,00	109,00
100	5960,00	595,80	100,00	7720,00	109,00
100	5960,00	595,60	100,00	7720,00	110,00
100	5960,00	595,70	100,00	7720,00	110,00
100	5960,00	595,50	100,00	7720,00	110,00
100	5960,00	595,70	100,00	7720,00	110,00
100	5950,00	595,30	100,00	7720,00	110,00
100	5960,00	595,50	100,00	7720,00	110,00
100	5950,00	595,20	100,00	7720,00	110,00
100	5950,00	595,40	100,00	7720,00	110,00
100	5950,00	595,10	100,00	7720,00	110,00
100	5950,00	595,10	100,00	7720,00	110,00
100	5950,00	595,00	100,00	7710,00	110,00
100	5950,00	595,00	100,00	7710,00	110,00
100	5950,00	594,90	100,00	7710,00	111,00
100	5950,00	594,80	100,00	7710,00	111,00
100	5950,00	594,80	100,00	7710,00	111,00
100	5950,00	594,60	100,00	7710,00	111,00
100	5950,00	594,70	100,00	7710,00	111,00
100	5950,00	594,50	100,00	7710,00	111,00
100	5950,00	594,70	100,00	7710,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/10

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	196,00	58,85	299,94	763,00	33,10
160	196,00	58,83	299,93	763,00	33,20
160	196,00	58,80	299,93	762,00	33,30
160	196,00	58,78	299,93	762,00	33,30
160	196,00	58,79	299,94	762,00	33,40
160	196,00	58,74	299,96	762,00	33,50
160	196,00	58,75	299,97	762,00	33,60
160	196,00	58,71	299,98	761,00	33,70
160	196,00	58,69	299,99	761,00	33,80
160	196,00	58,69	299,99	761,00	33,80
160	195,00	58,64	300,00	760,00	33,90
160	196,00	58,65	300,00	760,00	34,00
160	195,00	58,61	300,00	760,00	34,10
160	195,00	58,60	300,00	760,00	34,20
160	195,00	58,60	300,00	760,00	34,30
160	195,00	58,55	300,00	759,00	34,30
160	195,00	58,57	300,00	759,00	34,40
160	195,00	58,53	300,00	759,00	34,50
160	195,00	58,52	300,00	759,00	34,60
160	195,00	58,52	300,00	759,00	34,70
160	195,00	58,48	300,00	758,00	34,80
160	195,00	58,50	300,00	758,00	34,80
160	195,00	58,46	300,00	758,00	34,90
160	195,00	58,46	300,00	758,00	35,00
160	195,00	58,46	300,00	758,00	35,10
160	195,00	58,42	300,00	757,00	35,20
160	195,00	58,44	300,00	758,00	35,30
160	195,00	58,40	300,00	757,00	35,30
160	195,00	58,41	300,00	757,00	35,40
160	195,00	58,40	300,00	757,00	35,50
160	195,00	58,37	300,00	757,00	35,60
160	195,00	58,39	300,00	757,00	35,70
160	195,00	58,36	300,00	757,00	35,80
160	195,00	58,37	300,00	757,00	35,80
160	195,00	58,37	300,00	757,00	35,90
160	194,00	58,34	300,00	756,00	36,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/11

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	617,00	61,71	99,98	800,00	69,10
135	617,00	61,71	99,98	800,00	69,20
135	617,00	61,73	99,98	800,00	69,30
135	617,00	61,73	99,98	800,00	69,30
135	617,00	61,73	99,98	800,00	69,40
135	617,00	61,73	99,99	800,00	69,50
135	618,00	61,74	99,99	801,00	69,60
135	618,00	61,75	99,99	801,00	69,70
135	618,00	61,75	100,00	801,00	69,80
135	618,00	61,76	100,00	801,00	69,80
135	618,00	61,76	100,00	801,00	69,90
135	618,00	61,77	100,00	801,00	70,00
135	618,00	61,77	100,00	801,00	70,10
135	618,00	61,78	100,00	801,00	70,20
135	618,00	61,78	100,00	801,00	70,30
135	618,00	61,80	100,00	801,00	70,30
135	618,00	61,80	100,00	801,00	70,40
135	618,00	61,81	100,00	801,00	70,50
135	618,00	61,80	100,00	801,00	70,60
135	618,00	61,81	100,00	801,00	70,70
135	618,00	61,81	100,00	801,00	70,80
135	618,00	61,82	100,00	802,00	70,80
135	618,00	61,82	100,00	801,00	70,90
135	618,00	61,82	100,00	802,00	71,00
135	618,00	61,83	100,00	802,00	71,10
135	618,00	61,82	100,00	802,00	71,20
135	618,00	61,83	100,00	802,00	71,30
135	618,00	61,83	100,00	802,00	71,30
135	618,00	61,84	100,00	802,00	71,40
135	618,00	61,85	100,00	802,00	71,50
135	619,00	61,86	100,00	802,00	71,60
135	619,00	61,85	100,00	802,00	71,70
135	619,00	61,87	100,00	802,00	71,80
135	619,00	61,86	100,00	802,00	71,80
135	619,00	61,87	100,00	802,00	71,90
135	619,00	61,86	100,00	802,00	72,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of RTFOT-aged bitumen

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	RTFOT
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/12

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
100	6020,00	602,30	99,98	7810,00	108,00
100	6020,00	602,20	99,98	7810,00	108,00
100	6020,00	601,90	99,98	7800,00	108,00
100	6020,00	602,00	99,98	7800,00	108,00
100	6020,00	601,70	99,99	7800,00	108,00
100	6020,00	601,80	99,99	7800,00	109,00
100	6010,00	601,40	99,99	7800,00	109,00
100	6020,00	601,50	100,00	7800,00	109,00
100	6010,00	601,30	100,00	7800,00	109,00
100	6010,00	601,40	100,00	7800,00	109,00
100	6010,00	601,10	100,00	7790,00	109,00
100	6010,00	601,10	100,00	7790,00	109,00
100	6010,00	600,90	100,00	7790,00	109,00
100	6010,00	600,90	100,00	7790,00	109,00
100	6010,00	600,80	100,00	7790,00	109,00
100	6010,00	600,60	100,00	7790,00	109,00
100	6010,00	600,60	100,00	7790,00	109,00
100	6000,00	600,40	100,00	7780,00	110,00
100	6000,00	600,50	100,00	7790,00	110,00
100	6000,00	600,20	100,00	7780,00	110,00
100	6000,00	600,40	100,00	7780,00	110,00
100	6000,00	600,10	100,00	7780,00	110,00
100	6000,00	600,30	100,00	7780,00	110,00
100	6000,00	600,00	100,00	7780,00	110,00
100	6000,00	600,20	100,00	7780,00	110,00
100	6000,00	599,90	100,00	7780,00	110,00
100	6000,00	600,00	100,00	7780,00	110,00
100	6000,00	599,80	100,00	7780,00	110,00
100	6000,00	599,90	100,00	7780,00	110,00
100	6000,00	599,80	100,00	7780,00	111,00
100	6000,00	599,80	100,00	7780,00	111,00
100	6000,00	599,80	100,00	7780,00	111,00
100	6000,00	599,60	100,00	7770,00	111,00
100	6000,00	599,70	100,00	7780,00	111,00
100	6000,00	599,50	100,00	7770,00	111,00
100	6000,00	599,70	100,00	7780,00	111,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen

Data:	16/07/2025	**Strumento**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/13

Temperature [°C]	**Viscosity [mPa·s]**	**Shear Stress [Pa]**	**Shear Rate [1/s]**	**Torque [µNm]**	**Time [min]**
160	289,00	86,57	299,94	1120,00	33,10
160	289,00	86,61	299,93	1120,00	33,20
160	288,00	86,53	299,93	1120,00	33,30
160	288,00	86,49	299,93	1120,00	33,30
160	288,00	86,48	299,94	1120,00	33,40
160	288,00	86,40	299,96	1120,00	33,50
160	288,00	86,38	299,97	1120,00	33,60
160	288,00	86,30	299,98	1120,00	33,70
160	288,00	86,33	299,99	1120,00	33,80
160	288,00	86,35	299,99	1120,00	33,80
160	288,00	86,29	300,00	1120,00	33,90
160	288,00	86,28	300,00	1120,00	34,00
160	287,00	86,24	300,00	1120,00	34,10
160	287,00	86,20	300,00	1120,00	34,20
160	287,00	86,19	300,00	1120,00	34,30
160	287,00	86,13	300,00	1120,00	34,30
160	287,00	86,13	300,00	1120,00	34,40
160	287,00	86,08	300,00	1120,00	34,50
160	287,00	86,05	300,00	1120,00	34,60
160	287,00	86,04	300,00	1120,00	34,70
160	287,00	85,99	300,00	1110,00	34,80
160	287,00	86,00	300,00	1110,00	34,80
160	287,00	85,95	300,00	1110,00	34,90
160	286,00	85,94	300,00	1110,00	35,00
160	286,00	85,93	300,00	1110,00	35,10
160	286,00	85,89	300,00	1110,00	35,20
160	286,00	85,89	300,00	1110,00	35,30
160	286,00	85,84	300,00	1110,00	35,30
160	286,00	85,83	300,00	1110,00	35,40
160	286,00	85,82	300,00	1110,00	35,50
160	286,00	85,78	300,00	1110,00	35,60
160	286,00	85,78	300,00	1110,00	35,70
160	286,00	85,74	300,00	1110,00	35,80
160	286,00	85,73	300,00	1110,00	35,80
160	286,00	85,71	300,00	1110,00	35,90
160	286,00	85,67	300,00	1110,00	36,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged Bitumen

Data:	16/07/2025	**Strumento**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/14

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	1020,00	102,30	99,98	1330,00	69,10
135	1020,00	102,30	99,98	1330,00	69,20
135	1020,00	102,30	99,98	1330,00	69,30
135	1020,00	102,30	99,98	1330,00	69,30
135	1020,00	102,30	99,98	1330,00	69,40
135	1020,00	102,30	99,99	1330,00	69,50
135	1020,00	102,30	99,99	1330,00	69,60
135	1020,00	102,30	99,99	1330,00	69,70
135	1020,00	102,30	100,00	1330,00	69,80
135	1020,00	102,30	100,00	1330,00	69,80
135	1020,00	102,30	100,00	1330,00	69,90
135	1020,00	102,40	100,00	1330,00	70,00
135	1020,00	102,40	100,00	1330,00	70,10
135	1020,00	102,40	100,00	1330,00	70,20
135	1020,00	102,40	100,00	1330,00	70,30
135	1020,00	102,40	100,00	1330,00	70,30
135	1020,00	102,40	100,00	1330,00	70,40
135	1020,00	102,40	100,00	1330,00	70,50
135	1020,00	102,40	100,00	1330,00	70,60
135	1020,00	102,40	100,00	1330,00	70,70
135	1020,00	102,40	100,00	1330,00	70,80
135	1020,00	102,40	100,00	1330,00	70,80
135	1020,00	102,40	100,00	1330,00	70,90
135	1020,00	102,40	100,00	1330,00	71,00
135	1020,00	102,40	100,00	1330,00	71,10
135	1020,00	102,40	100,00	1330,00	71,20
135	1020,00	102,40	100,00	1330,00	71,30
135	1020,00	102,40	100,00	1330,00	71,30
135	1020,00	102,40	100,00	1330,00	71,40
135	1020,00	102,40	100,00	1330,00	71,50
135	1020,00	102,40	100,00	1330,00	71,60
135	1020,00	102,40	100,00	1330,00	71,70
135	1020,00	102,40	100,00	1330,00	71,80
135	1020,00	102,40	100,00	1330,00	71,80
135	1020,00	102,40	100,00	1330,00	71,90
135	1020,00	102,40	100,00	1330,00	72,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged Bitumen

Data:	16/07/2025	**Strumento**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/15

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
100	12900,00	1290,00	99,98	16700,00	108,00
100	12900,00	1289,00	99,98	16700,00	108,00
100	12900,00	1288,00	99,98	16700,00	108,00
100	12900,00	1287,00	99,99	16700,00	108,00
100	12900,00	1286,00	99,99	16700,00	108,00
100	12900,00	1285,00	99,99	16700,00	109,00
100	12900,00	1285,00	99,99	16700,00	109,00
100	12800,00	1284,00	100,00	16700,00	109,00
100	12800,00	1284,00	100,00	16600,00	109,00
100	12800,00	1284,00	100,00	16600,00	109,00
100	12800,00	1283,00	100,00	16600,00	109,00
100	12800,00	1283,00	100,00	16600,00	109,00
100	12800,00	1283,00	100,00	16600,00	109,00
100	12800,00	1282,00	100,00	16600,00	109,00
100	12800,00	1282,00	100,00	16600,00	109,00
100	12800,00	1281,00	100,00	16600,00	109,00
100	12800,00	1281,00	100,00	16600,00	109,00
100	12800,00	1280,00	100,00	16600,00	110,00
100	12800,00	1280,00	100,00	16600,00	110,00
100	12800,00	1280,00	100,00	16600,00	110,00
100	12800,00	1279,00	100,00	16600,00	110,00
100	12800,00	1279,00	100,00	16600,00	110,00
100	12800,00	1279,00	100,00	16600,00	110,00
100	12800,00	1279,00	100,00	16600,00	110,00
100	12800,00	1278,00	100,00	16600,00	110,00
100	12800,00	1278,00	100,00	16600,00	110,00
100	12800,00	1278,00	100,00	16600,00	110,00
100	12800,00	1278,00	100,00	16600,00	110,00
100	12800,00	1277,00	100,00	16600,00	110,00
100	12800,00	1277,00	100,00	16600,00	111,00
100	12800,00	1277,00	100,00	16600,00	111,00
100	12800,00	1277,00	100,00	16600,00	111,00
100	12800,00	1276,00	100,00	16500,00	111,00
100	12800,00	1277,00	100,00	16500,00	111,00
100	12800,00	1276,00	100,00	16500,00	111,00
100	12800,00	1276,00	100,00	16500,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged Bitumen

Data:	16/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/16

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	293,00	87,93	299,94	1140,00	33,10
160	293,00	87,95	299,93	1140,00	33,20
160	293,00	87,87	299,93	1140,00	33,30
160	293,00	87,94	299,93	1140,00	33,30
160	293,00	87,88	299,94	1140,00	33,40
160	293,00	87,86	299,96	1140,00	33,50
160	293,00	87,82	299,97	1140,00	33,60
160	293,00	87,76	299,98	1140,00	33,70
160	292,00	87,74	299,99	1140,00	33,80
160	292,00	87,67	299,99	1140,00	33,80
160	292,00	87,65	299,99	1140,00	33,90
160	292,00	87,62	300,00	1140,00	34,00
160	292,00	87,57	300,00	1140,00	34,10
160	292,00	87,57	300,00	1140,00	34,20
160	292,00	87,52	300,00	1130,00	34,30
160	292,00	87,50	300,00	1130,00	34,30
160	292,00	87,46	300,00	1130,00	34,40
160	291,00	87,43	300,00	1130,00	34,50
160	291,00	87,43	300,00	1130,00	34,60
160	291,00	87,37	300,00	1130,00	34,70
160	291,00	87,36	300,00	1130,00	34,80
160	291,00	87,32	300,00	1130,00	34,80
160	291,00	87,28	300,00	1130,00	34,90
160	291,00	87,27	300,00	1130,00	35,00
160	291,00	87,22	300,00	1130,00	35,10
160	291,00	87,22	300,00	1130,00	35,20
160	291,00	87,17	300,00	1130,00	35,30
160	290,00	87,15	300,00	1130,00	35,30
160	290,00	87,14	300,00	1130,00	35,40
160	290,00	87,09	300,00	1130,00	35,50
160	290,00	87,09	300,00	1130,00	35,60
160	290,00	87,05	300,00	1130,00	35,70
160	290,00	87,04	300,00	1130,00	35,80
160	290,00	87,03	300,00	1130,00	35,80
160	290,00	87,00	300,00	1130,00	35,90
160	290,00	87,01	300,00	1130,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged Bitumen

Data:	16/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/17

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	1040,00	103,90	99,98	1350,00	69,10
135	1040,00	103,90	99,98	1350,00	69,20
135	1040,00	103,90	99,98	1350,00	69,30
135	1040,00	103,90	99,98	1350,00	69,30
135	1040,00	103,90	99,98	1350,00	69,40
135	1040,00	103,90	99,99	1350,00	69,50
135	1040,00	103,90	99,99	1350,00	69,60
135	1040,00	103,90	99,99	1350,00	69,70
135	1040,00	103,90	100,00	1350,00	69,80
135	1040,00	103,90	100,00	1350,00	69,80
135	1040,00	103,90	100,00	1350,00	69,90
135	1040,00	103,90	100,00	1350,00	70,00
135	1040,00	103,90	100,00	1350,00	70,10
135	1040,00	103,90	100,00	1350,00	70,20
135	1040,00	103,90	100,00	1350,00	70,30
135	1040,00	103,90	100,00	1350,00	70,30
135	1040,00	103,90	100,00	1350,00	70,40
135	1040,00	103,90	100,00	1350,00	70,50
135	1040,00	103,90	100,00	1350,00	70,60
135	1040,00	103,90	100,00	1350,00	70,70
135	1040,00	103,90	100,00	1350,00	70,80
135	1040,00	103,90	100,00	1350,00	70,80
135	1040,00	103,90	100,00	1350,00	70,90
135	1040,00	103,90	100,00	1350,00	71,00
135	1040,00	103,90	100,00	1350,00	71,10
135	1040,00	103,90	100,00	1350,00	71,20
135	1040,00	103,90	100,00	1350,00	71,30
135	1040,00	103,90	100,00	1350,00	71,30
135	1040,00	103,90	100,00	1350,00	71,40
135	1040,00	103,90	100,00	1350,00	71,50
135	1040,00	103,90	100,00	1350,00	71,60
135	1040,00	103,90	100,00	1350,00	71,70
135	1040,00	103,90	100,00	1350,00	71,80
135	1040,00	103,90	100,00	1350,00	71,80
135	1040,00	103,90	100,00	1350,00	71,90
135	1040,00	103,90	100,00	1350,00	72,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged Bitumen

Data:	16/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/18

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
100	13000,00	1304,00	99,98	16900,00	108,00
100	13000,00	1302,00	99,98	16900,00	108,00
100	13000,00	1301,00	99,98	16900,00	108,00
100	13000,00	1301,00	99,99	16900,00	108,00
100	13000,00	1300,00	99,99	16800,00	108,00
100	13000,00	1299,00	99,99	16800,00	109,00
100	13000,00	1298,00	99,99	16800,00	109,00
100	13000,00	1298,00	100,00	16800,00	109,00
100	13000,00	1296,00	100,00	16800,00	109,00
100	13000,00	1296,00	100,00	16800,00	109,00
100	13000,00	1295,00	100,00	16800,00	109,00
100	13000,00	1295,00	100,00	16800,00	109,00
100	12900,00	1294,00	100,00	16800,00	109,00
100	12900,00	1294,00	100,00	16800,00	109,00
100	12900,00	1294,00	100,00	16800,00	109,00
100	12900,00	1294,00	100,00	16800,00	109,00
100	12900,00	1293,00	100,00	16800,00	109,00
100	12900,00	1293,00	100,00	16800,00	110,00
100	12900,00	1292,00	100,00	16800,00	110,00
100	12900,00	1292,00	100,00	16700,00	110,00
100	12900,00	1291,00	100,00	16700,00	110,00
100	12900,00	1291,00	100,00	16700,00	110,00
100	12900,00	1291,00	100,00	16700,00	110,00
100	12900,00	1290,00	100,00	16700,00	110,00
100	12900,00	1290,00	100,00	16700,00	110,00
100	12900,00	1290,00	100,00	16700,00	110,00
100	12900,00	1290,00	100,00	16700,00	110,00
100	12900,00	1289,00	100,00	16700,00	110,00
100	12900,00	1289,00	100,00	16700,00	110,00
100	12900,00	1288,00	100,00	16700,00	111,00
100	12900,00	1288,00	100,00	16700,00	111,00
100	12900,00	1288,00	100,00	16700,00	111,00
100	12900,00	1288,00	100,00	16700,00	111,00
100	12900,00	1287,00	100,00	16700,00	111,00
100	12900,00	1287,00	100,00	16700,00	111,00
100	12900,00	1287,00	100,00	16700,00	111,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022
SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/19

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	202,00	60,60	299,94	786,00	33,10
160	200,00	60,02	299,93	778,00	33,20
160	199,00	59,73	299,93	774,00	33,30
160	198,00	59,51	299,93	772,00	33,30
160	198,00	59,39	299,94	770,00	33,40
160	197,00	59,23	299,96	768,00	33,50
160	197,00	59,12	299,97	766,00	33,60
160	197,00	59,00	299,98	765,00	33,70
160	196,00	58,86	299,99	763,00	33,80
160	196,00	58,85	299,99	763,00	33,80
160	196,00	58,80	300,00	762,00	33,90
160	196,00	58,76	300,00	762,00	34,00
160	196,00	58,70	300,00	761,00	34,10
160	195,00	58,62	300,00	760,00	34,20
160	195,00	58,56	300,00	759,00	34,30
160	195,00	58,44	300,00	758,00	34,30
160	194,00	58,33	300,00	756,00	34,40
160	194,00	58,15	300,00	754,00	34,50
160	193,00	57,96	300,00	751,00	34,60
160	193,00	57,84	300,00	750,00	34,70
160	194,00	58,16	300,00	754,00	34,80
160	194,00	58,33	300,00	756,00	34,80
160	194,00	58,32	300,00	756,00	34,90
160	194,00	58,27	300,00	756,00	35,00
160	194,00	58,27	300,00	755,00	35,10
160	194,00	58,16	300,00	754,00	35,20
160	194,00	58,11	300,00	753,00	35,30
160	193,00	58,01	300,00	752,00	35,30
160	194,00	58,08	300,00	753,00	35,40
160	194,00	58,08	300,00	753,00	35,50
160	193,00	57,99	300,00	752,00	35,60
160	193,00	57,96	300,00	751,00	35,70
160	193,00	57,86	300,00	750,00	35,80
160	193,00	57,85	300,00	750,00	35,80
160	193,00	57,84	300,00	750,00	35,90
160	192,00	57,75	300,00	749,00	36,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/20

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	646,00	64,62	99,98	838,00	69,10
135	645,00	64,50	99,98	836,00	69,20
135	645,00	64,45	99,98	836,00	69,30
135	644,00	64,35	99,98	834,00	69,30
135	643,00	64,33	99,98	834,00	69,40
135	642,00	64,24	99,99	833,00	69,50
135	642,00	64,23	99,99	833,00	69,60
135	642,00	64,17	99,99	832,00	69,70
135	642,00	64,16	100,00	832,00	69,80
135	641,00	64,11	100,00	831,00	69,80
135	641,00	64,10	100,00	831,00	69,90
135	641,00	64,07	100,00	831,00	70,00
135	641,00	64,05	100,00	830,00	70,10
135	640,00	64,04	100,00	830,00	70,20
135	640,00	64,00	100,00	830,00	70,30
135	640,00	64,01	100,00	830,00	70,30
135	640,00	63,96	100,00	829,00	70,40
135	640,00	63,98	100,00	829,00	70,50
135	639,00	63,92	100,00	829,00	70,60
135	639,00	63,95	100,00	829,00	70,70
135	639,00	63,89	100,00	828,00	70,80
135	639,00	63,93	100,00	829,00	70,80
135	639,00	63,87	100,00	828,00	70,90
135	639,00	63,90	100,00	828,00	71,00
135	639,00	63,86	100,00	828,00	71,10
135	639,00	63,88	100,00	828,00	71,20
135	639,00	63,85	100,00	828,00	71,30
135	639,00	63,86	100,00	828,00	71,30
135	638,00	63,85	100,00	828,00	71,40
135	638,00	63,83	100,00	828,00	71,50
135	638,00	63,84	100,00	828,00	71,60
135	638,00	63,80	100,00	827,00	71,70
135	638,00	63,83	100,00	828,00	71,80
135	638,00	63,77	100,00	827,00	71,80
135	638,00	63,82	100,00	827,00	71,90
135	638,00	63,76	100,00	827,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/21

Temperature [°C]	**Viscosity [mPa·s]**	**Shear Stress [Pa]**	**Shear Rate [1/s]**	**Torque [µNm]**	**Time [min]**
100	7250,00	724,50	99,98	9390,00	108,00
100	7250,00	724,50	99,98	9390,00	108,00
100	7240,00	724,00	99,98	9390,00	108,00
100	7240,00	724,10	99,98	9390,00	108,00
100	7240,00	723,70	99,99	9380,00	108,00
100	7240,00	723,80	99,99	9380,00	109,00
100	7240,00	723,50	99,99	9380,00	109,00
100	7240,00	723,50	100,00	9380,00	109,00
100	7230,00	723,30	100,00	9380,00	109,00
100	7230,00	723,30	100,00	9380,00	109,00
100	7230,00	723,30	100,00	9380,00	109,00
100	7230,00	723,00	100,00	9370,00	109,00
100	7230,00	723,10	100,00	9380,00	109,00
100	7230,00	722,80	100,00	9370,00	109,00
100	7230,00	723,00	100,00	9370,00	109,00
100	7230,00	722,70	100,00	9370,00	109,00
100	7230,00	722,90	100,00	9370,00	109,00
100	7220,00	722,50	100,00	9370,00	110,00
100	7230,00	722,70	100,00	9370,00	110,00
100	7220,00	722,40	100,00	9370,00	110,00
100	7230,00	722,60	100,00	9370,00	110,00
100	7220,00	722,40	100,00	9370,00	110,00
100	7220,00	722,50	100,00	9370,00	110,00
100	7220,00	722,40	100,00	9370,00	110,00
100	7220,00	722,40	100,00	9370,00	110,00
100	7230,00	722,50	100,00	9370,00	110,00
100	7220,00	722,50	100,00	9370,00	110,00
100	7230,00	722,60	100,00	9370,00	110,00
100	7220,00	722,40	100,00	9370,00	110,00
100	7230,00	722,70	100,00	9370,00	111,00
100	7230,00	722,50	100,00	9370,00	111,00
100	7230,00	722,90	100,00	9370,00	111,00
100	7230,00	722,60	100,00	9370,00	111,00
100	7230,00	722,80	100,00	9370,00	111,00
100	7230,00	722,60	100,00	9370,00	111,00
100	7230,00	722,90	100,00	9370,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/22

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	208,00	62,27	299,94	807,00	33,10
160	207,00	62,23	299,93	807,00	33,20
160	207,00	62,19	299,93	806,00	33,30
160	207,00	62,14	299,93	806,00	33,30
160	207,00	62,12	299,94	805,00	33,40
160	207,00	62,04	299,96	804,00	33,50
160	207,00	62,03	299,97	804,00	33,60
160	207,00	61,97	299,98	803,00	33,70
160	206,00	61,93	299,99	803,00	33,80
160	206,00	61,92	299,99	803,00	33,80
160	206,00	61,86	300,00	802,00	33,90
160	206,00	61,85	300,00	802,00	34,00
160	206,00	61,81	300,00	801,00	34,10
160	206,00	61,77	300,00	801,00	34,20
160	206,00	61,77	300,00	801,00	34,30
160	206,00	61,71	300,00	800,00	34,30
160	206,00	61,71	300,00	800,00	34,40
160	206,00	61,67	300,00	800,00	34,50
160	205,00	61,64	300,00	799,00	34,60
160	205,00	61,64	300,00	799,00	34,70
160	205,00	61,59	300,00	799,00	34,80
160	205,00	61,60	300,00	799,00	34,80
160	205,00	61,56	300,00	798,00	34,90
160	205,00	61,54	300,00	798,00	35,00
160	205,00	61,55	300,00	798,00	35,10
160	205,00	61,49	300,00	797,00	35,20
160	205,00	61,52	300,00	798,00	35,30
160	205,00	61,47	300,00	797,00	35,30
160	205,00	61,46	300,00	797,00	35,40
160	205,00	61,46	300,00	797,00	35,50
160	205,00	61,41	300,00	796,00	35,60
160	205,00	61,44	300,00	797,00	35,70
160	205,00	61,39	300,00	796,00	35,80
160	205,00	61,38	300,00	796,00	35,80
160	205,00	61,41	300,00	796,00	35,90
160	204,00	61,33	300,00	795,00	36,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/23

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	681,00	68,04	99,98	882,00	69,10
135	681,00	68,06	99,98	882,00	69,20
135	681,00	68,08	99,98	883,00	69,30
135	681,00	68,08	99,98	883,00	69,30
135	681,00	68,10	99,98	883,00	69,40
135	681,00	68,10	99,99	883,00	69,50
135	681,00	68,12	99,99	883,00	69,60
135	681,00	68,12	99,99	883,00	69,70
135	681,00	68,14	100,00	883,00	69,80
135	681,00	68,14	100,00	883,00	69,80
135	681,00	68,14	100,00	883,00	69,90
135	682,00	68,16	100,00	884,00	70,00
135	681,00	68,14	100,00	883,00	70,10
135	682,00	68,16	100,00	884,00	70,20
135	682,00	68,15	100,00	884,00	70,30
135	681,00	68,14	100,00	883,00	70,30
135	682,00	68,15	100,00	884,00	70,40
135	681,00	68,15	100,00	884,00	70,50
135	681,00	68,15	100,00	884,00	70,60
135	682,00	68,16	100,00	884,00	70,70
135	681,00	68,15	100,00	884,00	70,80
135	682,00	68,16	100,00	884,00	70,80
135	682,00	68,16	100,00	884,00	70,90
135	682,00	68,16	100,00	884,00	71,00
135	682,00	68,16	100,00	884,00	71,10
135	682,00	68,16	100,00	884,00	71,20
135	682,00	68,16	100,00	884,00	71,30
135	682,00	68,15	100,00	884,00	71,30
135	682,00	68,17	100,00	884,00	71,40
135	681,00	68,14	100,00	883,00	71,50
135	682,00	68,16	100,00	884,00	71,60
135	681,00	68,15	100,00	884,00	71,70
135	681,00	68,14	100,00	883,00	71,80
135	681,00	68,15	100,00	884,00	71,80
135	681,00	68,14	100,00	883,00	71,90
135	681,00	68,13	100,00	883,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA4

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/24

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	7220,00	722,30	99,98	9370,00	108,00
100	7220,00	722,30	99,98	9360,00	108,00
100	7220,00	722,00	99,98	9360,00	108,00
100	7220,00	722,10	99,98	9360,00	108,00
100	7220,00	721,70	99,99	9360,00	108,00
100	7220,00	721,90	99,99	9360,00	109,00
100	7220,00	721,50	99,99	9350,00	109,00
100	7220,00	721,70	100,00	9360,00	109,00
100	7210,00	721,30	100,00	9350,00	109,00
100	7210,00	721,40	100,00	9350,00	109,00
100	7210,00	721,10	100,00	9350,00	109,00
100	7210,00	721,10	100,00	9350,00	109,00
100	7210,00	721,00	100,00	9350,00	109,00
100	7210,00	720,90	100,00	9350,00	109,00
100	7210,00	720,90	100,00	9350,00	109,00
100	7210,00	720,80	100,00	9340,00	109,00
100	7210,00	720,90	100,00	9350,00	109,00
100	7210,00	720,60	100,00	9340,00	110,00
100	7210,00	720,90	100,00	9350,00	110,00
100	7210,00	720,70	100,00	9340,00	110,00
100	7210,00	720,90	100,00	9350,00	110,00
100	7210,00	720,60	100,00	9340,00	110,00
100	7210,00	720,80	100,00	9350,00	110,00
100	7210,00	720,50	100,00	9340,00	110,00
100	7210,00	720,70	100,00	9340,00	110,00
100	7200,00	720,40	100,00	9340,00	110,00
100	7200,00	720,50	100,00	9340,00	110,00
100	7200,00	720,30	100,00	9340,00	110,00
100	7200,00	720,30	100,00	9340,00	110,00
100	7200,00	720,30	100,00	9340,00	111,00
100	7200,00	720,20	100,00	9340,00	111,00
100	7200,00	720,30	100,00	9340,00	111,00
100	7200,00	720,10	100,00	9340,00	111,00
100	7200,00	720,30	100,00	9340,00	111,00
100	7200,00	720,10	100,00	9340,00	111,00
100	7200,00	720,30	100,00	9340,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/25

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	164,00	49,10	299,94	637,00	33,10
160	163,00	48,99	299,93	635,00	33,20
160	163,00	48,92	299,93	634,00	33,30
160	163,00	48,83	299,93	633,00	33,30
160	163,00	48,79	299,94	633,00	33,40
160	162,00	48,71	299,96	632,00	33,50
160	162,00	48,66	299,97	631,00	33,60
160	162,00	48,61	299,98	630,00	33,70
160	162,00	48,54	299,99	629,00	33,80
160	162,00	48,52	299,99	629,00	33,80
160	161,00	48,45	300,00	628,00	33,90
160	161,00	48,42	300,00	628,00	34,00
160	161,00	48,38	300,00	627,00	34,10
160	161,00	48,32	300,00	626,00	34,20
160	161,00	48,31	300,00	626,00	34,30
160	161,00	48,25	300,00	626,00	34,30
160	161,00	48,22	300,00	625,00	34,40
160	161,00	48,18	300,00	625,00	34,50
160	160,00	48,13	300,00	624,00	34,60
160	160,00	48,12	300,00	624,00	34,70
160	160,00	48,05	300,00	623,00	34,80
160	160,00	48,03	300,00	623,00	34,80
160	160,00	47,97	300,00	622,00	34,90
160	160,00	47,92	300,00	621,00	35,00
160	160,00	47,90	300,00	621,00	35,10
160	159,00	47,81	300,00	620,00	35,20
160	159,00	47,79	300,00	620,00	35,30
160	159,00	47,72	300,00	619,00	35,30
160	159,00	47,66	300,00	618,00	35,40
160	159,00	47,62	300,00	617,00	35,50
160	158,00	47,53	300,00	616,00	35,60
160	158,00	47,51	300,00	616,00	35,70
160	158,00	47,42	300,00	615,00	35,80
160	158,00	47,36	300,00	614,00	35,80
160	158,00	47,32	300,00	614,00	35,90
160	157,00	47,22	300,00	612,00	36,00

Politecnico di Torino
Finanziato dall'Unione europea NextGenerationEU
MUR
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/26

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	530,00	52,94	99,98	686,00	69,10
135	530,00	52,95	99,98	686,00	69,20
135	530,00	52,96	99,98	687,00	69,30
135	530,00	52,97	99,98	687,00	69,30
135	530,00	52,97	99,98	687,00	69,40
135	530,00	52,98	99,99	687,00	69,50
135	530,00	52,99	99,99	687,00	69,60
135	530,00	52,99	99,99	687,00	69,70
135	530,00	53,01	100,00	687,00	69,80
135	530,00	53,01	100,00	687,00	69,80
135	530,00	53,01	100,00	687,00	69,90
135	530,00	53,02	100,00	687,00	70,00
135	530,00	53,01	100,00	687,00	70,10
135	530,00	53,02	100,00	687,00	70,20
135	530,00	53,01	100,00	687,00	70,30
135	530,00	53,02	100,00	687,00	70,30
135	530,00	53,01	100,00	687,00	70,40
135	530,00	53,02	100,00	687,00	70,50
135	530,00	53,01	100,00	687,00	70,60
135	530,00	53,01	100,00	687,00	70,70
135	530,00	53,02	100,00	687,00	70,80
135	530,00	53,00	100,00	687,00	70,80
135	530,00	53,02	100,00	687,00	70,90
135	530,00	53,00	100,00	687,00	71,00
135	530,00	53,00	100,00	687,00	71,10
135	530,00	53,00	100,00	687,00	71,20
135	530,00	52,99	100,00	687,00	71,30
135	530,00	53,00	100,00	687,00	71,30
135	530,00	53,00	100,00	687,00	71,40
135	530,00	52,99	100,00	687,00	71,50
135	530,00	53,01	100,00	687,00	71,60
135	530,00	53,00	100,00	687,00	71,70
135	530,00	53,01	100,00	687,00	71,80
135	530,00	53,00	100,00	687,00	71,80
135	530,00	53,01	100,00	687,00	71,90
135	530,00	53,00	100,00	687,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/27

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	5110,00	510,80	99,98	6620,00	108,00
100	5110,00	510,80	99,98	6620,00	108,00
100	5110,00	510,50	99,98	6620,00	108,00
100	5110,00	510,60	99,98	6620,00	108,00
100	5100,00	510,30	99,99	6620,00	108,00
100	5100,00	510,40	99,99	6620,00	109,00
100	5100,00	510,20	99,99	6610,00	109,00
100	5100,00	510,10	100,00	6610,00	109,00
100	5100,00	510,00	100,00	6610,00	109,00
100	5100,00	510,00	100,00	6610,00	109,00
100	5100,00	509,90	100,00	6610,00	109,00
100	5100,00	509,80	100,00	6610,00	109,00
100	5100,00	509,80	100,00	6610,00	109,00
100	5100,00	509,80	100,00	6610,00	109,00
100	5100,00	509,90	100,00	6610,00	109,00
100	5100,00	509,80	100,00	6610,00	109,00
100	5100,00	510,00	100,00	6610,00	109,00
100	5100,00	509,80	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	509,90	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	509,90	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	509,90	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	510,00	100,00	6610,00	110,00
100	5100,00	509,90	100,00	6610,00	110,00
100	5100,00	509,90	100,00	6610,00	111,00
100	5100,00	509,80	100,00	6610,00	111,00
100	5100,00	510,00	100,00	6610,00	111,00
100	5100,00	509,80	100,00	6610,00	111,00
100	5100,00	510,00	100,00	6610,00	111,00
100	5100,00	509,80	100,00	6610,00	111,00
100	5100,00	510,00	100,00	6610,00	111,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/28

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	156,00	46,86	299,94	608,00	33,10
160	155,00	46,59	299,93	604,00	33,20
160	155,00	46,45	299,93	602,00	33,30
160	154,00	46,06	299,93	597,00	33,30
160	152,00	45,71	299,94	593,00	33,40
160	153,00	45,92	299,96	595,00	33,50
160	153,00	45,76	299,97	593,00	33,60
160	152,00	45,60	299,98	591,00	33,70
160	152,00	45,50	299,99	590,00	33,80
160	152,00	45,53	299,99	590,00	33,80
160	151,00	45,43	300,00	589,00	33,90
160	151,00	45,41	300,00	589,00	34,00
160	151,00	45,36	300,00	588,00	34,10
160	151,00	45,28	300,00	587,00	34,20
160	151,00	45,26	300,00	587,00	34,30
160	151,00	45,15	300,00	585,00	34,30
160	150,00	45,15	300,00	585,00	34,40
160	150,00	45,04	300,00	584,00	34,50
160	150,00	45,01	300,00	584,00	34,60
160	150,00	44,97	300,00	583,00	34,70
160	150,00	44,87	300,00	582,00	34,80
160	149,00	44,72	300,00	580,00	34,80
160	149,00	44,62	300,00	579,00	34,90
160	149,00	44,65	300,00	579,00	35,00
160	149,00	44,66	300,00	579,00	35,10
160	148,00	44,49	300,00	577,00	35,20
160	149,00	44,60	300,00	578,00	35,30
160	148,00	44,40	300,00	576,00	35,30
160	148,00	44,34	300,00	575,00	35,40
160	148,00	44,44	300,00	576,00	35,50
160	148,00	44,31	300,00	575,00	35,60
160	148,00	44,26	300,00	574,00	35,70
160	147,00	44,19	300,00	573,00	35,80
160	147,00	44,11	300,00	572,00	35,80
160	147,00	44,06	300,00	571,00	35,90
160	146,00	43,93	300,00	570,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/29

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	502,00	50,24	99,98	651,00	69,10
135	501,00	50,11	99,98	650,00	69,20
135	501,00	50,06	99,98	649,00	69,30
135	500,00	49,96	99,98	648,00	69,30
135	500,00	49,95	99,98	648,00	69,40
135	499,00	49,87	99,99	647,00	69,50
135	499,00	49,88	99,99	647,00	69,60
135	498,00	49,81	99,99	646,00	69,70
135	498,00	49,82	100,00	646,00	69,80
135	498,00	49,77	100,00	645,00	69,80
135	498,00	49,77	100,00	645,00	69,90
135	497,00	49,75	100,00	645,00	70,00
135	497,00	49,73	100,00	645,00	70,10
135	497,00	49,73	100,00	645,00	70,20
135	497,00	49,70	100,00	644,00	70,30
135	497,00	49,71	100,00	645,00	70,30
135	497,00	49,67	100,00	644,00	70,40
135	497,00	49,70	100,00	644,00	70,50
135	496,00	49,65	100,00	644,00	70,60
135	497,00	49,69	100,00	644,00	70,70
135	496,00	49,63	100,00	644,00	70,80
135	497,00	49,68	100,00	644,00	70,80
135	496,00	49,63	100,00	643,00	70,90
135	497,00	49,67	100,00	644,00	71,00
135	496,00	49,64	100,00	644,00	71,10
135	497,00	49,66	100,00	644,00	71,20
135	496,00	49,65	100,00	644,00	71,30
135	497,00	49,65	100,00	644,00	71,30
135	497,00	49,66	100,00	644,00	71,40
135	496,00	49,65	100,00	644,00	71,50
135	497,00	49,67	100,00	644,00	71,60
135	496,00	49,63	100,00	644,00	71,70
135	497,00	49,67	100,00	644,00	71,80
135	496,00	49,62	100,00	643,00	71,80
135	497,00	49,67	100,00	644,00	71,90
135	496,00	49,62	100,00	643,00	72,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RA6

Data:	15/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/30

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	5030,00	503,00	99,98	6520,00	108,00
100	5030,00	502,90	99,98	6520,00	108,00
100	5030,00	502,60	99,98	6520,00	108,00
100	5030,00	502,60	99,98	6520,00	108,00
100	5020,00	502,30	99,99	6510,00	108,00
100	5020,00	502,30	99,99	6510,00	109,00
100	5020,00	502,20	99,99	6510,00	109,00
100	5020,00	502,10	100,00	6510,00	109,00
100	5020,00	502,00	100,00	6510,00	109,00
100	5020,00	501,90	100,00	6510,00	109,00
100	5020,00	501,90	100,00	6510,00	109,00
100	5020,00	501,70	100,00	6510,00	109,00
100	5020,00	501,80	100,00	6510,00	109,00
100	5020,00	501,60	100,00	6500,00	109,00
100	5020,00	501,70	100,00	6510,00	109,00
100	5020,00	501,60	100,00	6500,00	109,00
100	5020,00	501,70	100,00	6500,00	109,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,60	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,60	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,60	100,00	6500,00	110,00
100	5020,00	501,50	100,00	6500,00	110,00
100	5020,00	501,60	100,00	6500,00	110,00
100	5010,00	501,50	100,00	6500,00	110,00
100	5020,00	501,60	100,00	6500,00	111,00
100	5020,00	501,50	100,00	6500,00	111,00
100	5020,00	501,60	100,00	6500,00	111,00
100	5010,00	501,50	100,00	6500,00	111,00
100	5020,00	501,60	100,00	6500,00	111,00
100	5010,00	501,50	100,00	6500,00	111,00
100	5020,00	501,50	100,00	6500,00	111,00

PROGETTO PRIN 2022
SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements	
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4	

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/31

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	193,00	57,93	299,94	751,00	33,10
160	193,00	57,77	299,93	749,00	33,20
160	192,00	57,61	299,93	747,00	33,30
160	192,00	57,51	299,93	746,00	33,30
160	192,00	57,45	299,94	745,00	33,40
160	191,00	57,34	299,96	743,00	33,50
160	191,00	57,30	299,97	743,00	33,60
160	191,00	57,20	299,98	742,00	33,70
160	190,00	57,13	299,99	741,00	33,80
160	190,00	57,08	299,99	740,00	33,80
160	190,00	56,99	300,00	739,00	33,90
160	190,00	56,96	300,00	739,00	34,00
160	190,00	56,88	300,00	737,00	34,10
160	189,00	56,82	300,00	737,00	34,20
160	189,00	56,77	300,00	736,00	34,30
160	189,00	56,67	300,00	735,00	34,30
160	189,00	56,64	300,00	734,00	34,40
160	188,00	56,54	300,00	733,00	34,50
160	188,00	56,47	300,00	732,00	34,60
160	188,00	56,37	300,00	731,00	34,70
160	187,00	56,16	300,00	728,00	34,80
160	187,00	56,00	300,00	726,00	34,80
160	187,00	56,14	300,00	728,00	34,90
160	187,00	56,11	300,00	727,00	35,00
160	187,00	56,04	300,00	727,00	35,10
160	186,00	55,93	300,00	725,00	35,20
160	186,00	55,88	300,00	725,00	35,30
160	186,00	55,76	300,00	723,00	35,30
160	186,00	55,69	300,00	722,00	35,40
160	185,00	55,56	300,00	720,00	35,50
160	184,00	55,34	300,00	717,00	35,60
160	184,00	55,17	300,00	715,00	35,70
160	183,00	54,97	300,00	713,00	35,80
160	184,00	55,28	300,00	717,00	35,80
160	184,00	55,20	300,00	716,00	35,90
160	184,00	55,09	300,00	714,00	36,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements	
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4	

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/32

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	647,00	64,65	99,98	838,00	69,10
135	647,00	64,65	99,98	838,00	69,20
135	647,00	64,65	99,98	838,00	69,30
135	647,00	64,66	99,98	838,00	69,30
135	647,00	64,66	99,98	838,00	69,40
135	647,00	64,65	99,99	838,00	69,50
135	647,00	64,67	99,99	838,00	69,60
135	647,00	64,67	99,99	838,00	69,70
135	647,00	64,67	100,00	838,00	69,80
135	647,00	64,68	100,00	839,00	69,80
135	647,00	64,65	100,00	838,00	69,90
135	646,00	64,64	100,00	838,00	70,00
135	646,00	64,65	100,00	838,00	70,10
135	647,00	64,66	100,00	838,00	70,20
135	647,00	64,66	100,00	838,00	70,30
135	647,00	64,67	100,00	838,00	70,30
135	646,00	64,65	100,00	838,00	70,40
135	646,00	64,64	100,00	838,00	70,50
135	647,00	64,65	100,00	838,00	70,60
135	647,00	64,65	100,00	838,00	70,70
135	646,00	64,64	100,00	838,00	70,80
135	646,00	64,65	100,00	838,00	70,80
135	646,00	64,65	100,00	838,00	70,90
135	646,00	64,64	100,00	838,00	71,00
135	647,00	64,65	100,00	838,00	71,10
135	646,00	64,63	100,00	838,00	71,20
135	646,00	64,61	100,00	838,00	71,30
135	646,00	64,62	100,00	838,00	71,30
135	646,00	64,63	100,00	838,00	71,40
135	646,00	64,62	100,00	838,00	71,50
135	646,00	64,63	100,00	838,00	71,60
135	646,00	64,60	100,00	838,00	71,70
135	646,00	64,60	100,00	838,00	71,80
135	646,00	64,62	100,00	838,00	71,80
135	646,00	64,62	100,00	838,00	71,90
135	646,00	64,60	100,00	838,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements	
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4	

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/33

Temperature [°C]	**Viscosity [mPa·s]**	**Shear Stress [Pa]**	**Shear Rate [1/s]**	**Torque [µNm]**	**Time [min]**
100	6590,00	659,00	99,98	8540,00	108,00
100	6590,00	659,00	99,98	8540,00	108,00
100	6590,00	658,70	99,98	8540,00	108,00
100	6590,00	658,90	99,98	8540,00	108,00
100	6590,00	658,50	99,99	8540,00	108,00
100	6590,00	658,70	99,99	8540,00	109,00
100	6580,00	658,30	99,99	8540,00	109,00
100	6580,00	658,50	100,00	8540,00	109,00
100	6580,00	658,20	100,00	8530,00	109,00
100	6580,00	658,30	100,00	8530,00	109,00
100	6580,00	658,10	100,00	8530,00	109,00
100	6580,00	658,00	100,00	8530,00	109,00
100	6580,00	658,00	100,00	8530,00	109,00
100	6580,00	657,90	100,00	8530,00	109,00
100	6580,00	657,90	100,00	8530,00	109,00
100	6580,00	657,70	100,00	8530,00	109,00
100	6580,00	657,70	100,00	8530,00	109,00
100	6570,00	657,50	100,00	8520,00	110,00
100	6580,00	657,60	100,00	8530,00	110,00
100	6570,00	657,30	100,00	8520,00	110,00
100	6570,00	657,50	100,00	8520,00	110,00
100	6570,00	657,10	100,00	8520,00	110,00
100	6570,00	657,30	100,00	8520,00	110,00
100	6570,00	657,00	100,00	8520,00	110,00
100	6570,00	657,20	100,00	8520,00	110,00
100	6570,00	657,00	100,00	8520,00	110,00
100	6570,00	657,10	100,00	8520,00	110,00
100	6570,00	657,00	100,00	8520,00	110,00
100	6570,00	657,00	100,00	8520,00	110,00
100	6570,00	657,00	100,00	8520,00	111,00
100	6570,00	656,90	100,00	8520,00	111,00
100	6570,00	656,90	100,00	8520,00	111,00
100	6570,00	656,70	100,00	8510,00	111,00
100	6570,00	656,80	100,00	8520,00	111,00
100	6570,00	656,60	100,00	8510,00	111,00
100	6570,00	656,80	100,00	8520,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/34

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	197,00	59,09	299,94	766,00	33,10
160	195,00	58,54	299,93	759,00	33,20
160	194,00	58,31	299,93	756,00	33,30
160	194,00	58,13	299,93	754,00	33,30
160	193,00	57,99	299,94	752,00	33,40
160	193,00	57,91	299,96	751,00	33,50
160	193,00	57,78	299,97	749,00	33,60
160	192,00	57,73	299,98	749,00	33,70
160	192,00	57,64	299,99	747,00	33,80
160	192,00	57,58	299,99	746,00	33,80
160	192,00	57,53	299,99	746,00	33,90
160	191,00	57,45	300,00	745,00	34,00
160	191,00	57,40	300,00	744,00	34,10
160	191,00	57,24	300,00	742,00	34,20
160	191,00	57,30	300,00	743,00	34,30
160	191,00	57,27	300,00	743,00	34,30
160	191,00	57,20	300,00	742,00	34,40
160	191,00	57,19	300,00	741,00	34,50
160	190,00	57,12	300,00	741,00	34,60
160	190,00	57,09	300,00	740,00	34,70
160	190,00	57,06	300,00	740,00	34,80
160	190,00	57,00	300,00	739,00	34,80
160	190,00	57,00	300,00	739,00	34,90
160	190,00	56,92	300,00	738,00	35,00
160	190,00	56,90	300,00	738,00	35,10
160	190,00	56,87	300,00	737,00	35,20
160	189,00	56,80	300,00	736,00	35,30
160	189,00	56,80	300,00	736,00	35,30
160	189,00	56,72	300,00	735,00	35,40
160	189,00	56,70	300,00	735,00	35,50
160	189,00	56,65	300,00	734,00	35,60
160	189,00	56,58	300,00	734,00	35,70
160	189,00	56,57	300,00	733,00	35,80
160	188,00	56,48	300,00	732,00	35,80
160	188,00	56,45	300,00	732,00	35,90
160	188,00	56,39	300,00	731,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/35

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	647,00	64,72	99,98	839,00	69,10
135	647,00	64,73	99,98	839,00	69,20
135	648,00	64,75	99,98	839,00	69,30
135	648,00	64,77	99,98	840,00	69,30
135	648,00	64,77	99,98	840,00	69,40
135	648,00	64,79	99,99	840,00	69,50
135	648,00	64,77	99,99	840,00	69,60
135	648,00	64,77	99,99	840,00	69,70
135	648,00	64,78	100,00	840,00	69,80
135	648,00	64,78	100,00	840,00	69,80
135	648,00	64,76	100,00	840,00	69,90
135	648,00	64,77	100,00	840,00	70,00
135	648,00	64,78	100,00	840,00	70,10
135	648,00	64,78	100,00	840,00	70,20
135	648,00	64,79	100,00	840,00	70,30
135	648,00	64,76	100,00	840,00	70,30
135	648,00	64,77	100,00	840,00	70,40
135	648,00	64,78	100,00	840,00	70,50
135	648,00	64,78	100,00	840,00	70,60
135	648,00	64,77	100,00	840,00	70,70
135	648,00	64,79	100,00	840,00	70,80
135	648,00	64,78	100,00	840,00	70,80
135	648,00	64,79	100,00	840,00	70,90
135	648,00	64,79	100,00	840,00	71,00
135	648,00	64,77	100,00	840,00	71,10
135	648,00	64,77	100,00	840,00	71,20
135	648,00	64,79	100,00	840,00	71,30
135	648,00	64,79	100,00	840,00	71,30
135	648,00	64,80	100,00	840,00	71,40
135	648,00	64,81	100,00	840,00	71,50
135	648,00	64,79	100,00	840,00	71,60
135	648,00	64,81	100,00	840,00	71,70
135	648,00	64,81	100,00	840,00	71,80
135	648,00	64,80	100,00	840,00	71,80
135	648,00	64,81	100,00	840,00	71,90
135	648,00	64,83	100,00	841,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB4

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/36

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
100	6590,00	658,50	99,98	8540,00	108,00
100	6580,00	658,30	99,98	8530,00	108,00
100	6580,00	658,30	99,98	8530,00	108,00
100	6580,00	658,00	99,98	8530,00	108,00
100	6580,00	658,00	99,99	8530,00	108,00
100	6580,00	657,70	99,99	8530,00	109,00
100	6580,00	657,80	99,99	8530,00	109,00
100	6580,00	657,50	100,00	8520,00	109,00
100	6580,00	657,60	100,00	8530,00	109,00
100	6570,00	657,20	100,00	8520,00	109,00
100	6570,00	657,30	100,00	8520,00	109,00
100	6570,00	657,10	100,00	8520,00	109,00
100	6570,00	657,10	100,00	8520,00	109,00
100	6570,00	656,90	100,00	8520,00	109,00
100	6570,00	656,90	100,00	8520,00	109,00
100	6570,00	656,80	100,00	8510,00	109,00
100	6570,00	656,70	100,00	8510,00	109,00
100	6570,00	656,70	100,00	8510,00	110,00
100	6560,00	656,50	100,00	8510,00	110,00
100	6570,00	656,60	100,00	8510,00	110,00
100	6560,00	656,30	100,00	8510,00	110,00
100	6560,00	656,50	100,00	8510,00	110,00
100	6560,00	656,20	100,00	8510,00	110,00
100	6560,00	656,30	100,00	8510,00	110,00
100	6560,00	656,00	100,00	8510,00	110,00
100	6560,00	656,20	100,00	8510,00	110,00
100	6560,00	656,00	100,00	8500,00	110,00
100	6560,00	656,10	100,00	8510,00	110,00
100	6560,00	656,00	100,00	8500,00	110,00
100	6560,00	656,00	100,00	8510,00	111,00
100	6560,00	656,00	100,00	8510,00	111,00
100	6560,00	656,00	100,00	8510,00	111,00
100	6560,00	656,10	100,00	8510,00	111,00
100	6560,00	656,10	100,00	8510,00	111,00
100	6560,00	656,30	100,00	8510,00	111,00
100	6560,00	656,20	100,00	8510,00	111,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/37

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	156,00	46,81	299,94	607,00	33,10
160	156,00	46,75	299,93	606,00	33,20
160	156,00	46,73	299,93	606,00	33,30
160	156,00	46,67	299,93	605,00	33,30
160	156,00	46,66	299,94	605,00	33,40
160	155,00	46,59	299,96	604,00	33,50
160	155,00	46,56	299,97	604,00	33,60
160	155,00	46,54	299,98	603,00	33,70
160	155,00	46,48	299,99	603,00	33,80
160	155,00	46,48	299,99	603,00	33,80
160	155,00	46,42	300,00	602,00	33,90
160	155,00	46,40	300,00	602,00	34,00
160	155,00	46,37	300,00	601,00	34,10
160	154,00	46,32	300,00	600,00	34,20
160	154,00	46,31	300,00	600,00	34,30
160	154,00	46,25	300,00	600,00	34,30
160	154,00	46,21	300,00	599,00	34,40
160	154,00	46,19	300,00	599,00	34,50
160	154,00	46,14	300,00	598,00	34,60
160	154,00	46,16	300,00	598,00	34,70
160	154,00	46,09	300,00	598,00	34,80
160	154,00	46,08	300,00	597,00	34,80
160	153,00	46,04	300,00	597,00	34,90
160	153,00	46,00	300,00	596,00	35,00
160	153,00	46,00	300,00	596,00	35,10
160	153,00	45,94	300,00	596,00	35,20
160	153,00	45,93	300,00	596,00	35,30
160	153,00	45,89	300,00	595,00	35,30
160	153,00	45,85	300,00	594,00	35,40
160	153,00	45,85	300,00	594,00	35,50
160	153,00	45,78	300,00	594,00	35,60
160	153,00	45,77	300,00	593,00	35,70
160	152,00	45,72	300,00	593,00	35,80
160	152,00	45,68	300,00	592,00	35,80
160	152,00	45,67	300,00	592,00	35,90
160	152,00	45,59	300,00	591,00	36,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/38

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	470,00	46,96	99,98	609,00	69,10
135	469,00	46,92	99,98	608,00	69,20
135	469,00	46,91	99,98	608,00	69,30
135	469,00	46,87	99,98	608,00	69,30
135	469,00	46,86	99,98	608,00	69,40
135	468,00	46,83	99,99	607,00	69,50
135	468,00	46,83	99,99	607,00	69,60
135	468,00	46,80	99,99	607,00	69,70
135	468,00	46,80	100,00	607,00	69,80
135	468,00	46,79	100,00	607,00	69,80
135	468,00	46,78	100,00	607,00	69,90
135	468,00	46,77	100,00	606,00	70,00
135	468,00	46,76	100,00	606,00	70,10
135	468,00	46,76	100,00	606,00	70,20
135	467,00	46,75	100,00	606,00	70,30
135	468,00	46,75	100,00	606,00	70,30
135	467,00	46,73	100,00	606,00	70,40
135	467,00	46,74	100,00	606,00	70,50
135	467,00	46,72	100,00	606,00	70,60
135	467,00	46,74	100,00	606,00	70,70
135	467,00	46,72	100,00	606,00	70,80
135	467,00	46,73	100,00	606,00	70,80
135	467,00	46,71	100,00	606,00	70,90
135	467,00	46,73	100,00	606,00	71,00
135	467,00	46,72	100,00	606,00	71,10
135	467,00	46,72	100,00	606,00	71,20
135	467,00	46,72	100,00	606,00	71,30
135	467,00	46,71	100,00	606,00	71,30
135	467,00	46,71	100,00	606,00	71,40
135	467,00	46,70	100,00	605,00	71,50
135	467,00	46,71	100,00	606,00	71,60
135	467,00	46,69	100,00	605,00	71,70
135	467,00	46,70	100,00	605,00	71,80
135	467,00	46,68	100,00	605,00	71,80
135	467,00	46,70	100,00	605,00	71,90
135	467,00	46,67	100,00	605,00	72,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/39

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	4330,00	433,10	99,98	5610,00	108,00
100	4330,00	433,20	99,98	5620,00	108,00
100	4330,00	433,00	99,98	5610,00	108,00
100	4330,00	433,10	99,98	5620,00	108,00
100	4330,00	432,90	99,99	5610,00	108,00
100	4330,00	433,00	99,99	5610,00	109,00
100	4330,00	432,80	99,99	5610,00	109,00
100	4330,00	432,80	100,00	5610,00	109,00
100	4330,00	432,70	100,00	5610,00	109,00
100	4330,00	432,60	100,00	5610,00	109,00
100	4330,00	432,60	100,00	5610,00	109,00
100	4330,00	432,50	100,00	5610,00	109,00
100	4330,00	432,50	100,00	5610,00	109,00
100	4320,00	432,40	100,00	5610,00	109,00
100	4330,00	432,50	100,00	5610,00	109,00
100	4320,00	432,40	100,00	5610,00	109,00
100	4330,00	432,60	100,00	5610,00	109,00
100	4320,00	432,40	100,00	5610,00	110,00
100	4330,00	432,60	100,00	5610,00	110,00
100	4320,00	432,50	100,00	5610,00	110,00
100	4330,00	432,60	100,00	5610,00	110,00
100	4330,00	432,50	100,00	5610,00	110,00
100	4330,00	432,60	100,00	5610,00	110,00
100	4330,00	432,50	100,00	5610,00	110,00
100	4330,00	432,50	100,00	5610,00	110,00
100	4330,00	432,50	100,00	5610,00	110,00
100	4320,00	432,50	100,00	5610,00	110,00
100	4320,00	432,50	100,00	5610,00	110,00
100	4320,00	432,40	100,00	5610,00	110,00
100	4330,00	432,50	100,00	5610,00	111,00
100	4320,00	432,50	100,00	5610,00	111,00
100	4330,00	432,60	100,00	5610,00	111,00
100	4320,00	432,40	100,00	5610,00	111,00
100	4330,00	432,60	100,00	5610,00	111,00
100	4320,00	432,40	100,00	5610,00	111,00
100	4330,00	432,60	100,00	5610,00	111,00

Politecnico di Torino | Finanziato dall'Unione europea NextGenerationEU | MUR | Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/40

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	143,00	43,04	299,94	558,00	33,10
160	143,00	42,94	299,93	557,00	33,20
160	143,00	42,86	299,93	556,00	33,30
160	143,00	42,75	299,93	554,00	33,30
160	142,00	42,70	299,94	554,00	33,40
160	142,00	42,57	299,96	552,00	33,50
160	142,00	42,51	299,97	551,00	33,60
160	141,00	42,43	299,98	550,00	33,70
160	141,00	42,33	299,99	549,00	33,80
160	141,00	42,29	299,99	548,00	33,80
160	141,00	42,18	300,00	547,00	33,90
160	140,00	42,13	300,00	546,00	34,00
160	140,00	42,05	300,00	545,00	34,10
160	140,00	41,96	300,00	544,00	34,20
160	140,00	41,93	300,00	544,00	34,30
160	139,00	41,82	300,00	542,00	34,30
160	139,00	41,78	300,00	542,00	34,40
160	139,00	41,71	300,00	541,00	34,50
160	139,00	41,62	300,00	540,00	34,60
160	139,00	41,59	300,00	539,00	34,70
160	138,00	41,48	300,00	538,00	34,80
160	138,00	41,44	300,00	537,00	34,80
160	138,00	41,37	300,00	536,00	34,90
160	138,00	41,29	300,00	535,00	35,00
160	138,00	41,26	300,00	535,00	35,10
160	137,00	41,16	300,00	534,00	35,20
160	137,00	41,13	300,00	533,00	35,30
160	137,00	41,06	300,00	532,00	35,30
160	137,00	40,99	300,00	531,00	35,40
160	137,00	40,96	300,00	531,00	35,50
160	136,00	40,87	300,00	530,00	35,60
160	136,00	40,84	300,00	529,00	35,70
160	136,00	40,76	300,00	528,00	35,80
160	135,00	40,54	300,00	526,00	35,80
160	135,00	40,56	300,00	526,00	35,90
160	135,00	40,59	300,00	526,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/41

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	450,00	44,96	99,98	583,00	69,10
135	450,00	44,94	99,98	583,00	69,20
135	449,00	44,94	99,98	583,00	69,30
135	449,00	44,92	99,98	582,00	69,30
135	449,00	44,91	99,98	582,00	69,40
135	449,00	44,89	99,99	582,00	69,50
135	449,00	44,89	99,99	582,00	69,60
135	449,00	44,88	99,99	582,00	69,70
135	449,00	44,87	100,00	582,00	69,80
135	449,00	44,86	100,00	582,00	69,80
135	449,00	44,86	100,00	582,00	69,90
135	449,00	44,85	100,00	582,00	70,00
135	448,00	44,84	100,00	581,00	70,10
135	448,00	44,84	100,00	581,00	70,20
135	448,00	44,83	100,00	581,00	70,30
135	448,00	44,83	100,00	581,00	70,30
135	448,00	44,82	100,00	581,00	70,40
135	448,00	44,82	100,00	581,00	70,50
135	448,00	44,81	100,00	581,00	70,60
135	448,00	44,82	100,00	581,00	70,70
135	448,00	44,80	100,00	581,00	70,80
135	448,00	44,81	100,00	581,00	70,80
135	448,00	44,80	100,00	581,00	70,90
135	448,00	44,80	100,00	581,00	71,00
135	448,00	44,80	100,00	581,00	71,10
135	448,00	44,80	100,00	581,00	71,20
135	448,00	44,79	100,00	581,00	71,30
135	448,00	44,79	100,00	581,00	71,30
135	448,00	44,79	100,00	581,00	71,40
135	448,00	44,78	100,00	581,00	71,50
135	448,00	44,79	100,00	581,00	71,60
135	448,00	44,78	100,00	581,00	71,70
135	448,00	44,79	100,00	581,00	71,80
135	448,00	44,78	100,00	581,00	71,80
135	448,00	44,79	100,00	581,00	71,90
135	448,00	44,78	100,00	581,00	72,00

Politecnico di Torino 1859 — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RB6

Data:	17/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/42

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	4060,00	405,80	99,98	5260,00	108,00
100	4060,00	405,90	99,98	5260,00	108,00
100	4060,00	405,70	99,98	5260,00	108,00
100	4060,00	405,80	99,98	5260,00	108,00
100	4060,00	405,70	99,99	5260,00	108,00
100	4060,00	405,70	99,99	5260,00	109,00
100	4060,00	405,60	99,99	5260,00	109,00
100	4060,00	405,60	99,99	5260,00	109,00
100	4060,00	405,50	100,00	5260,00	109,00
100	4050,00	405,50	100,00	5260,00	109,00
100	4050,00	405,50	100,00	5260,00	109,00
100	4050,00	405,40	100,00	5260,00	109,00
100	4050,00	405,40	100,00	5260,00	109,00
100	4050,00	405,30	100,00	5250,00	109,00
100	4050,00	405,40	100,00	5260,00	109,00
100	4050,00	405,30	100,00	5250,00	109,00
100	4050,00	405,30	100,00	5260,00	109,00
100	4050,00	405,20	100,00	5250,00	110,00
100	4050,00	405,30	100,00	5250,00	110,00
100	4050,00	405,20	100,00	5250,00	110,00
100	4050,00	405,20	100,00	5250,00	110,00
100	4050,00	405,20	100,00	5250,00	110,00
100	4050,00	405,20	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	110,00
100	4050,00	405,00	100,00	5250,00	110,00
100	4050,00	405,10	100,00	5250,00	111,00
100	4050,00	405,00	100,00	5250,00	111,00
100	4050,00	405,10	100,00	5250,00	111,00
100	4050,00	405,00	100,00	5250,00	111,00
100	4050,00	405,10	100,00	5250,00	111,00
100	4050,00	405,00	100,00	5250,00	111,00
100	4050,00	405,10	100,00	5250,00	111,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/43

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	197,00	59,22	299,94	768,00	33,10
160	195,00	58,50	299,93	758,00	33,20
160	194,00	58,18	299,93	754,00	33,30
160	193,00	57,96	299,93	751,00	33,30
160	193,00	57,88	299,94	750,00	33,40
160	193,00	57,75	299,96	749,00	33,50
160	192,00	57,68	299,97	748,00	33,60
160	192,00	57,62	299,98	747,00	33,70
160	192,00	57,52	299,99	746,00	33,80
160	192,00	57,50	299,99	745,00	33,80
160	191,00	57,39	300,00	744,00	33,90
160	191,00	57,35	300,00	744,00	34,00
160	191,00	57,30	300,00	743,00	34,10
160	191,00	57,21	300,00	742,00	34,20
160	191,00	57,22	300,00	742,00	34,30
160	190,00	57,13	300,00	741,00	34,30
160	190,00	57,11	300,00	740,00	34,40
160	190,00	57,05	300,00	740,00	34,50
160	190,00	57,03	300,00	739,00	34,60
160	190,00	57,05	300,00	740,00	34,70
160	190,00	56,97	300,00	739,00	34,80
160	190,00	56,97	300,00	739,00	34,80
160	190,00	56,93	300,00	738,00	34,90
160	190,00	56,88	300,00	737,00	35,00
160	190,00	56,89	300,00	738,00	35,10
160	189,00	56,80	300,00	736,00	35,20
160	189,00	56,80	300,00	736,00	35,30
160	189,00	56,75	300,00	736,00	35,30
160	189,00	56,69	300,00	735,00	35,40
160	189,00	56,69	300,00	735,00	35,50
160	189,00	56,61	300,00	734,00	35,60
160	189,00	56,60	300,00	734,00	35,70
160	188,00	56,54	300,00	733,00	35,80
160	188,00	56,47	300,00	732,00	35,80
160	188,00	56,42	300,00	731,00	35,90
160	188,00	56,36	300,00	731,00	36,00

Politecnico di Torino

Finanziato dall'Unione europea NextGenerationEU

MUR

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/44

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	666,00	66,59	99,98	863,00	69,10
135	666,00	66,59	99,98	863,00	69,20
135	666,00	66,61	99,98	864,00	69,30
135	666,00	66,61	99,98	864,00	69,30
135	666,00	66,62	99,98	864,00	69,40
135	666,00	66,62	99,99	864,00	69,50
135	666,00	66,62	99,99	864,00	69,60
135	666,00	66,63	99,99	864,00	69,70
135	666,00	66,61	100,00	864,00	69,80
135	666,00	66,63	100,00	864,00	69,80
135	666,00	66,62	100,00	864,00	69,90
135	666,00	66,62	100,00	864,00	70,00
135	666,00	66,62	100,00	864,00	70,10
135	666,00	66,62	100,00	864,00	70,20
135	666,00	66,61	100,00	864,00	70,30
135	666,00	66,62	100,00	864,00	70,30
135	666,00	66,61	100,00	864,00	70,40
135	666,00	66,62	100,00	864,00	70,50
135	666,00	66,61	100,00	864,00	70,60
135	666,00	66,62	100,00	864,00	70,70
135	666,00	66,61	100,00	864,00	70,80
135	666,00	66,61	100,00	864,00	70,80
135	666,00	66,62	100,00	864,00	70,90
135	666,00	66,60	100,00	863,00	71,00
135	666,00	66,62	100,00	864,00	71,10
135	666,00	66,60	100,00	864,00	71,20
135	666,00	66,60	100,00	863,00	71,30
135	666,00	66,61	100,00	864,00	71,30
135	666,00	66,60	100,00	864,00	71,40
135	666,00	66,60	100,00	863,00	71,50
135	666,00	66,62	100,00	864,00	71,60
135	666,00	66,61	100,00	864,00	71,70
135	666,00	66,62	100,00	864,00	71,80
135	666,00	66,62	100,00	864,00	71,80
135	666,00	66,63	100,00	864,00	71,90
135	666,00	66,63	100,00	864,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/45

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
100	6960,00	695,60	99,98	9020,00	108,00
100	6960,00	695,60	99,98	9020,00	108,00
100	6950,00	695,10	99,98	9010,00	108,00
100	6950,00	695,10	99,98	9010,00	108,00
100	6950,00	694,60	99,99	9010,00	108,00
100	6950,00	694,60	99,99	9010,00	109,00
100	6940,00	694,20	99,99	9000,00	109,00
100	6940,00	694,00	100,00	9000,00	109,00
100	6940,00	693,80	100,00	8990,00	109,00
100	6940,00	693,60	100,00	8990,00	109,00
100	6930,00	693,40	100,00	8990,00	109,00
100	6930,00	693,20	100,00	8990,00	109,00
100	6930,00	693,10	100,00	8990,00	109,00
100	6930,00	692,80	100,00	8980,00	109,00
100	6930,00	692,90	100,00	8980,00	109,00
100	6930,00	692,50	100,00	8980,00	109,00
100	6930,00	692,60	100,00	8980,00	109,00
100	6920,00	692,30	100,00	8980,00	110,00
100	6920,00	692,40	100,00	8980,00	110,00
100	6920,00	692,10	100,00	8970,00	110,00
100	6920,00	692,40	100,00	8980,00	110,00
100	6920,00	692,20	100,00	8970,00	110,00
100	6920,00	692,30	100,00	8980,00	110,00
100	6920,00	692,20	100,00	8970,00	110,00
100	6920,00	692,20	100,00	8970,00	110,00
100	6920,00	692,10	100,00	8970,00	110,00
100	6920,00	692,10	100,00	8970,00	110,00
100	6920,00	692,10	100,00	8970,00	110,00
100	6920,00	691,80	100,00	8970,00	110,00
100	6920,00	691,90	100,00	8970,00	111,00
100	6920,00	691,70	100,00	8970,00	111,00
100	6920,00	691,90	100,00	8970,00	111,00
100	6920,00	691,70	100,00	8970,00	111,00
100	6920,00	691,90	100,00	8970,00	111,00
100	6920,00	691,70	100,00	8970,00	111,00
100	6920,00	692,00	100,00	8970,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/46

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
160	212,00	63,45	299,94	823,00	33,10
160	212,00	63,45	299,93	823,00	33,20
160	212,00	63,45	299,93	823,00	33,30
160	211,00	63,41	299,93	822,00	33,30
160	211,00	63,42	299,94	822,00	33,40
160	211,00	63,38	299,96	822,00	33,50
160	211,00	63,36	299,97	821,00	33,60
160	211,00	63,35	299,98	821,00	33,70
160	211,00	63,30	299,99	821,00	33,80
160	211,00	63,32	299,99	821,00	33,80
160	211,00	63,28	300,00	820,00	33,90
160	211,00	63,28	300,00	820,00	34,00
160	211,00	63,27	300,00	820,00	34,10
160	211,00	63,22	300,00	820,00	34,20
160	211,00	63,24	300,00	820,00	34,30
160	211,00	63,21	300,00	820,00	34,30
160	211,00	63,20	300,00	819,00	34,40
160	211,00	63,17	300,00	819,00	34,50
160	210,00	63,15	300,00	819,00	34,60
160	210,00	63,14	300,00	819,00	34,70
160	210,00	63,11	300,00	818,00	34,80
160	210,00	63,11	300,00	818,00	34,80
160	210,00	63,07	300,00	818,00	34,90
160	210,00	63,04	300,00	817,00	35,00
160	210,00	63,05	300,00	817,00	35,10
160	210,00	62,99	300,00	817,00	35,20
160	210,00	63,00	300,00	817,00	35,30
160	210,00	62,97	300,00	816,00	35,30
160	210,00	62,93	300,00	816,00	35,40
160	210,00	62,94	300,00	816,00	35,50
160	210,00	62,88	300,00	815,00	35,60
160	210,00	62,89	300,00	815,00	35,70
160	210,00	62,85	300,00	815,00	35,80
160	209,00	62,82	300,00	814,00	35,80
160	209,00	62,83	300,00	815,00	35,90
160	209,00	62,77	300,00	814,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/47

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
135	699,00	69,92	99,98	906,00	69,10
135	699,00	69,91	99,98	906,00	69,20
135	699,00	69,92	99,98	907,00	69,30
135	699,00	69,89	99,98	906,00	69,30
135	699,00	69,89	99,98	906,00	69,40
135	699,00	69,86	99,99	906,00	69,50
135	698,00	69,84	99,99	906,00	69,60
135	698,00	69,83	99,99	905,00	69,70
135	698,00	69,80	100,00	905,00	69,80
135	698,00	69,81	100,00	905,00	69,80
135	698,00	69,78	100,00	905,00	69,90
135	698,00	69,79	100,00	905,00	70,00
135	698,00	69,77	100,00	905,00	70,10
135	698,00	69,78	100,00	905,00	70,20
135	698,00	69,75	100,00	904,00	70,30
135	698,00	69,76	100,00	904,00	70,30
135	697,00	69,74	100,00	904,00	70,40
135	697,00	69,71	100,00	904,00	70,50
135	697,00	69,71	100,00	904,00	70,60
135	697,00	69,66	100,00	903,00	70,70
135	697,00	69,65	100,00	903,00	70,80
135	696,00	69,61	100,00	903,00	70,80
135	696,00	69,60	100,00	902,00	70,90
135	696,00	69,59	100,00	902,00	71,00
135	696,00	69,56	100,00	902,00	71,10
135	696,00	69,55	100,00	902,00	71,20
135	695,00	69,54	100,00	902,00	71,30
135	695,00	69,52	100,00	901,00	71,30
135	695,00	69,53	100,00	901,00	71,40
135	695,00	69,50	100,00	901,00	71,50
135	695,00	69,51	100,00	901,00	71,60
135	695,00	69,49	100,00	901,00	71,70
135	695,00	69,49	100,00	901,00	71,80
135	695,00	69,47	100,00	901,00	71,80
135	695,00	69,48	100,00	901,00	71,90
135	695,00	69,48	100,00	901,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC4

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/48

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	7460,00	746,00	99,98	9670,00	108,00
100	7460,00	745,90	99,98	9670,00	108,00
100	7450,00	745,20	99,98	9660,00	108,00
100	7450,00	745,20	99,98	9660,00	108,00
100	7450,00	744,60	99,99	9650,00	108,00
100	7450,00	744,70	99,99	9650,00	109,00
100	7440,00	744,20	99,99	9650,00	109,00
100	7440,00	744,30	100,00	9650,00	109,00
100	7440,00	744,10	100,00	9650,00	109,00
100	7440,00	744,30	100,00	9650,00	109,00
100	7440,00	744,50	100,00	9650,00	109,00
100	7450,00	744,60	100,00	9650,00	109,00
100	7450,00	745,00	100,00	9660,00	109,00
100	7450,00	745,20	100,00	9660,00	109,00
100	7460,00	745,80	100,00	9670,00	109,00
100	7460,00	746,00	100,00	9670,00	109,00
100	7470,00	746,70	100,00	9680,00	109,00
100	7470,00	746,80	100,00	9680,00	110,00
100	7470,00	747,40	100,00	9690,00	110,00
100	7470,00	747,50	100,00	9690,00	110,00
100	7480,00	748,10	100,00	9700,00	110,00
100	7480,00	748,20	100,00	9700,00	110,00
100	7490,00	748,70	100,00	9710,00	110,00
100	7490,00	748,90	100,00	9710,00	110,00
100	7490,00	749,30	100,00	9720,00	110,00
100	7500,00	749,60	100,00	9720,00	110,00
100	7500,00	749,90	100,00	9720,00	110,00
100	7500,00	750,20	100,00	9730,00	110,00
100	7500,00	750,10	100,00	9730,00	110,00
100	7500,00	750,40	100,00	9730,00	111,00
100	7500,00	750,20	100,00	9730,00	111,00
100	7500,00	750,40	100,00	9730,00	111,00
100	7500,00	750,10	100,00	9720,00	111,00
100	7500,00	750,40	100,00	9730,00	111,00
100	7500,00	750,20	100,00	9730,00	111,00
100	7510,00	750,80	100,00	9730,00	111,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/49

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	181,00	54,30	299,94	704,00	33,10
160	179,00	53,71	299,93	696,00	33,20
160	177,00	53,15	299,93	689,00	33,30
160	176,00	52,93	299,93	686,00	33,30
160	176,00	52,80	299,94	685,00	33,40
160	176,00	52,68	299,96	683,00	33,50
160	175,00	52,63	299,97	682,00	33,60
160	175,00	52,55	299,98	681,00	33,70
160	175,00	52,49	299,99	681,00	33,80
160	175,00	52,45	299,99	680,00	33,80
160	175,00	52,36	299,99	679,00	33,90
160	174,00	52,32	300,00	678,00	34,00
160	174,00	52,22	300,00	677,00	34,10
160	174,00	52,23	300,00	677,00	34,20
160	174,00	52,20	300,00	677,00	34,30
160	174,00	52,14	300,00	676,00	34,30
160	174,00	52,12	300,00	676,00	34,40
160	173,00	52,05	300,00	675,00	34,50
160	173,00	52,01	300,00	674,00	34,60
160	173,00	51,98	300,00	674,00	34,70
160	173,00	51,92	300,00	673,00	34,80
160	173,00	51,92	300,00	673,00	34,80
160	173,00	51,86	300,00	672,00	34,90
160	173,00	51,84	300,00	672,00	35,00
160	173,00	51,82	300,00	672,00	35,10
160	173,00	51,77	300,00	671,00	35,20
160	173,00	51,77	300,00	671,00	35,30
160	172,00	51,71	300,00	670,00	35,30
160	172,00	51,69	300,00	670,00	35,40
160	172,00	51,66	300,00	670,00	35,50
160	172,00	51,60	300,00	669,00	35,60
160	172,00	51,59	300,00	669,00	35,70
160	172,00	51,47	300,00	667,00	35,80
160	171,00	51,41	300,00	667,00	35,80
160	172,00	51,51	300,00	668,00	35,90
160	172,00	51,46	300,00	667,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/50

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	555,00	55,44	99,98	719,00	69,10
135	554,00	55,42	99,98	719,00	69,20
135	554,00	55,40	99,98	718,00	69,30
135	554,00	55,38	99,98	718,00	69,30
135	554,00	55,37	99,98	718,00	69,40
135	554,00	55,35	99,99	718,00	69,50
135	553,00	55,34	99,99	718,00	69,60
135	553,00	55,33	99,99	717,00	69,70
135	553,00	55,32	100,00	717,00	69,80
135	553,00	55,31	100,00	717,00	69,80
135	553,00	55,30	100,00	717,00	69,90
135	553,00	55,29	100,00	717,00	70,00
135	553,00	55,29	100,00	717,00	70,10
135	553,00	55,28	100,00	717,00	70,20
135	553,00	55,29	100,00	717,00	70,30
135	553,00	55,29	100,00	717,00	70,30
135	553,00	55,29	100,00	717,00	70,40
135	553,00	55,29	100,00	717,00	70,50
135	553,00	55,29	100,00	717,00	70,60
135	553,00	55,30	100,00	717,00	70,70
135	553,00	55,29	100,00	717,00	70,80
135	553,00	55,30	100,00	717,00	70,80
135	553,00	55,30	100,00	717,00	70,90
135	553,00	55,30	100,00	717,00	71,00
135	553,00	55,30	100,00	717,00	71,10
135	553,00	55,30	100,00	717,00	71,20
135	553,00	55,30	100,00	717,00	71,30
135	553,00	55,30	100,00	717,00	71,30
135	553,00	55,30	100,00	717,00	71,40
135	553,00	55,30	100,00	717,00	71,50
135	553,00	55,30	100,00	717,00	71,60
135	553,00	55,29	100,00	717,00	71,70
135	553,00	55,30	100,00	717,00	71,80
135	553,00	55,29	100,00	717,00	71,80
135	553,00	55,30	100,00	717,00	71,90
135	553,00	55,29	100,00	717,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	1
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/51

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	5700,00	569,90	99,98	7390,00	108,00
100	5700,00	570,00	99,98	7390,00	108,00
100	5700,00	569,90	99,98	7390,00	108,00
100	5700,00	570,00	99,98	7390,00	108,00
100	5700,00	569,90	99,99	7390,00	108,00
100	5700,00	570,00	99,99	7390,00	109,00
100	5700,00	569,80	99,99	7390,00	109,00
100	5700,00	569,90	100,00	7390,00	109,00
100	5700,00	569,70	100,00	7390,00	109,00
100	5700,00	569,70	100,00	7390,00	109,00
100	5700,00	569,60	100,00	7390,00	109,00
100	5700,00	569,50	100,00	7380,00	109,00
100	5690,00	569,50	100,00	7380,00	109,00
100	5690,00	569,30	100,00	7380,00	109,00
100	5690,00	569,30	100,00	7380,00	109,00
100	5690,00	569,10	100,00	7380,00	109,00
100	5690,00	569,10	100,00	7380,00	109,00
100	5690,00	568,90	100,00	7380,00	110,00
100	5690,00	569,00	100,00	7380,00	110,00
100	5690,00	568,80	100,00	7370,00	110,00
100	5690,00	568,80	100,00	7370,00	110,00
100	5690,00	568,60	100,00	7370,00	110,00
100	5690,00	568,60	100,00	7370,00	110,00
100	5680,00	568,50	100,00	7370,00	110,00
100	5680,00	568,50	100,00	7370,00	110,00
100	5680,00	568,40	100,00	7370,00	110,00
100	5680,00	568,40	100,00	7370,00	110,00
100	5680,00	568,40	100,00	7370,00	110,00
100	5680,00	568,40	100,00	7370,00	110,00
100	5690,00	568,50	100,00	7370,00	111,00
100	5690,00	568,50	100,00	7370,00	111,00
100	5690,00	568,60	100,00	7370,00	111,00
100	5690,00	568,50	100,00	7370,00	111,00
100	5690,00	568,70	100,00	7370,00	111,00
100	5690,00	568,60	100,00	7370,00	111,00
100	5690,00	568,70	100,00	7370,00	111,00

Politecnico di Torino — Finanziato dall'Unione europea NextGenerationEU — MUR — Italiadomani

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/52

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
160	187,00	55,99	299,94	726,00	33,10
160	187,00	55,95	299,93	725,00	33,20
160	187,00	55,97	299,93	726,00	33,30
160	187,00	55,94	299,93	725,00	33,30
160	187,00	55,96	299,94	725,00	33,40
160	186,00	55,93	299,96	725,00	33,50
160	186,00	55,93	299,97	725,00	33,60
160	186,00	55,92	299,98	725,00	33,70
160	186,00	55,87	299,99	724,00	33,80
160	186,00	55,93	299,99	725,00	33,80
160	186,00	55,90	300,00	725,00	33,90
160	186,00	55,89	300,00	725,00	34,00
160	186,00	55,88	300,00	725,00	34,10
160	186,00	55,84	300,00	724,00	34,20
160	186,00	55,87	300,00	724,00	34,30
160	186,00	55,83	300,00	724,00	34,30
160	186,00	55,82	300,00	724,00	34,40
160	186,00	55,80	300,00	723,00	34,50
160	186,00	55,76	300,00	723,00	34,60
160	186,00	55,77	300,00	723,00	34,70
160	186,00	55,72	300,00	722,00	34,80
160	186,00	55,73	300,00	723,00	34,80
160	186,00	55,70	300,00	722,00	34,90
160	186,00	55,66	300,00	722,00	35,00
160	186,00	55,66	300,00	722,00	35,10
160	186,00	55,66	300,00	722,00	35,20
160	186,00	55,68	300,00	722,00	35,30
160	186,00	55,65	300,00	722,00	35,30
160	185,00	55,63	300,00	721,00	35,40
160	186,00	55,66	300,00	722,00	35,50
160	185,00	55,64	300,00	721,00	35,60
160	186,00	55,65	300,00	722,00	35,70
160	185,00	55,63	300,00	721,00	35,80
160	185,00	55,60	300,00	721,00	35,80
160	185,00	55,63	300,00	721,00	35,90
160	185,00	55,62	300,00	721,00	36,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/53

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [μNm]	Time [min]
135	600,00	59,95	99,98	777,00	69,10
135	600,00	59,96	99,98	777,00	69,20
135	600,00	59,95	99,98	777,00	69,30
135	599,00	59,93	99,98	777,00	69,30
135	600,00	59,94	99,98	777,00	69,40
135	599,00	59,94	99,99	777,00	69,50
135	599,00	59,94	99,99	777,00	69,60
135	600,00	59,95	99,99	777,00	69,70
135	600,00	59,95	100,00	777,00	69,80
135	600,00	59,97	100,00	778,00	69,80
135	600,00	59,97	100,00	778,00	69,90
135	600,00	59,99	100,00	778,00	70,00
135	600,00	60,00	100,00	778,00	70,10
135	600,00	60,01	100,00	778,00	70,20
135	600,00	60,03	100,00	778,00	70,30
135	600,00	60,03	100,00	778,00	70,30
135	600,00	60,03	100,00	778,00	70,40
135	601,00	60,05	100,00	779,00	70,50
135	600,00	60,05	100,00	778,00	70,60
135	601,00	60,05	100,00	779,00	70,70
135	601,00	60,05	100,00	779,00	70,80
135	601,00	60,05	100,00	779,00	70,80
135	601,00	60,05	100,00	779,00	70,90
135	600,00	60,03	100,00	778,00	71,00
135	600,00	60,04	100,00	778,00	71,10
135	600,00	60,01	100,00	778,00	71,20
135	600,00	59,98	100,00	778,00	71,30
135	600,00	59,97	100,00	778,00	71,30
135	599,00	59,94	100,00	777,00	71,40
135	599,00	59,91	100,00	777,00	71,50
135	599,00	59,89	100,00	777,00	71,60
135	599,00	59,86	100,00	776,00	71,70
135	598,00	59,83	100,00	776,00	71,80
135	598,00	59,80	100,00	775,00	71,80
135	598,00	59,78	100,00	775,00	71,90
135	598,00	59,75	100,00	775,00	72,00

PROGETTO PRIN 2022

SMASHit - Sustainable Maintenance of Asphalt Surfaces with Hybrid solutions for secondary ITalian road networks

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.1.2 - Dynamic Viscosity of PAV-aged bitumen+RC6

Data:	18/07/2025	**Strumento:**	MCR 301	**Aging:**	PAV
Unità:	POLITO	**Geometria:**	CC-17	**Ripetizione:**	2
Operatore:	Federica RAIMO	**Materiale:**	70100	**RdP n°:**	3.1/3.1.1.2/54

Temperature [°C]	Viscosity [mPa·s]	Shear Stress [Pa]	Shear Rate [1/s]	Torque [µNm]	Time [min]
100	5870,00	587,40	99,98	7620,00	108,00
100	5870,00	587,30	99,98	7610,00	108,00
100	5870,00	586,90	99,98	7610,00	108,00
100	5870,00	586,80	99,98	7610,00	108,00
100	5870,00	586,50	99,99	7600,00	108,00
100	5860,00	586,40	99,99	7600,00	109,00
100	5860,00	586,00	99,99	7600,00	109,00
100	5860,00	585,80	100,00	7600,00	109,00
100	5860,00	585,60	100,00	7590,00	109,00
100	5850,00	585,40	100,00	7590,00	109,00
100	5850,00	585,30	100,00	7590,00	109,00
100	5850,00	585,00	100,00	7590,00	109,00
100	5850,00	585,00	100,00	7580,00	109,00
100	5850,00	584,70	100,00	7580,00	109,00
100	5850,00	584,70	100,00	7580,00	109,00
100	5840,00	584,40	100,00	7580,00	109,00
100	5840,00	584,50	100,00	7580,00	109,00
100	5840,00	584,20	100,00	7570,00	110,00
100	5840,00	584,20	100,00	7570,00	110,00
100	5840,00	584,00	100,00	7570,00	110,00
100	5840,00	584,10	100,00	7570,00	110,00
100	5840,00	583,90	100,00	7570,00	110,00
100	5840,00	583,90	100,00	7570,00	110,00
100	5840,00	583,80	100,00	7570,00	110,00
100	5840,00	583,70	100,00	7570,00	110,00
100	5840,00	583,70	100,00	7570,00	110,00
100	5840,00	583,50	100,00	7570,00	110,00
100	5840,00	583,50	100,00	7570,00	110,00
100	5830,00	583,30	100,00	7560,00	110,00
100	5830,00	583,40	100,00	7560,00	111,00
100	5830,00	583,10	100,00	7560,00	111,00
100	5830,00	583,30	100,00	7560,00	111,00
100	5830,00	583,00	100,00	7560,00	111,00
100	5830,00	583,10	100,00	7560,00	111,00
100	5830,00	583,00	100,00	7560,00	111,00
100	5830,00	583,10	100,00	7560,00	111,00